FloaTEM mapping Sunds lake - HydroGeophysics Group - Aarhus University

FloaTEM Mapping Sunds lake

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GEUS

Herning Kommune

midt Central Denmark Region

TOPSOIL Interreg North Sea Region European Regional Development Fund EUROPEAN UNION

HydroGeophysics Group AARHUS UNIVERSITY

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1. INTRODUCTION

In September, 2018, a geophysical mapping with the ground based transient electromagnetic method FloaTEM was carried out on Sunds lake, Denmark. The mapping project was conducted in a cooperation between the HydroGeophysics Group, Aarhus University, Denmark, GEUS, Herning Municipality, and Central Denmark Region, Denmark as a part of the European union funded project Topsoil. The overall objective of the project is the joint development of methods to describe and manage the uppermost 30m of the subsurface, in order to improve the climate resilience of the North Sea Region.

In the project there are 24 partners from five different countries in the north-sea region including; Denmark, Belgium, Germany, Netherlands and the United Kingdom.

In the pilot area of Sunds, the project aim to deal with high groundwater table in the town Sunds. Basements are getting flooded, something, we hope to prevent by improving the understanding of the hydrogeological setting through mapping with geophysical methods such as tTEM and FloaTEM. The geophysical results will form the basis of a hydrogeological model, which GEUS will setup. GEUS will also be involved in creating the groundwater model, which will be used to understand the water flow around and under Sunds lake. The model can be used to simulate the effect of different climate scenarios.

This report primarily presents the geophysical results (resistivity maps and cross sections) and documents the data collection, processing, and inversion of the FloaTEM data. Chapters 2 - 4 describe the data collection, processing, and inversion. Chapter 5 explains the various types of geophysical maps and cross section placed in Appendix I: - III.

This report does not address a geological interpretation of the obtained geophysical mapping results.

FloaTEM survey, Sunds lake	
Client	Topsoil project
Key persons	**HGG, Aarhus University, Denmark** *Senior geophysicist &, project manager Jesper B. Pedersen,* *Postdoc Geophysicist. Pradip Maurya* *MSc. geology Tore Eiskjær* **Central Denmark Region, Denmark** *Geologist, Jes Pedersen* *Geologist, Rolf Johnsen* *Geologist, Flemming Jørgensen* **Herning Municipality, Denmark** *Geologist, Thomas Gad* *Biologist, Søren Brandt* **GEUS, Denmark** *Geologist, Anders Juhl Kallesøe*
Locality	Sunds lake, Denmark
Survey period	September 6, 2018
Line km acquired	15,6 km
Line spacing	60 m

2. DATA COLLECTION

2.1 The Survey Area

The FloaTEM survey was carried out on September 6, 2018, and covers a total of 15,6 line km of data (Figure 1). The lines strike west-east with a line spacing of 60 m. The mapping speed was roughly 10 km/h.

Figure 1. Survey area, with FloaTEM lines in black. Each black dot corresponds to one FloaTEM sounding. The line spacing is ~60 m.

2.2 The FloaTEM System

The FloaTEM instrument is a time-domain electromagnetic system designed for hydrogeophysical and environmental investigations. The FloaTEM system measures continuously while towed on the river/lake surface. It is designed for a very high near-surface resolution with very early time gates and a fast repetition frequency. The following is a general introduction to the FloaTEM system. A more thorough description of TEM methods in general can be found in Christiansen *et al.* (2006) .

Instrument

Figure 2 shows the FloaTEM system. The FloaTEM uses an off-set loop configuration, with the receiver coil (Rx-coil) approximately 7.0 m behind the transmitter coil (Tx-coil). The Rx-coil is horizontal, i.e. measauring the z-component of the magnetic fields. A boat tows the FloaTEM-system, and the distance between the boat and the Tx coil is 3 m. The Tx-coil is located inside a 2 m x 4 m rectangular hollow composite frame (Tx-frame), which is carried on two pontoons. GPSs are located at the front of the Tx-frame and at the Rx-coil for accurate positioning of the system. The Rx-coil is placed on a small rubber boat, and it is suspended to avoid motion induced noise. The transmitter electronics, receiver, power supply, etc. is located at the back of the boat together with an echo sounder for water depth measurements.

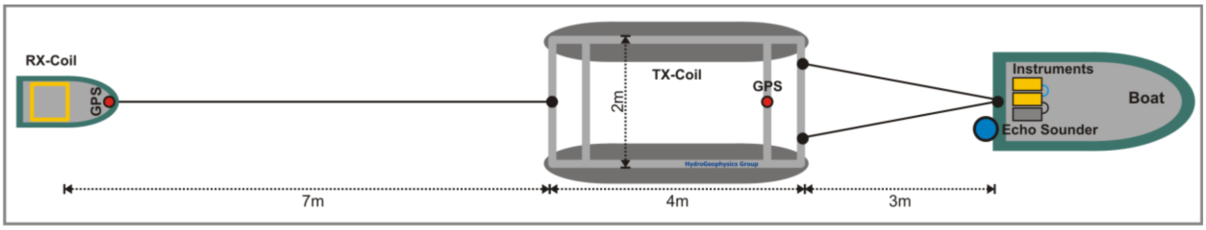

Figure 2. The FloaTEM system. Rx-Coil indicates the receiver coil and Tx-coil indicates the transmitter coil both sitting on a rubber boat and pontoons respectively. The yellow boxes on the boat indicate the receiver and transmitter electronics and grey box is the battery-box for power supply. GPSs are marked with red dots. The exact distance and device positions are listed in Table 1.

During data collection, the driver can monitor key data parameters and positioning in real time on a tablet on the boat.

Measurement Procedure

Measurements are carried out with two transmitter moments. The standard configuration uses a low and a high transmitter moment applied sequentially. A high and low moment sequence typically takes 0.5 seconds and includes several hundred individual transient measurements.

The mapping speed is adjusted to the survey area and target. It will normally not exceed 10 km/h.

Apart from GPS and TEM data, a number of instrument parameters are monitored and stored for quality control when the data are processed. These parameters include transmitter temperature, current and voltage levels of the instrument.

Depth of Investigation (DOI)

The depth of investigation for the FloaTEM system depends on the transmitter moment, the geological setting, the background noise level, and also the mapping speed, which influence the motion noise and the stack-size for a certain sounding distance. Normally, a DOI of 60-70 m can be achieved in a subsurface layering with an average resistivity of 40 ohm-m. The DOI will be larger at higher resistivities and less at lower resistivities. During the inversion, the DOI is estimated for each resistivity model (see section 4.3).

2.3 FloaTEM - Technical Specifications

This section lists detailed technical specifications of the FloaTEM system setup for the survey.

The FloaTEM system is configured in a standard two-moment set-up (low moment, LM, and high moment, HM). The system instrument setup is shown in Figure 2. The positioning of the instruments and the corners of the transmitter coil are listed in Table 1. The origin is defined as the center of the transmitter coil.

The specifications of the LM an HM moments are summarized in Table 2. The waveforms for the LM and HM moments are shown in Figure 3. The exact waveforms are listed in Table 3.

Device Positions, nominal

Unit	X (m)	Y (m)	Z(m)
GP_Tx (GPS)	1.40	0.00	-1.20
RxZ (Z-receiver coil)	-10.28	0.00	-0.43
Tx-Coil, center	0.00	0.00	-0.22
Tx-Coil corner 1	-02.00	-01.00	-0.22
Tx-Coil corner 2	02.00	-01.00	-0.22
Tx-Coil corner 3	02.00	01.00	-0.22
Tx-Coil corner 4	-02.00	01.00	-0.22

Table 1. Nominal equipment, receiver and transmitter coils positioning. The origin is defined as the center of the transmitter coil. Z is positive towards the ground.

Transmitter, Receiver Specifications

Parameter	LM	HM
No. of turns	1	1
Transmitter area (m^2)	8 m^2	8 m^2
Tx Current	~ 2.8 A	~ 30 A
Tx Peak moment	~ 22.4 Am^2	~ 240 Am^2
Repetition frequency	1055 Hz	330 Hz
Raw Data Stack size	422	264
Raw Moment cyclus time	0.22 s	0.40 s
Tx on-time	0.2 ms	0.45 ms
Duty cycle	42 %	30%
Turn-off time	2.5 µs at 2.8 Amp	4.0 µs at 30 Amp
Number of gates	15	23
Gate time interval	4 µs – 33 µs	10 µs – 900 µs
Front-gate time (nominal)	2 µs	5 µs
Front-gate delay	1.9 µs	1.9 µs

Table 2. Low moment (LM) and high moment (HM) specifications.

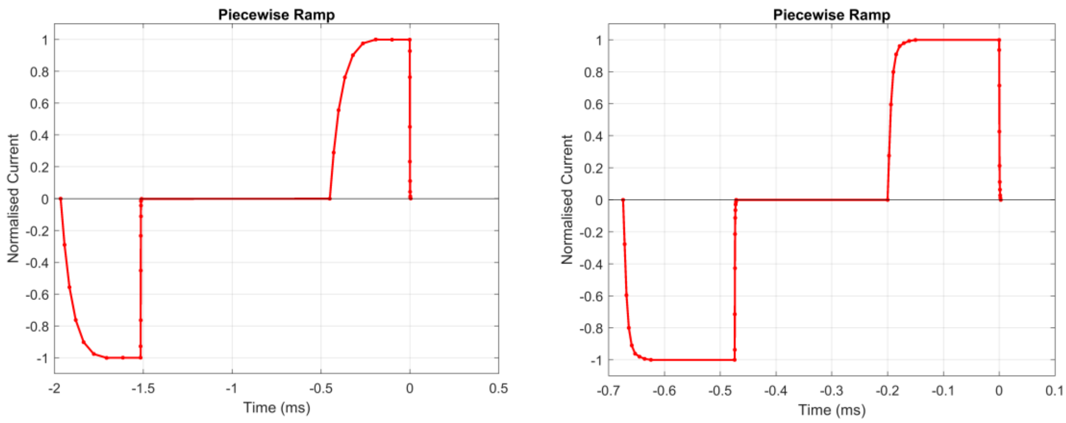

Figure 3. Waveforms for the LM (left) and the HM (right). The red line segments indicate the piecewise linear modelling of the waveforms.

