



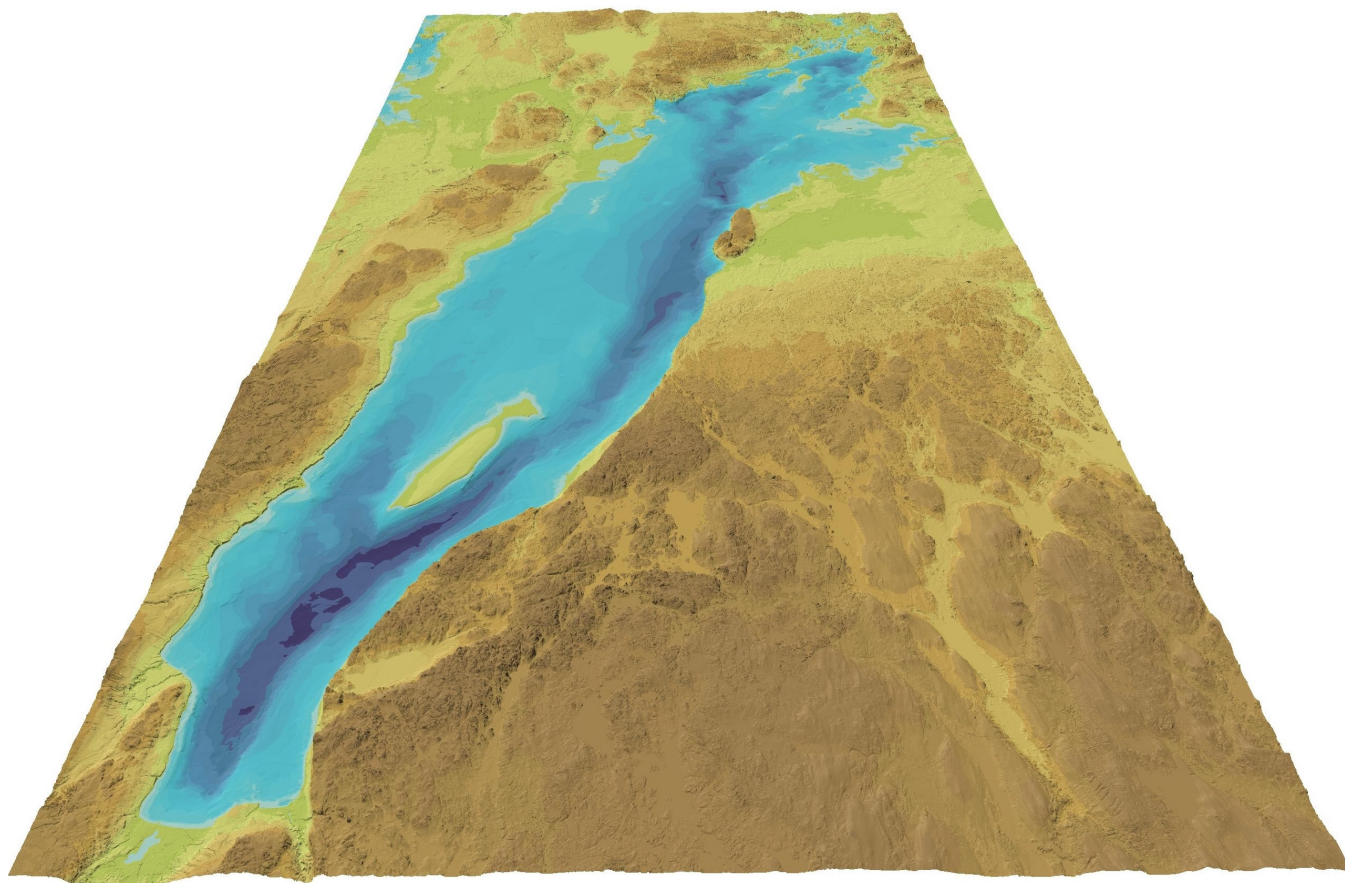
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Master Thesis

Degree Project in
Marine Geology 60 hp

A new bathymetric model of Lake Vättern, Southern Sweden

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ABSTRACT

Lake Vättern is situated in Southern Sweden, and is the second largest lake in the country. The lake floor has been mapped over the years by several institutions, using a range of geophysical mapping equipment. No publically available Digital Bathymetric Model (DBM) exists for this lake. The main objective of this Master's Thesis has therefore been to compile a new DBM making use of all bathymetric data recorded up until the start of this thesis work and set the framework for continued updates of this DBM as new bathymetric data become available. In addition, the method of Satellite Derived Bathymetry (SDB) has been carried out to estimate the lake floor depths along the shoreline; and different gridding algorithms have been applied and compared (Surface Spline with Tension (SPT), Delaunay Triangulation, and Nearest Neighbor) to see how they affect the final DBM. How these gridding algorithms performed on heterogeneous data was specifically investigated, as well as to what extent the SDB can be used considering the uncertainties of the predicted depths.

The three different gridding algorithms applied in this thesis portrayed the general trend of the lake similarly, but artefacts arising due to the sparse data coverage became more readily visible in the DBMs compiled using triangulation and nearest neighbor. The SPT algorithm was therefore selected for the production of the final DBM. Three soundings digitized from the published nautical chart by the Swedish Maritime Administration were considered to be outliers since nearby depth data did not support the anomalous bathymetry they caused. These were removed in the compilation of the final DBM.

The SDB had a resolution of 30 m, originating from the resolution of the used Landsat 8 satellite imagery. The SDB portrayed features such as underwater ridges and the roughness of the lake floor rather well, to an average depth of 11 m. Though contour lines of this bathymetry follow the charted contour lines fairly well, the inaccuracies when compared to mapped bathymetry can range up to as much ± 7 m. This could likely be much improved by using satellite imagery with higher resolution than Landsat 8 and taken from times of the year when the lake water is as clear as possible.

This Thesis produced the first publically available DBM of Lake Vättern, which can be downloaded and used as a resource for different kinds of spatial planning, risk assessments of spreading of pollutions, and scientific analyses. An online interface to view and download the DBM is under development at the Department of Geological Sciences, Stockholm University.

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1. INTRODUCTION

Lake Vättern is the second largest lake in Sweden regarding both area and volume. With an estimated area of $\sim 1893 \text{ km}^2$ (Jakobsson *et al.*, 2014) and volume of $\sim 77.6 \text{ km}^3$ (Swärd, 2015) it is approximately 66.5 % respective 49.3 % smaller than Sweden's largest Lake Vänern (Philipson *et al.*, 2016). While several aspects of the lake have been studied since the 1700's, a bathymetric map showing the depth and shape of the lake floor was first published by Norrman (1964) (Fig. 1). This map was based on a sparse set of depth soundings, however, it revealed that the lake floor is generally characterized by a relatively narrow and partly $>100 \text{ m}$ deep bathymetric region that stretches along nearly the entire length of the ca 135 km long lake.

Lake Vättern will potentially become the main source of drinking water for the surrounding municipalities (Jönköping municipality, 2015), so the water quality is monitored closely (Jönköping municipality, 2018), and all parameters characterizing the lake, such as bathymetry and geology, have been brought into recent focus. Physical and geological parameters are required to carry out risk assessments involving modeling of the potential impact from a pollution source (Hu, 2016). Systematic remote sensing of the lake shoreline has been performed through an aerial photography technique (Swedish Maritime Administration [SMA], 1988), but no further information regarding when this took place and what type of remote sensing that was performed could be found. No detailed Digital Bathymetric Model (DBM) is publicly available for Lake Vättern. However, the Swedish University of Agricultural Sciences (SLU) has for many years collected data with so-called fisheries sonars and used these soundings together with the depths from the published nautical charts to produce a DBM for internal use in their ongoing research and monitoring activities.

The Department of Geological Sciences (IGV) at Stockholm University has over the last decade performed a series of geophysical mapping campaigns to study the geology of Lake Vättern. Bathymetric data have been collected using multi- and single-beam echo sounders and information about the lake floor sediments and uppermost bedrock has been acquired using sub-bottom profilers and single channel seismic reflection (Greenwood *et al.*, 2015, Jakobsson *et al.*, 2014, O'Regan *et al.*, 2015, Swärd *et al.*, 2015, Swärd, 2018). This began with a multibeam (MB) survey in 2008 in the southern part of the strait between Visingsö and Gränna, aimed to test a Kongsberg EM3002 MB echo sounder (Jakobsson *et al.*, 2014). The MB mapping continued in 2013, improving the already mapped area as well as extending the lake floor mapping further south and north (Jakobsson *et al.*, 2014; Swärd, 2015). In 2017, IGV provided the Jönköping County Administrative Board (CAB) with a bathymetric data logger for their supervision boat.

All these bathymetric data together with data from SLU have in this project been processed and used for the compilation of a new DBM of Lake Vättern. In addition to the data collected by various echo sounders, the depths along Lake Vättern's shoreline have been estimated through the use of satellite imagery.

1.1 BACKGROUND

1.1.1 Geological background

Lake Vättern is located in the southern central of Sweden. It is elongated, with a NNE-SSW main axis orientation (Norrman, 1964). The lake is 135 km long, has a maximum width of 35 km, and a maximum depth of 119 m (Swärd *et al.*, 2015; Swärd, 2015). Lake Vättern is located inside the Transcandinavian

Igneous Belt (TIB) consisting mostly of granites, which around 1.86-1.66 Ga intruded the Paleoproterozoic Svecofennian crust (Bingen *et al.*, 2008). The granites west of the lake are part of the Sveconorwegian orogeny, which was formed after continent-continent collision (Andréasson & Rodhe, 1990). In turn the granites east of the lake belong to the Svecokarelian orogeny (Fig. 2)¹. Between the two granites a zone of sedimentary rocks exists, consisting of sandstone, limestone and shales with ages between 720 and 444 Ma. Along the east coast of Lake Vättern a fault zone exists,

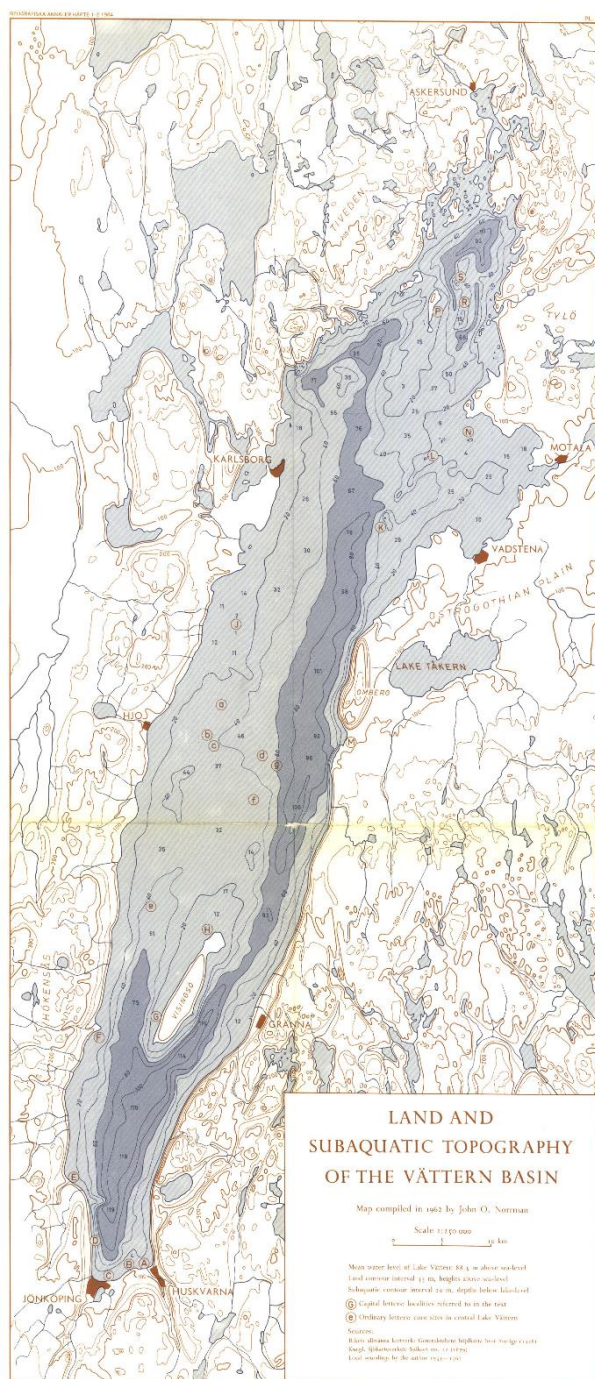


Figure 1. Bathymetric map of Lake Vättern published by Norrman (1964).

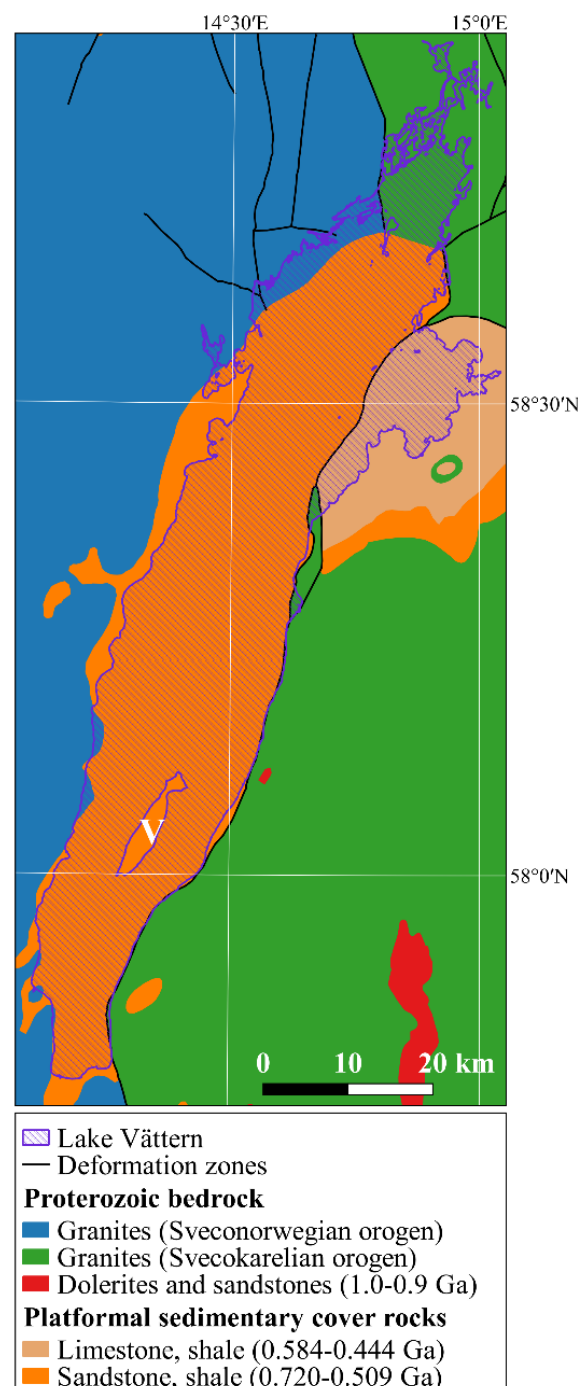


Figure 2. Geologic map¹ of the Lake Vättern area, including deformation zones. V = Visingsö.

¹ Geologic map of the Lake Vättern area was produced by the use of the SGU *Bergrund 1:1 miljon* product, downloaded as ESRI shape, and visualized in QGIS.

with deformation zones to the north and to the south. These are called the Sveconorwegian frontal deformation zone (SFDZ) and the Protogine zone (PZ), respectively (Bingen *et al.*, 2008). The bathymetric depression that Lake Vättern resides in was formed as a half-graben that began forming at 700-800 Ma, as an effect of extensional faulting (Andréasson & Rodhe, 1990; Måansson, 1996).

During the Weichselian glaciation, the Scandinavian Ice Sheet (SIS) covered Sweden (Andrén *et al.*, 2011; Hughes *et al.*, 2016). As the deglaciation commenced, the ice sheet began to retreat northward. During the retreat, the ice sheet underwent momentary standstills and re-advances, which left ice marginal deposits around Sweden, one such example is the Middle Swedish End Moraine Zone (MSEMZ) (Greenwood *et al.*, 2015). The melt water from the retreating ice sheet together with the isostatic uplift and damming of Öresund resulted in that the Baltic Ice Lake (BIL) formed around 16.0 ka BP (Björck, 1995). As the deglaciation progressed, the area that now is Lake Vättern became increasingly uncovered by ice. An initial drainage of the BIL may have occurred at ca 13.0 cal ka BP (Stroeve *et al.*, 2016), which shaped the BIL to approximately look like what is illustrated in Figure 3a at ca 12.0 ka BP. This was followed by a second drainage at ca 11.65±0.28 cal. ka BP (Swärd *et al.*, 2017) when an area just north of Mt. Billingen was exposed. A water surface drop of 25 m occurred, which formed the Yoldia Sea (Jakobsson *et al.*, 2007) The Yoldia Sea (Fig. 3b) lasted for about 800 years (Björck, 1995) and had a brackish water environment as a consequence from the established connection to the North Sea through the 'Närke strait' (Swärd, 2015). Lake Vättern was first estimated to have been isolated from the Yoldia Sea about 500 years after the BIL drainage, due to the general isostatic uplift of the region (Norrman, 1964). The age of the isolation has recently been refined to have occurred at about 9530 ±50 cal. yrs. BP by Swärd *et al.* (2018). This isostatic uplift eventually caused the Närke strait to close, which formed the Ancylus Lake (Fig. 3c) (Swärd, 2015). As the isostatic uplift continued, it became increasingly uneven along the axis of Lake Vättern. The northern parts of the lake rose faster, which tipped the lake. This caused a drainage of 5-10 m into the Ancylus Lake, an estimated 2000 years after the lake was isolated (Swärd, 2015; Norrman, 1964).

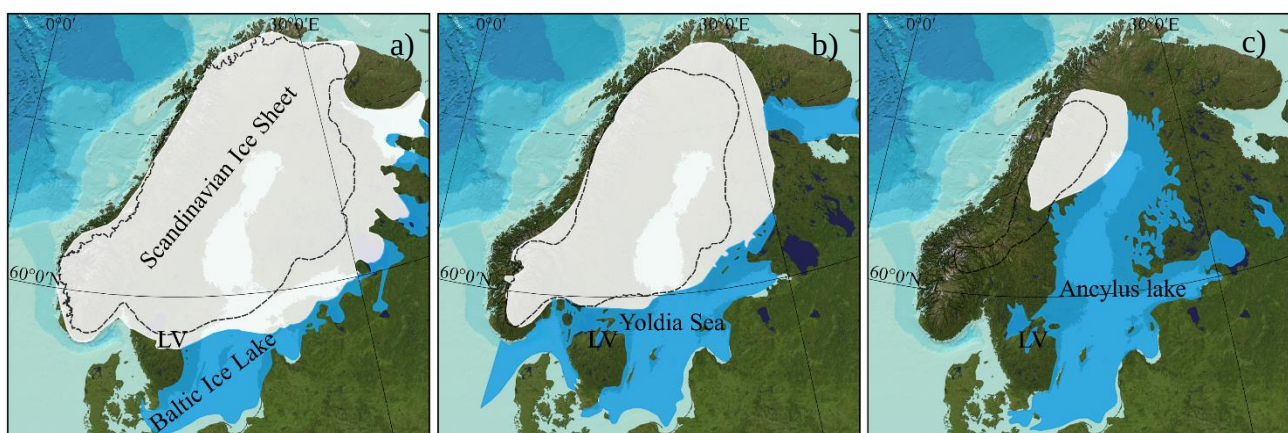


Figure 3. The retreat of the Scandinavian Ice Sheet during the Weichselian deglaciation. LV = Lake Vättern. Dashed lines = most credible ice extent according to Hughes *et al.* (2016). a) ca 12.0 ka BP, the Baltic Ice Lake stage. b) ca 11.0 ka BP, the Yoldia Sea stage. c) ca 10 ka BP, the Ancylus Lake stage. The lake extents are from the digital material supplied by the book "Developments in Quaternary Sciences" by Ehlers and Gibbard (2004).

1.1.2 Satellite Derived Bathymetry

Water depths can be estimated by the utilization of remote sensing. A multi-spectral scanner (MSS) can measure the light and its relative intensity reflected from the lake or ocean bottom in a clear shallow area at different intervals in the visual spectrum. Through comparisons of these visual spectrum intervals, or bands, water depth can be derived (Polcyn *et al.* 1970). This can be used for remote marine areas (Stumpf *et al.*, 2003), or marine areas that are too shallow for survey vessels to access. The method of deriving shallow water depths from satellite images is however inhibited by water turbidity and restricted by light penetration. (Stumpf *et al.*, 2003). There is an optical depth limit for deducing bathymetry, which is called the extinction depth and is empirically determined (Pe’eri *et al.*, 2014).

The use of MSS instead of aerial photography permits correction for variables such as surface reflectance, and automatic identification of bottom features. An algorithm for deriving water depth from the sensor data was produced, but it needed the adjustments with respect to five criterions, and did not acquire depths where the albedo of the bottom was very low (Lyzenga, 1978).

The algorithm was further developed by Stumpf *et al.* (2003), which utilized passive multi-spectral IKONOS satellite imagery with a 3.2 m spatial resolution at the nadir to create Satellite Derived Bathymetry (SDB). Any multi-spectral satellite can be utilized to derive bathymetry from acquired imagery. Free, publicly available images exist, such as imagery from the Landsat 8 satellite, with a 30 m spatial resolution (Pe’eri *et al.*, 2016), as well as the European Space Agency’s Sentinel 2a and 2b satellites, which have 10 m spatial resolution (Drusch *et al.*, 2012).

Since Lyzenga (1978) demonstrated that combining two bands could support albedo corrections, green and blue bands were selected by Stumpf *et al.* (2003) to be used in their SDB procedure, since the green and blue bands penetrate the water column the deepest in the visual spectra (Lyzenga, 1978). Since the green and blue bands have different water absorptions, they will decrease at different speeds when the depth increases. This will increase the ratio between the two bands, but since the albedo change is similar for both, the change in depth affects the ratio more. This means that the ratio at a constant depth will remain the same regardless of the albedo, which in turn means that the ratio can estimate depth independently from the albedo. This simplifies the algorithm as it is only required to scale the band ratio to the actual depth (Stumpf *et al.*, 2003). Through this scaling the extinction depth can be estimated Pe’eri *et al.* (2014).

1.1.3 Digital Bathymetric Model (DBM)

The use of digital computers to generate Digital Terrain Models (DTMs) was introduced by Miller (1957) in the field of photogrammetry. A DTM was originally defined as a statistical portrayal of the continued surface of the landscape by a number of chosen points. These points are referenced horizontally by an XY coordinate system and the terrain elevation by Z-values. (Miller & Laflamme, 1958; Doyle, 1978). The most common DTMs are in the form of regular grids, however, the terrain may be represented also by a Triangular Irregular Network (TIN). A Digital Bathymetric Model (DBM) is simply a specific DTM representing the sea or lake floor (Hell & Jakobsson, 2011). In order to produce a regular grid, a discreet amount of measured heights or depths are used to generate new data points at regular intervals that not necessarily fall exactly at the measured input values. The process of producing values in between existing values is known as interpolation. If the new values fall outside of the bound for measured values, the process is called extrapolation. Interpolation is required to produce DTMs in areas that have sparse data coverage. If the data density is higher than

the target DTM, statistical methods to subsample values must instead be used. Numerous interpolation algorithms exist, some of which are more fitting for earth sciences. Some of the most common interpolation algorithms applied in this thesis are explained in the methods.

The use for terrain models in a marine setting became more prevalent during the 1990's, as the DBM was emerging as the standard way of representing a bathymetric surface, well suited for various statistical analysis and geologic interpretation in different software (e.g. Herzfeld, 1990; Hinze, 1994; Hall, 1996; Jakobsson *et al.*, 2016).

1.2 THESIS OBJECTIVES

A publicly available DBM derived from all the bathymetric data acquired by IGV and SLU as well as the soundings collected by the SMA for their nautical charting production does not exist for Lake Vättern. SMA has utilized aero photography to estimate bathymetry in shallow waters, but an SDB of these areas has not been produced. A new DBM made available in public domain will provide a resource that can be used for various kinds of spatial planning, risk assessments of spreading of pollutions, and scientific analyses.

The main objective of this thesis is therefore to produce a DBM of Lake Vättern utilizing all the available bathymetric data along with SDB along the shoreline based on the freely available Landsat 8 imagery. The produced DBM will comprise the first version that will be placed in public domain (see <https://bathy.geo.su.se/>). This DBM will be regularly updated by IGV when new data become available. The documentation of the methods in this thesis should be sufficient to permit the future update of the DBM.

The specific aims with this thesis work are to:

- provide proficiency in treatment of bathymetric data collected with single- and multibeam echo sounders;
- provide proficiency in gridding of depth data with different mathematical algorithms as well as calculation of estimated bathymetry using satellite imagery;
- provide proficiency in analyzing a digital depth model.

The following research questions will be addressed:

- How do different grid algorithms affect the final depth model?
- What geological analyzes can be performed with a DBM?
- How are geological analyzes affected by heterogeneous data and any artifacts that arise in the gridding process?
- To what extent can satellite images be used for shallow water mapping along the Lake Vättern shoreline, and how large is the uncertainty in the derived depth data?

2. METHODS

2.1 SATELLITE DERIVED BATHYMETRY

The method for creating SDB in this thesis is based on the concept presented in Pe'eri *et al.* (2016). The description of this method and how it is applied here is divided into the following steps: pre-processing; spatial filtering and land/water separation; SDB algorithm application and extinction depth calculation; vertical referencing; and post-processing. The post-processing was added for removing superfluous data for a cleaner presentation and easier analysis. The workflow is shown in Figure 4.

2.1.1 Pre-processing

The Geographical Information System software QGIS (v. 2.18.12 - 2.18.19) was used to pre-process and visualize the geospatial data, including various kinds of depth data. These data include the existing raster nautical charts of Lake Vättern produced and published by SMA (1988). The charts were projected to UTM33N (WGS84). Depths displayed on these nautical charts, were provided in vector format (shape file) by Martin Jakobsson and imported into QGIS for the purpose of being used as control points in the SDB process.

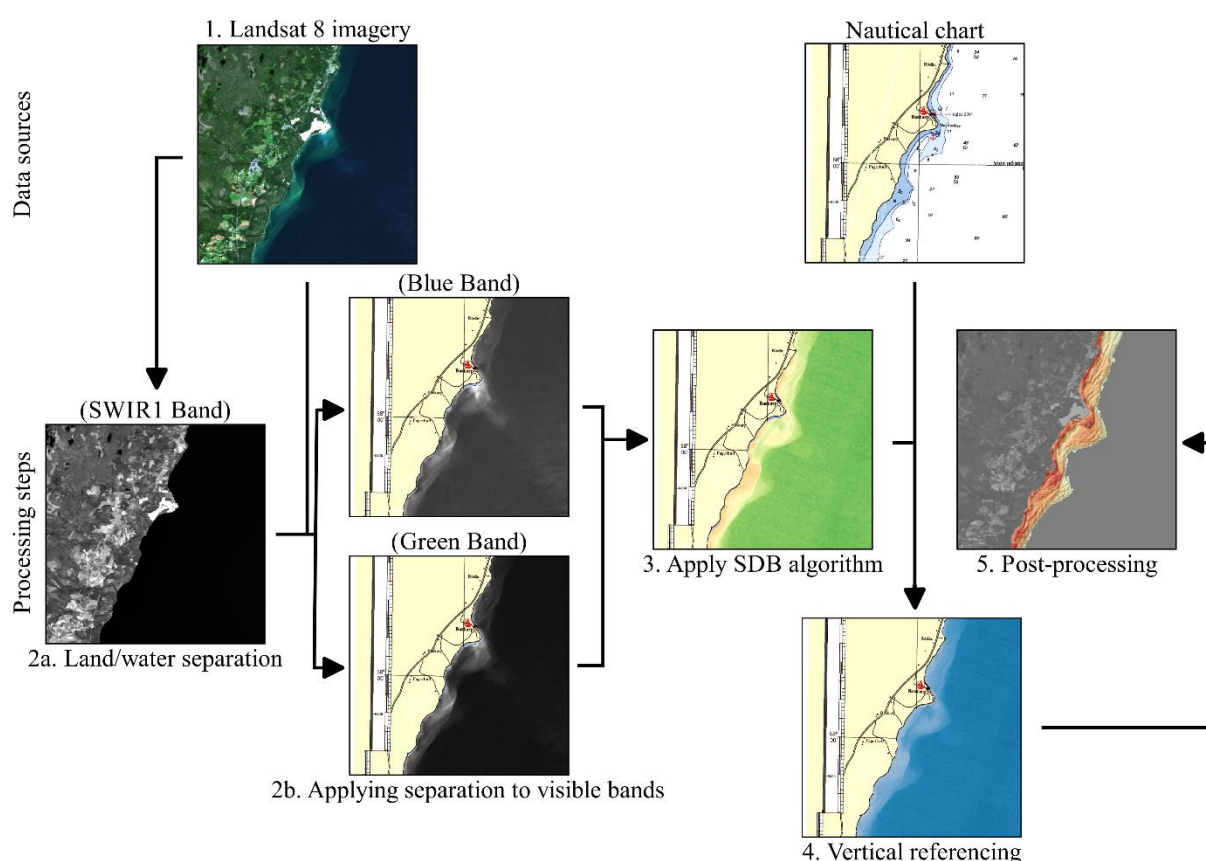


Figure 4. The different steps in order to create Satellite Derived Bathymetry (SDB). Imagery from the Landsat 8 satellite is downloaded (1) and a procedure to separate water from land is performed (2a). The green and blue bands of the water body is extracted (2b) and a natural logarithmic band ratio calculation is performed (3). These values are referenced to digitized depths from the nautical chart (4). Depths deeper than the extinction depth are removed (5) and the remaining bathymetry is visualized. Figure adapted from Pe'eri *et al.* (2013).

Table 1. Landsat 8 satellite images downloaded and used for the Satellite Derived Bathymetry

LANDSAT Product ID	Date acquired	Project name
LC08_L1TP_195019_20150814_20170406_01_T1	2015-08-14	2015-08-14
LC08_L1TP_194019_20150823_20170405_01_T1	2015-08-23	2015-08-23a
LC08_L1TP_194020_20150823_20170405_01_T1	2015-08-23	2015-08-23b
LC08_L1TP_194019_20160606_20170324_01_T1	2016-06-06	2016-06-06a
LC08_L1TP_194020_20160606_20170324_01_T1	2016-06-06	2016-06-06b
LC08_L1TP_195019_20170224_20170301_01_T1	2017-02-24	2017-02-24
LC08_L1TP_195019_20170328_20170414_01_T1	2017-03-28	2017-03-28
LC08_L1TP_194019_20170524_20170614_01_T1	2017-05-24	2017-05-24a
LC08_L1TP_194020_20170524_20170614_01_T1	2017-05-24	2017-05-24b
LC08_L1TP_194019_20170711_20170726_01_T1	2017-07-11	2017-07-11a
LC08_L1TP_194020_20170711_20170726_01_T1	2017-07-11	2017-07-11b

The satellite data utilized in the SDB process were from the Landsat 8 satellite. The individual spectral band images were 16-bit grayscale GeoTIFFs (Geographic tagged image file format, only called TIFFs hereon) and portrayed radiance values as quantized and calibrated to scaled Digital Numbers ([DN], United States Geological Survey [USGS], 2016.). Satellite scenes (sequence of satellite images) of a cloudless Lake Vättern (or as little cloud cover as possible) were chosen (Table 1), and downloaded from the USGS Earth Explorer website² as L8 OLI/TIRS C1 Level-2 products. The TIFFs of the blue, green, and Shortwave Infrared (SWIR) bands (labeled as bands 2, 3, and 6, respectively) were imported into QGIS. Some of the data required the merger of two TIFFs (a+b, see Table 1) to fully cover Lake Vättern, while others covered irrelevant areas. All TIFFs were cropped to the coordinates 445434.950529/520666.260952/6401768.38482/6527860.29947 (xMin/xMax/yMin/yMax). 7 scenes were used, and the steps below were repeated for every scene. The scenes that consisted of merged (a+b) imagery will be called by the project name without letters.