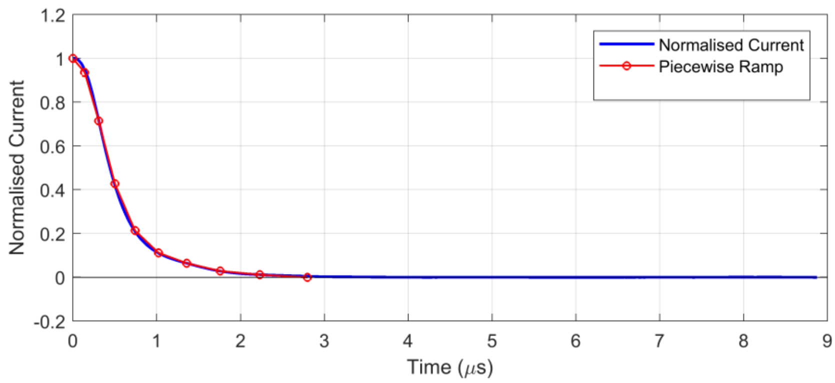

Figure 4. Close-up on ramp down for LM. The red line segments indicate the piecewise linear modelling of the waveform.

Waveform, LM and HM

LM time	LM amplitude	HM time	HM amplitude
-6.7400e-04 s	-0.000	-1.9650e-03 s	-0.000
-6.7250e-04 s	-0.496	-1.9483e-03 s	-0.316
-6.7071e-04 s	-0.658	-1.9279e-03 s	-0.532
-6.6859e-04 s	-0.784	-1.9030e-03 s	-0.710
-6.6605e-04 s	-0.865	-1.8725e-03 s	-0.845
-6.6303e-04 s	-0.925	-1.8351e-03 s	-0.933
-6.5944e-04 s	-0.963	-1.7894e-03 s	-0.981
-6.5516e-04 s	-0.978	-1.7334e-03 s	-1.001

-6.5007e-04 s	-0.989	-1.6650e-03 s	-1.000
-6.4400e-04 s	-1.000	-1.5150e-03 s	-1.000
-4.7400e-04 s	-1.000	-1.5148e-03 s	-0.967
-4.7387e-04 s	-0.953	-1.5146e-03 s	-0.859
-4.7373e-04 s	-0.812	-1.5143e-03 s	-0.662
-4.7355e-04 s	-0.559	-1.5139e-03 s	-0.381
-4.7334e-04 s	-0.332	-1.5135e-03 s	-0.155
-4.7309e-04 s	-0.175	-1.5131e-03 s	-0.053
-4.7279e-04 s	-0.086	-1.5125e-03 s	-0.017
-4.7243e-04 s	-0.041	-1.5118e-03 s	-0.007
-4.7200e-04 s	-0.016	-1.5110e-03 s	-0.000
-4.7150e-04 s	-0.000	-4.5000e-04 s	0.000
-2.0000e-04 s	0.000	-4.3333e-04 s	0.316
-1.9850e-04 s	0.496	-4.1294e-04 s	0.532
-1.9671e-04 s	0.658	-3.8799e-04 s	0.710
-1.9459e-04 s	0.784	-3.5745e-04 s	0.845
-1.9205e-04 s	0.865	-3.2009e-04 s	0.933
-1.8903e-04 s	0.925	-2.7438e-04 s	0.981
-1.8544e-04 s	0.963	-2.1844e-04 s	1.001
-1.8116e-04 s	0.978	-1.5000e-04 s	1.000
-1.7607e-04 s	0.989	0.0000e+00 s	1.000
-1.7000e-04 s	1.000	2.0384e-07 s	0.967
0.0000e+00 s	1.000	4.3584e-07 s	0.859
1.2589e-07 s	0.953	7.2384e-07 s	0.662
2.6989e-07 s	0.812	1.0598e-06 s	0.381
4.5389e-07 s	0.559	1.4598e-06 s	0.155
6.6189e-07 s	0.332	1.9398e-06 s	0.053
9.0989e-07 s	0.175	2.5078e-06 s	0.017
1.2139e-06 s	0.086	3.1878e-06 s	0.007
1.5659e-06 s	0.041	4.0000e-06 s	0.000
1.9979e-06 s	0.016		
2.5000e-06 s	0.000		

Table 3. Waveforms for LM and HM, listed as time and nominal amplitude.

2.4 Calibration of the FloaTEM system

Prior to the survey, the FloaTEM equipment was calibrated at the Danish national TEM test-site near Aarhus, Denmark (Foged *et al.*, 2013). The calibration is performed to establish the absolute time shift and data level in order to facilitate precise modeling of the data. No additional leveling or drift corrections are applied subsequently.

In order to perform the calibration, all system parameters (transmitter waveform, low pass filters, etc.) must be known to allow accurate modeling of the FloaTEM setup.

The calibration constants are determined by comparing a recorded FloaTEM response on the test site with the reference response. The reference response is calculated from the test site reference model for the used FloaTEM configuration.

Acceptable calibration was achieved with the calibration constants stated in Table 4. The calibration was performed on September 4, 2018. Calibration plots for both moments are shown in *Figure 5* and *Figure 6* .

Moment	Time Shift	Scale Factor
LM	-1.0 µs	1.00
HM	-1.2 µs	1.03

Table 4. Calibration constants.

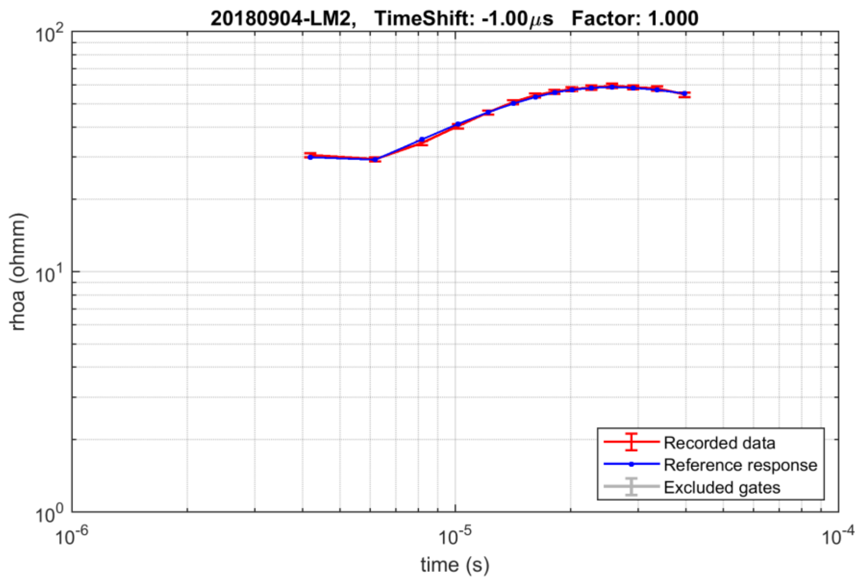

Figure 5. Calibration plot for the LM. The red curve is the recorded data with calibration factors applied, and the blue curve is the forward response from the national geophysical test-site in Denmark. Note that only the first 4 LM gates are used for inversion

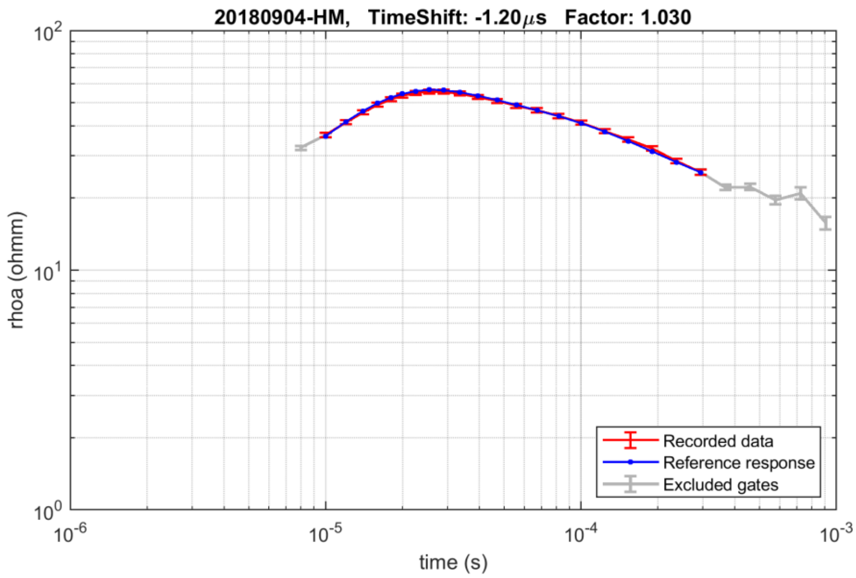

Figure 6. Calibration plot for the HM. The red curve is the recorded data with calibration factors applied, and the blue curve is the forward response from the national geophysical test-site in Denmark.

3. PROCESSING OF THE FLOATEM DATA

3.1 Data Processing – Workflow

The software package Aarhus Workbench is used for processing the FloaTEM data.

The aim of the processing is to prepare data for the geophysical interpretation. The processing primarily includes filtering and averaging of data as well as culling and discarding of distorted or noisy data.

The data processing is divided into four steps:

1. Import of raw data into a fixed database structure. The raw data appear in the form of .skb-, .sps- and .geo-files. Skb-files contain the actual transient data from the receiver. Sps-files contain GPS positions, transmitter currents etc., and the geo-file contains system geometry, low-pass filters, calibration parameters, turn-on and turn-off ramps, calibration parameters, etc.
2. Automatic processing: First, an automatic processing of the two data types is applied. These are GPS-, and TEM data. This automatic processing is based on a number of criteria adjusted to the given survey.
3. Manual processing: Inspection and correction of the results of the automatic processing for the data types in question.
4. Adjustment of the data processing based on preliminary inversion results.

All data are recorded with a common time stamp, which is used to link data from different data types. The time stamp is given as the GMT time.

In the following, short descriptions of the processing of the different data types are shown. A more thorough description of the TEM data processing can be found in Auken *et al.* (2009).

3.2 GPS-Positioning

The position of the FloaTEM-system is recorded continuously with two independent GPS receivers. Furthermore, the GPS data are shifted to the optimum focus point of the FloaTEM system.

3.3 Voltage Data Processing

The voltage data from the receiver system are gathered continuously along the driving lines (Figure 7). The processing of voltage data is carried out in a two-step process; an automatic and a manual part. In the former, a number of filters designed to cull coupled or noise-influenced data are used. Furthermore, raw data are stacked to increase the signal-to-noise ratio. The averaging width of late-time data is typically wider than that of early-time data, referred to as trapez-filter, as seen in Table 5. The data uncertainty is calculated directly from the data stack, with an additional 3% uniform data uncertainty. Typically, the stacked data (soundings) are generated for every 10 m depending on mapping speed, FloaTEM setup and target. Each sounding location will produce a 1D resistivity model when the data are inverted.

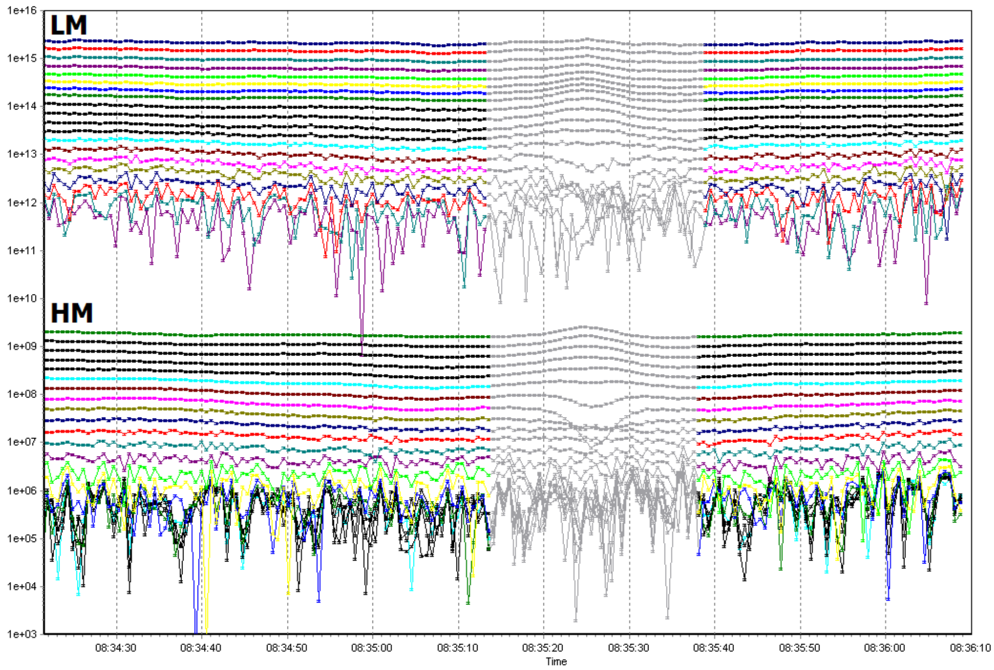

Figure 7. Data section example with coupled data. The section displays 2 minutes (~0.5 km) of data. Each of the curves shows raw low-moment or high-moment data for a given gate time. The green line represents gate 1 of the high moment, the black line gate 2 etc. The grey lines represent data that have been removed due to couplings. A coupling can clearly be identified at 08:35:12 to 08:35:37. In this case the coupling is associated with a buried power cable.

The automatic processing is followed by a manual inspection and correction. A number of power lines, roads, railroads, etc. typically cross survey areas. As data near such installations often are heavily disturbed (coupled to the installations), it is necessary to remove these data, in order to produce geophysical maps without artifacts from these man-made installations. The automatic processing does not remove all coupled data and hence, a manual inspection and removal of coupled data is essential to obtain high quality models in the end. In some cases, the source of the coupling cannot be identified even though evident in the data.

Figure 7 shows an example of strongly coupled data. First, the coupled data parts are removed. Then data are stacked into soundings, and finally the late-time part of the sounding curves below the background noise level is excluded.

3.4 Processing - Technical Specifications

Table 5 shows key processing settings in the Aarhus Workbench, used for this survey.

Item		Value
Noise Processing	Data uncertainty Uniform data STD	From data stack 3%
Averaging filter	Sounding distance LM, width HM, width At gate times	2 s (~5 m) 2 s 2 s, 10 s 1e-5 s, 1e-4 s

Table 5. Processing settings.

4. INVERSION OF THE FLOATEM DATA

Inversion of the dataset and evaluation of the inversion results are carried out using the Aarhus Workbench software package. The underlying inversion code (AarhusInv) is developed by the HydroGeophysics Group, Aarhus University, Denmark (Kirkegaard *et al.*, 2015) and Auken *et al.* (2015)

The inversion is a 1D full non-linear damped least-squares solution in which the transfer function of the instrumentation is modeled. The transfer function includes turn-on and turn-off ramps, front gate, low-pass filters, and transmitter and receiver positions.

4.1 Spatially Constrained Inversion

The spatially constrained inversion (SCI) (Viezzoli *et al.*, 2008) scheme is used when inverting the FloaTEM data. The SCI scheme uses constraints between the 1D-models, both along and across the mapping lines, as shown in Figure 8. The constraints are scaled according to the distance between soundings.

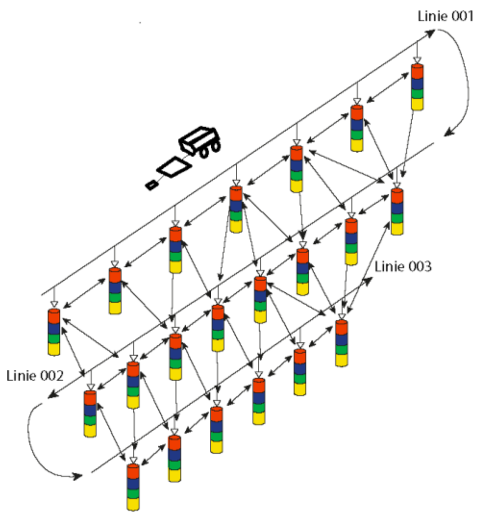

Figure 8. Schematic presentation of the SCI setup. Constraints connect not only soundings located along the mapping lines, but also those across them.

The connection pattern of the constraints is determiend by a Delaunay triangulation, which connects *natural* neighbor models. For line oriented data the Delaunay triangulation results in a model being connected to the two neighbor models at the mapping line and typically 2-3 models at each of the adjacent mapping lines, (see Figure 9). The SCI constraints ensures that no line-orientation artifacts will be visible the inverted datasets.

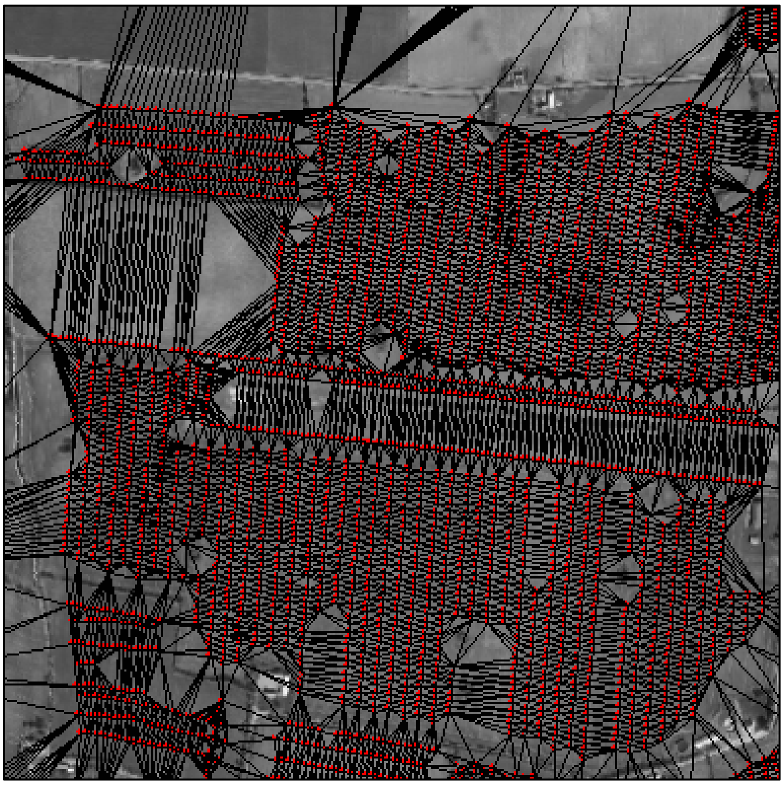

Figure 9. Example of SCI-constraints. The red points are the model positions. The black lines show the constraints created with the Delaunay triangles. The line distance in this example is 20 m, sounding distance is 10 m and the area is approximately 1 x 1 km.

Constraining the parameters enhances the resolution of resistivities and layer interfaces, which are not well resolved in an independent inversion of the soundings.

SCI-setup parameters for this survey are listed in section 4.4.

4.2 Smooth and blocky Inversion

Both a smooth and a blocky model inversion have been carried out. Both inversion types use the SCI-setup, but the regularization scheme is different.