2.1.2 Spatial filtering and land/water separation

In the SWIR TIFFs, the DN values were identified on land and in the water using the ‘Identify features’ function in QGIS, in order to obtain a threshold value at the shoreline. It was estimated to 300, where values less or equal to 300 represented water bodies, and above 300 represented land, or cloud cover.

Using the GdalTools plugin (‘Translate (convert format)’ function), each cell value in all TIFFs were converted into a floating-point representation. Float32 was the type chosen, and no compression of the new TIFFs were performed.

In order to avoid speckle noises, a smoothing Low Pass Filter (LPF) was performed on all TIFFs utilizing the GRASS (7.2.1) r.neighbors function. The ‘Average’ neighborhood operation was chosen, the neighborhood size set to 3, and the remaining settings were set to default. Both filtered and unfiltered TIFFs of each band were used in each step, for subsequent analysis.

In order to separate land from water in the green and blue band TIFFs the Raster calculator in QGIS was used (TIFFs are a type of raster file). An expression was written - (‘SWIR_TIFF’ <= 300) * ‘blue/green TIFF’ - that turned all values above 300 from the SWIR TIFFs to False (0), and all values equal or less than 300 to True (1). These 1 and 0 values were multiplied with the green, and blue band TIFFs, and new TIFFs were produced containing ideally only water bodies.

² <https://earthexplorer.usgs.gov/>

The next step was to make all the 0 values in the new TIFFs into NoData. Again the Translate (Convert format) GDAL function was used, in which the NoData value was set to 0 in the new TIFFs. In some TIFFs there was an additional step, due to the fact that they already had NoData values in them. When the NoData values was converted to 0, the previous NoData value of $-3.40282e+38$ became visualized. Thus the Raster calculator was used again, and an expression removing all values below -2000 was written - ('TIFF_Y' >= -2000) * 'TIFF_Y'. In the end TIFFs only containing water data, filtered and unfiltered, of Lake Vättern from all scenes were produced.

2.1.3 Applying the SDB algorithm and calculating extinction depth

The procedure to derive bathymetry from satellite scenes applied in this thesis is based upon the concept of Stumpf *et al.* (2003), which was further developed by Pe'eri *et al.* (2014), resulting in the following equation:

$$Z = m_1 \frac{\ln(L_{obs}(\lambda_i))}{\ln(L_{obs}(\lambda_j))} - m_o \quad (1)$$

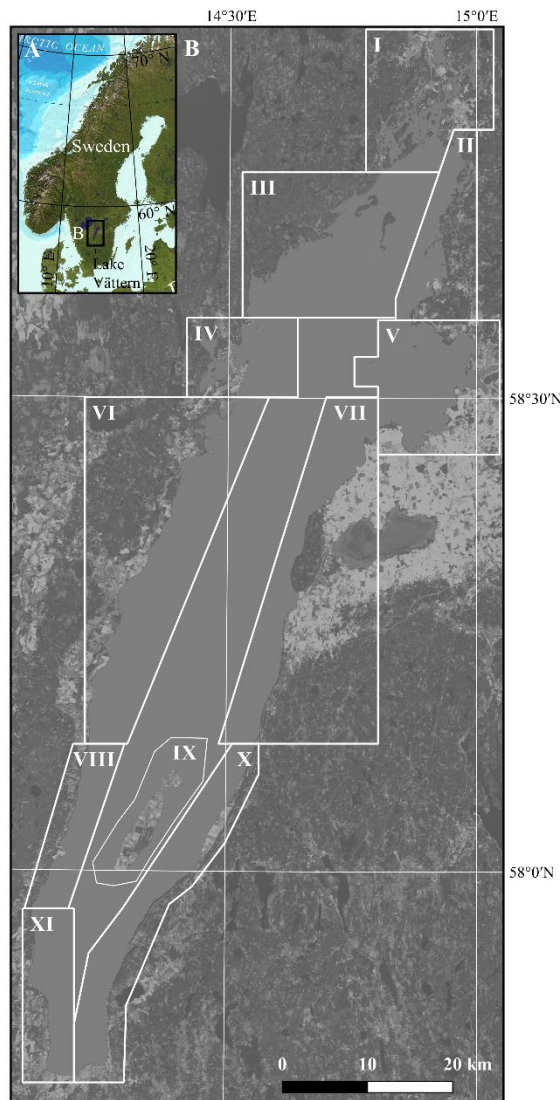


Figure 5. Map of Lake Vättern with the data sections included that were inferred to achieve the best possible SDB from the Landsat 8 imagery.

where Z is the depth, the Gain, m_1 , is an adjustable constant to proportion the ratio to depth, L_{obs} is the observed radiance, λ_i and λ_j are two different spectral bands, and m_0 is the Offset for 0 m depth ($Z = 0$). m_1 and m_0 are empirically ascertained. In the case of Stumpf *et al.* (2003) and in this work, λ_i and λ_j were the blue and green bands, respectively.

The first step is comprised of calculating the band ratio. The natural logarithm of the blue band TIFF is divided by the natural logarithm of the green band TIFF – $\ln(\text{'blue TIFF'}) / \ln(\text{'green TIFF'})$ – utilizing the Raster calculator. The new TIFF was overlain by the control points.

In order to calculate the extinction depth, several steps were taken. The lake was divided into several sections (Fig. 5), and polygon shape files were created for each of them. Control points within these sections were extracted to new point vector layers using the SAGA (2.3.2) Polygon clipping tool. The extracted control points' depths, and band ratio values of the new TIFFs at the same location, were exported to an MS Office XML spreadsheet. For each section, band ratio results of each scene were included.

Each section's exported point file was opened up in LibreOffice Calc Version: 5.3.2.2 (x64). The data was reviewed for possible null values, and the depths were sorted in an ascending order. Unique depth values were copied into a new column and averages of the band ratio values for each unique depth were calculated. The unique charted depths and average band ratio results were visualized in an XY scatter plot. Where the plotted points no longer portrayed a linear trend but started to curve the extinction depth is found. (Fig. 6a). Beyond the extinction depth, the method is not capable of deriving depths from a satellite image.

2.1.4 Vertical referencing

A new plot was made with values from 1-2 m down to the extinction depth (Fig. 6b). A linear regression line was fitted through the data using the least square method and the coefficient of

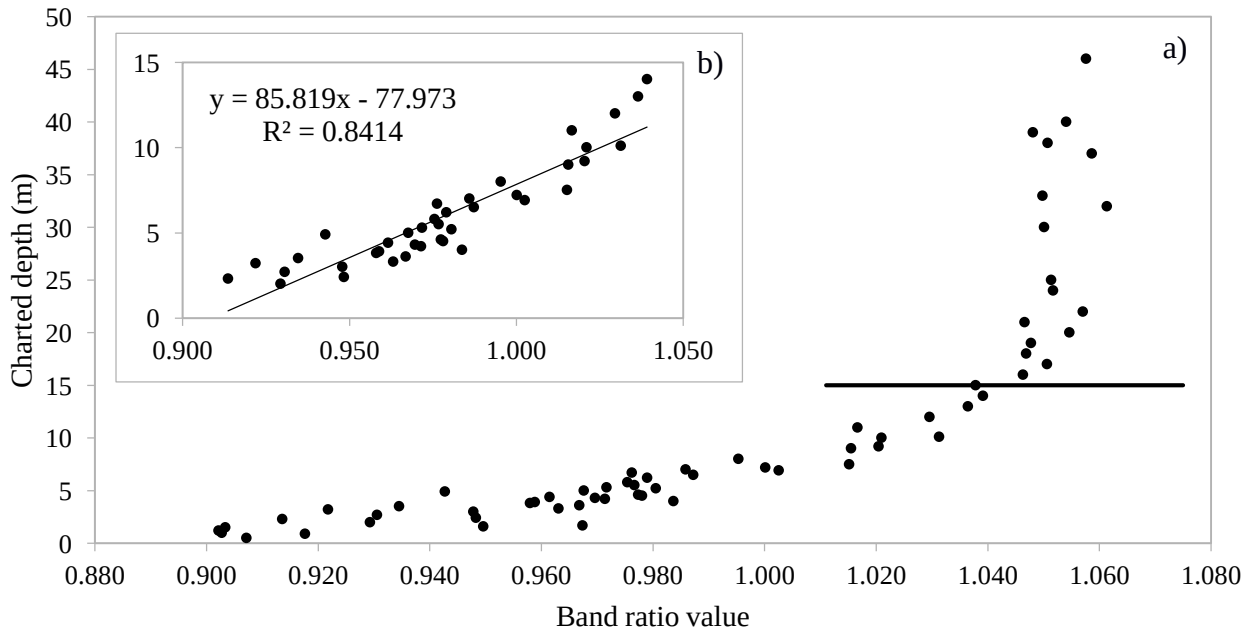


Figure 6. Graph portraying the correlation between the band ratio values and the charted depths from section V, in order to estimate the extinction depth in the SDB process. a) The extinction depth is estimated to 15 m (black line). b) Graph values from 1-2 m down to the extinction depth, and the derived Gain (85.819) and Offset (77.973), from applying a linear regression through the data.

determination, R^2 , was calculated. The coefficient of x is in the derived regression equation referred to as Gain and the constant is referred to as Offset. Plots for each scene were produced and the one with the highest R^2 value was chosen for each section and its Gain and Offset used for calculating bathymetry in that section. The scene for each section with the best R^2 value and resulting equation is listed in Table 2.

To apply the Gain and Offset the raster calculator in QGIS was used. The TIFFs with the band ratio results were multiplied by the Gain and subtracted by the Offset. The new TIFFs contained the depths from the SDB, which permits comparisons with the control points.

2.1.5 Post-processing of SDB

SDB was derived for all of Lake Vättern, although the scenes also included nearby water bodies, and depths were also derived for these. In addition, clouds caused readily distinguishable artefacts. All derived depths beyond Lake Vättern were removed, cloud artefacts were accounted for, and all depths deeper than the estimated different extinction depths in the different regions shown in Figure 5 were excluded.

The derived depths beyond Lake Vättern were removed in a similar way as the control points were extracted (see 2.1.3). A polygon shape file for the entire Lake Vättern was created, following the shoreline precisely. Once the polygon was closed to encompass Lake Vättern it was used as the mask layer in the Clipper tool on every TIFF consisting of calculated bathymetry.

The previously utilized control points with charted depths were subsequently exported for each section, this time, along with the SDB depth of the same location. The depth differences between the charted depth and the SDB are shown for section X in Figure 7 plotted against the SDB. This shows that the depth differences between the SDB and charted depth in section X are small in the range 0-11 m. Deeper than 11 m the depth differences begin to increase. This exercise was carried out for each section, and the determined usable SDB ranges are listed in Table 2. Finally, the Raster calculator was utilized to create new TIFFs for each section, which only included depths in the determined SDB

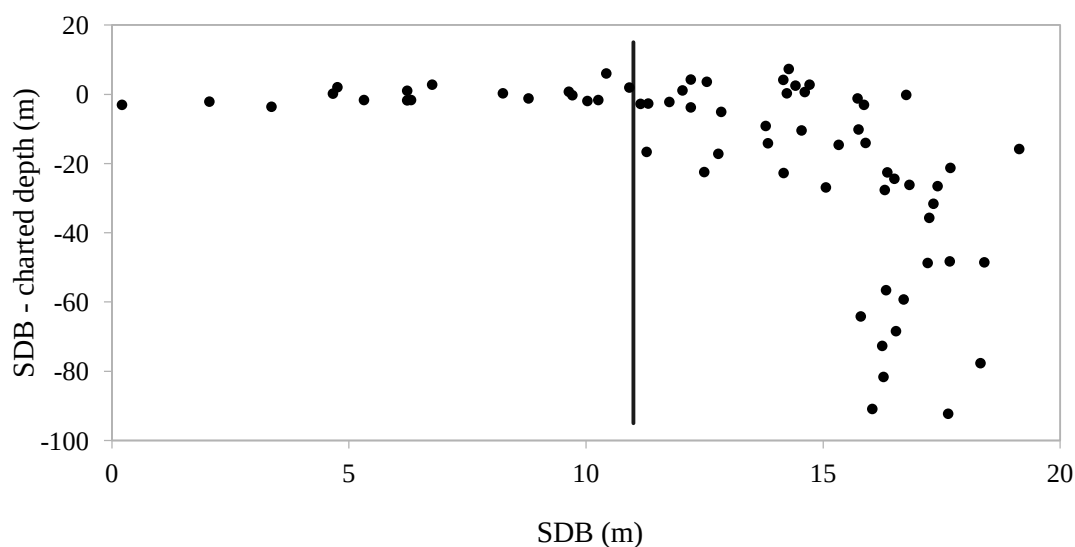


Figure 7. Graph with SDB in the X axis and the charted depth subtracted from the SDB in the Y axis from section X. This graph was created in order to see to what depths the SDB could be used before the errors became too great. In this instance the depth was estimated to 11 m, as displayed by the black line.

Table 2. Sections from Figure 5, with scenes with best R² values, equation, SDB range, extinction depth.

Section	Scene	R ²	Equation	SDB range (m)	Extinction depth (m)
I	2017-07-11	0.468	$f(x) = 129.160 x - 112.864$	0-20	20
II	2015-08-14	0.528	$f(x) = 148.266 x - 131.613$	0-13	30
III	2017-05-24	0.261	$f(x) = 91.661 x - 83.970$	0-8	20
IV	2017-03-28	0.814	$f(x) = 111.087 x - 100.137$	0-11	15
V	2015-08-23	0.841	$f(x) = 85.819 x - 77.973$	0-10	15
VI	2015-08-23	0.912	$f(x) = 50.360 x - 41.263$	0-9	12
VII	2015-08-23	0.776	$f(x) = 99.174 x - 92.360$	0-10	15
VIII	2017-05-24	0.881	$f(x) = 80.537 x - 69.378$	0-12	18
IX	2017-02-24	0.698	$f(x) = 81.568 x - 73.249$	0-12	20
X	2017-05-24	0.627	$f(x) = 114.824 x - 101.118$	0-11	19
XI	2016-06-06	0.510	$f(x) = 112.092 x - 103.250$	0-10	20

range. For example, the range of 0-10 m was extracted by: ('SDB_TIFF' <= 10 AND 'SDB_TIFF' >= 0) * 'SDB_TIFF'.

A new polygon shape file for each section including all charted depths deeper than the SDB range was created, and all calculated bathymetry still present after the initial filtering that were within this polygon file were removed. Steps in order to handle NoData values as in 2.1.2 were taken, and these new TIFFs were visualized. The SDB could now more easily be compared to measured bathymetry. Every section was exported as *.xyz-files for analysis, and for the DBM process.

2.1.6. SDB accuracy

The accuracy of bathymetric surveys can be assessed in accordance with the International Hydrographic Organization (IHO) standards for hydrographic surveys (S-44). Finland and Sweden have a joint initiative to implement this standard, called the FSIS-44 (SMA, 2010). Requirements for surveys are issued in the IHO S-44 publication, with the orders Special, 1a, and 1b being applicable to surveys shallower than 100 m. (IHO, 2008). The total vertical uncertainty (TVU) is calculated using Equation 2:

$$\pm\sqrt{a + (b \times d)^2} \quad (2)$$

, where a = 0.25 m, b = 0.0075 m (Special); or a= 0.5 m, b = 0.013 m (1a+1b); d = depth. For the depths 3, 6, and 9 m the TVU for the different orders are displayed in Table 3.

Table 3. The TVU of specific depths according to specific S-44 orders.

Depth (m)	Special	1a	1b
3	±0.251	±0.502	±0.502
6	±0.254	±0.506	±0.506
9	±0.259	±0.514	±0.514

The Special order requires the smallest TVU, since the order is defined to apply to areas where the clearance below the keel is crucial (IHO, 2008).

The SDB was compared to available MB data over Lake Vättern where these overlapped. Since the MB depths were not used in the SDB process, it is an independent check on the SDB bathymetry, however, the comparison will also reflect differences between the depth plotted on the nautical charts and the MB data. Contour lines of the MB depths 3, 6 and 9 m were produced for this comparison. SDB depths along the contour lines were extracted from the TIFFs by the point sampling tool, and the values were exported to Excel sheets. The difference between the SDB and the MB depth along the contours (3, 6, and 9 m) was then further analyzed statistically. In addition, the SDB data were imported into QGIS as a Delimited Text Layer, along with the MB in raster format. The MB depths were extracted for every SDB point by the Point sampling tool, and the absolute differences between the two for all the areas where the two data sets overlapped were further analyzed.

2.2 DIGITAL BATHYMETRIC MODEL

Three different gridding methods were utilized for creating various DBMs: Nearest Neighbor, Delaunay triangulation, and Surface Spline with Tension (SPT). These gridding methods were applied using Generic Mapping Tools (GMT; Wessel & Smith, 1991) and are here briefly described.

Nearest Neighbor

The exact approach how to derive the weighting to be applied to the nearest values within a given search radius from a grid node, when calculating the average to be assigned to this grid node varies slightly between software. Here the approach applied in GMT is explained. Within a specified radius s around the grid node, a number of sectors are defined. The average value is calculated as a weighted mean (Eq. 3) of the nearest point from each defined sector within the specified search radius (Wessel *et al.*, 2018; Huang *et al.*, 2012). The weighting function make use of the distance from the grid node r to the points within the search radius s . The weight is calculated by:

$$w(r) = \frac{1}{s^2} \quad (3)$$

and d is defined by

$$s = \frac{3d}{r} \quad (4)$$

The weight applied to each point in the sector is then scaled by the number of sectors used.

Delaunay triangulation

This interpolation method connects the known data points in a Triangular Irregular Network (TIN). It is considered a Delaunay triangulation if the circumcircles of every triangle in the TIN are empty, i.e. they only contain the three points that establishes it (Bern & Eppstein, 1992). This implies that the facets of the triangles have the shortest possible sides.

Surface Spline in Tension

Interpolation by using SPT is a form of low degree polynomial interpolation. The SPT method is performed by fitting a polynomial function through all the available data points striving to reach the minimum curvature of the fitted surface. The SPT can be constrained by a tension parameter (T), which determines how much the SPT bends to fit the data. The mathematics of the SPT algorithm is rather complex and its implementation in GMT is explained by Smith & Wessel (1990).

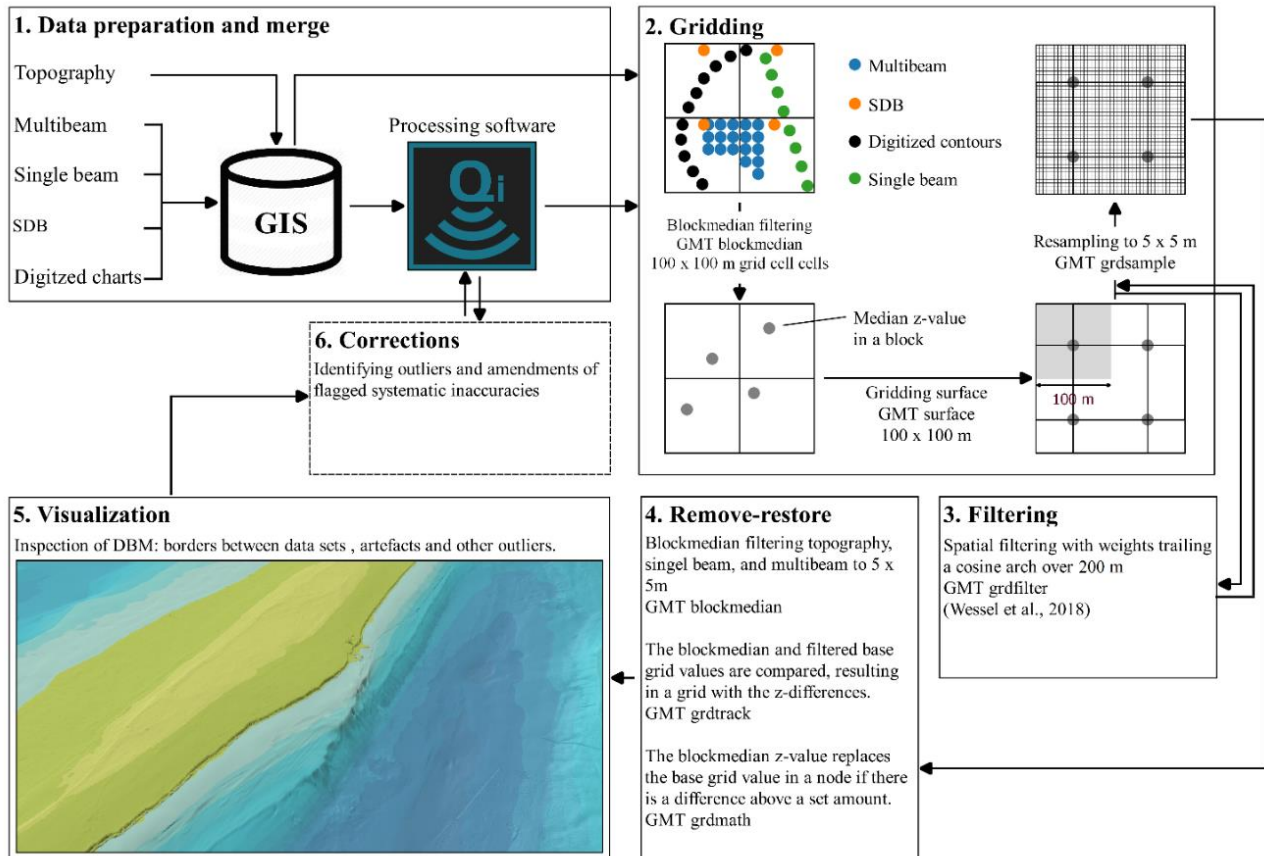


Figure 8. Steps 1-6 depict the essential stages in the Lake Vättern DBM process. Figure is adapted from Jakobsson *et al.* (2012). 1. The data is first prepared, so all use the same horizontal datum and vertical datum. They are later checked for errors and artefacts. 2. Once “cleaned”, the data is gridded using GMT (Generic Mapping Tool). First the data is block median filtered, so only one median z value exists in each 100 m grid cell. The filtered data is gridded (above shown is the SPT, but also either triangulation or Nearest neighbor) to 100 m resolution. Before the data is re-sampled to 5 m resolution, it is filtered (3). 4. High-resolution bathymetry along with topography is filtered to the same resolution as base-grid, and placed on top of the base grid. 5. Once the grid is produced it is visualized and inspected. 6. If outlier or artefacts are found, they are removed and a new DBM is made.

In order to create a DBM of Lake Vättern many different types of bathymetry data were utilized. The SDB data that was constructed during this thesis, MB data provided by Martin Jakobsson at Stockholm University, digitized charted depths and shoreline from the nautical charts, and single beam bathymetry (SB) data, provided by CAB and SLU. Data of the surrounding land topography would also be utilized. The procedure from data preparation to quality control of the compiled DBM is outlined in Figure 8.

2.2.1 Data preparation

Before the gridding of the DBM could take place, the data needed to go through a disambiguation process. All data provided were in different formats, resolutions, and from different contributors. Steps to prepare the data were necessary, especially a uniform use of horizontal datum and vertical datum. The horizontal datum was selected to be WGS84, and the vertical datum RH2000, which can be considered a close representation of MSL (Mean Sea Level). Most of the data had lake depths in a negative format, which would be used until the MSL corrections were performed. All data sets were formatted to a Lat/Long/Depth format, either as *.xyz-, or *.csv-files. All data are visible in Figure 9.

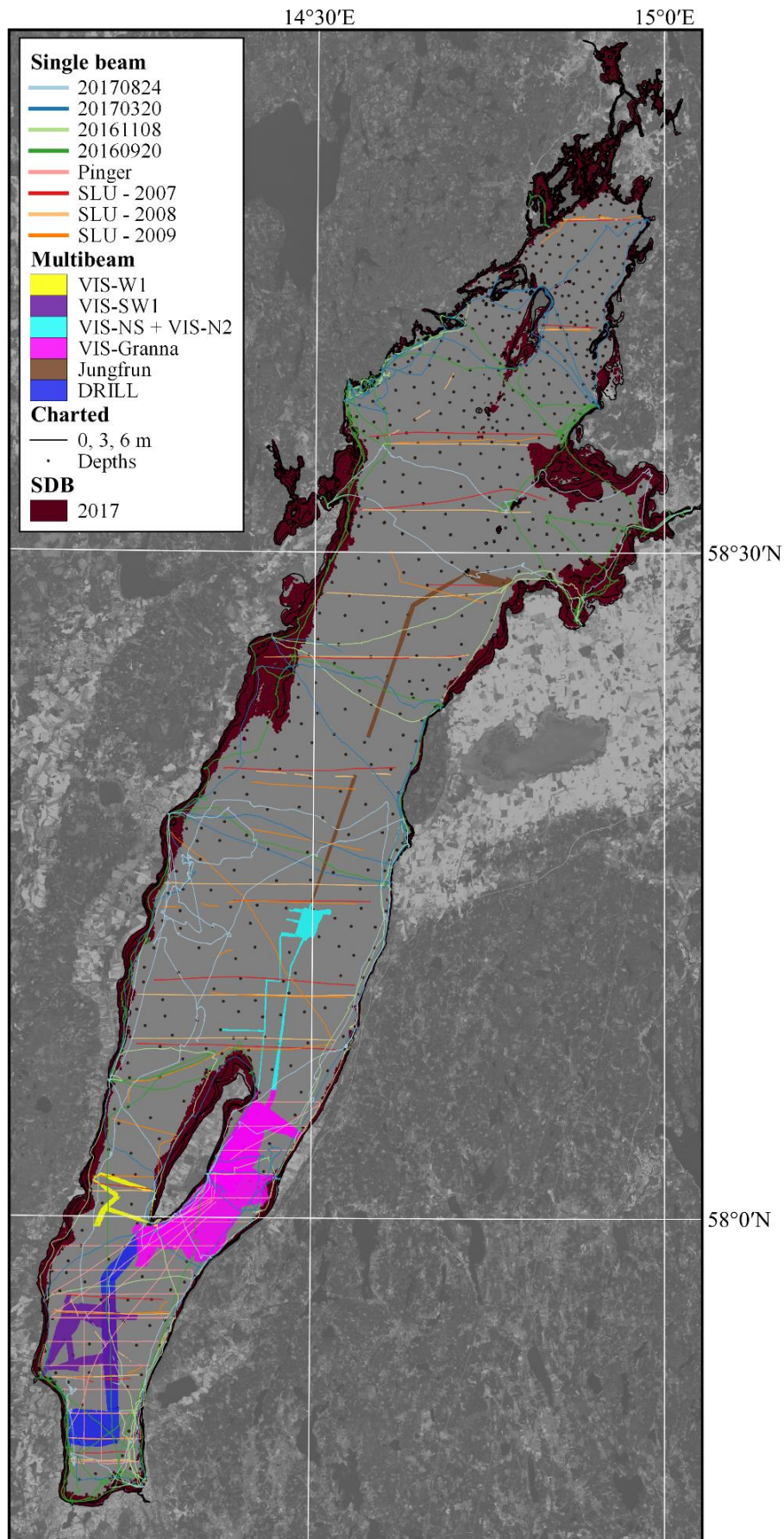


Figure 9. All bathymetric data included in the gridding procedure, such as single beam, multibeam, charted, and SDB.

Single beam bathymetry

The data collected by the data logger provided to CAB between 2016-2017 were in a NMEA2000 format, edition 3.00, consisting of multiple lines conveying various pieces of GPS information. The information relevant to this study were the longitude, latitude, and the water depth as well as information related to the vertical reference of the echosounder transducer. In Figure 10 an excerpt of such lines are visible. The line \$GPGGA contains GPS fix data, including the latitude (5836.4756, N) and longitude (01454.4065, E). However, these coordinates are in a DDMM.MMMM format (D = Degrees, M = Minutes), and needs to be reformatted to a DD.DDDD format. The line \$SDDBT contains the depth below transducer (DBT), in feet (2.2,f), meters (0.6,M), and fathoms (0.3,F) (Raymond, 2016). The transducer was mounted 0.2 m below the surface, so the accurate water depth is the depth from \$SDDBT + 0.2 m. A python script was written (Appendix A), extracting the latitude and longitude, reformatting them, and extracting the DBT while adding the 0.2 m. Files with data recorded on the same day were merged into one *.xyz-file. A total of 4 files were generated.

SB data collected 2007-2009 by SLU were imported into QGIS with the coordinates as latitude longitude referenced to WGS 84. The gridding would be performed outside of QGIS in a Cartesian coordinate system, which was selected to be that of Universal Transverse Mercator (UTM) Zone 33. In the Attribute Table of the imported data, new fields were therefore created and populated with the x and y coordinates of the features in UTM Zone 33 projection. The imported surveys were subsequently exported as *.csv-files for gridding. The 2016-2017 SB data were imported and exported following the same procedure. Data collected by Stockholm University using a 28 kHz SB echosounder (named 'Pinger' in Fig. 9) were also included. These were provided in a *.DAT-file, already in a UTM Zone 33N format.

Multibeam bathymetry

The high resolution bathymetry data sets that were included in this model are listed in Appendix D. These were provided as processed grids in UTM Zone 33N format and with the lake depths as positive values. The only processing these grids required comprised of turning the depths into negative values.

```
NMEA Data logger version 3.00
$GPGGA,075737,5836.4756,N,01454.4065,E,1,08,1.10,89,M,32.0,M,*,*5E
$GPGLL,5836.4756,N,01454.4065,E,075737,A,A*4D
$GPRMC,075737,A,5836.4756,N,01454.4065,E,0.1,315.0,260816,4.4,E,A*1C
$GPVTG,315.0,T,310.6,M,0.1,N,0.2,K,A*23
$GPAPB,,,,,,,,,,,,,N*26
$GPRMB,,,,,,,,,,,,,N*04
$GPXTE,,,,,N,N*5E
$SDDBT,2.2,f,0.6,M,0.3,F*03
$SDMTW,17.3,C*01
$SDHDG,,,,,*70
$SDHDG,,,,,*70
```

Figure 10. Outtake from NMEA data collected by the Jönköping County Administrative Board, with each line conveying specific information about the data retrieval. Latitude, longitude and water depth are relevant here. \$GPGGA conveys GPS Fix Data, and \$SDDBT conveys depth below transducer.