The smooth regularization scheme penalizes the resistivity changes, resulting in smooth resistivity transitions both vertically and horizontally. The blocky regularization scheme is a L1 norm, resulting in model sections with few, but relatively large resistivity transitions. Normally the FloaTEM data are fitted almost equally well with the two inversion types.

Assuming a layered geological environment, picking geological layer boundaries will be less subjective in a blocky model result compared to a smooth model. Contrary, the smooth inversion result can reveal vague resistivity signatures that may be suppressed in the blocky results.

4.3 Depth of Investigation

For each resistivity model a depth of investigation (DOI) is estimated, as described in Christiansen and Auken (2012). The DOI calculation takes into account the FloaTEM system transfer function, the number of data points, the data uncertainty, and the resistivity model.

EM fields are diffusive, and there is no discrete depth where the information on the resistivity structure stops. Therefore, we provide a conservative and a standard DOI estimate. As a guideline, the resistivity structures above the DOI conservative value are strongly represented in the FloaTEM data, and resistivity structures below the DOI standard value are poorly represented in the data and should normally be disregarded.

The DOI conservative and DOI standard estimates are included as point themes maps in Appendix I: The cross sections in Appendix II: are blanked at the DOI standard values. Furthermore, the resistivity models are blanked below the DOI-standard value when compiling the mean resistivity maps.

4.4 Inversion - Technical Specifications

The inversion settings for the smooth and blocky inversions in Aarhus Workbench are listed in Table 6.

Item		Value
Model setup	Number of layers Starting resistivities [Ωm] Thickness of first layer [m] Depth to last layer [m] Thickness distribution of layers	35 50 ohmm 0.4 120.0 Log increasing with depth
Smooth model (L2 norm): Constraints/ Prior constraints	Horizontal constraints on resistivities [factor] Reference distance [m] Constraints distance scaling Vertical constraints on resistivities [factor] Prior, thickness Prior, resistivities Minimum number of gates per moment	1.1 5 $(1/\text{distance})^1$ 2.0 Fixed None 3
Blocky model (L1 norm): Constraints/ Prior constraints	Horizontal constraints on resistivities [factor] Reference distance [m] Constraints distance scaling Vertical constraints on resistivities [factor] Prior, thickness Prior, resistivities Minimum number of gates per moment	1.1 5 $(1/\text{distance})^1$ 2.0 Fixed None 3

Table 6. Inversion settings, smooth and blocky SCI setup

5. THEMATIC MAPS AND CROSS SECTIONS

To visualize the resistivity structures in the mapping area, a number of geophysical maps and cross sections have been created. Furthermore, a location map and a number of maps made for quality control (QC-maps) are found in the appendices.

5.1 Location Map, QC-maps

A location map and quality control maps (QC) described below are located in Appendix I:

Model Location and Lines
This map shows the actual survey lines. Black dots mark where data are disregarded due to line turns or coupling. Red dots mark where data is kept and inverted to a resistivity model.

A decent amount of data is disregarded due to coupling, and the coupled data are primarily associated with electrical cables, buildings, and roads.

Number of Time Gates in Use
This maps shows the number of time gates (high and low moment) in use for each resistivity model. Few time gates correlate to areas with a low signal level (very resistive areas).

Data Residual
The data residual expresses how well the obtained resistivity models fit the recorded data. The data residual values are normalized with the data standard deviation, so a data residual below one corresponds to a fit within one standard deviation.

The data residual map in Appendix I: is for the smooth inversion. Some areas have relatively high data residual values (>2). This is primarily due to data with a high noise level, which again is associated with a low signal over resistive ground. In general, the data residuals are low, which is expected for this type of environment and geological setting.

Depth of Investigation (DOI)
This map shows the DOI estimates for the smooth model inversion result (see section 4.3 for a description of the DOI-calculation). DOI maps in elevation and depths are included in the appendix.

5.2 Cross Sections

Cross sections of selected mapping lines are located in Appendix II: Each section holds the smooth inversion model bars, which are blanked at the DOI- standard value. Cross section of all mapping lines are available in the delivered Workspace.

5.3 Mean Resistivity Maps

To make depth or horizontal slices, the mean resistivity in the depth or elevation intervals is calculated for each resistivity model and then interpolated to regular grids.

Figure 10 shows how the resistivities of the layers in a model influence the calculation of the mean resistivity in a depth interval [A, B]. d_0 is the surface, d_1, d_2 and d_3 are the depths to the layer boundaries in the model. ρ_1, ρ_2, ρ_3 and ρ_4 are the resistivities of the layers.

The model is subdivided into sub-thicknesses $\Delta t_{1\text{-}3}$. The mean resistivity (ρ_{vertical}) is calculated as:

$$\rho_{vertical} = \frac{\rho_1 \cdot \Delta t_1 + \rho_2 \cdot \Delta t_2 + \rho_3 \cdot \Delta t_3}{\Delta t_1 + \Delta t_2 \cdot \Delta t_3}$$

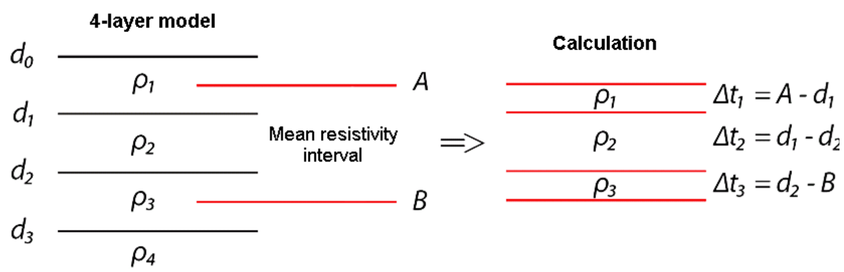

Figure 10. The figure illustrates how the resistivities of the layers influence the mean resistivities in a depth interval [A:B]

In the general term the mean resistivities in a depth interval is calculated as:

$$\bar{\rho} = \frac{\sum_{i=1}^{n} \rho_i \cdot \Delta t_i}{\sum_{i=1}^{n} \Delta t_i}$$

where i runs through the interval from 1 to the number of sub-thicknesses. The mean resistivity calculated by the above formula ($\rho_{vertical}$) is called a vertical mean resistivity - equal to the total resistance if a current flows vertically through the interval.

By mapping with a TEM method, the current flows only horizontally in the ground. It is therefore more correct to perform the mean resistivity calculation in conductivity, called the horizontal mean resistivity ($\rho_{horizontal}$). The horizontal mean resistivity is equal to the reciprocal of the mean conductivity (σ_{mean}) and is calculated as:

$$\rho_{horizontal} = \frac{1}{\sigma_{mean}} = \left[\frac{\sum_{1=1}^{n} \left(\frac{1}{\rho_i}\right) \cdot \Delta t_i}{\sum_{i=1}^{n} \Delta t_i} \right]^{-1}$$

For this survey, horizontal mean resistivity themes have been generated from the smooth model inversion result in 5 m depth intervals from 0 to 30 m, and in 10 m intervals from 30 to 80 m. The resistivity models have been blanked below the DOI standard depth.

The interpolation of the mean resistivity values to regular grids is performed by kriging interpolation (Pebesma and Wesseling, 1998), with a node spacing of 5 m and a search radius of 150 m. Addition linear pixel smoothing was subsequently applied. The mean resistivity maps are located in Appendix III:

5.4 Deliverables

Digital

- This report incl. theme maps and profiles as PDF-files.

- Aarhus Workbench workspace holding raw data, processed data, inversion results, theme maps, and profiles. The workspace holds both the smooth and the blocky inversion results.
  The workspace can be delivered upon request.

Note: All digital maps and data are geo-referenced to coordinate system WGS84, UTM zone 32N.

6. CONCLUSION

The FloaTEM survey was carried out successfully and a careful data processing has been performed. Subsequently the data was inverted to produce both a smooth and a blocky resistivity model which describes the resistivity structures of the soil down to more than 70 m depth. The FloaTEM survey reveals a detailed resistivity picture of the geological setting beneath Sunds lake, due to the close line spacing and lateral resolution along the mapping lines. The final resolution is a 60x5 measurement grid. The lake took 1 day to map, resulting in 15,6 km of data and 4777 models (after processing).

Some of the resistivity structures in and under Sunds lake can be viewed in appendix II and II, which highlights the resistivity profiles and mean-resistivity maps. As a next step in the project, geologists and hydrologist from GEUS will take the geophysical results and transfer them into a hydrological model by comparing geophysics and borehole knowledge.

7. REFERENCES

Auken, E., Christiansen, A.V., Fiandaca, G., Schamper, C., Behroozmand, A.A., Binley, A., Nielsen, E., Effersø, F., Christensen, N.B., Sørensen, K.I., Foged, N. & Vignoli, G., 2015. An overview of a highly versatile forward and stable inverse algorithm for airborne, ground-based and borehole electromagnetic and electric data, *Exploration Geophysics,* 2015**,** 223-235.

Auken, E., Christiansen, A.V., Westergaard, J.A., Kirkegaard, C., Foged, N. & Viezzoli, A., 2009. An integrated processing scheme for high-resolution airborne electromagnetic surveys, the SkyTEM system, *Exploration Geophysics,* 40**,** 184-192.

Christiansen, A.V. & Auken, E., 2012. A global measure for depth of investigation, *Geophysics,* 77**,** WB171-WB177.

Christiansen, A.V., Auken, E. & Sørensen, K.I., 2006. 6 The transient electromagnetic method. *in Groundwater Geophysics. A tool for hydrogeology*, pp. 179-224, ed. Kirsch, R. Springer.

Foged, N., Auken, E., Christiansen, A.V. & Sørensen, K.I., 2013. Test site calibration and validation of airborne and ground based TEM systems, *Geophysics,* 78**,** E95-E106.

Kirkegaard, C., Andersen, K., Boesen, T., Christiansen, V., Auken, E. & Fiandaca, G., 2015. Utilizing massively parallel co-processors in the AarhusInv 1D forward and inverse AEM modelling code, *ASEG Extended Abstracts,* 2015**,** 1-3.

Pebesma, E.J. & Wesseling, C.G., 1998. Gstat: A Program for geostatistical Modelling, Prediction and Simultation, *Computers & Geosciences,* 24**,** 17-31.

Viezzoli, A., Christiansen, A.V., Auken, E. & Sørensen, K.I., 2008. Quasi-3D modeling of airborne TEM data by Spatially Constrained Inversion, *Geophysics,* 73**,** F105-F113.

APPENDIX I: LOCATION MAPS, QC MAPS

This appendix includes maps of:

- Model location and mapping lines
- Data residual
- Number of data points
- Depth of investigation, in elevation and depth

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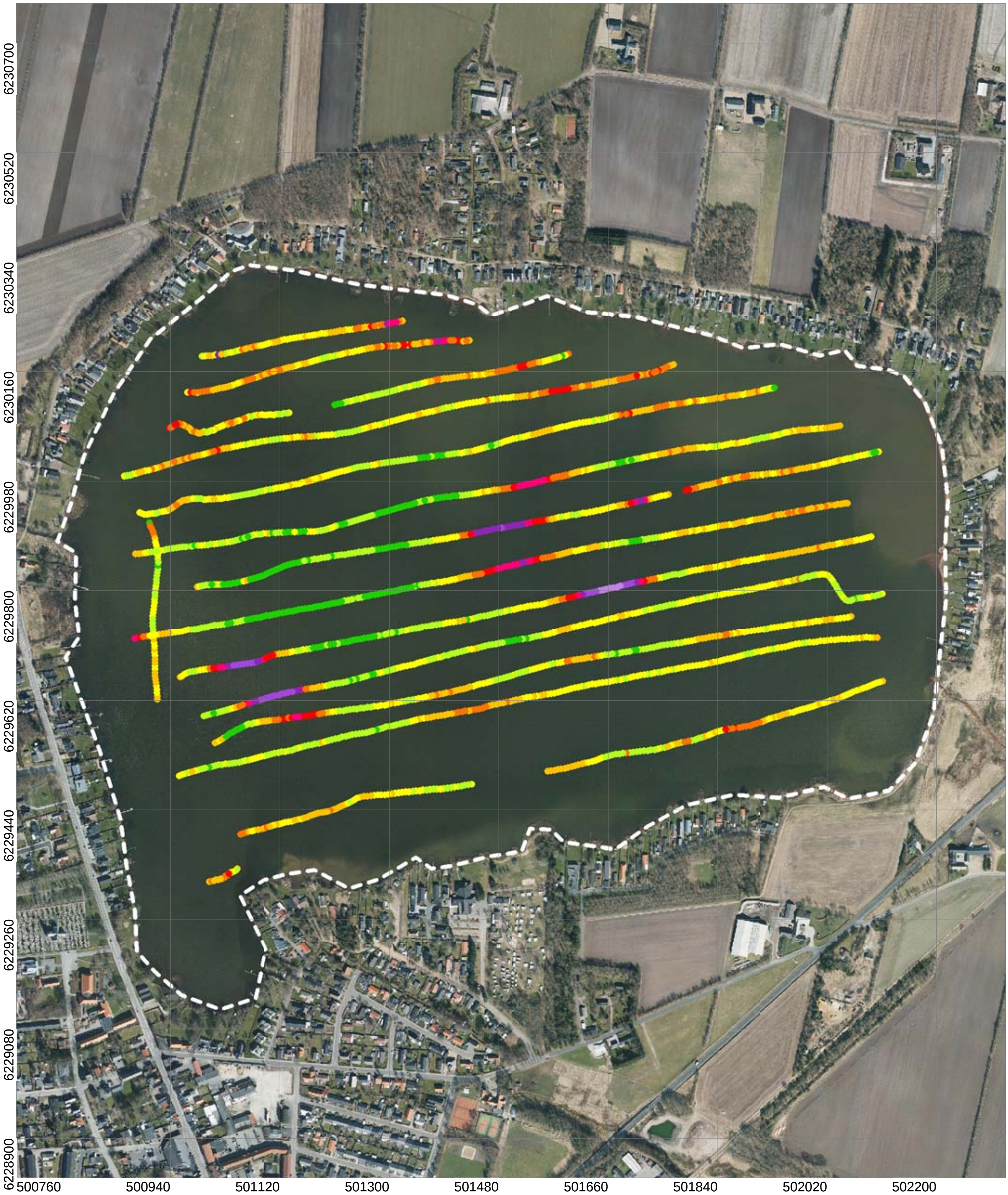
Loation Map, Sunds

Black: FloaTEM lines, Red: FloaTEM Model Position

UTM 32N WGS84

0.5 km



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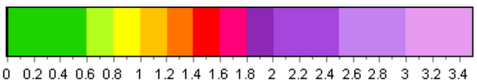
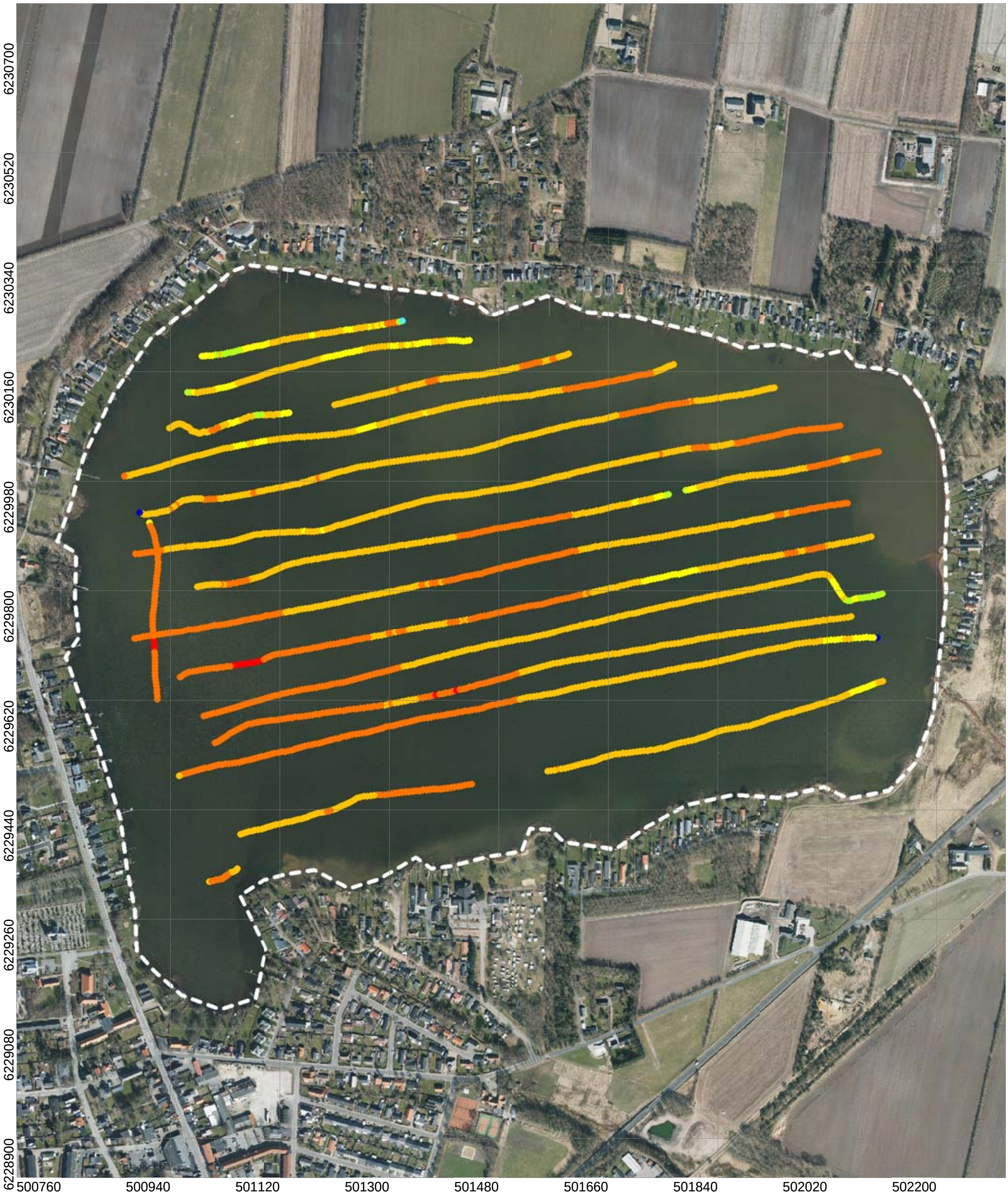