Two data sets, VIS-SW1_Cube2m and VIS-W1_Cube2m, were in a TIFF format with positive depth values, not as text documents like the others. These two were imported into the QPS software Fledermaus (v. 7.8.1, 64-bit edition), and exported as *.xyz-files.

Charted depths

All digitized charted depths with their corresponding coordinates were exported as a *.csv-file. The shoreline of Lake Vättern from the nautical chart was digitized in QGIS as a polygon shapefile, representing the mean lake level at +88.41 m (RH00). The “Extract nodes” tool was used, and coordinates for these nodes were generated in the Attribute Table, just as for the 2007-2009 SB data. The depth contour lines for 3 m and 6 m displayed on the nautical charts were also digitized, and coordinates generated just as for the shoreline. The shoreline, 3 m and 6 m bathymetry were exported together as a *.csv-file, with the depths converted to negative values.

Topography

Topographic data was included in the DBM to constrain the shoreline, better than the digitized shoreline from the nautical chart. The Swedish government agency Lantmäteriet has a digital topographic model of Sweden, which is available as the product *GSD-Höjddata, grid 2+*. This product has a horizontal grid size of 2 m, and can be accessed online³ through the Geodata Extraction Tool operated by SLU. Just like the USGS Earth Explorer, areas can be selected and downloaded. The land surrounding Lake Vättern was downloaded as several TIFFs, and imported into QGIS. The CRS for these TIFFs are SWEREF99TM, implying that they all had to be re-projected to UTM Zone 33N before for the final gridding with all bathymetric data. All topography files (Appendix D, and visualized in Fig. 11a) were cropped to 445000/505750/6401500/6528200 (xMin/xMax/yMin/yMax). The topography is referenced to RH2000 (geoid model SWEN17), and in some of the topography data sets elevation of the lake surface was included. These different topographic data sets were recorded at different times; thus the elevation of the lake surface differed between them. The different elevations are colored in Figure 11a, and specified in Table 4. The lake elevation data had to be removed, which was done by using the Raster calculator. All values equal or lower than the lake surface elevation were removed and turned into NoData, like in 2.1.2. This procedure was repeated for each applicable data set, and after all sets were merged into three regions (Fig. 11b) to avoid one large file and slow processing. These regions were imported into Fledermaus as TIFFs and later exported as *.xyz-files, excluding all NoData values.

Vertical referencing

Most bathymetric data sets to be included in the gridding had depths referenced to different levels. Some lacked a precise vertical referencing, which therefore had to be estimated. The goal was to reference all depths to RH2000 and a lake level of +88.97 m, which represents the average lake elevation 1959-2017 (H. Tengbert, personal communication, November 27, 2017). The topography data was already referenced to RH2000. The bulk of the data was referenced to the older RH00 (Rikets höjdsystem 1900), because this vertical datum has commonly been used for nautical charts and by government agencies. The main difference between the two vertical datums is the inclusion of isostatic uplift corrections in RH2000 (Lantmäteriet, 2018a). To fully convert all depths to RH2000, the uplift

³ <https://zeus.slu.se/get/?drop=>

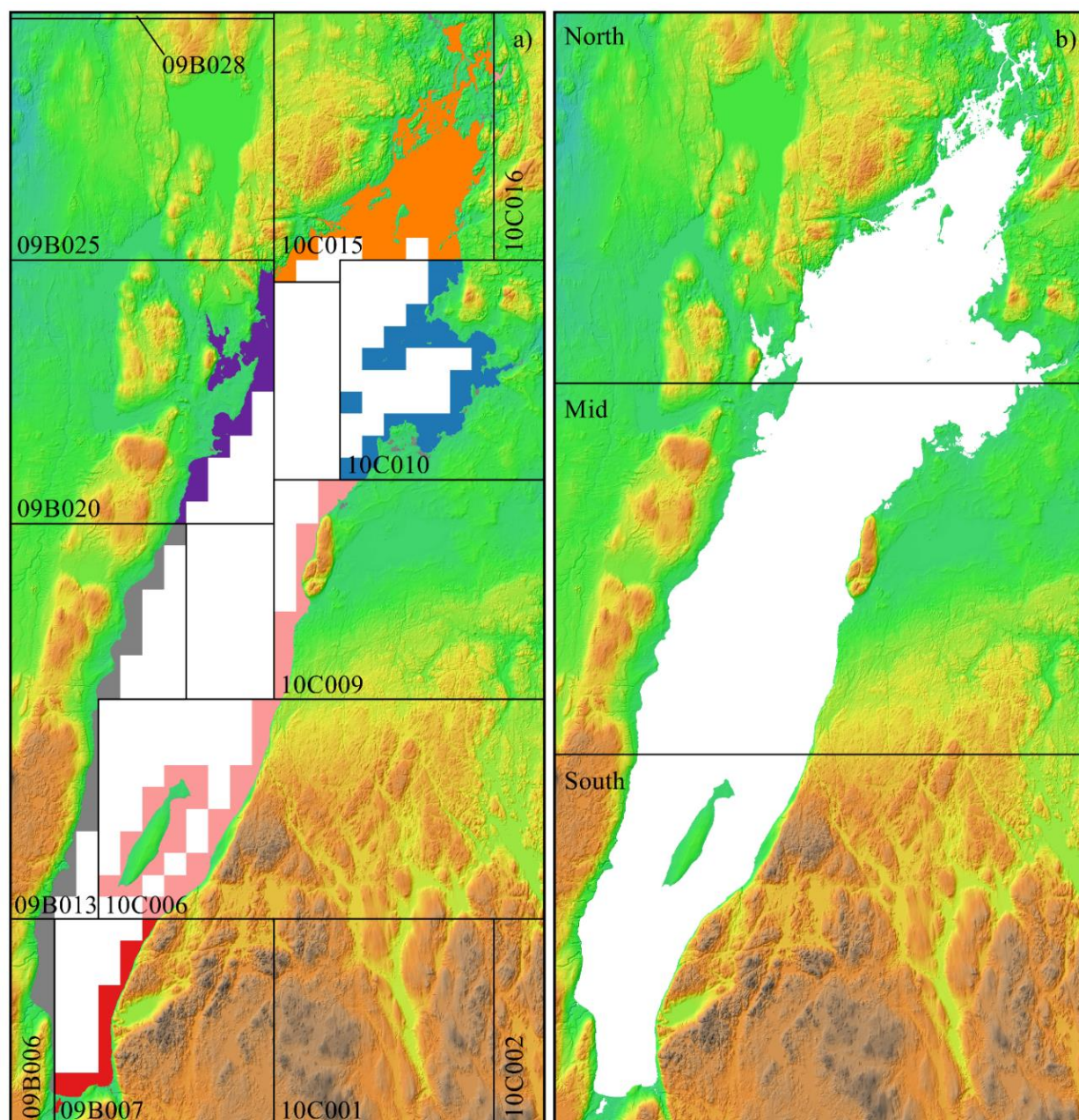


Figure 11. Topography data from Lantmäteriet's product *GSD-Höjddata, grid 2+*. a) 13 data sets covered the selected area surrounding Lake Vättern. Elevation data (referenced to RH2000) of the lake is present in data sets that overlap the lake surface. These elevations differ between data sets, and have been colored to distinguish them. 88.85 m = blue, 88.90 m = pink, 88.94 m = purple, 89.0 m = orange, 89.06 m = red, and 89.13 m = green. b) Topography data with lake elevations removed and divided into three regions (North, Mid, South) in order to avoid large file sizes.

Table 4. Elevations of the lake surface with corresponding color in Figure Za and data set(s)		
Elevation (m, RH2000)	Color	Data set(s)
88.85	Blue	10C010
88.90	Pink	10C006 + 10C009 + 10C016
88.94	Purple	09B020
89.00	Orange	10C015
89.06	Red	09B007
89.13	Grey	09B006 + 09B013

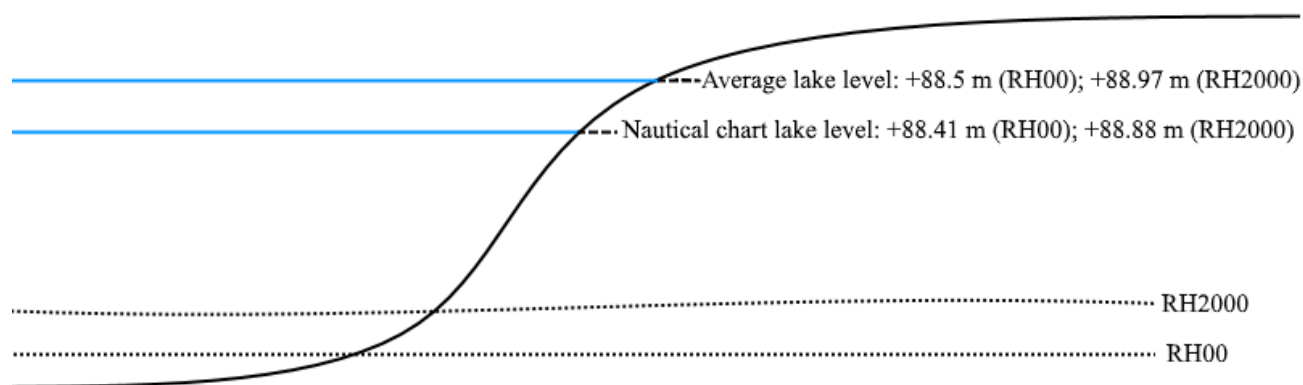


Figure 12. Graphical representation of the two vertical datums RH2000 and RH00, and how the lake level is referenced to them. Not to scale.

needed to be taken into consideration. The two vertical datums and the lake level is visualized in Figure 12.

The uplift model NKG2016LU, created by the Nordic Geodetic Commission, was utilized for this endeavor, which was imported to QGIS as a TIFF. The model portrays the uplift in mm/year, and since there is a 100-year difference between RH00 and RH2000, a significant difference is present. A new TIFF was created with this 100-year change applied, which was then used in the calculations for the referencing.

SLU collected their SB data during the first half of September each year 2007-2009. Only depth data was supplied by them, so the average depth of Lake Vättern over these time periods was estimated and used as a reference (SMHI, 2018), which was +88.67 m (RH00). In QGIS the calculated uplift was extracted by the point sampling tool at each sounding, and the file generated containing the x and y coordinates, the depth, and the uplift value, was exported as a *.csv-file. A Python script was written, which re-calculated the depths to be referenced to the average lake level in RH00, which is +88.5 m (H. Tengbert, personal communication, November 27, 2017). The uplift value for each sounding was added, and a new *.xyz-file was generated, containing x, y coordinates in UTM zone 33N, and depths referred to +88.97 m (RH2000).

The depths from the CAB data sets did not have a specified vertical datum, so a similar approach to that of the SLU data was taken. This time however the lake level of each day (in RH00) was used, which was 2016-09-20: +88.37 m; 2016-11-08: +88.23 m; 2017-03-20: +88.17 m; and 2017-08-24: +88.22 m (SMHI, 2018). The uplift for the soundings of each data set was extracted, and new files were exported in *.csv-format. All soundings were re-referenced to +88.97 m (RH2000), and exported as new files in *.xyz-format.

The data collected by the SB “Pinger” was referenced directly in RH2000. To compare this data to the rest all soundings were subtracted by 88.97 m, to be referenced the same as the other data.

The MB depths were already referenced in RH2000 (geoid model SWEN08), but to +88.5 m. All depths were increased by 0.47 m, thus re-referenced to +88.97 m (RH2000), and exported as new *.xyz-files.

The SDB data was created by using depths referenced to + 88.41 m (RH00). They were re-referenced to +88.97 m (RH2000) and exported as *.xyz-files, in a procedure similar to the one for the SB data.

2.2.2 Data merge and analysis

A new project was started in the QPS software Qimera (v. 1.5.7, 64-bit Edition), with the project CRS set to WGS84 / UTM zone 33N. All bathymetry data sets were imported as Processed Point Files. All were selected and a Dynamic Surface was created, CUBE enabled and with a 30m resolution. These settings enabled editing of each data set, if artefacts were found during inspection.

Since the MB data had already been processed only minor editing was necessary. Wherever MB data was present other data types were removed, since the MB is the most exact.

With actual soundings the SDB could be better constrained. SDB soundings at depths below 10-12 m were removed, and whenever SDB covered the same area as SB or MB, SDB would be deemed the least accurate and removed. The SDB was also constrained by the shoreline nodes. Any data extruding outside of the shoreline, or covering some parts of islands, were removed.

Once the cleaning of the data was concluded, they were exported together as one large file, but each data set were also exported as separate *.xyz-files. These would be used in the gridding process, along with the topography data.

Contour lines

The merged data file of all soundings were imported into QGIS as a Delimited Text Layer. The Contour plugin (v. 1.4.4) was started, and contour lines selected to be contoured. The plugin uses the python matplotlib contouring function (Crook & Roubeyrie, 2017). To avoid too many points point thinning was applied with a radius of 5. 11 contour lines were chosen ranging between depths of 10 m to 110 m for the entire lake with 10 m intervals. The output vector layer containing the contour lines were generated, and the nodes of each line was extracted. X and Y coordinates were generated for each node. All nodes generated that covered an area the same as MB data were removed. The remaining nodes were exported as a *.csv-file, and converted to a *.xyz-file.

2.2.3 Gridding

The gridding of the Lake Vättern DBM was executed on a PC with Windows 10 Pro (64-bit) by applying GMT routines (Generic Mapping Tool, 5.3.3) that were included in a pair of python scripts. One script created the “base grid”, which integrates all the available data and interpolates areas of sparse data coverage. The file containing the charted depth shoreline data was not included in the gridding process, since the topographic data was included to better constrain the shoreline. The other script replaces “base grid” values with those of high resolution data sets where they are situated. This is called the “remove-restore procedure”. This diminishes the risk of losing detail in the final grid. A Command prompt was used to implement the Python scripts, with GMT specific commands being operated in Python using: `os.system('gmtcommand')` (Jakobsson *et al.*, 2016).

Base grid

The process began with modifying the script present in Jakobsson *et al.*, 2016 to fit Lake Vättern. The modified script is included in Appendix B. The first modifications required were finding proper values for the different variables. The gridding cell size (S_I) with the accompanying Blockmedian filter bin size (BM_I) were set to 100 m. The resampling grid size (R_I) were set to 5m; the filter size for smoothing (FILT) to double the gridding cell size, so 200. The gridding region (BM_R) was set to

445300/503150/6401600/6528100. Three different gridding algorithms would be used separately, with different variables.

For the SPT interpolation the ‘GMT surface’ function would be used. The T was set to 0.32, due to IBCAO’s success with a similar value (Jakobsson *et al.*, 2016); the max iterations in each gridding cycle (N_I) was set to 1500; and the upper z limit (L_U) was set to 88.96 m. A separate function making sure the z-min/max of the input file (L_U) was not exceeded in the grid was also added (n).

The Delaunay triangulation was performed by the ‘GMT triangulate’ function. The only variables necessary for this gridding method were the ones in regard to cell size and smoothing.

The ‘GMT nearneighbor’ function performed the Nearest neighbor interpolation. Variables for this function were the search radius (S_R), which was set to 500 (m), and N_S, which divided the search radius into sectors. The default value of 4 was selected. In the script the gridding functions that were not to be used were marked off by adding a “#” in front of them.

The second modification was to re-reference all elevations to RH2000, by adding a few lines of code that added 88.97 m to all elevations below or equal to zero. The script was run and a base grid file was produced, in a *.grd-format.

Remove-restore

Like for the base grid, the first step for the remove-restore (RR) procedure was to modify the pre-existing script to fit Lake Vättern. The modified grid is included in Appendix C. The blockmedian filter bin size (BM_I) was set to the base grid’s resampled grid size, so 5 m; the difference criteria that needed to be passed to update the grid (DIFF_P) was set to 0, which meant that all areas covered by MB or topography would be automatically replaced by MB and topography data. The re-referencing code to MSL in the base grid was added in this script as well. The script was run and the RR grid was produced, in a *.grd-format

2.2.4 Lake analysis

Once the DBMs were created, the area, volume, maximum depth, and mean depth of the lake were calculated, for comparisons between the DBMs, but to other published values as well. All DBMs were imported into QGIS, whose CRS’ were set to WGS84 by default. WGS84 / UTM zone 33N was selected as the DBMs new CRS, and they were saved as TIFFs. A new polygon vector layer was created, and set to encircle the lake and the immediate surrounding land, in order to exclude all other areas within the DBM that were below the set lake level. Once the layer was created and saved, the Raster Clipper tool was selected. Each DBM was selected in turn as the Input file, and the “Mask layer” Clipping mode was chosen. The “Crop the extent of the target dataset to the extent of the outline” option was toggled, so the output file extents matched the vector layer. New TIFFs were created for each DBM, only containing the lake.

The new “lake only” TIFFs of each DBM were imported into Fledermaus and new *.sd-files for each TIFF was created. The Surface Difference Tool was selected, and one of the new *.sd-files was chosen as the “Surface of Interest”. The chosen lake level, +88.97 m (RH2000), was set when completing the “Select Plane at Height” step, and only data below the plane was elected in the Operation ordering. No constraints were chosen, and the Tool was Finished. The process was repeated so all *.sd-files were analyzed.

3. RESULTS

3.1 SATELLITE DERIVED BATHYMETRY

The SDB in sections I-XI are shown in Figure 13. Finer lake floor structures and features are visible in Figures 14-18. In Figure 14a the SDB of the most northern part of Lake Vättern is shown. In this area it was possible to derive bathymetry to a depth of 20 m, the deepest of any sections, with a gradual increase in lake depth southward. The SDB generally portrays the lake floor as rather featureless. In Figure 14b depth contour lines of 3 m and 6 m are displayed. They hardly follow the nautical contour lines (3 m – darker blue area; 6 m – lighter blue area), and portrays depth increases along the shoreline and around the islands poorly.

In the eastern bay of Lake Vättern it was possible to derive SDB to a depth of 10 m (Fig. 15a). There is a shoal clearly visible in the SDB of the northern part of this area, and in the southern part some ridges can be seen protruding outward from the shoreline, in a semicircular fashion. The shallower areas are visible through the contour lines as well (Fig. 15b). When comparing the SDB contour lines to the ones in the nautical chart they correspond fairly well, especially the 3 m contour lines. The 6 m SDB line deviate from its nautical counterpart to some extent, but have the same general trend.

In Figure 16a-b the lake depths around Karlsborg are visible, displaying the depth to 11 m. The SDB (Fig. 16a) portrays several shallower areas in the bay east of Karlsborg (Arrow 1), while Bottensjön has a very flat and featureless lake floor. The SDB depth in Bottensjön is shallower than 6 m, which is visible more clearly with the contour lines (Fig. 16b). Going south along the shoreline underwater ridges are visible (Arrow 2), with a similar orientation as the shoreline. Another small bay lies to the south of Bottensjön (Arrow 3), with small shallow areas, but some areas of the bay has not had depths derived by the SDB. In Bottensjön no 6 m contour lines are present except in the northernmost area. The 3 m contour line does not follow the charted contour line, and consists of many separate lines. The contour lines of the SDB coincide with the nautical contour lines seemingly well east of Karlsborg.

Visingsö is the largest island in Lake Vättern, with a steeper lake floor around its southern edge and along its eastern shoreline, while the depth increases more gradual towards the west and north (Fig. 17a). This is more evident when looking at the distance between the contour lines in Figure 17b. The SDB is between 0-12 m, and the lake floor is not smooth, but quite rough. North-east of the northern tip of Visingsö, some areas of the lake floor have no SDB (highlighted by arrow), and in the same area the SDB portrays the lake floor to be steeper than in the nautical charts, by having the contour lines closer to the shoreline (Fig. 17b).

Several structures exist in the SDB along the south-western shoreline of Lake Vättern (Fig. 18a). Underwater ridges are visible along the entire shoreline, with a general orientation of NNE- SSW, but their orientations vary somewhat. The ridges have a similar orientation as the nearest shoreline. The SDB contour lines follow the general trend of the charted contour lines but differ somewhat in the southern half of the displayed area. (Fig. 18b). North of Baskarp the lake floor is more shallow according to the SDB 6 m contour line, extending further east than the charted counterpart (Arrow 1). South of Baskarp a shallow area protruding south from land (Arrow 2). Moving further south the 6m contour lines match fairly well, while the SDB 3m contour line a less uniform depth, with several smaller areas portrayed (Arrow 3).

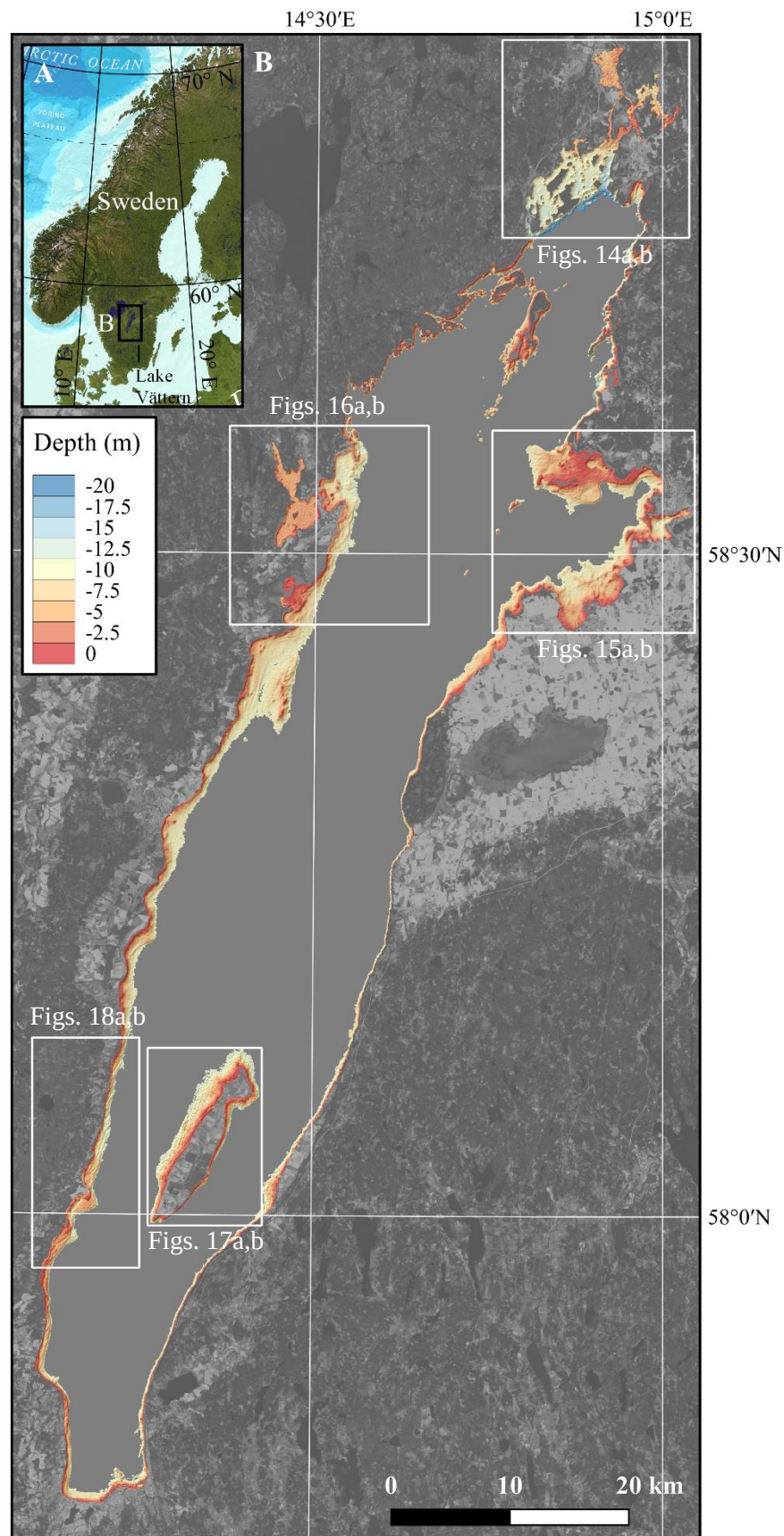


Figure 13. Map of the resulting SDB. The lake floor down to 20 m' depth along the shoreline and islands have been derived from Landsat 8 satellite imagery, utilizing natural logarithmic ratio algorithm of the green and blue bands. SDB was derived to depths ranging from 8 to 20 m depth.

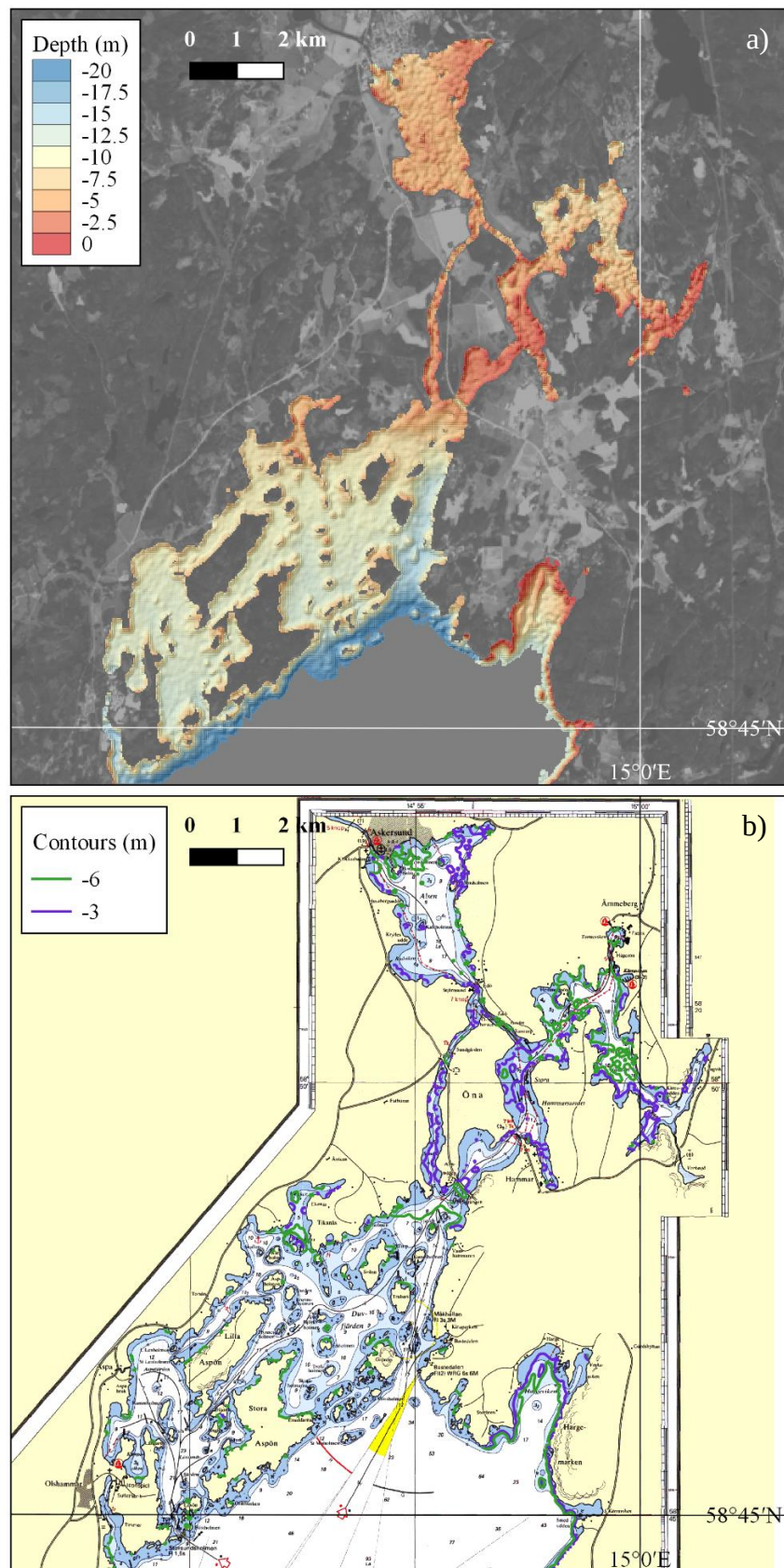


Figure 14. Close-up of the northernmost area of Lake Vättern. a) Portrays the SDB, which is rather featureless with a gradual increase in depth southward. b) the contour lines of the SDB depths 3 and 6 m on top of the charted contour lines (3 m – darker blue area; 6 m – lighter blue area). The SDB contour lines hardly follow the nautical contour lines, poorly displaying the shallow areas along the shoreline and around the islands.

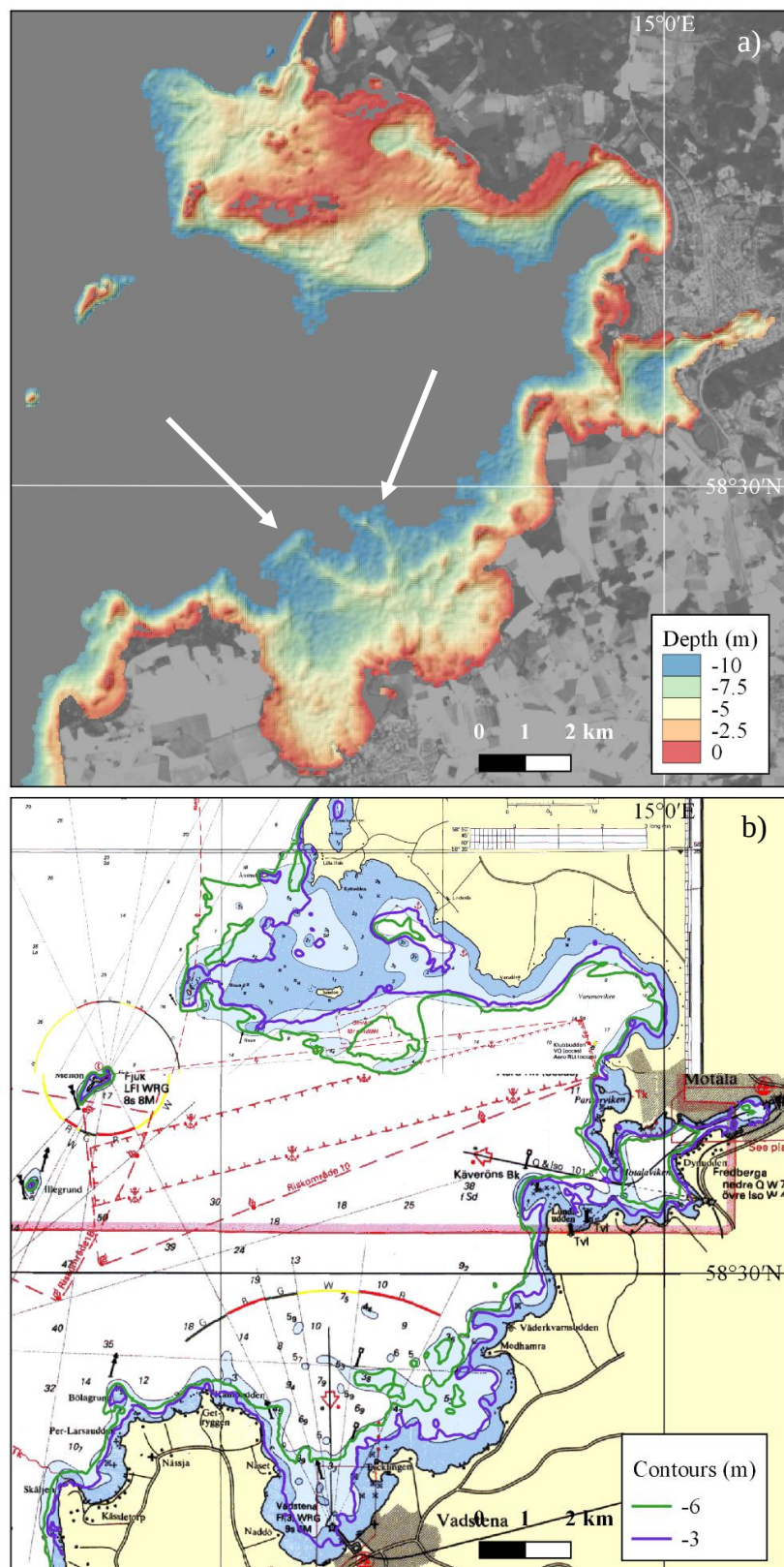


Figure 15. Close-up of the eastern bay of Lake Vättern. a) A clearly visible shoal occupies the northernmost part of this area, while ridges (highlighted by white arrows) can be seen protruding outward from the shoreline in a semi-circular fashion in the southern part). b) the contour lines of the SDB depths 3 m and 6 m on top of the charted contour lines (3 m – darker blue area; 6 m – lighter blue area). SDB contour line of 3 m follow its nautical counterpart fairly well, while the 6 m SDB contour line follows the general trend of the 6 m nautical contour line, but displays a more dynamic lake floor.