Data Residual

Below one corresponds to a fit within one standard deviation

UTM 32N WGS84

0.5 km



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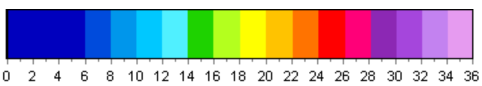
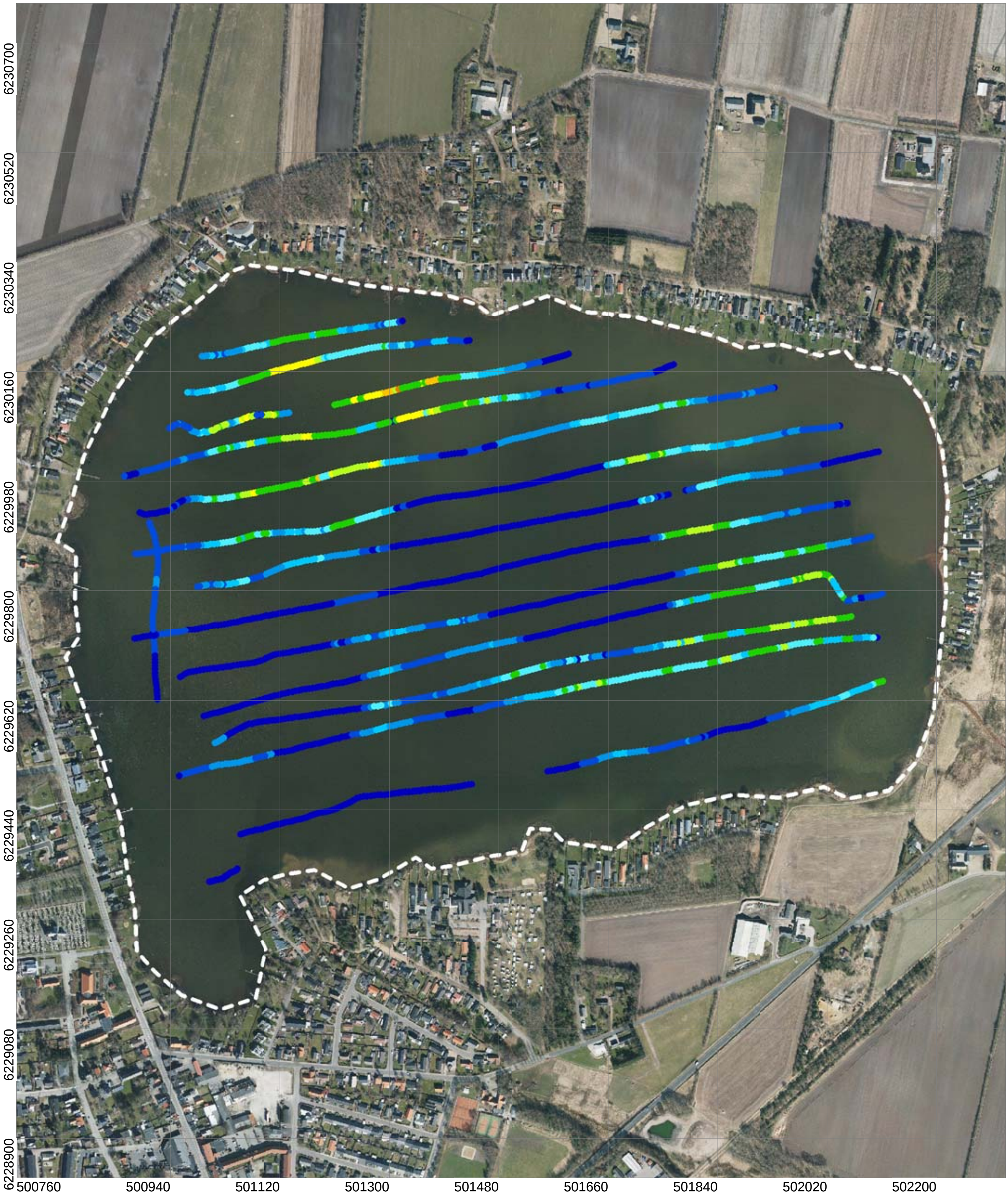


Number of data points

Number of Gates used for inversion

UTM 32N WGS84

0.5 km



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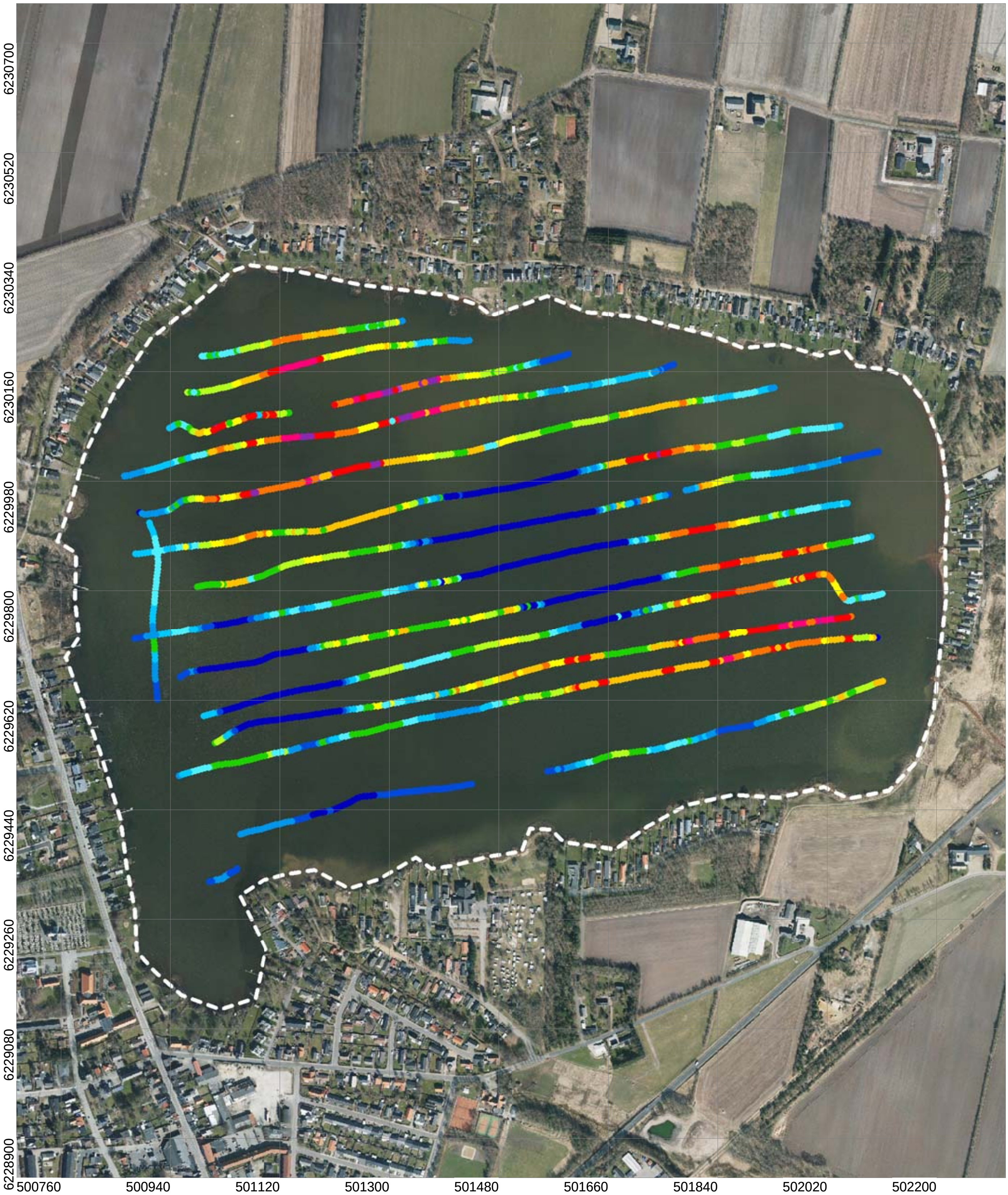
Depth of Investigation, Conservative

Depth, Meters

40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120
Depth [m]

UTM 32N WGS84

0.5 km



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40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120

Depth [m]