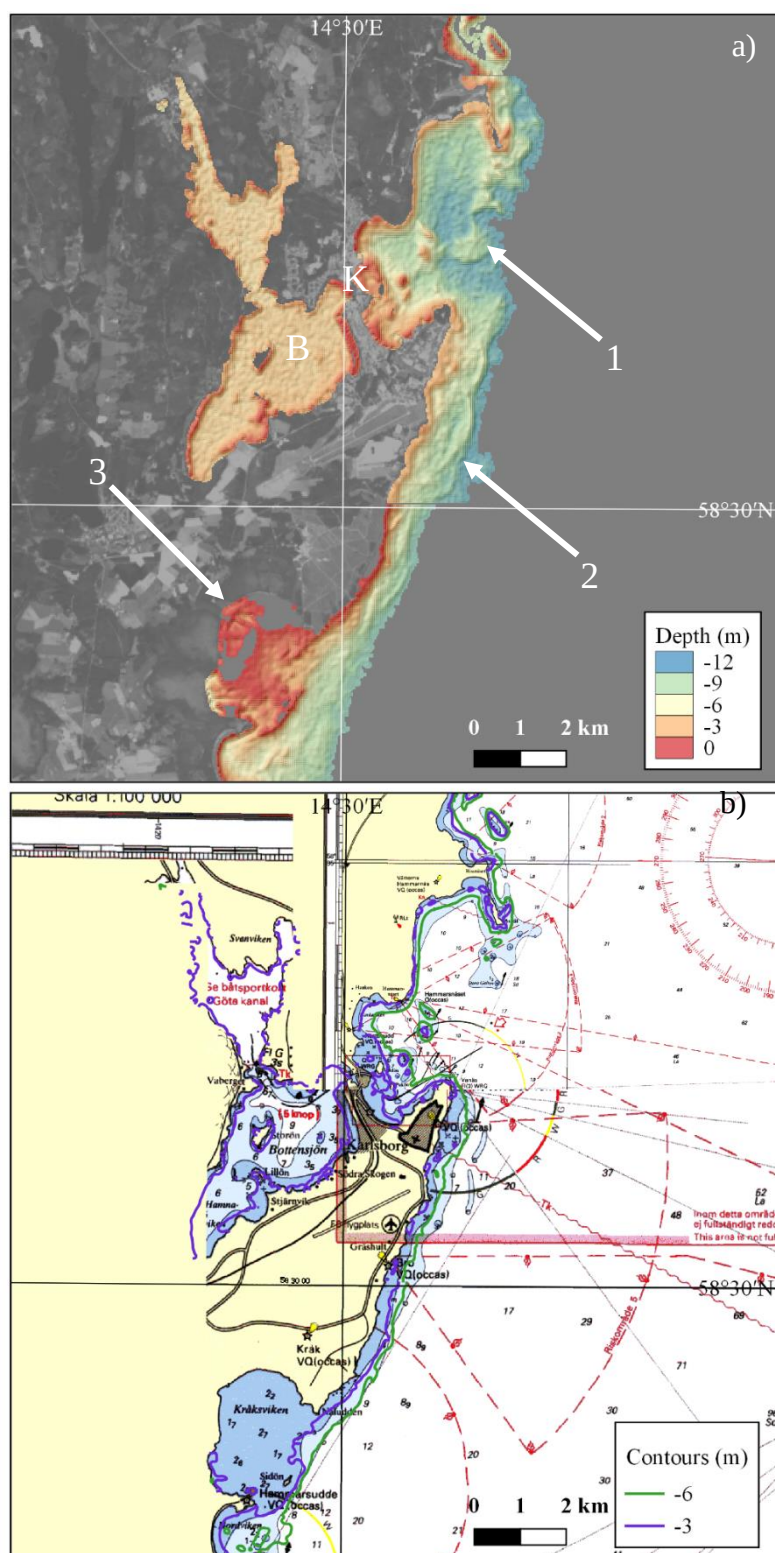


Figure 16. Close-up of the port of Karlsborg, and Bottensjön. K = Karlsborg, B = Bottensjön. a) The SDB portrays Bottensjön as featureless, with a flat lake floor. The bay east of Karlsborg is more featured, with several shallow areas (Arrow 1). Moving south along the shoreline underwater ridges are visible, with a similar orientation as the shoreline (Arrow 2). Another small bay lies to the south of Bottensjön, with small shallow areas (Arrow 3), but some areas of the bay has not had depths derived by the SDB. b) The contour lines of the SDB depths 3 and 6 m on top of the charted contour lines (3 m – darker blue area; 6 m – lighter blue area). In Bottensjön no 6 m contour lines are present except in the northernmost area. The 3 m contour line does not follow the charted contour line, and consists of many separate lines. East of Karlsborg the SDB contour lines follow the nautical ones seemingly well.

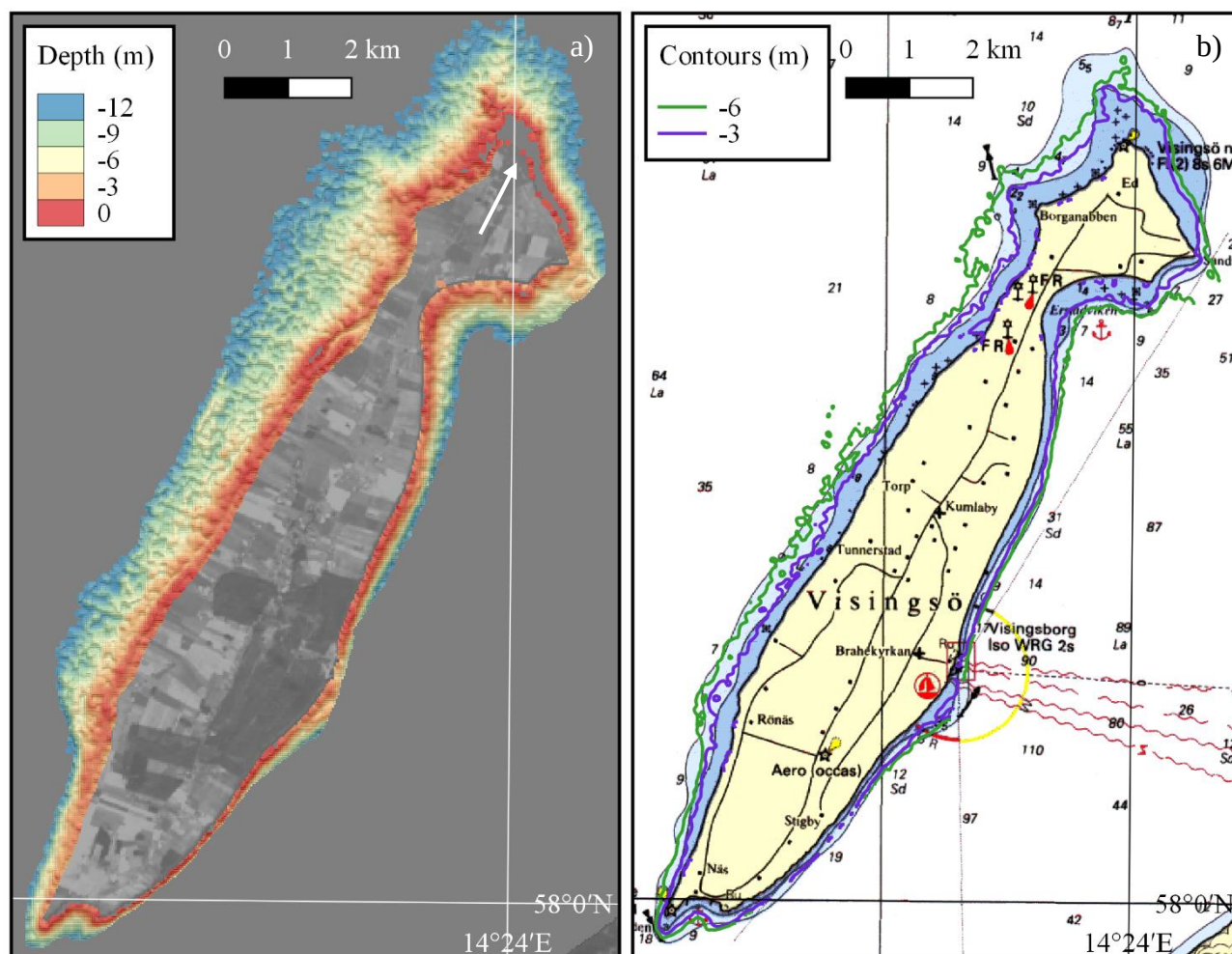


Figure 17. Close-up of the island Visingsö. a) The SDB portrays a steeper lake floor around its southern edge and along its eastern shoreline, while the depth increases more gradual towards the west and north. The SDB is between 0-12 m, and the lake floor is not smooth, but quite rough. b) The contour lines of the SDB depths 3 and 6 m on top of the charted contour lines (3 m – darker blue area; 6 m – lighter blue area). The distance between the SDB contour lines further portrays the steep nature of the lake floor to the south-east, as well as the more gradual increase in depth towards the north-west. Off the north-eastern edge of the island the SDB portrays the lake floor to be steeper than in the nautical chart.

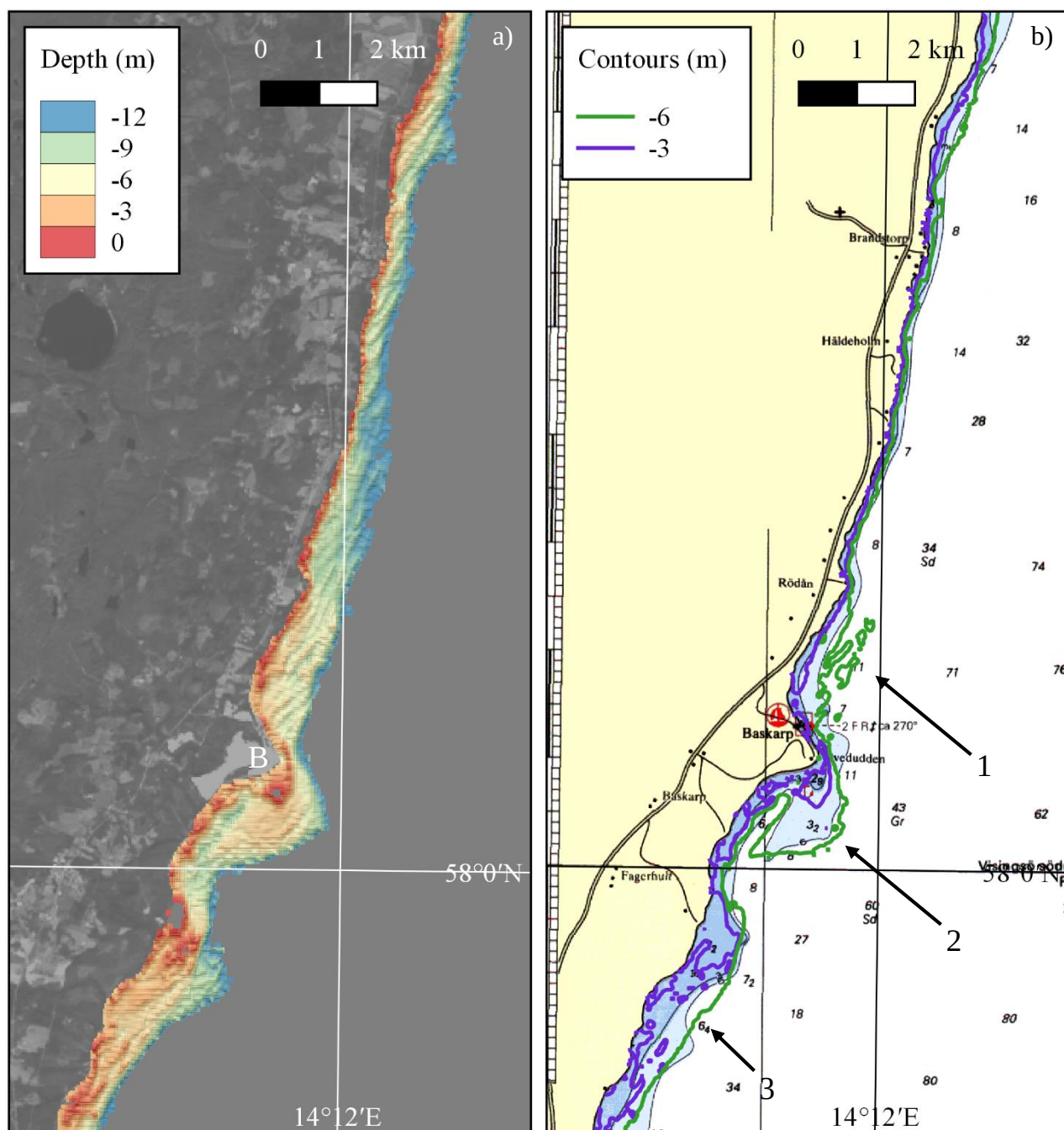


Figure 18. Close-up of the south-western shoreline of Lake Vättern. B = Baskarp. a) Underwater ridges exist along the entire shoreline, with NNE-SSW orientation. b) The contour lines of the SDB depths 3 and 6 m on top of the charted contour lines (3 m – darker blue area; 6 m – lighter blue area). The SDB contour lines follow the general trend of the charted contour lines but differ somewhat in the southern half of the displayed area. North of Baskarp the lake floor is shallower according to the SDB contour lines (Arrow 1), The shallow area protruding south match fairly well with the contour lines (Arrow 2), and the 3m SDB contour lines portrays a less uniform depth than the charted contour lines (Arrow 3)

3.1.1 SDB Accuracy

In Lake Vättern, SDB is here shown to be used to be applicable from the shoreline to a depth of about 20 m in certain parts, but more generally to depths of 10 and 12 m. However, the quality of these derived depths must be investigated. When comparing the contour lines of the SDB depths 3 m and 6 m to the same on the nautical charts (Figures 15b-18b) they correlate seemingly well, Figure 14b excluded.

Considering that the SDB was created by referencing the band ratio results to the charted depths, it is however not surprising they correlate well. When comparing the SDB to MB data, there are larger differences. Figure 19 portrays the SDB-MB difference where these two overlap. The largest difference is 19.54 m off the eastern shore of the island Visingsö. Overall the largest differences are along the eastern shore of Visingsö, which is comprised of an extremely steep slope towards the >100 m deep strait between Visingsö and Gränna.

The difference in depth along the 3, 6, 9 m contour lines derived from the MB data and the SDB was calculated and plotted as Kernel density charts in Figures 20a-c). If the difference is negative, it means the SDB was shallower than the MB, and positive means deeper. At 3 m depth the SDB differ from the MB as seen in Figure 20a. The mean difference was +1.2 m, with a median of +0.5 m and a standard deviation (SD) of 3.1 m, meaning the SDB estimated the lake floor to be generally deeper than the MB, considering the median is higher than 0. To meet the S-44 Special order, the depth could not differ more than ± 0.251 m at this depth. The vast majority of the SDB do not meet the Special order. Nor do the SDB meet the 1a or 1b orders, where the limit was ± 0.502 m. Only 4.8 % of the SDB meet the Special order, while 19.9 % meet orders 1a and 1b.

The SDB-MB difference at 6 m depth portrays a different distribution than at 3 m (Fig. 20b). An almost bi-modal symmetrical distribution is present, with a mean of -0.8 m, a median of -0.7 m and a SD of 1.7 m. The two peaks are at 0 m and -2 m, which along with the median shows that the SDB estimated the lake floor to be generally shallower than the MB. At 6m the SDB does not meet the Special order, nor the order 1a and 1b, which have TVUs of ± 0.254 , ± 0.506 , and ± 0.506 m, respectively. 16.3 % of the SDB meet the special order at 6 m, and 26.7 % meet the orders 1a and 1b.

The SDB differ from the MB differently yet again at 9 m depth (Fig. 20c). The mean of -1 m, the median of -0.7 m and the SD of 2.3 portrays a slight left skewness, with medium spread values. The majority of the data lies as a negative difference, meaning the SDB estimate the lake floor to be generally shallower than the MB. The SDB in total does not meet any of the S-44 orders, which have TVUs ± 0.259 , ± 0.514 , and ± 0.514 for the Special, 1a, and 1b orders, respectively. 12.1 % meet the Special order, while 22.3 % meet orders 1a + 1b.

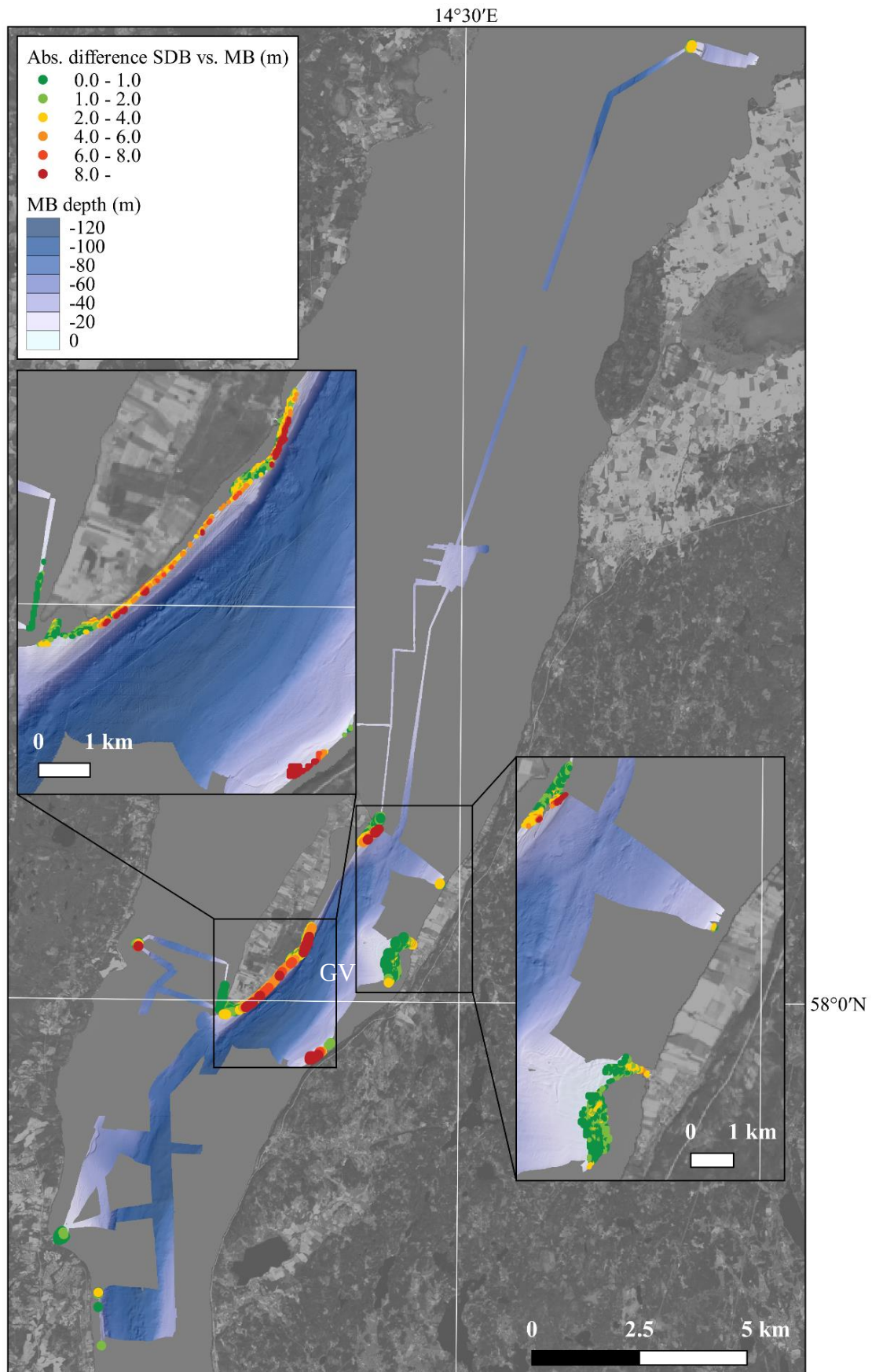
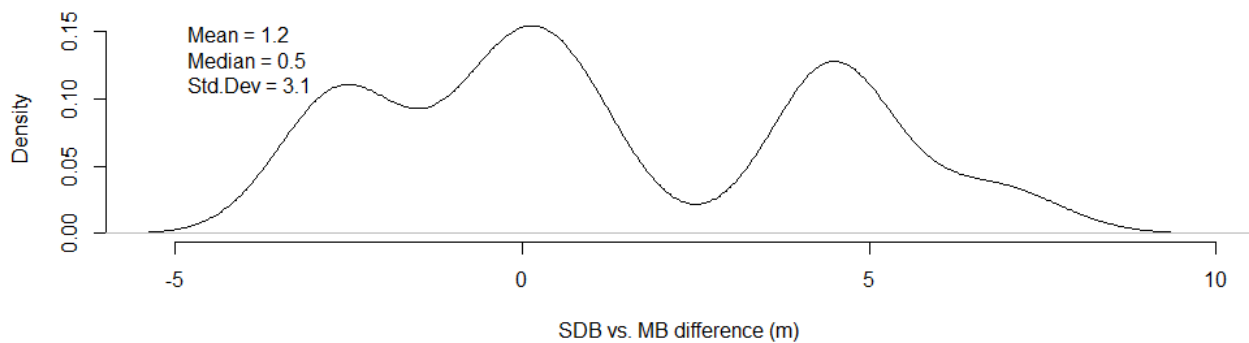
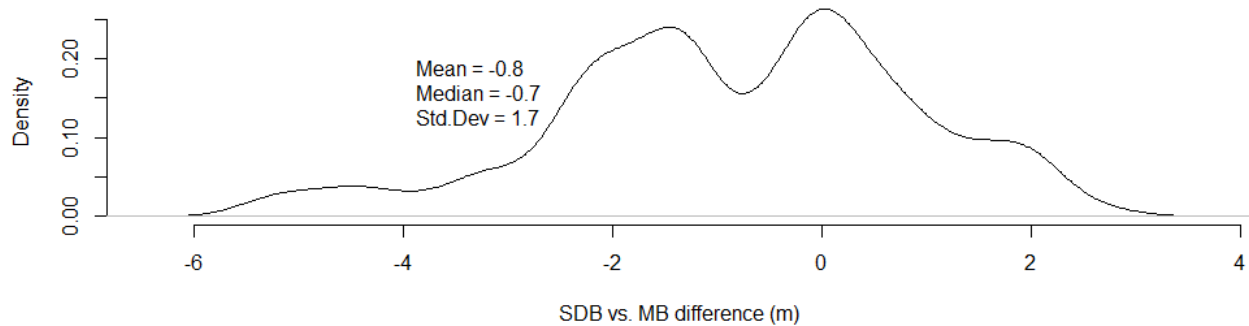


Figure 19. Map of the comparison between SDB and MB in Lake Vättern. Point values are how much the SDB differs from the MB in absolute values. Largest differences are close to rapid depth increases, like in the Gränna-Visingsö strait. GV = Gränna-Visingsö strait.

a)



b)



c)

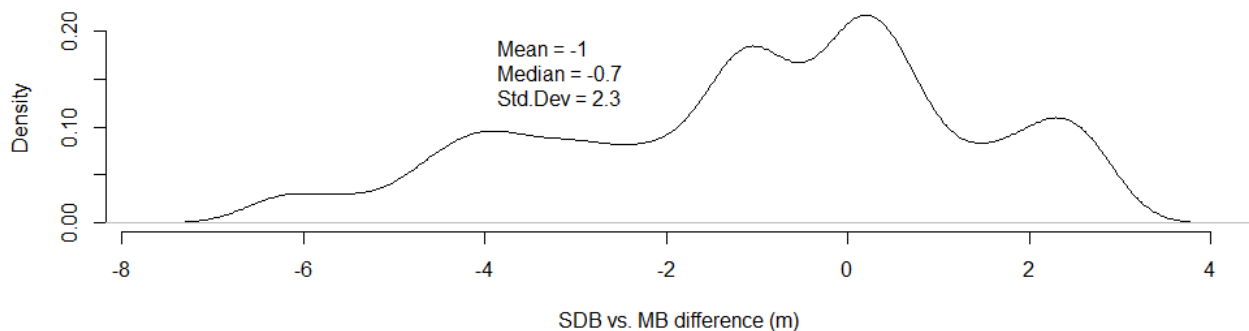


Figure 20. Kernel Density charts portraying how much the SDB varies compared to the MB at selected depths. Charts created using the R Studio software (v.1.1.453). a) 3 m. Similar to a bi-modal distribution, but non-symmetrical. The data is right skewed, and the standard deviation indicates a high spread in the values. b) 6 m. Almost a symmetrical bi-modal distribution. The lowest standard deviation, with a general low value spread. c) 9 m. The values are slightly left skewed, with a middle standard deviation value.

3.2 DIGITAL BATHYMETRIC MODEL

The resulting DBMs are shown in Figures 21a-c, 22a-c, and in Appendix E.

All DBMs were gridded with WGS 84 / UTM zone 33N as their CRS, and illuminated from the north-west with a 6x vertical exaggeration.

3.2.1 Surface Spline in Tension

Version 1

The DBM of the SPT gridding is presented in Figure 21a. A deeper area extends north from the south of the lake, dividing into two sections south of Visingsö. The eastern section is deeper and extends further north, along the eastern shoreline. At around 58° 25' N the deeper area turns north and leaves the shoreline, ending at 58° 40' N.

South of Visingsö some areas that were overlain by MB data through the RR function exhibit a checkered pattern (Fig. 23a). The checkered pattern consists of square features, with sizes of 25 x 25 m and distanced about 10 m from each other. In this area they have a N-S orientation.

Along the deeper bathymetric region several areas exist with singular points deeper than the surrounding areas, creating a “bloated” lake floor, an example of which is visible in Figure 24a.

An elevation difference between the base-grid and the RR overlain data can be seen in varying ranges throughout the entire lake. An example of this is seen in Figure 25a, which portrays an area east of northern Visingsö. An elevation difference of up to 9 m can be observed (Fig. 25c).

Version 2

A new DBM was created, in an attempt to reduce the checkered pattern, the elevation differences between the base-grid and the RR data, and the “bloated” lake floor (Fig. 22a).

To reduce the checkered pattern, the MB data was investigated again. Wherever data-sets overlapped, the newer one or the one with the highest resolution was selected, with the other data sets being removed. The new MB data sets were included in the basegrid and RR scripts. In Figure 23b the result is presented. The checkered pattern is substantially reduced. It is however not completely removed, but is far less apparent than in the 1.0 DBM.

Depth contour lines 10-110 m based on the existing soundings (see 2.2.2) were inferred in an attempt to decrease the “bloated” lake floor. The depth nodes from the contour lines were included in the gridding, with the resulting bathymetry portrayed in Figure 24b. The bloated lake floor is gone, portraying the deeper area in a smoother fashion. But in some areas the lake floor appears to be more angular. The contour lines are computer generated, which results in straight lines between points, which become more pronounced when there is a sparse data coverage. This translates to angular features in the grid.

The elevation differences were sought to be diminished by increasing the resolution of the base grid. The gridding cell size and the blockmedian filter bin size were changed from 100 m to 75 m, and the filter size for smoothing was changed from 200 to 150. The new base grid had a reduced border to the RR data (Fig. 25b), with the elevation now differing up to 6m (Fig. 25d). These changes also resulted in a grid with higher resolution than the previous.

In Figure 14b it is visible how the contour lines of the SDB match the contour lines of the nautical chart in the north part of the lake. A poor correlation exists, which is why a new DBM excluding SDB data of this area was produced. The area was instead gridded based on charted depth data, SB and

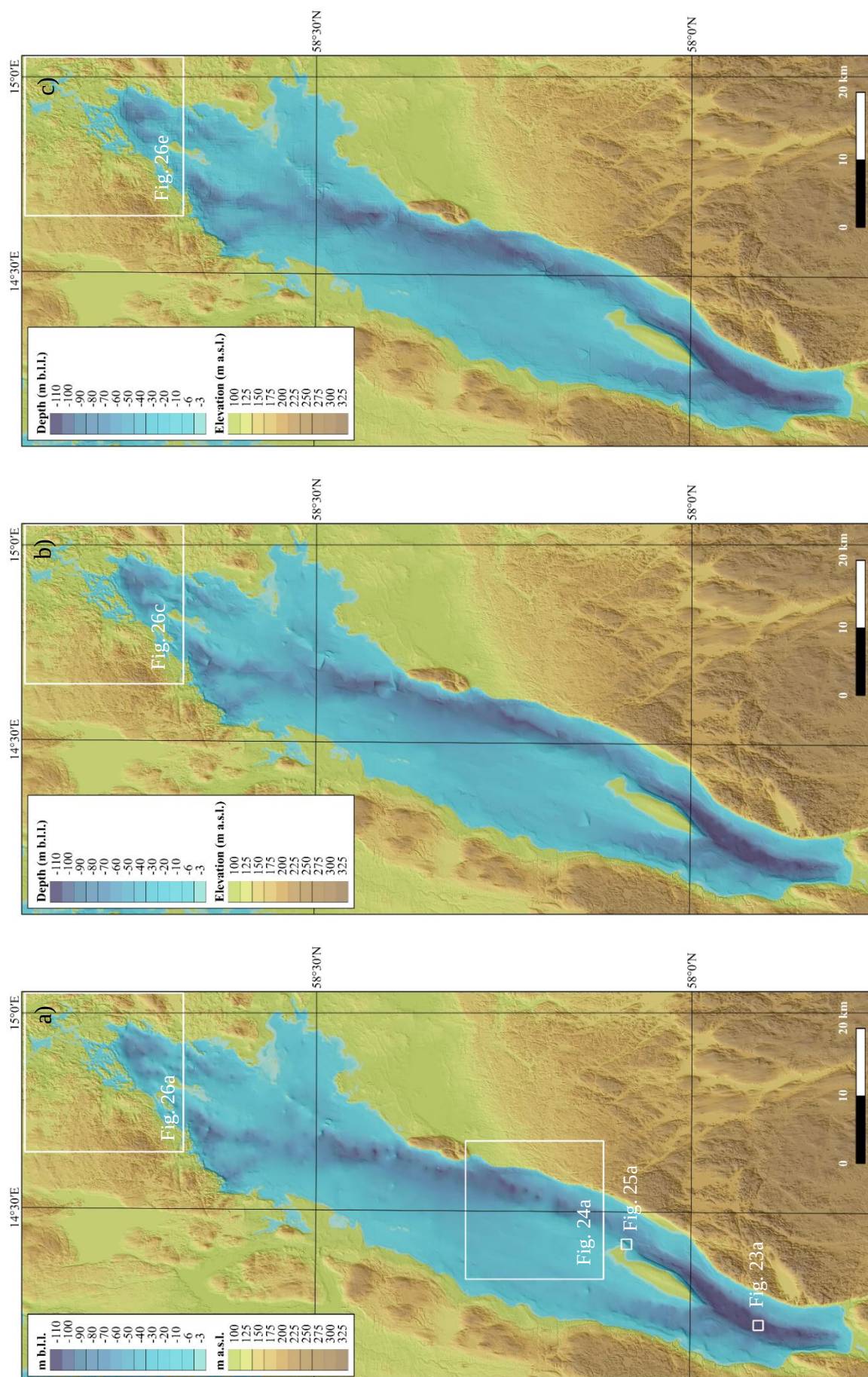


Figure 21. Version 1 of the DBMs of Lake Vättern. b.l.l. = below lake floor. a.s.l. = above sea level. a) SPT DBM 1.0 b) Triangulation DBM 1.0 c) Nearest Neighbor DBM 1.3

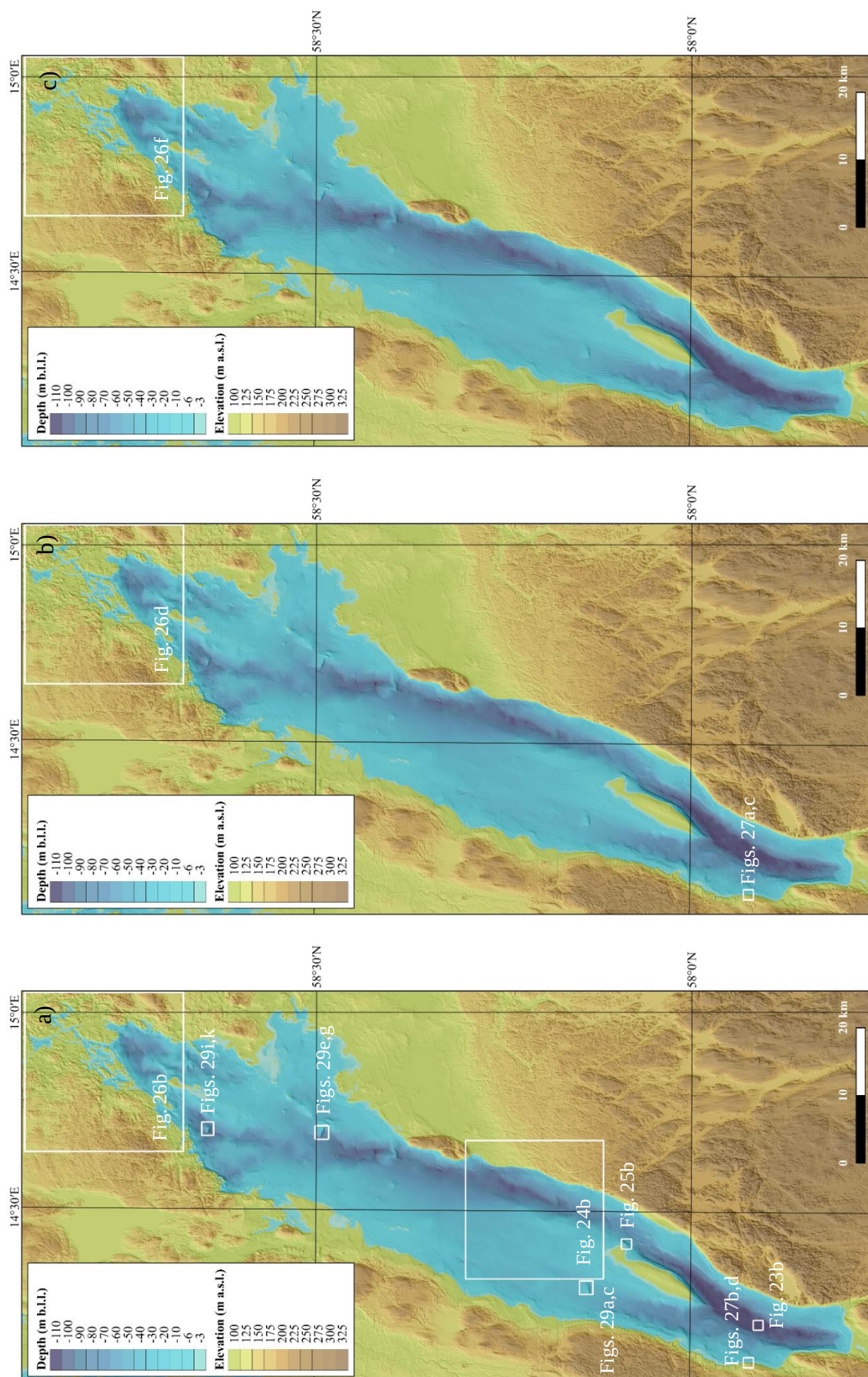


Figure 22. Version 2 of the DBMs of Lake Vättern. b.l.l. = below lake floor. a.s.l. = above sea level. a) SPT DBM 2.0 b) Triangulation DBM 2.0 c) Nearest Neighbor DBM 2.0

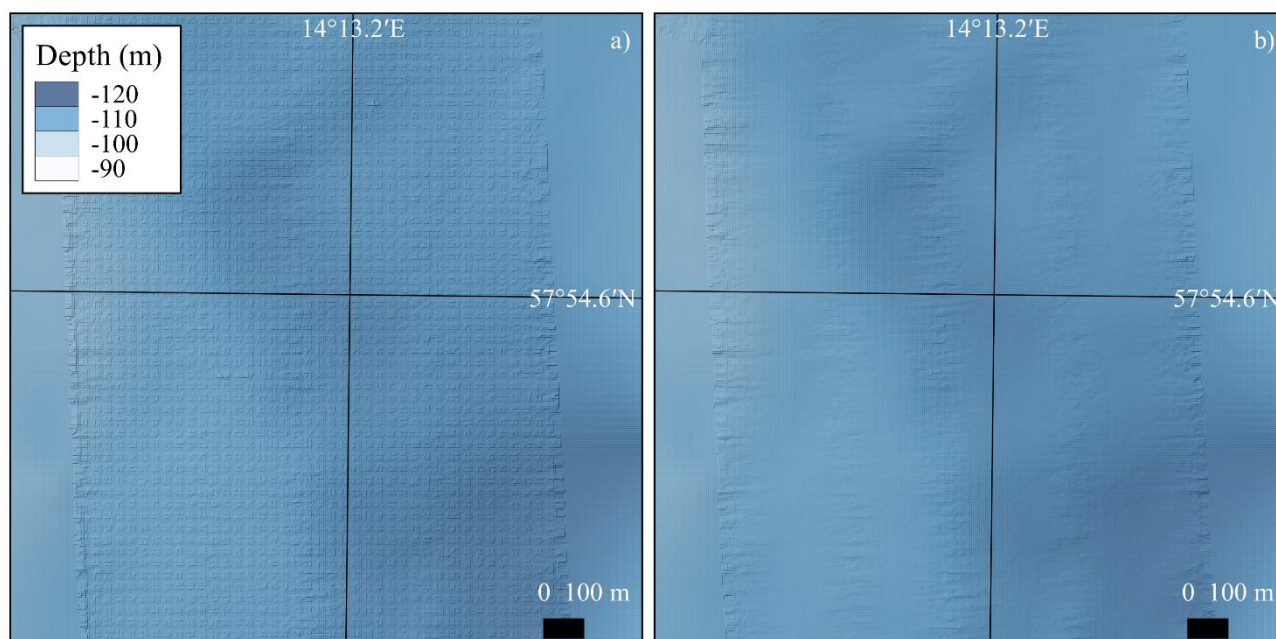


Figure 23. One feature that needed to be addressed before creating the final grid. a) DBM SPT 1.0 - Checkered pattern caused by overlapping of MB data in the RR step. b) DBM SPT 2.0 - The result after editing the MB data so the remaining data is either the newest or the one with the highest resolution. The checkered pattern is reduced.

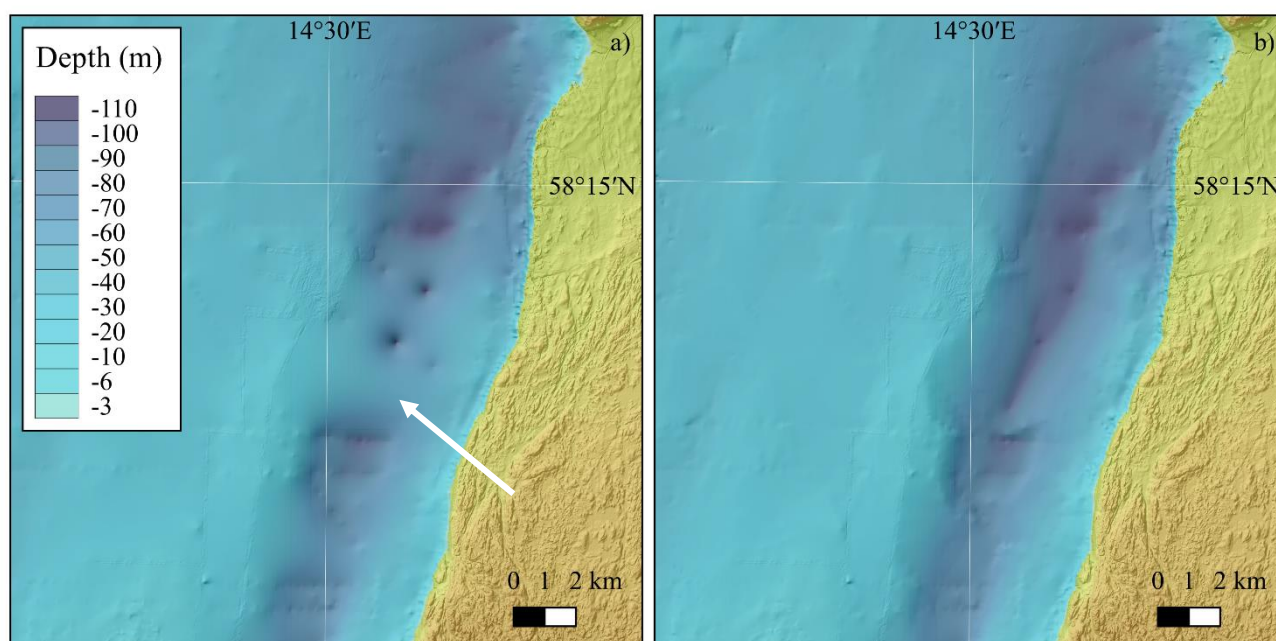


Figure 24. The difference before and after applying contour lines in SPT DBMs. a) DBM SPT 1.0 - In the initial grid a "bloated" lake floor is present (arrow) around the lake where data is sparse. b) DBM SPT 2.0 after applying contour lines every 10 m based of all data these "bloated" lake floors disappear and the grid becomes more congruent.

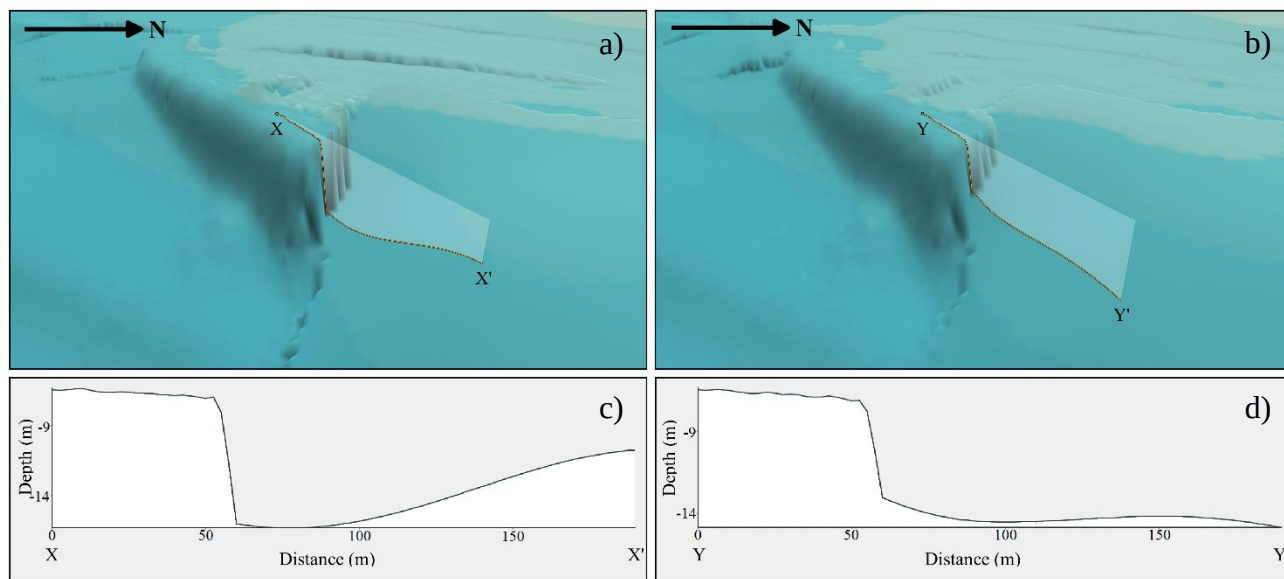


Figure 25. The border between the base grid and the data overlapped by the RR function north-east of the island Visingsö. a) DBM SPT 1.0 - The base grid (areas with depths around 7 m) was generated with S_I set to 100 m and FILT to 200m. An elevation difference is seen between the base grid and the RR data, so new variables for the base grid were chosen. b) DBM SPT 2.0 - The new base grid had S_I set to 75m (R_I to 75 m) and FILT to 150. This reduced the elevation difference. c) DBM SPT 1.0 - The elevation difference between the base grid and RR data in 19a was up to 9 m. d) DBM SPT 2.0 - with an altered base grid, the elevation difference between the base grid and the RR data in 19b was reduced, now differing up to 6 m.

depth nodes from new contour lines, now based on existing soundings only for the northern part of Lake Vättern, SDB excluded. The contour lines were produced as in 2.2.2, but instead contour lines were generated between 8-22 m depth, at 2 m intervals.

3.2.2 Delaunay Triangulation

Version 1

The DBM produced using Delaunay triangulation (TRI) is shown in Figure 21b. The DBM was gridded utilizing the same relevant variables as the v.1 SPT DBM.

The triangulation DBM portrays the deep area as the SPT DBM, but with a bathymetry that differs from the SPT grid. No “bloated” lake floor features are visible, with smoother increases in depth, but still choppy in some areas. The lake floor has triangular features, which are most evident in the northern half of the lake, with several angular features present as well. As in the DBM SPT 1.0, checkered patterns in the RR overlain data is present here as well.

Version 2

A new DBM, this time containing all the variables and files created for the v.2 SPT DBM was created using the triangulation method. The resulting grid is visible in Figure 22b. No larger changes in the bathymetry occurred, only that the new grid has a higher resolution. The added contour lines did not contribute greatly in this gridding method. The checkered pattern is reduced, like in the 2.0 SPT DBM, with some minor areas where it remains.

3.2.3 Nearest Neighbor

Version 1.0 - 1.3

When version 1.0 of the nearest neighbor (NN) grid was produced, large gaps were present. In order to grid the entire lake floor, the search radius was incrementally increased by 500: v.1.1 – 1000, v.1.2 – 1500, 1.3 – 2000. When the search radius was set to 2000, the DBM covered the lake (Fig 21c). Angular shapes can be found all over the lake, especially where there has been sparse data coverage. Terraced areas even more pronounced once the entire lake floor was interpolated.

No “bloated” areas exist in this DBM, but the same checkered pattern as the other v.1 DBMs.

Version 2

This iteration implemented the same variables as the second version of the other gridding functions, the result of which is seen in Figure 22c.

As in the other 2.0 grids, a deep area extending from the south of the lake towards the north along the eastern shore and veering north is visible. It is more defined now compared to the NN 1.3, with depth increases being smoother, due to the added contour lines. The angular nature of the NN grid is now more terraced, but represents the increase in depth similarly as the other 2.0 DBMs. Similarly, are also the extent of the areas with remaining checkered patterns.

3.2.4. DBM comparisons

When looking closer at a specific area (Figs. 26a-f), the differences between the different DBMs become clearer. In all the 1.0 DBMs, the northernmost part of Lake Vättern is represented similarly, by a flat lake floor poor in features, and a gradual increase in depth as you go south (inset in Fig. 26e). When you look at this area in the 2.0 DBMs, a more varied lake floor is visible. Shallower areas surround the islands, and the depths from the shoreline are more gradual, portraying deeper areas than in the 1.0 DBMs (inset in Fig. 26f).

When inspecting the larger deep area of this section of the lake, the portrayal of it differs more prominently between the DBMs. In DBM SPT 1.0 (Fig. 26a) “bloated” lake floor features with singular deep points are present. DBM SPT 2.0 (Fig. 26b) do not have this “bloated” feature, but do have clear angular features due to the contour lines. DBM TRI 1.0 portrays a very angular lake floor, but presents the changes in depth similarly as DBM SPT 2.0. The 2.0 DBM made from Delaunay triangulation (Fig. 26d) have a similar representation of the lake floor as 1.0, but the angular features are more uneven, almost choppy. DBM NN 1.0 (Fig. 26e) portrays heavily angular lake floor, becoming deeper in an uneven manner. The difference between 1.0 and 2.0 of the NN grid is clear, with terraced depths in the latter (Fig. 26f), and a lake floor depth progression similar to the other 2.0 DBMs.

The TRI and NN differ significantly from the SPT DBMs when it comes to how the shoreline is represented. When looking at the inset in Figures 26d, some narrows and areas between islands are presented as land in TRI and NN DBMs, while they are not so in the SPT DBMs (inset in Fig. 26b). When inspecting the shoreline more closely, you can see that part of the lake floor extends above the set lake level (Fig. 27 a), sometimes as much as 6 m (Fig. 27c). This figure portrays an area of DBM TRI 2.0, but the same features can be seen in the other NN and TRI DBMs. In Figure 27b the SPT DBM portrays no such lake floor features, with the elevation being smoother (Fig. 27d). Since the upper z value can be limited to the set lake level in the SPT function, no areas exceeding the level can be produced in the

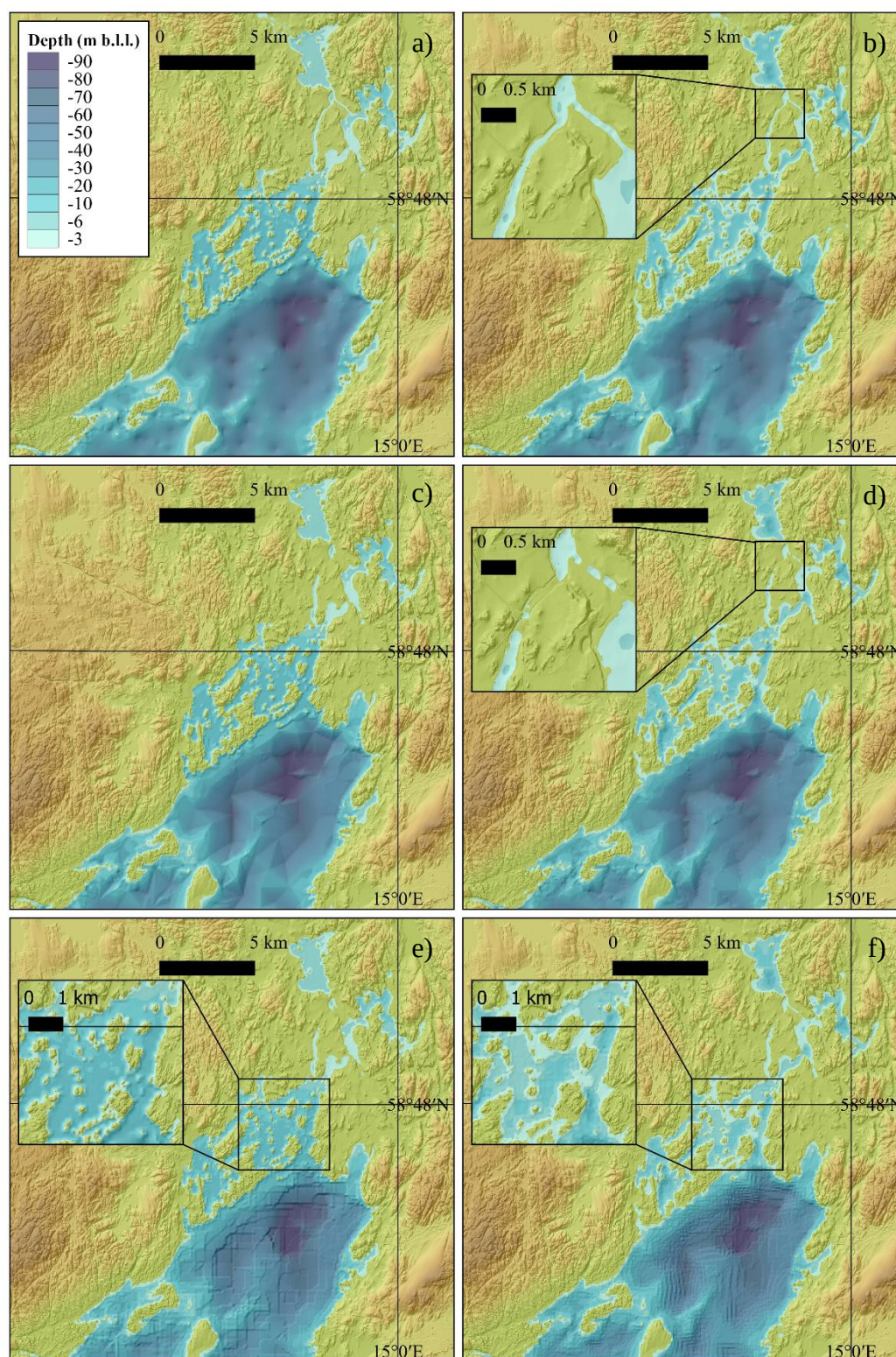


Figure 26. Northern part of the lake DBMs. a) DBM SPT 1.0 b) DBM SPT 2.0. Inset highlights how the shoreline is and narrow lake area are represented. c) DBM triangulation 1.0 d) DBM Triangulation 2.0. Inset highlights how the shoreline is and narrow lake area are represented. TRI 1.0, NN 1.3 and NN 2.0 have similar results e) DBM Nearest Neighbor 1.3. Inset highlights the gridding of the northernmost part of the lake based on SDB. A more uniform lake floor without gradual depth increases around islands and the shoreline is present. f) DBM Nearest Neighbor 2.0. Inset highlights the gridding of the northernmost part of the lake without the use of SDB. A more varying lake floor is present, with deeper areas, and shallower depths around the islands and near the shoreline.

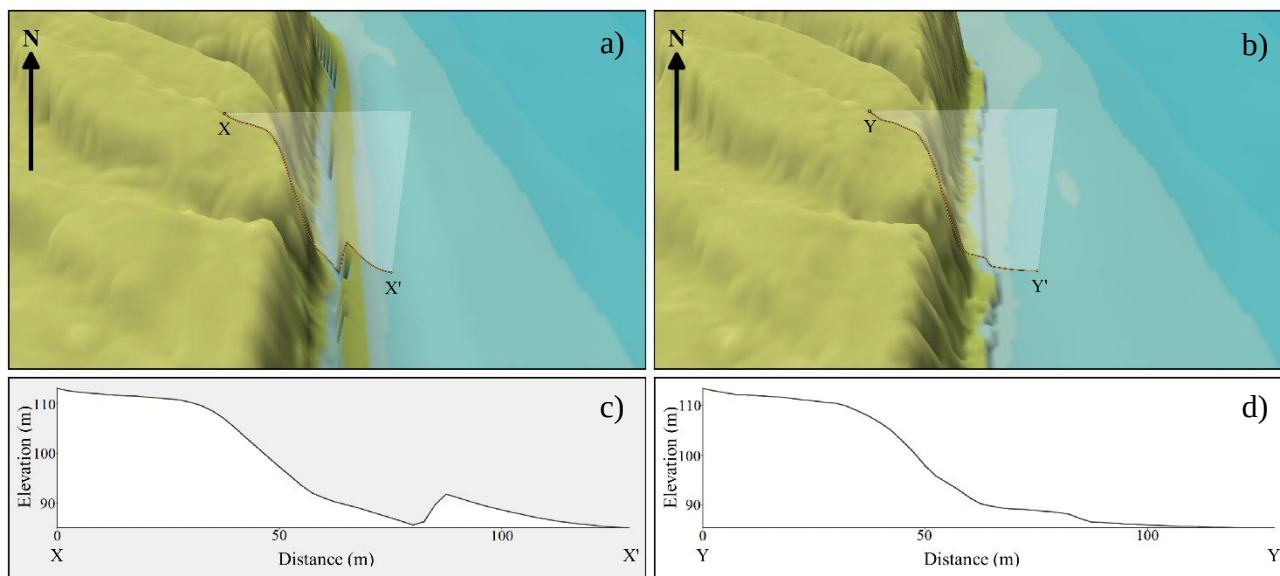


Figure 27. The shoreline accuracy compared between the triangulation and the SPT gridding. a) DBM TRI 2.0. The shoreline is badly constrained, due to the difference between the base grid and the RR step, that adds the high-resolution topography. b) DBM SPT 2.0. Since the upper z value can be elected in the SPT gridding method, it can constrain the shoreline and all elevation above the set lake level can be removed in the base grid. This creates a smoother shoreline when the RR data is overlain. c) Depth profile of the shoreline in DBM TRI 2.0. The elevated feature is 6 m shallower than the surrounding lake floor d) Depth profile of the shoreline in DBM SPT 2.0. Here no such elevated feature is present.

base grid process. The lower resolution of the base grid skews the location of the shoreline, which when overlain by the RR data creates this elevated feature.

3.2.5. Charted uncertainties

At three locations around Lake Vättern (white squares in Fig. 28; also in Fig. 22a) there were charted depths that were significantly shallower than the surrounding data. When gridded these created features that protruded from the general trend in the bathymetry. Another grid was made where these three uncertain charted soundings (UCS) were removed from the DBM SPT 2.0, resulting in DBM SPT 2.0 UR (Uncertainties removed). In Figures 29a-l the difference between the 2.0 DBM and the UR DBM can be seen.

At location 1, the UCS created a lake floor with a depth of 12.5 m (Fig. 29a+c). This elevated area is the only one that shallow, the neighboring soundings are at depths of ca 30-40 m. When removed the lake floor becomes more even (Fig. 29b), with a depth of around 42 m (Fig. 29d), a difference of above 29 m.

At location 2, a UCS has a depth of ca 28 m (Fig. 29g). 180 m south, SB data is present, which exhibits depths of 80 m or deeper, a difference exceeding 50 m. This created a shallow area in the DBMs (Fig. 29e), which extends the shallow area around the island of Jungfrun to the south-east. When this singular sounding is removed, this extended shallow area disappears (Fig. 29f), with the area having depth of about 55-80 m instead (Fig. 29f), and a more gradual depth difference.

Location 3 has a UCS at a depth of ca 39 m (Fig. 29k), with SB soundings around it. These soundings are at depths ranging from 70 to 100 m. In the DBMs this produced a singular elevated feature, significantly shallower than the surrounding area (Fig. 29i). Once this sounding was removed, the lake floor becomes smoother (Fig. 29j), with depths below 84 m (Fig. 29l).

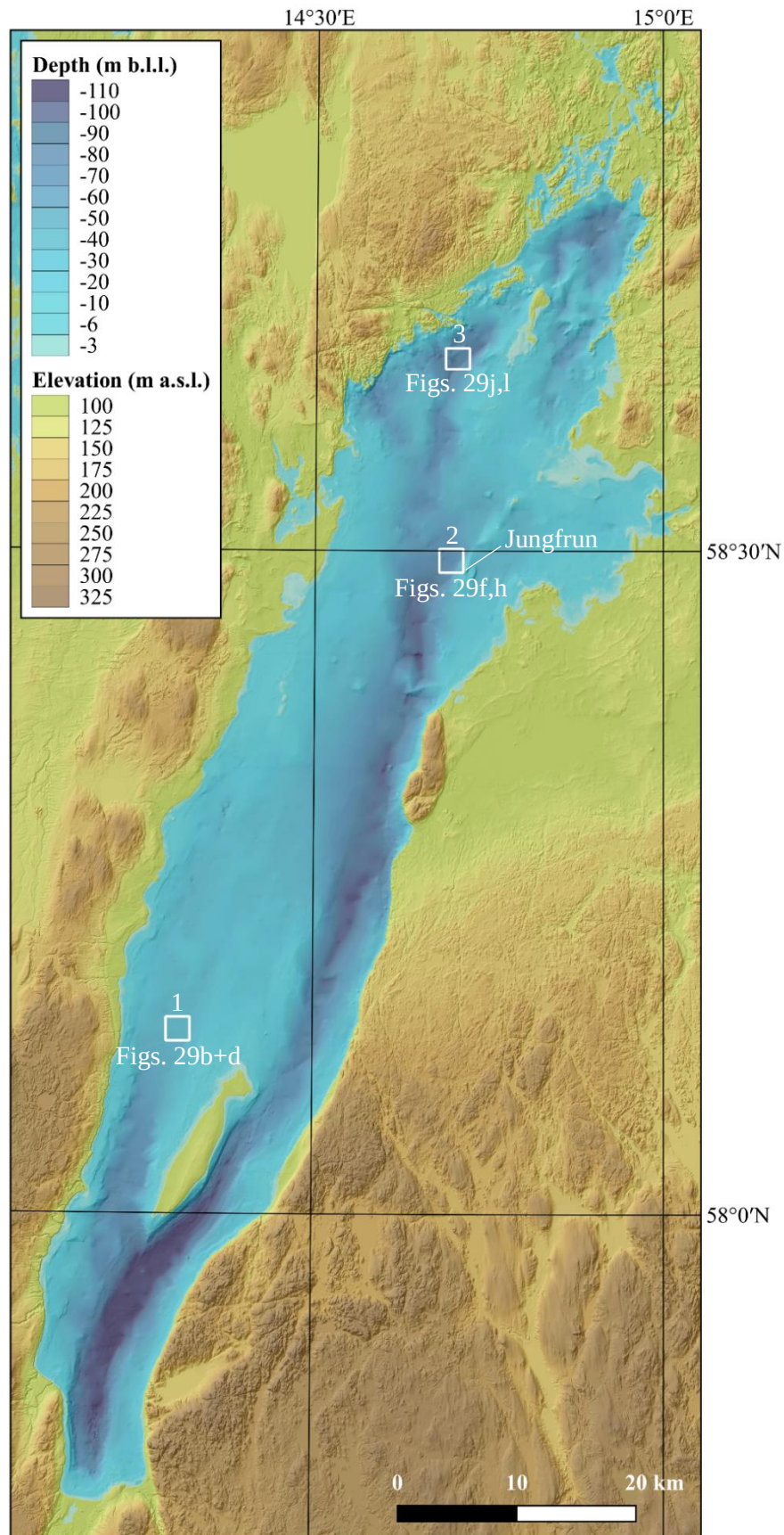


Figure 28. DBM SPT 2.0 UR. The three charted sounding uncertainties highlighted by white squares and numbered have been removed in this DBM. The three elevated features disappeared.