Depth of Investigation, Standard

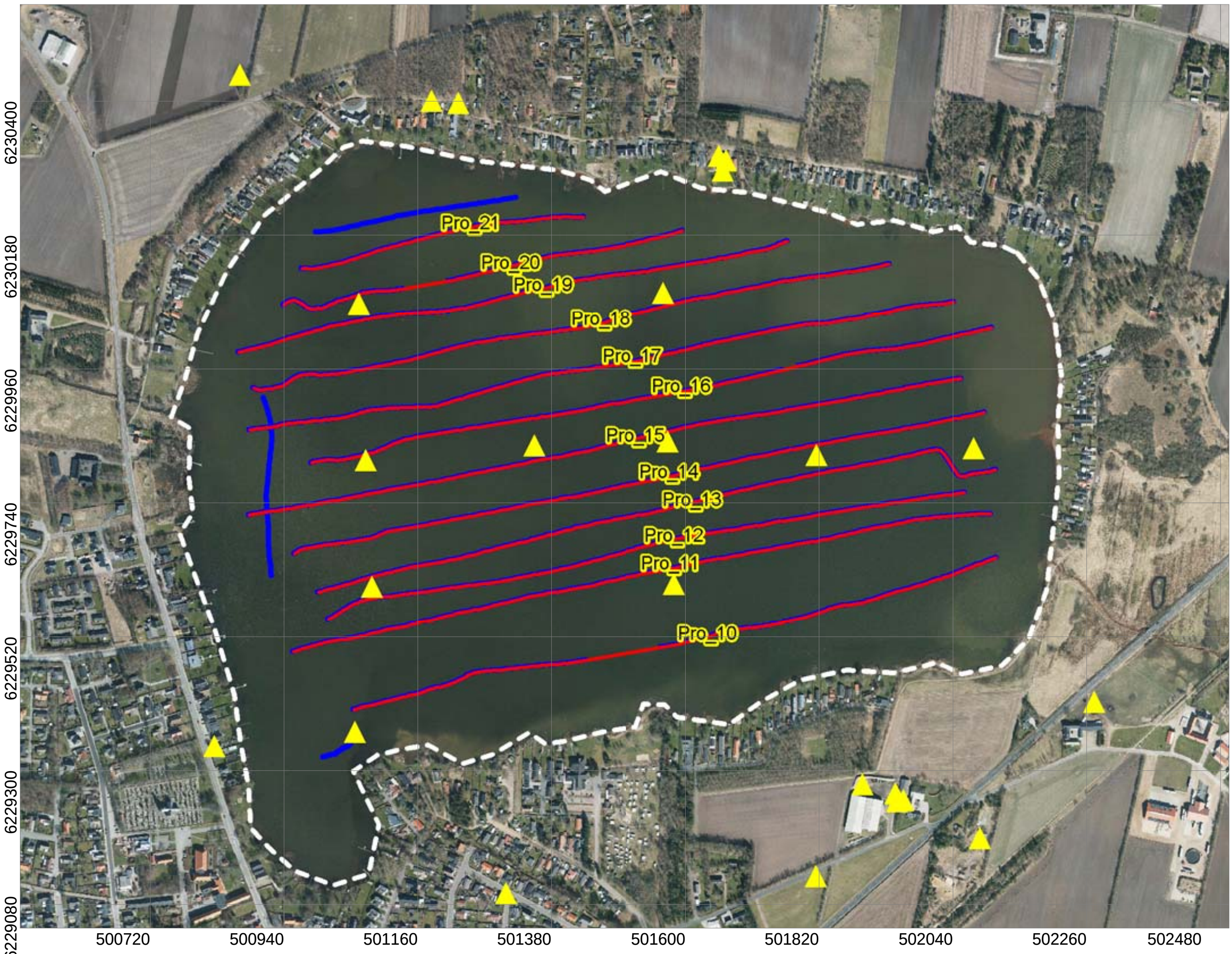
Depth, Meters

UTM 32N WGS84

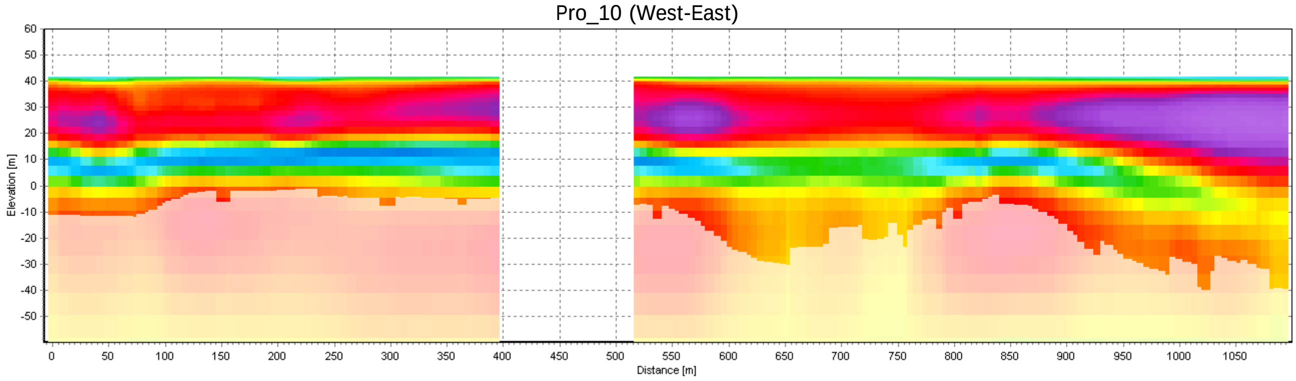
0.5 km

APPENDIX II: CROSS SECTIONS

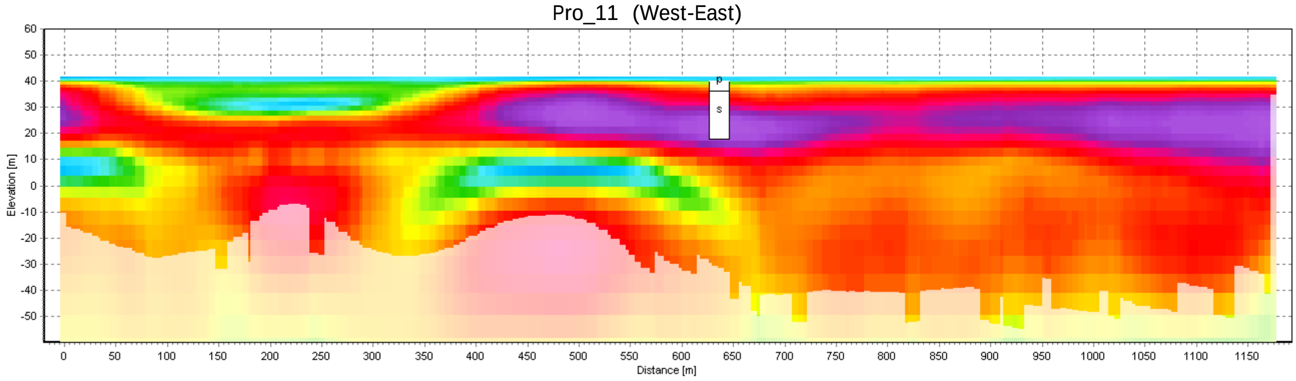
Selected cross sections for the smooth inversion are included. Each section holds the model bars blanked at the DOI- standard value. Sections for all the mapping lines are available in the delivered Workspace. Boreholes have been plotted on top of the cross-sections. The distance between the boreholes and cross-sections can be seen in the maps. Boreholes are highlighted as yellow triangles.



Pro_10 (West-East)



Pro_11 (West-East)



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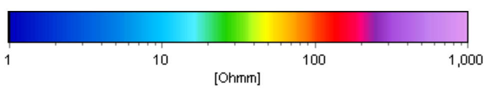
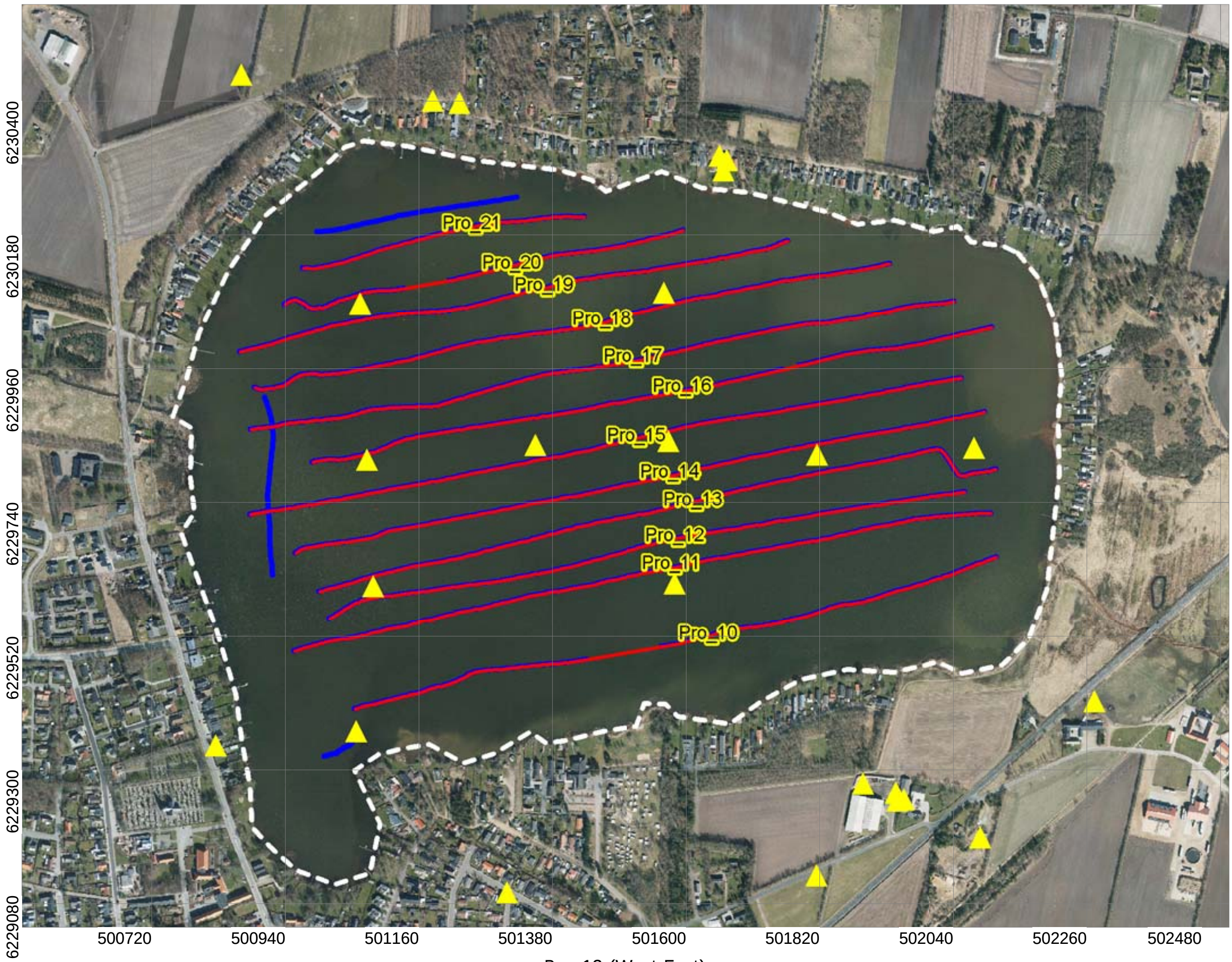
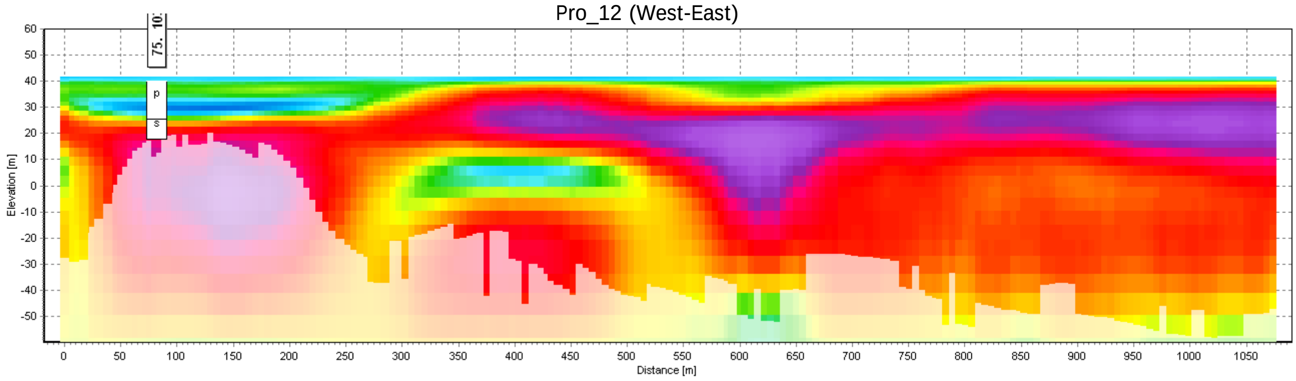