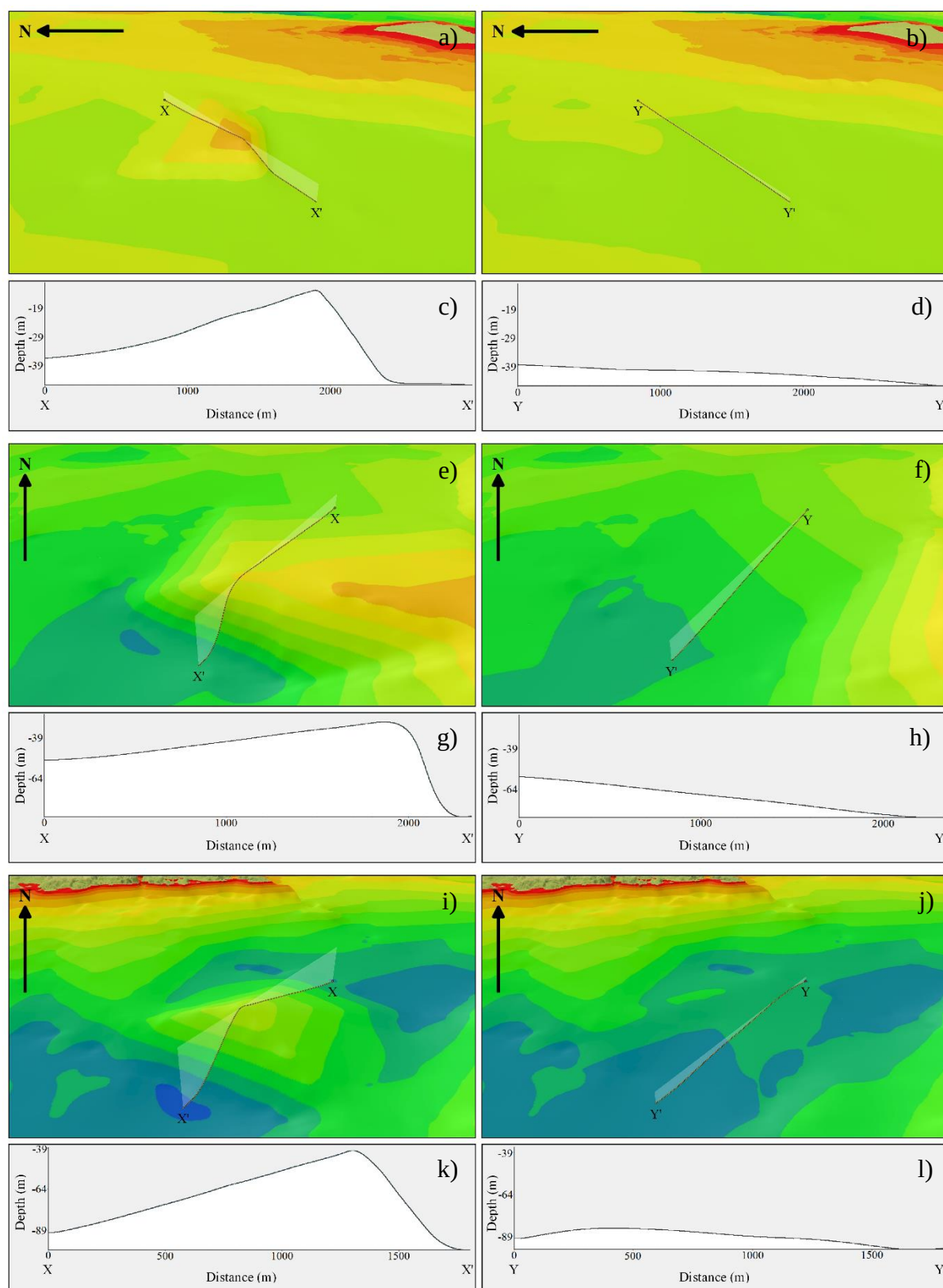


Figure 29. Three uncertain charted soundings (UCS), included in DBM SPT 2.0 and excluded in DBM SPT 2.0 UR (uncertainties removed) a) An elevated feature as a result of an UCS being included in the gridding. c) The elevation of the underwater hill rendered is 12.75 m. b) When the UCS is excluded in the UR version the area portrays no elevated feature d) With the UCS removed, the depth is 42 m, a difference of over 29m. e) An UCS west of the island Jungfrun was included in the gridding, rendering a shallow area extending west from the island. j) When the uncertain sounding is removed, the lake floor is smoother. k) Shallow feature with a depth of 39 m l) In the UR version of the grid this area has depths below 84 m.

3.2.6. Lake analysis

The DBMs representing Lake Vättern were analyzed with respect to physical dimensions and depth using the Fledermaus Surface difference Tool. The resulting areas, volumes, maximum depths and mean depths are listed in Table 5.

The areas calculated using the compiled DBMs in this thesis ranges between ca 1860 and 1888 km² depending on which DBM is used. The DBMs SPT 1.0, SPT 2.0 and SPT 2.0 UR have the largest calculated areas. These three vary slightly, with a range of 0.29 km². When looking at the areas within each gridding method, the area has generally become larger with the later DBM versions.

The DBM lake volumes range from ca 72.8 to 73.5 km³. DBM SPT 2.0 UR and DBM TRI 1.0 have the largest volumes. The volume of the lake is larger in the 2.0 DBMs compared to the earlier versions, except in the case of the triangulation DBMs, where it decreases.

The maximum depth of the DBMs do not vary much between them, with the mean being -117.61 m.

The mean depth in the DBMs lies between ca 38.6 and 39.6 m. The mean depth increases in the later versions, except for the TRI DBMs, where the opposite occurs.

Table 5. Lake analysis results from the Fledermaus Surface difference Tool.

DBM	Lake area (km ²)	Lake volume (km ³)	Max. depth (m)	Mean depth (m)
SPT 1.0	1887.96	72.84	117.64	38.58
SPT 2.0	1887.67	73.39	117.63	38.88
SPT 2.0 UR	1887.73	73.53	117.60	38.95
NN 1.3	1859.74	73.11	117.59	39.31
NN 2.0	1861.02	73.35	117.59	39.41
TRI 1.0	1862.22	73.51	117.64	39.47
TRI 2.0	1864.36	73.37	117.60	39.35

4. DISCUSSION

4.1 SATELLITE DERIVED BATHYMETRY

4.1.1 SDB extent

The extent to which satellite images can be used for shallow water mapping along the Lake Vättern shoreline was evaluated. The extinction depth, i.e. the max depth the method permits, limits the method and so does the quality of the derived depths. These two parameters are discussed here.

The extinction depths vary in different sections, between 12 m and 30 m (Table 2). These variations in extinction depth are due to a number of factors. For example, the maximum depth of the section and the time of year the image was taken, which affects the amount of turbidity and biological productivity in the water (Stewart & Martin, 1982), and the accuracy of the estimation of the extinction depth. The estimation is based on a visual inspection of where the trend changes in charted depths versus band satellite ratio, which leave room for interpretations (Fig. 6). The data did not always look as good as in Figure 6, which made it more difficult to estimate the extinction depth. Considering the SDB ranges, with maximum depths varying between 8 and 20 m (Table 2), the average maximum depth is 12 m. Since the SDB results in section I are poor, that SDB range can be omitted, giving a new average depth extent from the lake surface down to 11 m. When compared to the water transparency of Lake Vättern, which has a mean value of 11.6 m (Vatteninformationssystem Sverige, 2013), this depth extent is very reasonable.

4.1.2 SDB accuracy

The underlying reason for why the SDB failed to accurately portray the lake bottom in northern Lake Vättern could be that one of the major inlets to Lake Vättern is located in the north. A water inlet increases the turbidity that affects the SDB accuracy negatively (Pe'eri *et al.*, 2016), which makes the process of deriving bathymetry difficult. Vatteninformationssystem Sverige ([VISS], 2018) provides turbidity values of inlets to Lake Vättern, and many inlets with the higher turbidity values are located in sections where the R^2 values (see Table 2) are lower. This is the case for section I (Fig. 5). This supports the decision taken in this work to create a DBM without the SDB from this area.

The lake floor that was not estimated by the SDB in Figures 16a and 17a were the result of the SDB values being negative, the result of the ratios values being low. These were removed in the post-processing.

The accuracy of the SDB produced in this thesis compared to MB data was presented in 3.1.1. It should be noted that the SDB that overlaps the MB was not used to compile any of the DBMs. However, most of the SDB did not overlap MB and was therefore used. The general accuracy of the SDB not overlapping with MB is addressed through the contour line comparison between the SDB and charted depths. Besides for in the northernmost part of the lake, the generated depth contours follow each other quite well, suggesting that the SDB is not completely off. Properly constrained, and realizing the limits of the SDB, it can be used where no other data is available. However, the age and quality of the depth soundings digitized from nautical charts of Lake Vättern (Fig. 30a)⁴ imply that

⁴ The thematic map portraying the quality of the depth information of Lake Vättern was produced by using the Swedish Maritime Administration map service, available at <http://www.sjofartsverket.se/Snabblankar/Kartviewers/Sjofartsverkets-karttjanster/>

they do not meet hydrographic survey standards. Since the depths the SDB have been referenced to originate from these soundings there are inherited quality problems already to begin with. Figure 30b clearly reveals that the accuracy of the charted soundings used in the SDB vertical referencing is questionable.

4.1.3 SDB improvements

One way to improve the SDB is to choose satellite imagery with a higher resolution. Landsat 8 was used in this thesis due to the availability (cost-free), and that instructions for how to produce SDB by using Landsat 8 imagery were available (Pe'eri *et al.*, 2016). However, the 30 m resolution limits how precise the SDB can be, in turn influencing the size of lake floor features that can be analyzed in the final DBM. The ESA Sentinel Mission is another freely available image source with a 10 m resolution in selected bands (Drusch *et al.*, 2012). The WorldView2 satellite has multi-spectral imagery with 2 m resolution, although these are not free (Bramante *et al.*, 2013; Leder & Leder, 2017)

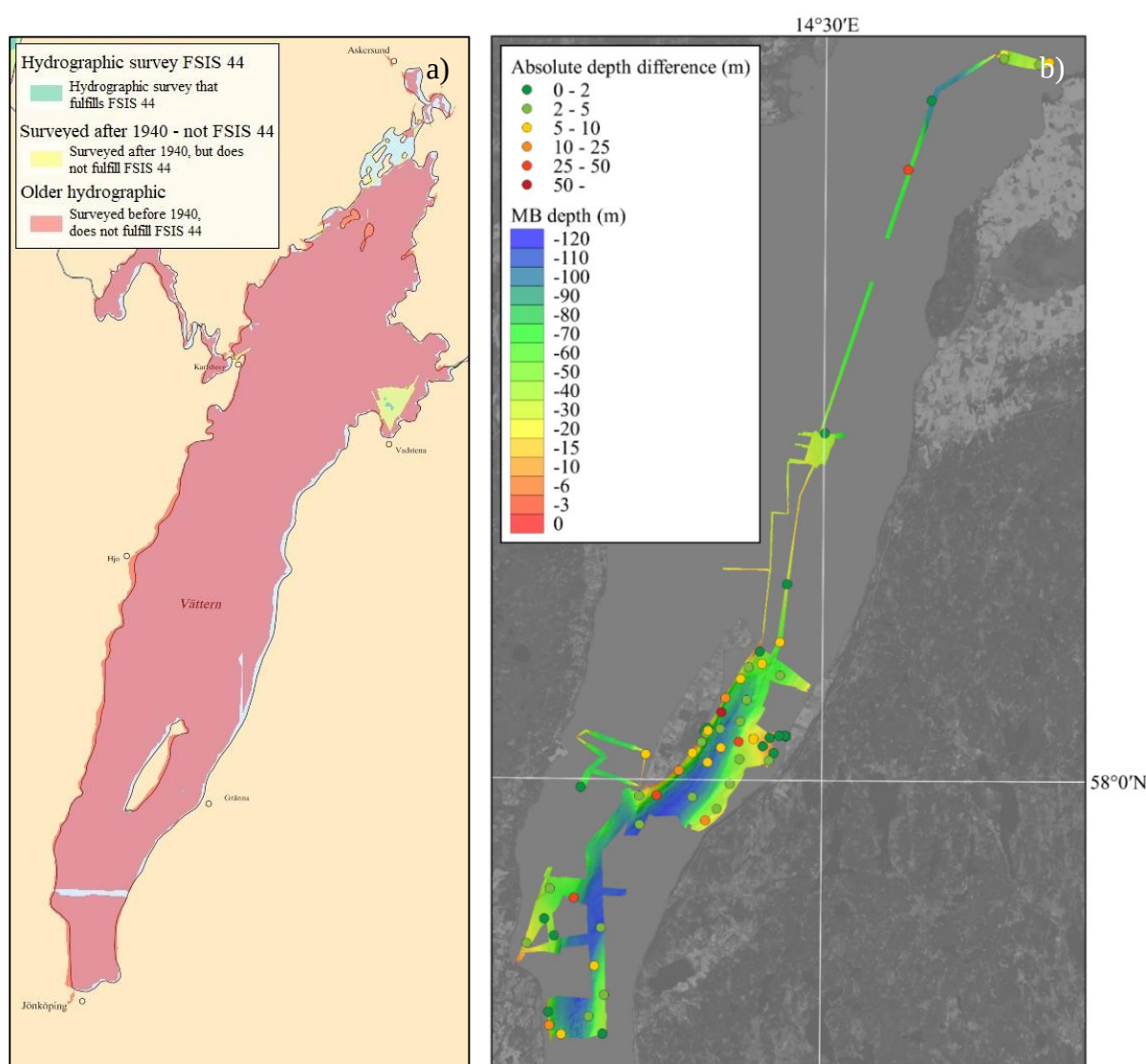


Figure 30. Figures portraying the uncertainty of the depths in the nautical charts. a) Map of the quality of the depth information in Lake Vättern⁴, how the charted depths fulfill the FSIS-44 standards. b) How much the charted depths differ from the MB surveyed depths. Absolute differences are portrayed, with some charted soundings differing to the MB more than 50 m. The actual sounding can be correct, but the positioning could be wrong.

Another way to improve the SDB is to better choose what scenes from a satellite that should be utilized. The time of year when the imagery was acquired influences the water attenuation of the light. Lake turbidity may also vary between seasons, with high turbidity during the spring due to turnover, high turbidity during the autumn due to mixing, and low turbidity during the summer and winter (Stewart & Martin, 1982). Ice cover and the low angle of the sun make it problematic to choose scenes from the winter, and algal blooms with accompanying increasing chlorophyll-a concentration increase the turbidity during the summer (Mavraeidopoulos *et al.*, 2017). However, according to VISS (2017; 2018) the water transparency in Lake Vättern does not generally vary much between seasons suggesting that the turbidity should not vary much either. If this is true it should not matter much when scenes were recorded, with respect to turbidity. Cloud cover and other aerosols is on the other hand problem. Depending on the size of the survey area, finding singular scenes that is completely cloudless is possible, but far not easy.

Another potential way to improve the SDB is to further optimize the vertical referencing procedure. The nautical charts from where the depths used to reference the SDB algorithm results originates were published in 1988, with some depths measured during the 1800's (SMA, 1988). Utilizing the most up to date nautical chart could be an improvement. Edition no. 9 of the nautical chart of Lake Vättern is available, which includes corrections made up to 2015-12-08. New nautical charts that will utilize an updated vertical datum which accounts for the isostatic uplift are being developed (H. Tengbert, personal communication, June 8 2018), that could further increase the confidence in SDB results. The SDB will always be limited by the quality of the depths they are referenced to. As seen in Figure 30a, the quality of the depth data in Lake Vättern is rather poor and most do not meet the latest more rigorous standards set by the IHO and Sweden in regards to safety of navigation. The SMA has likely not issued new nautical charts of Lake Vättern because there is a rather limited boating traffic. While SDB has been utilized in nautical charts (Mavraeidopoulos *et al.*, 2017), and Dekker *et al.* (2012, June) produced SDB that met IHO Orders 1a and 1b, there are questions raised if the uncertainties ever will be possible to lower enough to meet the highest IHO standards.

4.2 DIGITAL BATHYMETRIC MODEL

4.2.1 Lake analyses

The area of Lake Vättern varies slightly in different publications. The lake area is calculated to ~ 1893 km² by Jakobsson *et al.* (2014), and it is 1885 km² according to SMHI (2009), a rather small difference of about 0.4 %. The DBMs SPT 1.0, SPT 2.0 and SPT 2.0 UR yield areas close to these published values (Fig. 31). Here the actual calculation of the lake area excludes any area above the set lake level, implying that islands within the lake are not part of it, i.e. the calculated area is the water surface. Artefacts as seen in the Figure 26d inset are not present in the SPT grids, which increases the water surface and thus the calculated lake area. The larger lake areas in later DBM versions could be due to better portrayed depth trends, reducing artefacts around the shallow water areas. There are lake volumes published as well. The volume of Lake Vättern is estimated to 77.6 km³ by Swärd (2015), and 73.5 km³ by SMHI (2009). The calculated DBM lake volumes in this work are closer to the value by SMHI (2009), with DBM SPT 2.0 UR and DBM TRI 1.0 being the closest (Fig. 32). The larger volumes in later versions are most likely due to better constrained lake depths. DBM 2.0 UR has the largest volume since the shoreline artefacts present in the NN and TRI gridding methods do not occur, and that the artefacts from the previous version have been mostly addressed, with the “bloated” lake

floor feature prominently made the lake floor appear more shallow. The three UCS' were removed in the UR version as well, which additionally increases the lake volume.

Maximum depth of Lake Vättern is stated to be 120 m by SMHI (2009), and 119 m by Swärd (2015). Jakobsson *et al.* (2016) reported a maximum depth of 117 m where they MB mapped, which the maximum depth of the DBMs is nearest. Considering the data recorded by Jakobsson *et al.* (2016) is included in these DBMs, this is not surprising.

The mean depth is estimated to be 40 m by SMHI (2009). The DBMs that yield mean depths closest to the published mean depth are DBM TRI 1.0 and DBM NN 2.0 with 39.47 m and 39.41 m, respectively. In fact, rounded this is the same (40 m) as published by SMHI (2009). The SPT DBM mean depths are the lowest. This is due to the shoreline artefacts not being present in these. Since the other DBMs have fewer areas with shallow features that extend above the set lake level, the mean depth increases. The opposite occurs in the SPT DBMs, since these areas do not have artefacts and are seen as lake areas with shallow depths (Fig. 33).

When comparing the 2.0 versions of the DBMs, the SPT method seems to be the most accurate. No shoreline artefacts are present after utilizing this gridding method (Fig. 27b), and the lake floor has a smoother, more natural appearance at larger depths (Fig. 26b, d, f). The lack of shoreline artefacts and

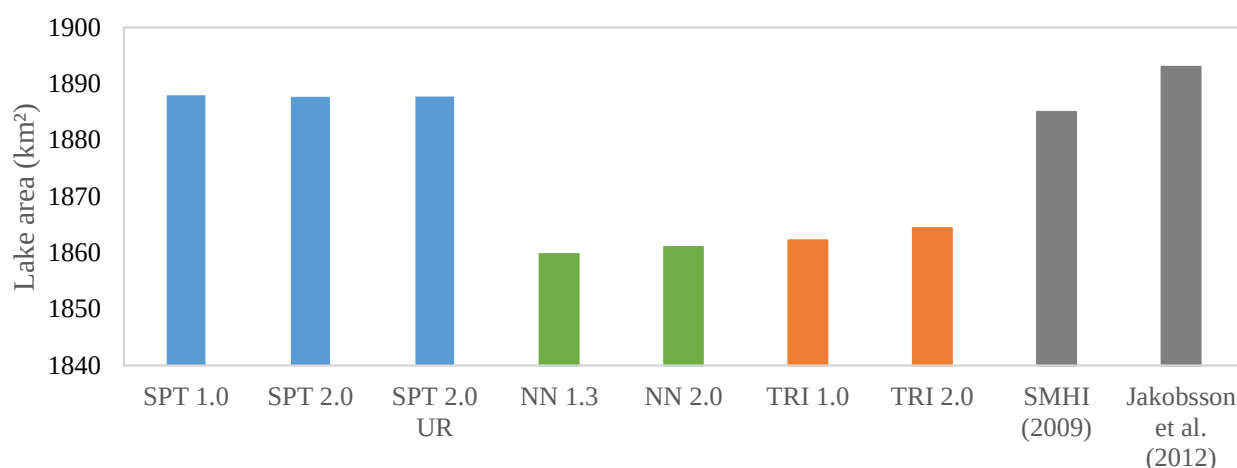


Figure 31. Bar chart of the calculated lake areas of the DBMs, as well as published values. The SPT DBMs yielded areas close to the published values.

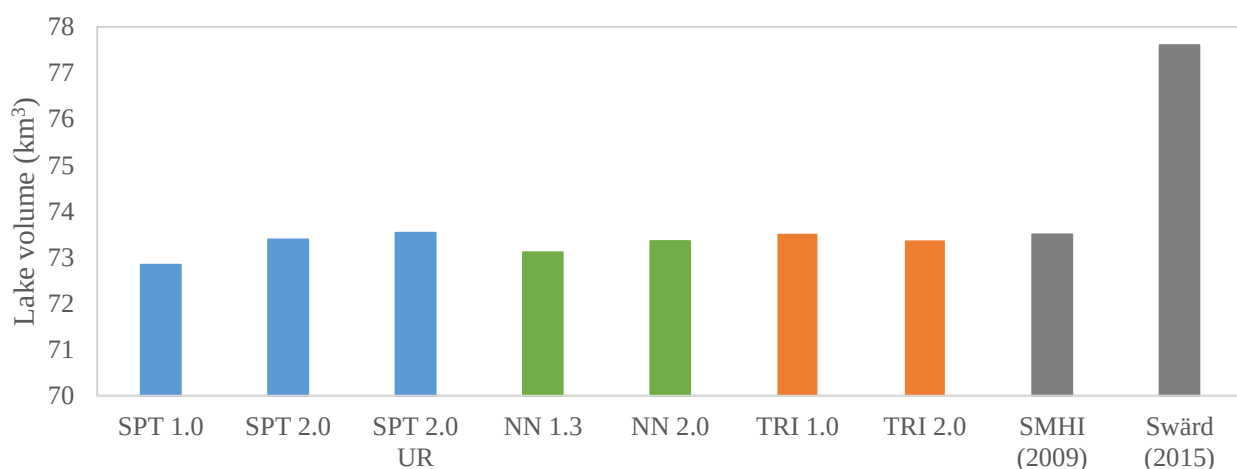


Figure 32. Bar chart of the calculated lake volumes of the DBMs, as well as published values. The DBM yielded volumes are more similar to the volume published by SMHI (2009) than by Swärd (2015).

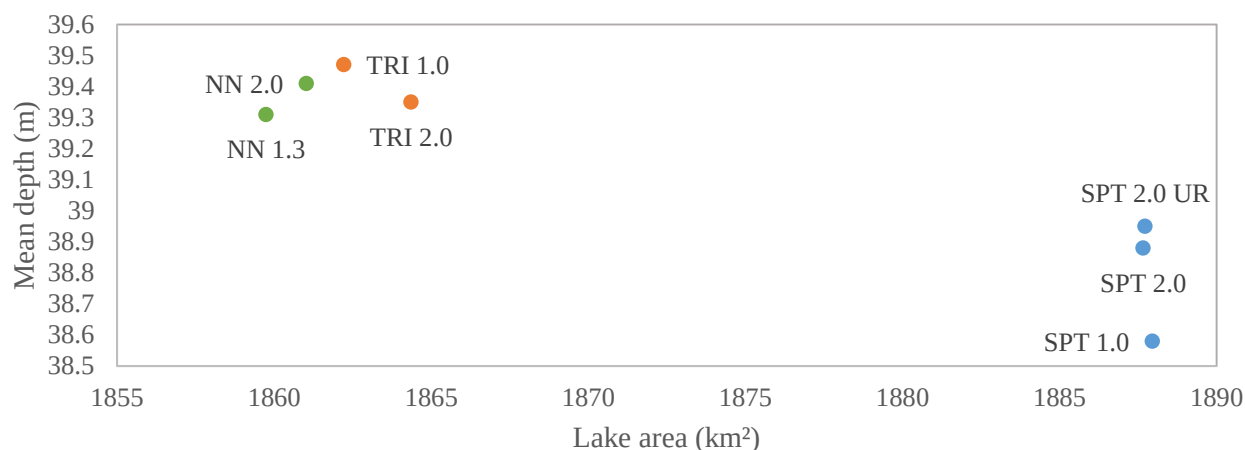


Figure 33. XY scatter chart of the yielded DBM lake areas and mean depths. The NN and TRI DBMs have yielded smaller lake areas, with corresponding higher mean depths. Since these DBMs have shoreline artefacts that extend above the set lake level, these are not included in the lake calculations. Thus the areas are smaller, and the mean depths are higher, since there are less shallow depths included in the mean depth calculations. Since the shoreline artefacts are not present in the SPT DBMs, more of the lake floor is present, leading to larger yielded lake areas and lower mean depths.

better constrained depths have yielded lake areas and volumes that are generally the closest to published values (Figs. 31 and 32). The mean depths are also close to the published value.

4.2.2 DBM input data quality

The quality of the data used to create the grid needs to be addressed as well. The SDB quality has been previously discussed, however, not in the context of forming a considerable source data contribution to the DBM. The finer lake floor structures in the SDB (Figs. 14-18) were visible at 30 m resolution. During the base-grid process, all data was filtered to a lower resolution (v. 1 – 100 m, v. 2 – 75 m), and later resampled to 5 m, increasing the resolution but remaining the same level of detail. In this stage a lot of detail in the initial data sets is lost, which is one of the reasons the RR process is included. The finer SDB structures are lost in the base grid, which reduces the accuracy of the final DBM.

The SB data were not collected to the same standards as the MB data. Proper metadata for the SB has not been available, forcing the estimation of the vertical referencing in some instances. A logical procedure was applied for this endeavor, but uncertainties still occur. The system utilized for the recording of soundings are in some cases only a “fisheries sonar”, which is quite inferior to proper SB transducers.

The MB is the most accurate data set, but is not without errors either. Several data sets are joined to create the MB data, and the borders between them are not always smooth or even. This creates artefacts, called offsets by Jakobsson *et al.* (2016), who also describe certain offsets as “flappy” outer beams, caused by inadequate sound speed control. “Flappy” offsets are present in the MB utilized in this thesis.

All land data was referenced to RH2000 with geoid model SWEN17. This includes the topographic data from Lantmäteriet. The MB data were also referenced to RH2000, but with geoid model SWEN08. Differences between these two geoid models occur over the Lake Vättern area (Lantmäteriet, 2018b), but as the difference is 4.5 cm at the most, and in areas where the lake is deep for the most part, no corrections were made.

The three depths highlighted as UCS (see 3.2.5.) were removed in one iteration of the final grid (DBM SPT 2.0 UR). When considering the age of some soundings, the inaccuracies of the charted depths, when looking at how the quality these depths stand up to hydrographic standards (Fig. 30a), but also compared to MB (Fig. 30b) it becomes feasible to remove them. It may be that the soundings were correct in regard to the measured depth, but the positions may be wrong. Bathymetric mapping of these areas is needed to estimate the validity of these uncertainties. Due to the uncertainty of these soundings, DBM SPT 2.0 UR was selected as the final model.

4.2.3 DBM improvements

Even though the gridding artefacts are the least occurring in the SPT DBM, there are still artefacts present. The contour lines used to better constrain the depth procession created clear angular features. The best way to reduce these artefacts is to reduce the need for the contour lines in the first place. This can be performed by further bathymetric mapping. The charted depths, both spot soundings and contour lines, were utilized only where data was too sparse, and the hope is that in the future they will no longer be needed, like one of the aims of the IBCAO (Jakobsson *et al.*, 2016).

The elevation difference between the base grid and the RR data is quite severe in some areas. The increased resolution by changing the blockmedian filter bin size from 100 m to 75 m reduced this, but not entirely. The high-resolution MB data overlain improves the detail of the grid, so the trade-off is something that needs to be taken into consideration. Further gridding with higher resolution could reduce these differences, but the risk of artefacts increases as well. A resolution where these two factors are at their most favorable may exist, but more testing is required to either refute or prove this. Another variable to be tested is the T (tension parameter) as well. IBCAO 3.0 utilized T values ranging from 0.32 to 0.4. While several different T values were attempted in this thesis, it was not investigated enough. Wessel *et al.* (2018) recommend a T value of ~ 0.35 for steep topography/bathymetry. More testing is required to find the best T value.

The difference between the geoid models in RH2000 were not corrected in this thesis. Maps of the differences are available (Lantmäteriet, 2018b), so for an upcoming iteration of the Lake Vättern DBM, this could be performed. By using data with a higher initial resolution, the need for low grid and bin cell sizes in the gridding process, in order to reduce the risk of artefacts, will decrease. Since the SDB has the lowest resolution, the best way to improve the resolution of the final DBM, is to use satellite imagery with higher resolution.

5. CONCLUSIONS

By using bathymetric data from multi-, and single-beam echo sounders, charted soundings, Satellite Derived Bathymetry, and topographic data, Digital Bathymetric Models of Lake Vättern were produced. The general bathymetric trend was similar in the 2.0 versions, but artefacts due to the gridding method were too profound in the triangulation and nearest neighbor versions. The limitations in the gridding of Delaunay triangulation and Nearest neighbor created misrepresented shorelines, with lake areas between islands, and narrows being gridded with elevation above the set lake level, and mapped as land. The lake floor interpolated through the SPT method was smooth, while the Delaunay triangulation created an angular lake floor, while the nearest neighbor DBMs were heavily terraced. The DBM SPT 2.0 UR was selected as the most accurate.

The DBMs could be analyzed for lake area, volume, maximum depth, and mean depth. These values were heavily influenced by the limitations of the gridding methods, and artefacts created from sparse data coverage. The calculated area was affected by all lake areas mistakenly gridded as land, reducing the actual lake area. The volume was also affected by these artefacts, as well as a poorly constrained lake floor, which created an erroneous volume. Contour lines reduced this, but the terracing or angular features of the second DBM versions influenced the volume still. The maximum depth is the analytical value least affected by artefacts, thanks to most of the the deepest parts of the lake being properly mapped by MB echo sounders. However, a wrongly decided tension parameter can create areas that exceed the maximum depth, and if the maximum depth is not already mapped, it will not be properly represented by the Delaunay triangulation nor the nearest neighbor gridding methods. The mean depth is affected by all inaccuracies of the lake floor gridding, where lake areas gridded as land increases the mean depth, since fewer shallow areas are present.

The use of satellites to estimate bathymetry is an effective tool in areas otherwise difficult to survey. In Lake Vättern the SDB could be utilized for depths between 0-11 meters, but the uncertainty in the data can be up to ± 7 m. The majority of the SDB does not meet the requirements of S-44 orders, but can be accurate enough for a rough estimation of the lake floor.

The DBM of Lake Vättern is a first effort to represent the bathymetry of Sweden's second largest lake. Further mapping of the lake is necessary to better represent the lake floor, and tweaks in the gridding variables can reduce the elevation difference between the base grid and overlain data. The shoreline can be better estimated from SDB made from higher resolution satellite imagery that is taken at the time of the year when the lake water is as clear as possible. This will also lead to a DBM with higher resolution, since the need to use lower resolution to reduce the risk of gridding artefacts will not be as urgent.

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APPENDIX A, NMEA EXTRACTION SCRIPT

```

1.  #Program that reconfigures nmea data so you get a new file with coordinates and depth
2.  import math                                #Imports math functions
3.  ans=True
4.  while ans:
5.      print ("""
6.      1.Convert and create output list
7.      2.Convert and append to output list
8.      3.Exit/Quit
9.      """)
10.  ans=raw_input("What would you like to do? ")
11.  if ans=="1":
12.      newdata = raw_input("Enter filename you wish to convert: ")
13.      converted = raw_input("Enter filename of converted data: ")
14.      in_file = open(newdata, "r")           #Reads the file with data into program
15.      out_file = open(converted, "w")        #Makes a new file that data is put into
16.      while True:                            #Goes through all lines
17.          in_line = in_file.readline()
18.          if not in_line:
19.              break
20.          if in_line.startswith("$GPGGA"):    #Picks lines that start with '$GPGGA'
21.              in_line2 = in_line.split(",")  #Splits lines into a list, to be able to use spcific parts
22.              if in_line2[3] == []:
23.                  pass
24.              elif in_line2[3] == "S":        #Stored data made either positive (N) or negative (S)
25.                  in_line2[2] = -float(in_line2[2])
26.              if in_line2[5] == []:
27.                  pass
28.              elif in_line2[5] == "W":        #Stored data made either positive (E) or negative (W)
29.                  in_line2[4] = -float(in_line2[4])
30.              x = in_line2[2]                 #Picks latitude from list
31.              y = in_line2[4]                 #Picks longitude from list
32.              if not x:
33.                  pass
34.              elif not y:
35.                  pass
36.              else:
37.                  DD = float(x[0:2])          #Reconfigures the latitude data from DDMM.MMMMM to DD.DDDDD
38.                  mm = float(x[2:10])
39.                  MM = mm/60
40.                  lat = DD+MM
41.                  EE = float(y[0:3])          #Reconfigures the longitude data from ddmm.mmmmm to dd.ddddd
42.                  nn = float(y[3:11])
43.                  NN = nn/60
44.                  lon = EE+NN
45.          if in_line.startswith("$SDBT"):    #Picks lines that start with '$SDBT'
46.              in_line3 = in_line.split(",")
47.              if not x:
48.                  pass
49.              elif not y:
50.                  pass
51.              elif not in_line3[3]:
52.                  pass
53.              elif in_line3[3] == "M":
54.                  pass
55.              else:
56.                  dbt = -
                    (float(in_line3[3])+0.2)    #Picks out the depth below transducer. The 0.2 added is the depth below the water surface the t
                    ransducer is located.
57.                  out_file.write("%0.6ft%0.6ft%0.2ft \n"%(lon,lat,dbt))
58.
59.          in_file.close()                    #Closes input file
60.          out_file.close()                  #Closes output file
61.      elif ans=="2":

```

```

62. newdata = raw_input("Enter filename you wish to convert: ")
63. converted = raw_input("Enter filename to append data: ")
64. in_file = open(newdata, "r")      #Reads the file with data into program
65. out_file = open(converted, "a")   #Makes a new file that data is put into
66. while True:                      #Goes through all lines
67.     in_line = in_file.readline()
68.     if not in_line:
69.         break
70.     if in_line.startswith("$GPGGA"): #Picks lines that start with '$GPGGA'
71.         in_line2 = in_line.split(",") #Splits lines into a list, to be able to use spcific parts
72.         if in_line2[3] == []:
73.             pass
74.         elif in_line2[3] == "S":      #Stored data made either positive (N) or negative (S)
75.             in_line2[2] = -float(in_line2[2])
76.         if in_line2[5] == []:
77.             pass
78.         elif in_line2[5] == "W":      #Stored data made either positive (E) or negative (W)
79.             in_line2[4] = -float(in_line2[4])
80.         x = in_line2[2]               #Picks latitude from list
81.         y = in_line2[4]               #Picks longitude from list
82.         if not x:
83.             pass
84.         elif not y:
85.             pass
86.         else:
87.             DD = float(x[0:2])         #Reconfigures the latitude data from DDMM.MMMMM to DD.DDDDD
88.             mm = float(x[2:10])
89.             MM = mm/60
90.             lat = DD+MM
91.             EE = float(y[0:3])         #Reconfigures the longitude data from ddmm.mmmmm to dd.ddddd
92.             nn = float(y[3:11])
93.             NN = nn/60
94.             lon = EE+NN
95.         if in_line.startswith("$SDDBT"): #Picks lines that start with '$SDDBT'
96.             in_line3 = in_line.split(",")
97.             if not x:
98.                 pass
99.             elif not y:
100.                 pass
101.             elif not in_line3[3]:
102.                 pass
103.             elif in_line3[3] == "M":
104.                 pass
105.             else:
106.                 dbt = (float(in_line3[3])+0.2) #Picks out the depth below transducer. The 0.2 added is the depth below the
water surface the transducer is located.
107.                 out_file.write("%0.6ft%0.6ft%0.2ft \n"%(lon,lat,dbt))
108.
109.     in_file.close()                 #Closes input file
110.     out_file.close()               #Closes output file
111.     if ans=="3":
112.         print("\n Goodbye")
113.         break
114.     elif ans != "":
115.         print("\n Not Valid Choice Try again")

```

APPENDIX B, BASE GRID SCRIPT

```

1.  #- coding: cp1252 -*-
2.  #####
3.  # "Stage 1: generating a base grid for Lake Vattern Version 1.0"
4.  ##
5.  # This script contains the procedure used in stage 1 of the IBCAO 3.0 grid generation process. It covers the generation
6.  # of a base grid based on all the available bathymetric source data. Stage 2 of the process involves adding high density
7.  # data on top of the base grid using the 'remove-restore' procedure. This is covered in a separate script.
8.  # The script has been modified in order to properly function on Lake Vättern, a lake in the south central of Sweden.
9.  # Modifications include proper variables for the area and conversion of elevations to MSL.
10. ##
11. # The script will perform the following:
12. # 1. Setup of variables
13. # 2. Creation of file list for input to gridding
14. # 3. Check data consistency and merge files
15. # 4. Segment the data set into regions to handle large data amounts with GMT "blockmedian".
16. # 5. Block median filtering
17. # 6. Merge block median filtered segments into one file
18. # 7. Gridding, crop, filter, and resampling
19. # 7.1. Gridding using surface.
20. # 7.2. Crop and filter the grid
21. # 7.3 Resampling of the grid.
22. ##
23. # Written by Martin Jakobsson; and modified by Alexander Backstrom
24. # Department of Geological Sciences
25. # Stockholm University
26. ##
27. # September 23, 2012; and January 27, 2018
28. #####
29. from __future__ import division #This line includes the true division avoiding problems with unwanted floor division
30. import fileinput
31. import os
32. #####
33. # 1: Setup of variables
34. #####
35. Cint=0 #Counter for loop in section 3
36. DIRstr='D:\Alexander_Backstrom\Examensarbete\DBM\Gridding_files_MSL\' #Path to data files
37.
38. DATAstr='DBMinput.xyz' #Main file holding the source data for gridding. It consists of a merge of all input files.
39.
40. # GMT input variables
41. BM_I='75' # Blockmedian filter bin size, this should be the same as will be used for the gridding work,
42. BM_R='445300/503150/6401600/6528100' #Blockmedian region set for GMT. This is the regional set in UTM zone 33N
    coordinates for the DBM gridding.
43. # The user must change this to the appropriate region for the task. It could be set in any coordinate system or lat lon if a
44. # geographic grid is created. Note that this region should extend slightly outside of the final grid boundaries to account for edge effects.
45. BM_R1='477650/503150/6464850/6528100' #Region 1 for subset tiling. This tiling is only required for very large data sets (
    100 million soundings or more).
46. BM_R2='477650/503150/6401600/6464850' #Region 2 for subset tiling
47. BM_R3='445300/477650/6401600/6464850' #Region 3 for subset tiling
48. BM_R4='445300/477650/6464850/6528100' #Region 4 for subset tiling
49. # Output files from the subset tiling
50. R1='R1.xyz'
51. R2='R2.xyz'
52. R3='R3.xyz'
53. R4='R4.xyz'
54. # Output files from the Blockmedian filtering of the different regions
55. BM_OUTPUT1='OUTFILE_BM1.xyz'
56. BM_OUTPUT2='OUTFILE_BM2.xyz'
57. BM_OUTPUT3='OUTFILE_BM3.xyz'
58. BM_OUTPUT4='OUTFILE_BM4.xyz'
59. BM_OUTPUT='OUTFILE_BM.xyz' #Output file of the entire region

```

```

60. S_I='75' #Gridding cell size.
61. R_I='5' #Resampling grid size
62. FILT='150' #Filter size for smoothing (double the gridding cell size).
63. S_T='0.32' #Tension parameter, for use with GMT's surface
64. N_I='1500' #Max iterations in each gridding cycle. Default is set to 250
65. LU='88.97' #Value constraining the upper limit of the grid, upper z range.
66. n='+c' #Ensures the z-min/max of output grid does not exceed input grid values.
67. N_S=4 #Sectors for dividing search radius
68. S_R='1500' #Search radius.
69. S_grd_out='out_grd.grd' #Grid output file, unfiltered
70. CUT_R='445300/503150/6401600/6528100' #Geographic region of the final grid
71. CUT_grd_out='out_grd01.grd' #Cropped grid
72. FILT_grd_out='filt_grd01.grd' #Filtered grid
73. RESAMP_grd_out='resamp_grd01_NI1500_LU88.53_RI5m_3.0_final.grd' #Resampled grid at the spacing set by R_I
74. #####
75. # Point 2: Creation of filelist for input to the gridding procedure
76. # Note that there is not a separation of the data here into different categories, this is done in the remove-restore procedure
77. #####
78. # Input files are listed below, for additional files increase the list
79. FILElist=['20160920_UTM33N_31_out22.xyz', '20161108_UTM33N_32_out21.xyz', '20170320_UTM33N_33_out20.xyz',
80.           '20170824_UTM33N_34_out19.xyz', 'contourlines_dynamicsurface_lc_soundings_10-110m_3.0.xyz',
81.           'djupdata_vattern_slu-2007-2009_UTM33N_xyz_35_out18.xyz', 'Djupdata28kHzPinger_Vattern-P28-
82.           88.5m_UTM33N_88.5_36_out17.xyz', 'DRILL-1_CUBE-c_2m_negative_1_out17_4_out0.xyz',
83.           'DRILL-VIS-Trans1_CUBE_3m_negative_2_out16_5_out4.xyz', 'DRILL-VIS-
84.           Trans2_CUBE_2m_negative_3_out15_6_out3.xyz', 'Jungfrun_negative_45_out15_55_out5.xyz', 'sec1bEx_14aug_LPF_30m
85.           _MSL_0-13_37_out16.xyz',
86.           'sec1bWx_may_LPF_20m_MSL_0-8_38_out15.xyz', 'sec1W_mar_LPF_15m_MSL_0-
87.           11_39_out14.xyz', 'contourline_sec1ax_DBM_CL_8-22m_2_out0.xyz', 'sec2E_23aug_LPF_12m_MSL_0-
88.           9_MB2_40_out0.xyz',
89.           'sec2W_23aug_LPF_15m_MSL_0-10_41_out12.xyz', 'sec3aW_jun_LPF_20m_MSL_0-
90.           10_MB_42_out11.xyz', 'sec3bW_may_LPF_18m_MSL_0-12_MB_43_out10.xyz', 'sec3E_may_LPF_19m_MSL_0-
91.           12_MB3_44_out0.xyz',
92.           'sec4.2_23aug_LPF_15m_MSL_0-10_45_out8.xyz', 'sec5_feb_LPF_20m_MSL_0-
93.           12_MB4_46_out7.xyz', 'strandlinje_3m_6m_UTM33N_NEW_49_out0.xyz', 'VIS-Granna-N-
94.           CUBE_2m_negative_9_out9_8_out0.xyz',
95.           'VIS-Granna-NS_5m_negative_10_out8_9_out0.xyz', 'VIS-Granna-SWA-5m-
96.           e_int2008_negative_12_out6_13_out0.xyz', 'VIS-N2_negative_49_out13_57_out3.xyz', 'VIS-
97.           SW1_Cube2m_84_out12_58_out2_2_out6.xyz',
98.           'VIS-
99.           W1_Cube2m_85_out11_59_out1.xyz', 'xyz_coordinates_UTM33N_neg_63_out0.xyz', 'contourlines_DynamicSurface_LC_so
100.          undings_2.2_secY_22.5-67.5m.xyz',
101.          'vattern_topo_nolake_MSL_UTM33N_2.0_north.xyz', 'vattern_topo_nolake_MSL_UTM33N_2.0_mid.xyz', 'vattern_t
102.          opo_nolake_MSL_UTM33N_2.0_south.xyz']
103.
104. print FILElist
105. #####
106. # Point 7: Gridding, crop, filter and resampling
107. #####
108. def grid():
109.     #####
110.     # 7.1a. Grid the data using GMT surface (SPT Interpolation)
111.     os.system('surface %s\\%s -R%s -I%s -N%s -T%s -G%s\\%s -Lu%s -
112.     V' % (DIRstr, BM_OUTPUT, BM_R, S_I, N_I, S_T, DIRstr, S_grd_out, LU))
113.     #####
114.     # 7.1b. Grid the data using GMT triangulate (Delaunay Triangulation)
115.     os.system('triangulate %s\\%s -R%s -I%s -G%s\\%s -V' % (DIRstr, BM_OUTPUT, BM_R, S_I, DIRstr, S_grd_out))
116.     #####
117.     # 7.1c. Grid the data using GMT nearneighbor (Nearest Neighbor)
118.     os.system('nearneighbor %s\\%s -R%s -I%s -N%s -G%s\\%s -S%s -
119.     V' % (DIRstr, BM_OUTPUT, BM_R, S_I, N_S, S_T, DIRstr, S_grd_out, S_R))
120.     #####
121.
122. # 7.2. Crop and filter the grid
123. os.system('grdcut %s\\%s -R%s -G%s\\%s' % (DIRstr, S_grd_out, CUT_R, DIRstr, CUT_grd_out))
124. os.system('grdfilter %s\\%s -G%s\\%s -R%s -D0 -
125. Fc%s' % (DIRstr, CUT_grd_out, DIRstr, FILT_grd_out, CUT_R, FILT))

```



```

108. #####
109. # 7.3 Resampling of the DBM grid
110. os.system('grdsample %s\\%s -G%s\\%s -R%s -I%s -
V' % (DIRstr, FILT_grd_out, DIRstr, RESAMP_grd_out, CUT_R, R_I))
111. #####
112. exit()
113. #####
114. # Point 3: Check the data for consistency (no empty lines or large outliers) and file merge
115. #####
116. F=open(r'%s\\%s' % (DIRstr,DATAstr), 'w+')
117. print 'input file directory %s\\n' % (DIRstr)
118. print '1. The following files will be scanned and checked for consistency\\n'
119. print '%s' % (FILElist)
120.
121. while Cint <= len(FILElist)-1:
122.     G=open('%s%s' % (DIRstr,FILElist[Cint]), 'r' )
123.     while 1:
124.         line=G.readline()
125.         line_items=line.split()
126.         if not line:break
127.         if len(line_items) == 3:
128.             elev = float(line_items[2])
129.             if elev <= 10: #Converts all values below or equal to 10 to RH2000, so all data points are referenced equally
130.                 elev2 = elev+88.97
131.                 new_line = str(line_items[0]),str(line_items[1]), str(elev2)
132.                 line = ",".join(new_line)
133.                 F.write(str(line) + '\\n')
134.
135.         Cint +=1
136.     G.close()
137. F.close()
138. #####
139. # Point 4: Segment the data set into regions to handle large data amounts with GMT "blockmedian"
140. #####
141. os.system('set EMM=RAM')
142. os.system('set dos=high, umb')
143. os.system('gmtselect -R%s -V %s\\%s > %s\\%s' % (BM_R1,DIRstr, DATAstr, DIRstr, R1))
144. os.system('gmtselect -R%s -V %s\\%s > %s\\%s' % (BM_R2,DIRstr, DATAstr, DIRstr, R2))
145. os.system('gmtselect -R%s -V %s\\%s > %s\\%s' % (BM_R3,DIRstr, DATAstr, DIRstr, R3))
146. os.system('gmtselect -R%s -V %s\\%s > %s\\%s' % (BM_R4,DIRstr, DATAstr, DIRstr, R4))
147. #####
148. # Point 5: Block median filtering
149. #####
150. os.system('set EMM=RAM')
151. os.system('set dos=high, umb')
152. os.system('blockmedian -R%s -I%s -V -Q %s\\%s > %s\\%s' % (BM_R1,BM_I, DIRstr, R1, DIRstr, BM_OUTPUT1))
153. os.system('blockmedian -R%s -I%s -V -Q %s\\%s > %s\\%s' % (BM_R2,BM_I, DIRstr, R2, DIRstr, BM_OUTPUT2))
154. os.system('blockmedian -R%s -I%s -V -Q %s\\%s > %s\\%s' % (BM_R3,BM_I, DIRstr, R3, DIRstr, BM_OUTPUT3))
155. os.system('blockmedian -R%s -I%s -V -Q %s\\%s > %s\\%s' % (BM_R4,BM_I, DIRstr, R4, DIRstr, BM_OUTPUT4))
156. #####
157. # Point 6 in the explanation. Merge all the block median data into one file
158. #####
159. I=open(r'%s\\%s' % (DIRstr,BM_OUTPUT), 'w+')
160. H=open('%s%s' % (DIRstr,BM_OUTPUT1), 'r' )
161. while 1:
162.     line=H.readline()
163.     if not line: break
164.     I.write(line)
165. H.close()
166.
167. J=open('%s%s' % (DIRstr,BM_OUTPUT2), 'r' )
168. while 1:
169.     line=J.readline()
170.     if not line: break
171.     I.write(line)
172. J.close()

```

```
173.
174. K=open('%s%s' % (DIRstr,BM_OUTPUT3), 'r' )
175. while 1:
176.     line=K.readline()
177.     if not line: break
178.     I.write(line)
179. K.close()
180.
181. L=open('%s%s' % (DIRstr,BM_OUTPUT4), 'r' )
182. while 1:
183.     line=L.readline()
184.     if not line: break
185.     I.write(line)
186. L.close()
187.
188. I.close()
189. #####
190. # Point 7 in the explanation, see function in the beginning of the script.
191. #####
192. grid()
193.
```

APPENDIX C, REMOVE RESTORE SCRIPT

```

1.  #- coding: cp1252 -*-
2.  #####
3.
4.  # "Stage 2: Remove-restore for DBM Lake Vattern Version 1.0"
5.  ##
6.  # This script is stage 2 in the procedure used in generating IBCAO 3.0 from the GEBCO Cook Book. It uses embedded GMT
   routines.
7.  # The script uses a number of variables which are setup in Point 8. These variables were modified to match this gridding
   project.
8.  ##
9.  # The script will perform the following:
10. # 8. Setup of the variables
11. # 9. Creation of an input file for gridding
12. # 10. Segment the data into regions to handle large data amounts with GMT "blockmedian"
13. # 11. Block median filtering
14. # 12. Merge block median filtered segments into one file
15. # 13. Find the depth in the 'base grid' at the location of the block median filtered data points
16. # 14. Compute the difference in z-values between the block median data and the base grid
17. # 15. Create a difference grid
18. # 16. Merge the difference grid on top of the base grid
19. ##
20. # This script originated from the remove-restore script written by D. Sandwell 08/08/07
21. # Written by Martin Jakobsson November 27 2011; and modified by Alexander Backstrom March 13 2018.
22. ##
23. from __future__ import division #This line includes the true division avoiding problems with unwanted floor division
24. import fileinput
25. import os
26. #####
27. # Point 8: Setup of the variables
28. #####
29. DIRstr='D:\Alexander_Backstrom\Examensarbete\DBM\Gridding_files_MSL\' #Directory path to the data files, change
   to your path
30. DATAstr='DBM_RR.xyz' #The input ASCII file of all multibeam and dense single beam echo soundings and land topog
   raphy.
31. DATAstr2='DBM_RR_SEGMENT.xyz' #This is a file that consists of all merged blockmedian files.
32. BM_R='445300/503150/6401600/6528100' #Blockmedian region set in GMT, this must fit the geographic extent of the grid
   which is going to be updated
33. #It could be any coordinate system, the main point is that the region fits the geographic region of the base grid to be
   updated
34. #The following are the output files from the Blockmedian filtering from each of the segmented regions for use in remove
   restore
35. BM_RR_OUTPUT1='OUTFILE_RR_BM_1.xyz'
36. BM_RR_OUTPUT2='OUTFILE_RR_BM_2.xyz'
37. BM_RR_OUTPUT3='OUTFILE_RR_BM_3.xyz'
38. BM_RR_OUTPUT4='OUTFILE_RR_BM_4.xyz'
39. BM_I='5' # Blockmedian filter bin size, this should be the same as the cell size of the resampled base grid.
40. DBM_resamp='resamp_grd01_FILT175_SI75_RI5m_3.0_final.grd' #The base grid
41. DBM_resamp_predict='resamp_grd01_UR_pred.xyz' #This is the interpolated values output from grdtrack
42. DBM_resamp_diff='DBM_diff.xyz' #Points that are different when from the old DBM after check with grdtrack against the
   new data
43. DBM_resamp_diff_GRD='DBM_diff.grd'
44. DBM_final='DBM_final_RR_FILT175_SI75_RI5m_3.0.grd' #The final grid file
45. DIFF_P='0.0' #the difference criteria that need to be passed for updating of grid. In other words, the data sets need to be
   different by at least this amount for an update to take place
46. S_C='0.001' #Iteration parameter
47. S_T='0.32' #Tension variable for use with the GMT surface gridding command
48. #In order to handle large volumes of data with Blockmedian, it may be necessary to cut the full area into
49. #sections. The user must change the values given here to those appropriate for their own gridding project.
50. #Values can be set in any coordinate system or latitude or longitude if a geographic grid is created. Note that
51. #this region should extend slightly outside of the final grid boundaries to account for edge effects.
52. BM_R1='477650/503150/6464850/6528100' #Region 1 for subset tiling. This tiling is only required for very large data sets (
   100 million soundings or more).
53. BM_R2='477650/503150/6401600/6464850' #Region 2 for subset tiling
54. BM_R3='445300/477650/6401600/6464850' #Region 3 for subset tiling

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55. BM_R4='445300/477650/6464850/6528100' #Region 4 for subset tiling
56. #Output files from the subset tiling
57. R1='R1_RR.xyz'
58. R2='R2_RR.xyz'
59. R3='R3_RR.xyz'
60. R4='R4_RR.xyz'
61. #####
62. # Point 9: Creation of an input file for gridding ('DBM_RR.xyz').
63. #####
64. FILElist=['Jungfrun_negative_45_out15_55_out5.xyz', 'DRILL-1_CUBE-c_2m_negative_1_out17_4_out0.xyz','DRILL-
VIS-Trans1_CUBE_3m_negative_2_out16_5_out4.xyz',
65. 'DRILL-VIS-Trans2_CUBE_2m_negative_3_out15_6_out3.xyz', 'VIS-Granna-N-
CUBE_2m_negative_9_out9_8_out0.xyz','VIS-Granna-NS_5m_negative_10_out8_9_out0.xyz',
66. 'VIS-Granna-SWA-5m-e_int2008_negative_12_out6_13_out0.xyz', 'VIS-N2_negative_49_out13_57_out3.xyz','VIS-
SW1_Cube2m_84_out12_58_out2_2_out6.xyz', 'VIS-W1_Cube2m_85_out11_59_out1.xyz',
67. 'vattern_topo_nolake_MSL_UTM33N_2.0_north.xyz','vattern_topo_nolake_MSL_UTM33N_2.0_mid.xyz','vattern_to
po_nolake_MSL_UTM33N_2.0_south.xyz'] #All input files should be listed here.
68. print '%s' % (FILElist)
69. F=open(r'%s\\%s' % (DIRstr,DATAstr), 'w+')
70. Cint=0
71. while Cint <= len(FILElist)-1:
72.     G=open('%s%s' % (DIRstr,FILElist[Cint]), 'r')
73.     while 1:
74.         line=G.readline()
75.         line_items=line.split()
76.         if not line:break
77.         if len(line_items) == 3:
78.             elev = float(line_items[2])
79.             if elev <= 0: #This if function converts all values below or equal to 0 to RH2000, so all data points are referenced eq
ually
80.                 elev2 = elev+88.97
81.                 new_line = str(line_items[0]),str(line_items[1]), str(elev2)
82.                 line = ",".join(new_line)
83.                 F.write(str(line) + '\n')
84.             Cint +=1
85.             G.close()
86. F.close()
87. #####
88. # Point 10: Segment the data into regions to handle large data amounts with GMT "blockmedian"
89. #####
90. os.system('set EMM=RAM')
91. os.system('set dos=high, umb')
92. os.system('gmtselect -R%s -V %s\\%s > %s\\%s' % (BM_R1,DIRstr, DATAstr, DIRstr, R1))
93. os.system('gmtselect -R%s -V %s\\%s > %s\\%s' % (BM_R2,DIRstr, DATAstr, DIRstr, R2))
94. os.system('gmtselect -R%s -V %s\\%s > %s\\%s' % (BM_R3,DIRstr, DATAstr, DIRstr, R3))
95. os.system('gmtselect -R%s -V %s\\%s > %s\\%s' % (BM_R4,DIRstr, DATAstr, DIRstr, R4))
96. #####
97. # Point 11: Block median filtering
98. #####
99. os.system('set EMM=RAM')
100. os.system('set dos=high, umb')
101. os.system('blockmedian -R%s -I%s -V -Q %s\\%s > %s\\%s' % (BM_R1,BM_I, DIRstr, R1, DIRstr, BM_RR_OUTPUT1))
102. os.system('blockmedian -R%s -I%s -V -Q %s\\%s > %s\\%s' % (BM_R2,BM_I, DIRstr, R2, DIRstr, BM_RR_OUTPUT2))
103. os.system('blockmedian -R%s -I%s -V -Q %s\\%s > %s\\%s' % (BM_R3,BM_I, DIRstr, R3, DIRstr, BM_RR_OUTPUT3))
104. os.system('blockmedian -R%s -I%s -V -Q %s\\%s > %s\\%s' % (BM_R4,BM_I, DIRstr, R4, DIRstr, BM_RR_OUTPUT4))
105. #####
106. # Point 12: Merge the blockmedian filtered segments. Creates 'DBM_RR_SEGMENT.xyz'.
107. #####
108. L=open(r'%s\\%s' % (DIRstr,DATAstr2), 'w+')
109. FILElist2=['OUTFILE_RR_BM_1.xyz','OUTFILE_RR_BM_2.xyz','OUTFILE_RR_BM_3.xyz','OUTFILE_RR_BM_4.xyz']

110. Cint2=0
111. while Cint2 <= len(FILElist2)-1:
112.     K=open('%s%s' % (DIRstr,FILElist2[Cint2]), 'r')
113.     while 1:
114.         line=K.readline()

```



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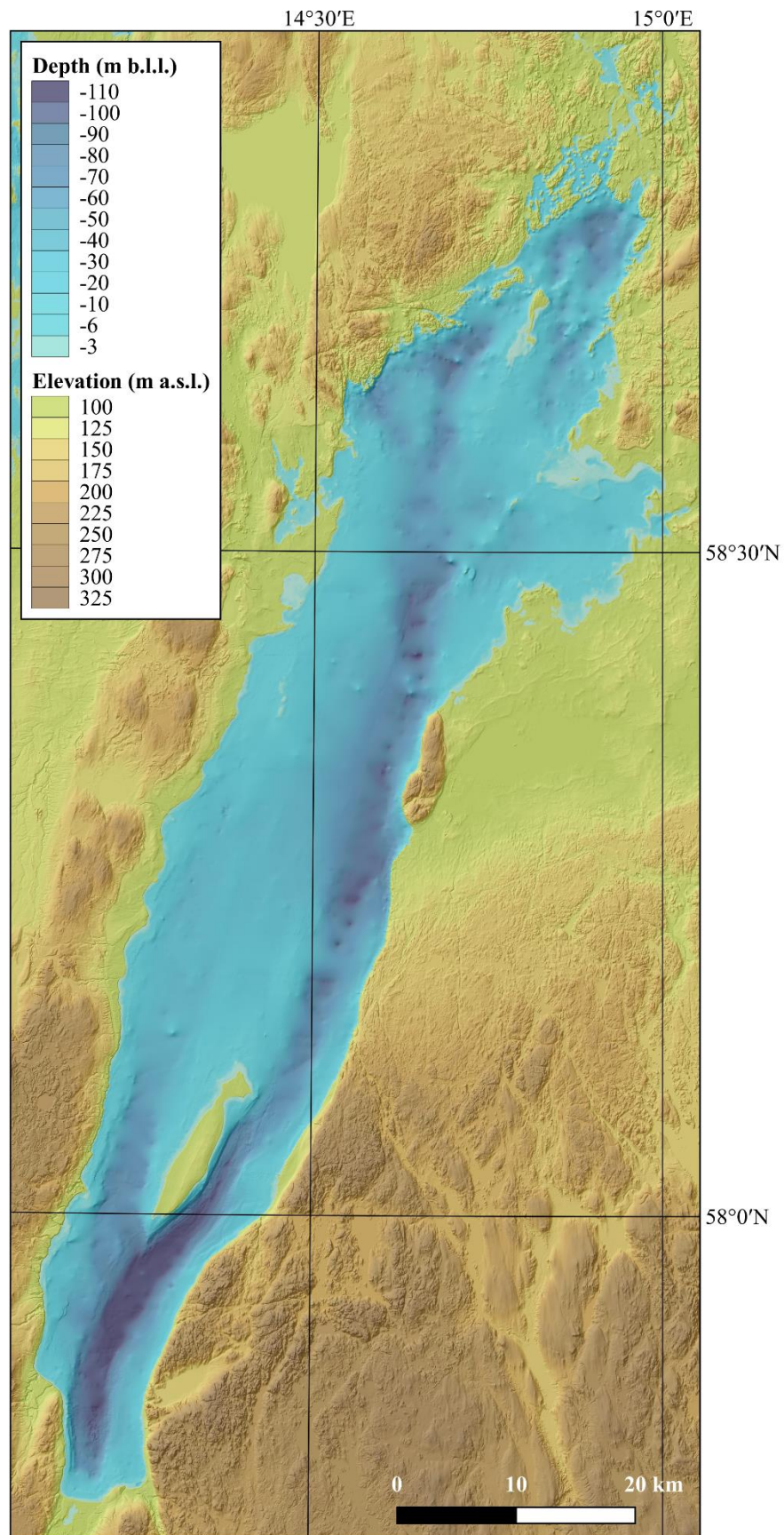
115.     line_items=line.split()
116.     if not line: break
117.     if len(line_items) == 3:
118.         L.write(line)
119.     Cint2 +=1
120.     K.close()
121. L.close()
122. #####
123. # Point 13: Find the depth in the 'base grid' at the location of the blockmedian filtered data points. Creates 'resamp_grd01_U
    R_pred.xyz'.
124. #####
125. os.system('grdtrack %s\\%s -G%s\\%s -V -
    S > %s\\%s' %(DIRstr, DATAstr2, DIRstr, DBM_resamp, DIRstr, DBM_resamp_predict))
126. #####
127. # Point 14: Compute the difference in z-values between the blockmedian data and the base grid. Creates 'DBM_diff.xyz'.
128. #####
129. I=open('%s\\%s' % (DIRstr,DBM_resamp_diff), 'w+')
130. H=open('%s\\%s' % (DIRstr,DBM_resamp_predict), 'r')
131. while 1:
132.     line2=H.readline()
133.     if not line2: break
134.     X_str,Y_str,Z1_str,Z2_str=line2.split()
135.     X_f=float(X_str)
136.     Y_f=float(Y_str)
137.     Z1_f=float(Z1_str)
138.     Z2_f=float(Z2_str)
139.     DIFF_1=Z2_f-Z1_f
140.     DIFF_2=Z1_f-Z2_f
141.     DIFF_P_f=float(DIFF_P)
142.     if DIFF_1 > DIFF_P_f or DIFF_2 > DIFF_P_f:
143.         I.write('%s %s %s\n' % (X_str,Y_str,DIFF_2))
144. H.close()
145. I.close()
146. #####
147. # Point 15: Create a difference grid
148. #####
149. #Create a grid using the GMT nearneighbor routine, that consist of the differences between the blockmedian filtered data and
    the base grid ('DBM_diff.grd'
150. os.system('nearneighbor %s\\%s -G%s\\%s -R%s -I%s -S20 -N4 -E0 -
    V' %(DIRstr, DBM_resamp_diff, DIRstr, DBM_resamp_diff_GRD, BM_R,BM_I))
151. #####
152. # Point 16: Merge the difference grid on top of the base grid
153. #####
154. #This step adds the difference grid on top of the base grid using grdmath from GMT
155. os.system('grdmath %s\\%s %s\\%s ADD = %s\\%s' % (DIRstr, DBM_resamp, DIRstr, DBM_resamp_diff_GRD, DIRstr, D
    BM_final))
156. #os.system('grdfilter %s\\%s -G%s\\%s -R%s -D0 -
    Fc%s' % (DIRstr, CUT_grd_out, DIRstr, FILT_grd_out, CUT_R, FILT))

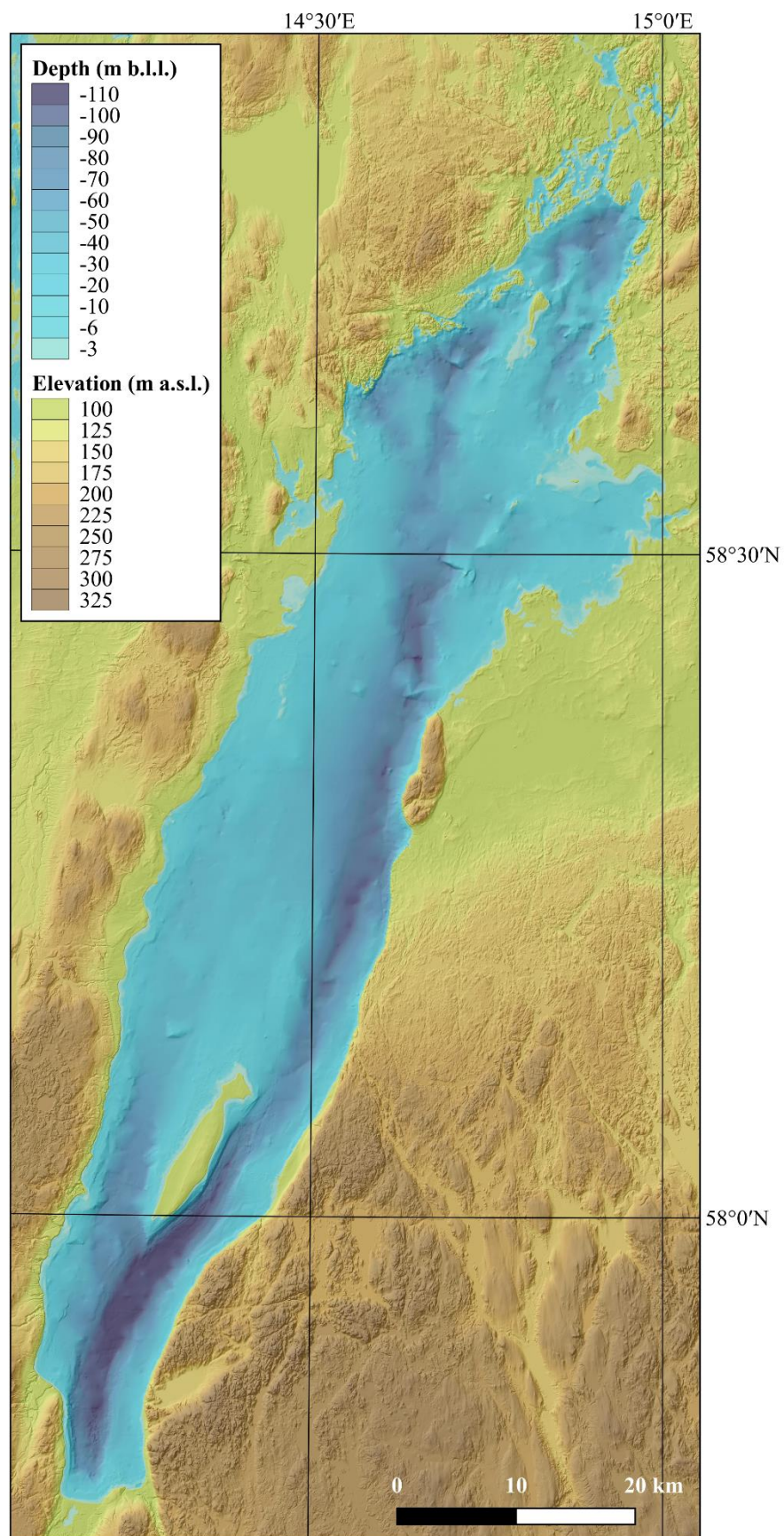
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APPENDIX D, INPUT DATA TO DBM

CONTRIBUTOR	DATA NAME	DATA TYPE	SYSTEM	VESSEL	YEAR	MONTH	NAVIGATIONAL SYSTEM	ORIGINAL HOR DATUM	VERTICAL DATUM
Stockholm University	DRILL-1_CUBE-e_2m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	DRILL-VIS-Trans1_CUBE_3m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	DRILL-VIS-Trans2_CUBE_2m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	Jungfrun-Nordevall_CUBE_2m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	Jungfrun-trans1_CUBE_2m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	Jungfrun-trans2_CUBE_2m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	Jungfrun-trans3_CUBE_2m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	VIS-Granna-N_CUBE_2m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	VIS-Granna-NS_5m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	VIS-Granna-SWA-5m-e_int2008	MB	Kongsberg, EM2002D, 300 kHz	Capella	2008		Hemisphere A100 GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	VIS-N2_CUBE_1m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	VIS-N2-trans1_CUBE_3m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	VIS-NS-trans2_CUBE_3m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2013	June	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	VIS-SW1_Cube2m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2014	May	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
Stockholm University	VIS-W1_Cube2m	MB	Kongsberg, EM2040, 300 kHz	RV Skidbladner	2014	May	Hemisphere R320 RTK GPS	WGS84	+88.5 m (SWEN08_RH2000)
SLU	2007 (Djupdata_Vattem_SLU-2007-09)	SB	Sinrad, ES120-7C, 120 kHz + Sinrad EK60	U/F Ancylus	2007	Sep	GPS Unknown	WGS84	+88.67 m (RH00)
SLU	2008 (Djupdata_Vattem_SLU-2007-09)	SB	Sinrad, ES120-7C, 120 kHz + Sinrad EK60	U/F Asterix	2008	Sep	GPS Unknown	WGS84	+88.67 m (RH00)
SLU	2009 (Djupdata_Vattem_SLU-2007-09)	SB	Sinrad, ES120-7C, 120 kHz + Sinrad EK60	U/F Asterix	2009	Sep	GPS Unknown	WGS84	+88.67 m (RH00)
CAB	Djupdata28kHzFinger_Vattem-P28-88.5m	SB	Single beam echosounder 28 kHz	Hannien	2013	June	Hemisphere A100 GPS	WGS84 /UTM33N	RH2000
CAB	20160920	SB	Lowrance, HDS-10 Gen2, 200 Hz	Crescent Virgo	2016	Sep	Lowrance, HDS-10 Gen2, 200 Hz	WGS84	+88.37 m (RH00)
CAB	20161108	SB	Lowrance, HDS-10 Gen2, 200 Hz	Crescent Virgo	2016	Nov	Lowrance, HDS-10 Gen2, 200 Hz	WGS84	+88.23 m (RH00)
CAB	20170320	SB	Lowrance, HDS-10 Gen2, 200 Hz	Crescent Virgo	2017	Mar	Lowrance, HDS-10 Gen2, 200 Hz	WGS84	+88.17 m (RH00)
CAB	20170824	SB	Lowrance, HDS-10 Gen2, 200 Hz	Crescent Virgo	2017	Aug	Lowrance, HDS-10 Gen2, 200 Hz	WGS84	+88.22 m (RH00)
Lantmäteriet	09B006	Topo	Leica ALSS0-II/69	Airplane	2011	Sep	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	09B007	Topo	Leica ALSS0-II/69	Airplane	2011	Apr-May	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	09B013	Topo	Leica ALSS0-II/69	Airplane	2011	Sep-Oct	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	09B020	Topo	Leica ALSS0-II/69	Airplane	2011	May	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	09B025	Topo	Leica ALSS0-II/69	Airplane	2011	April	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	09B028	Topo	Leica ALS60/23	Airplane	2011	April	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	10C001	Topo	Optech ALTM Gemini/61	Airplane	2011	Sep	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	10C002	Topo	Leica ALS60/14	Airplane	2011	Sep	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	10C006	Topo	Optech ALTM Gemini/80/61	Airplane	2011	Sep-Oct	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	10C009	Topo	Leica ALS60/14	Airplane	2010-2011	Oct-Apr	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	10C010	Topo	Optech ALTM Gemini/80	Airplane	2012	Mar	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	10C015	Topo	Leica ALS70HA/7186	Airplane	2013	May	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000
Lantmäteriet	10C016	Topo	Optech ALTM Gemini/61	Airplane	2011-2012	Oct-Mar	GPS Unknown	SWEREF 99 TM	SWEN17_RH2000

Appendix D. All multi-, single beam, and topographic data included in the Digital Bathymetric Model. Information about the topography data was from Lantmäteriet (2017).

APPENDIX E, DBM MAPS**Figure A. DBM SPT 1.0**

**Figure B.** DBM SPT 2.0

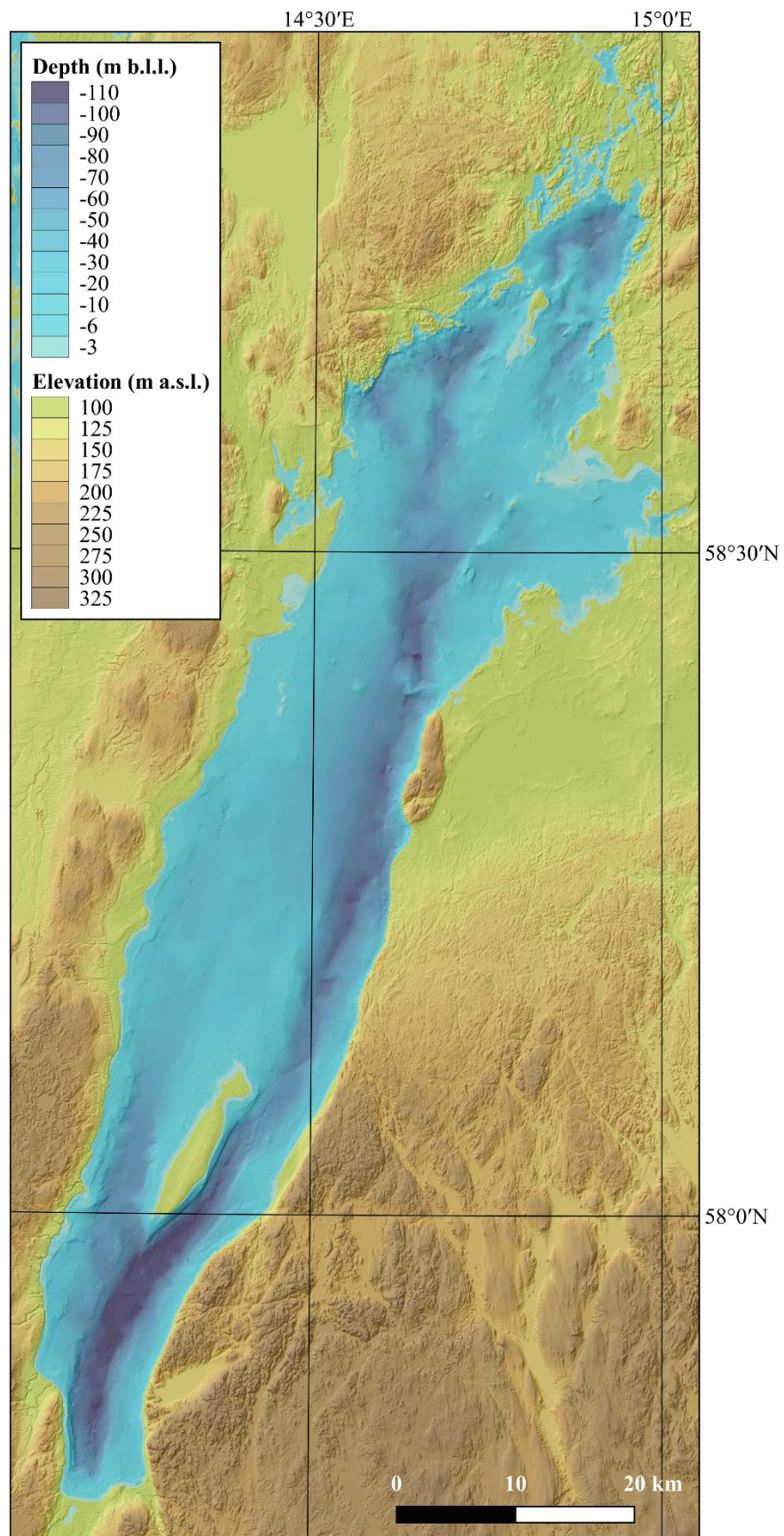


Figure C. DBM SPT 2.0 UR

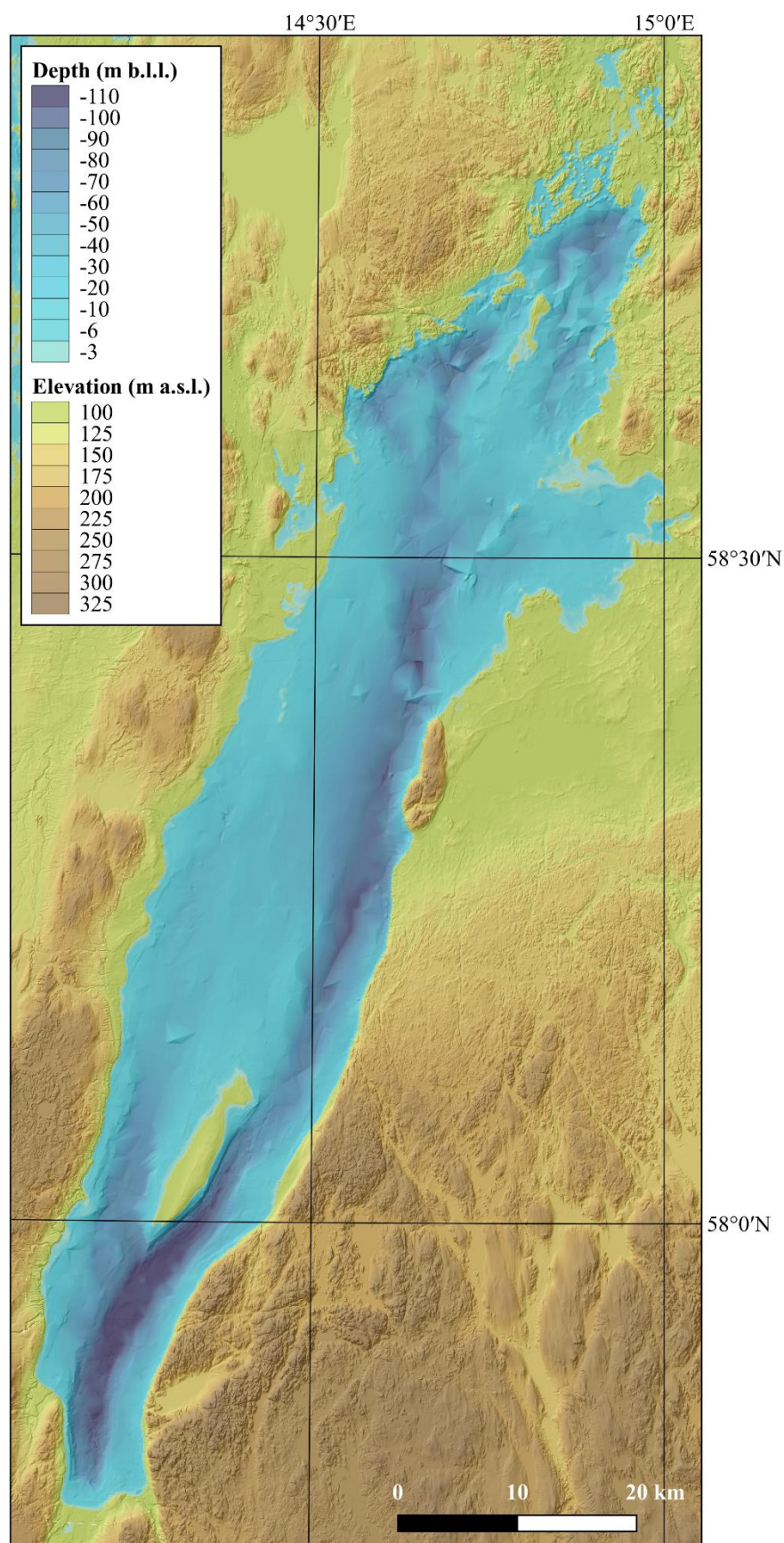


Figure D. DBM triangulation 1.0

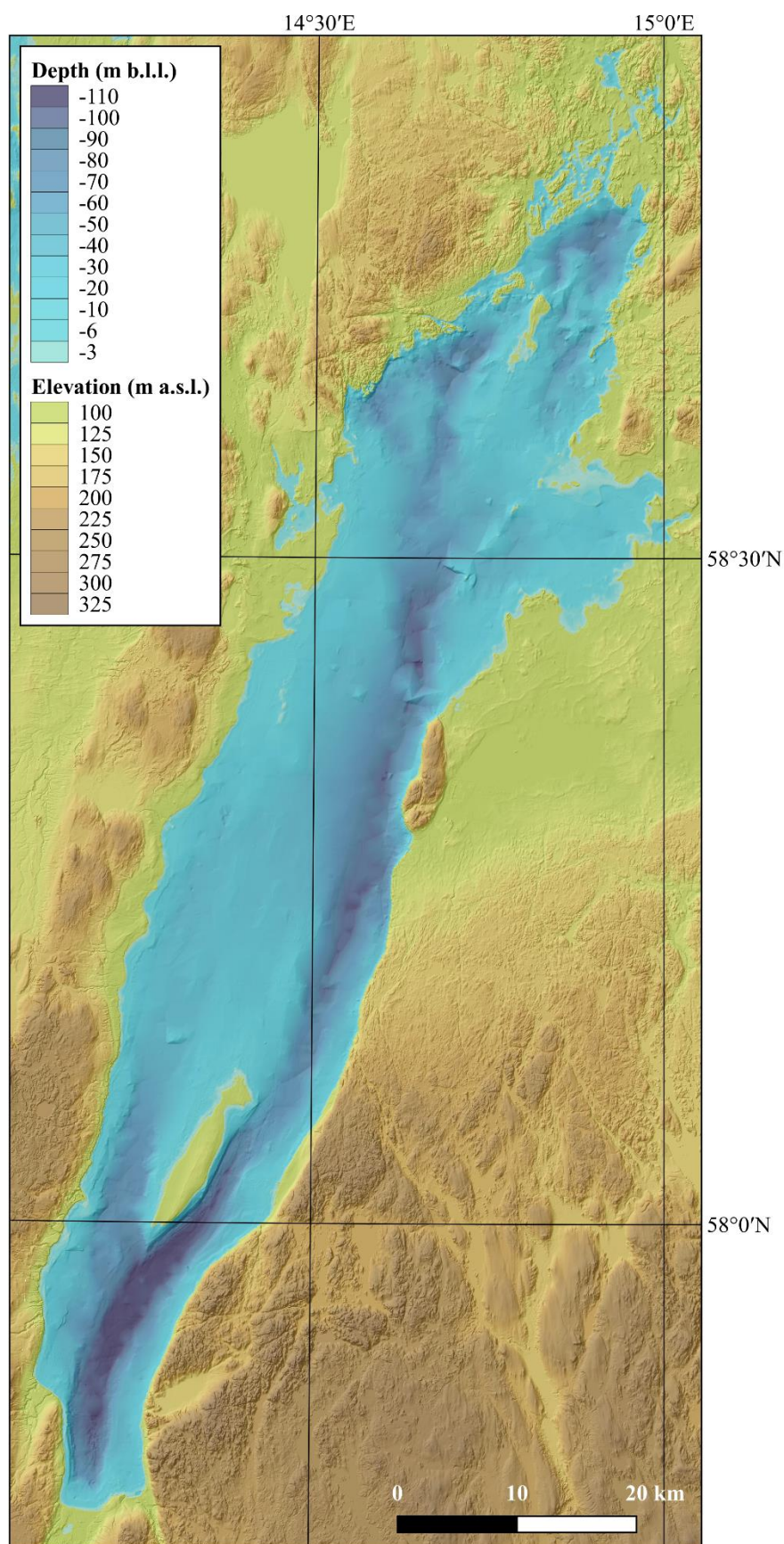


Figure E. DBM triangulation 2.0

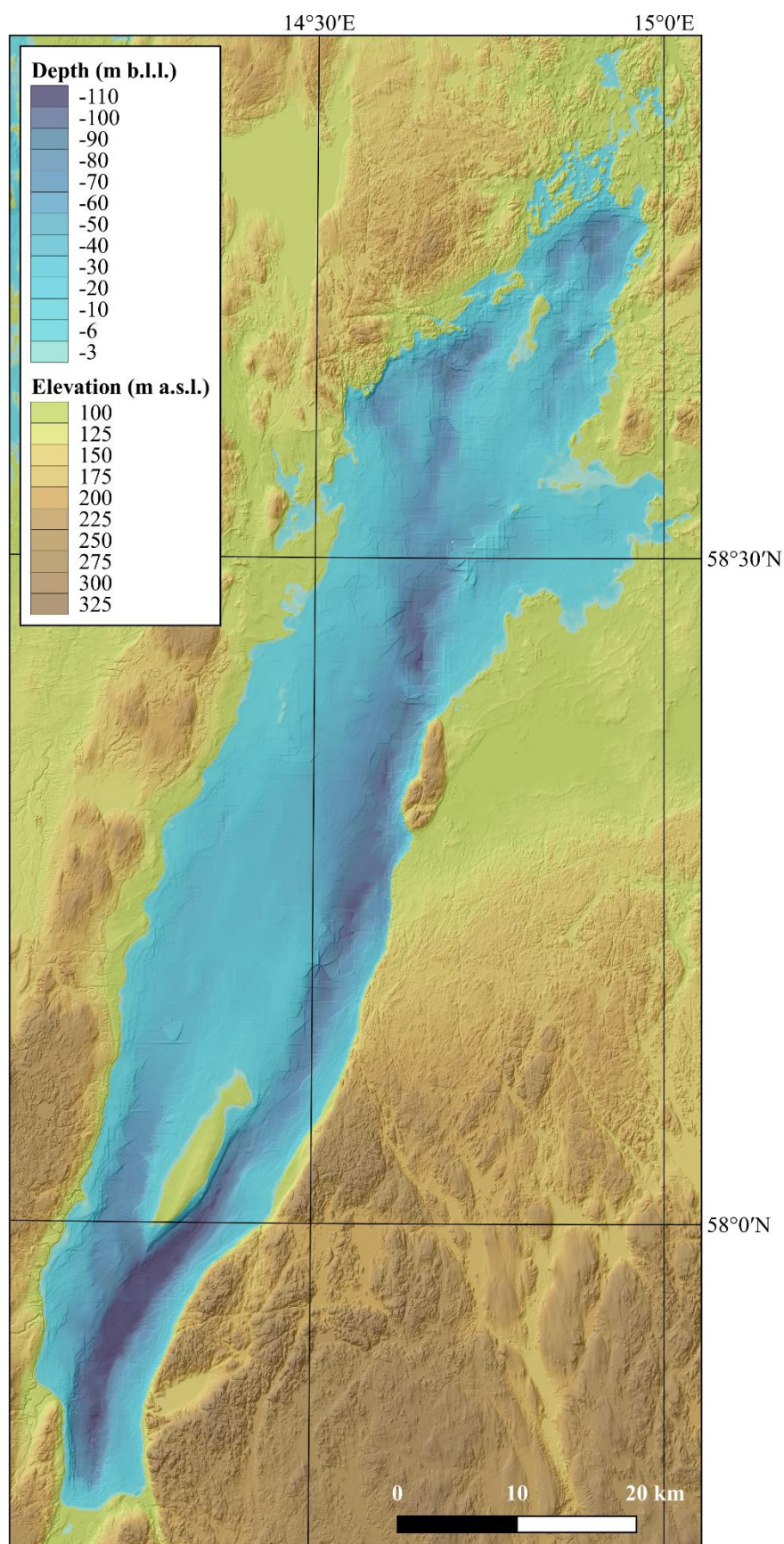


Figure F. DBM Nearest Neighbor 1.3

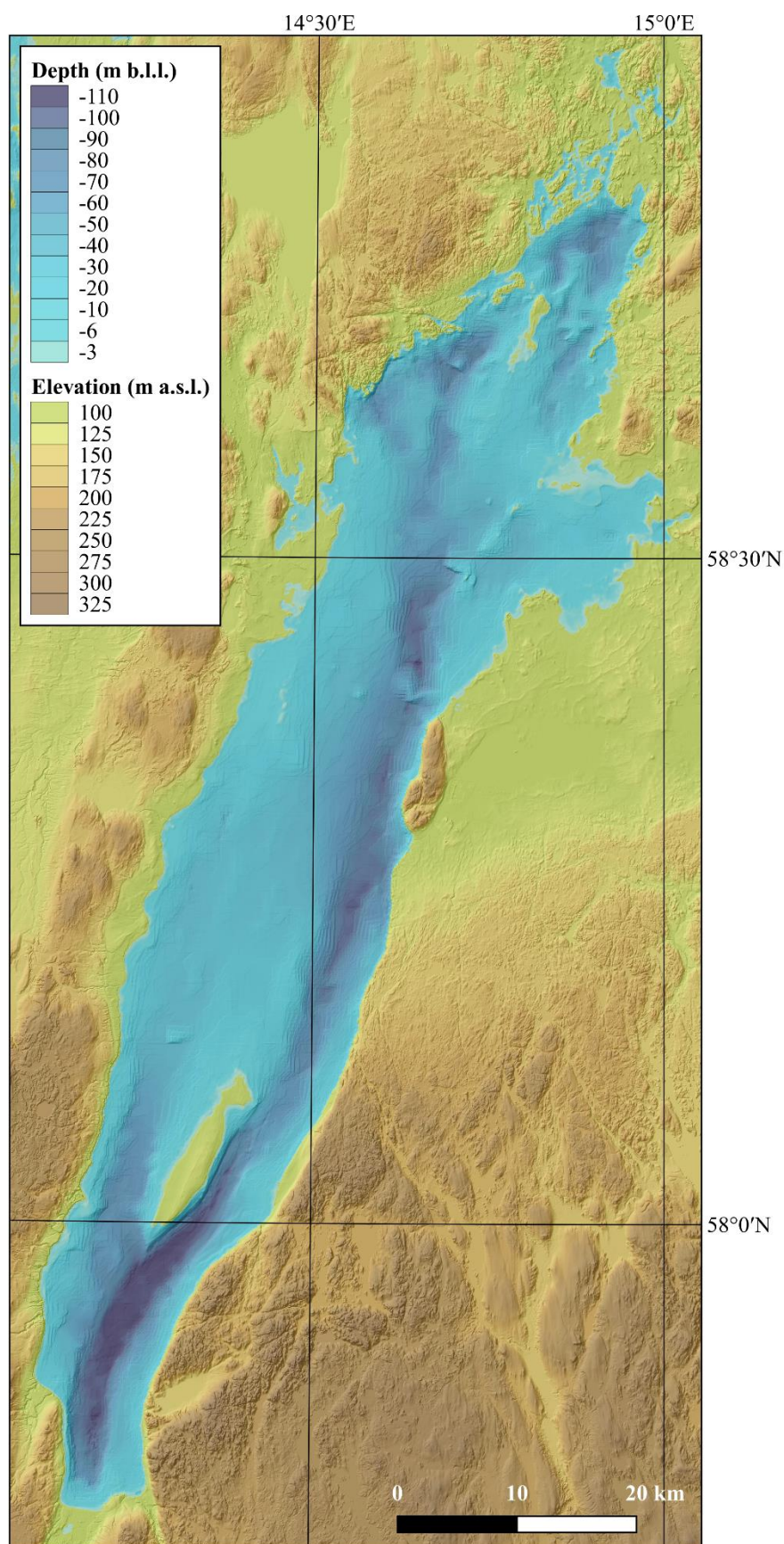


Figure G. DBM Nearest Neighbor 2.0