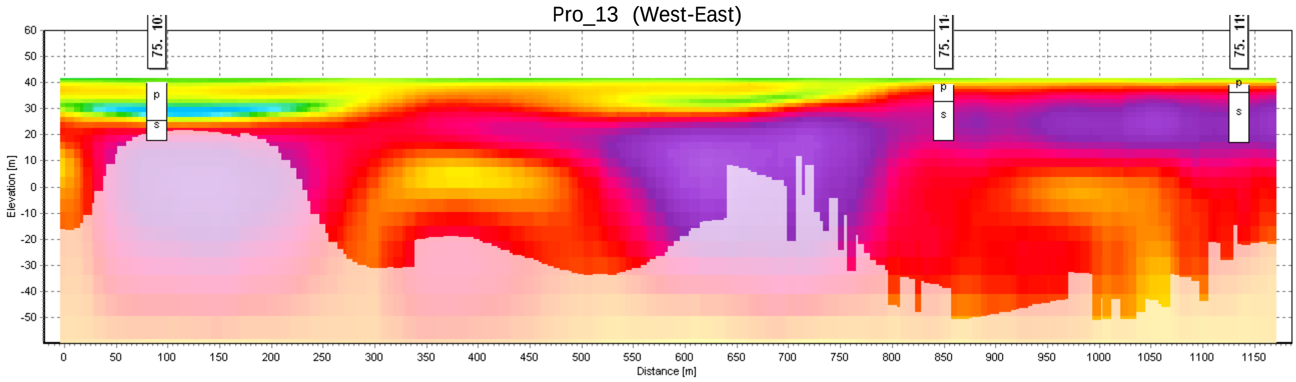
Resistivity Profiles (ohm-m)

Smooth SCI Model

The profiles display model bars from the smooth inversion results
Models have been blanked by 75% below the DOI Standard.







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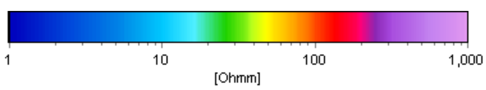
Resistivity Profiles (ohm-m)

Smooth SCI Model



The profiles display model bars from the smooth inversion results
Models have been blanked by 75% below the DOI Standard.

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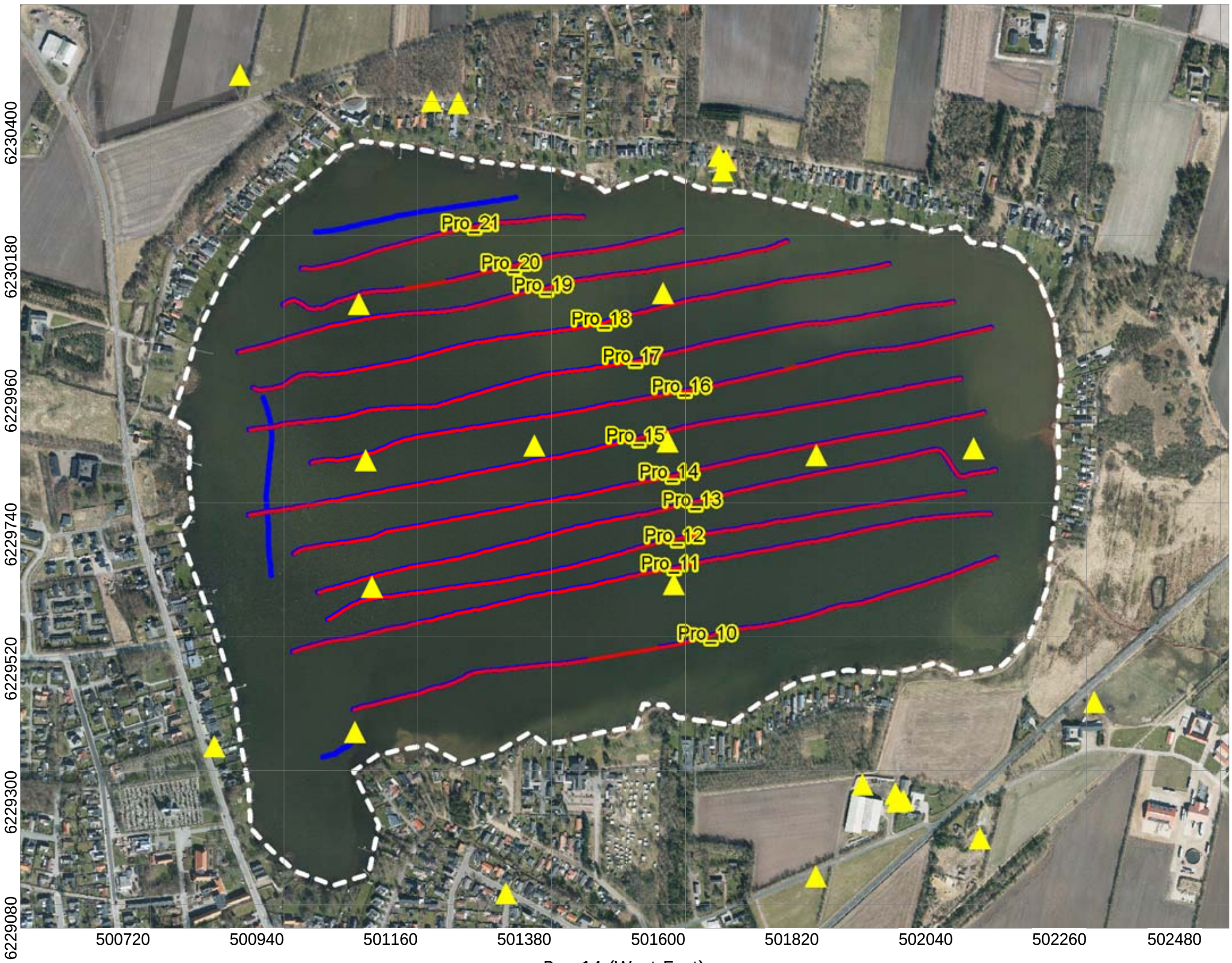

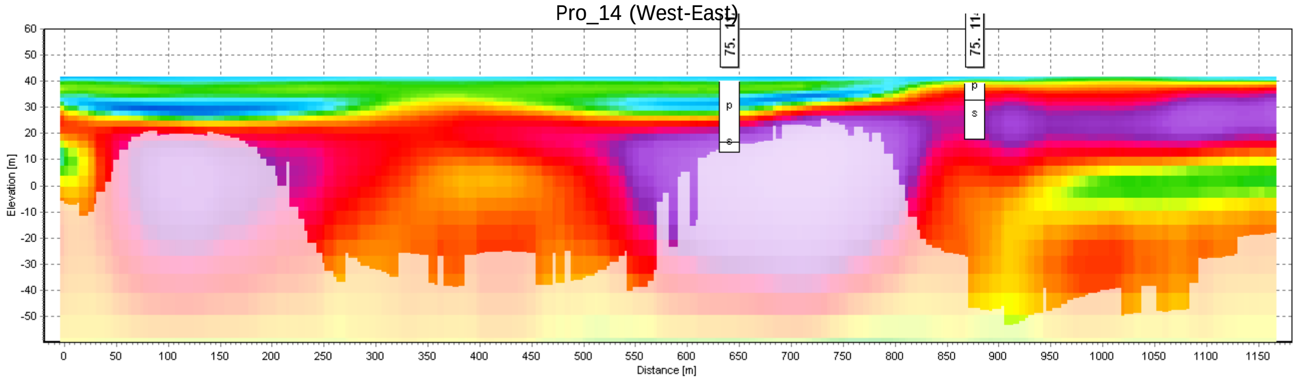

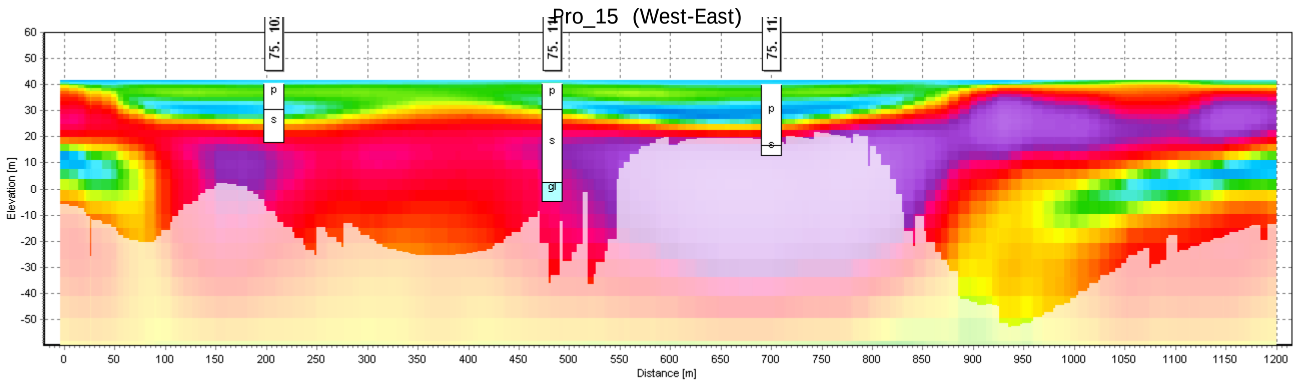

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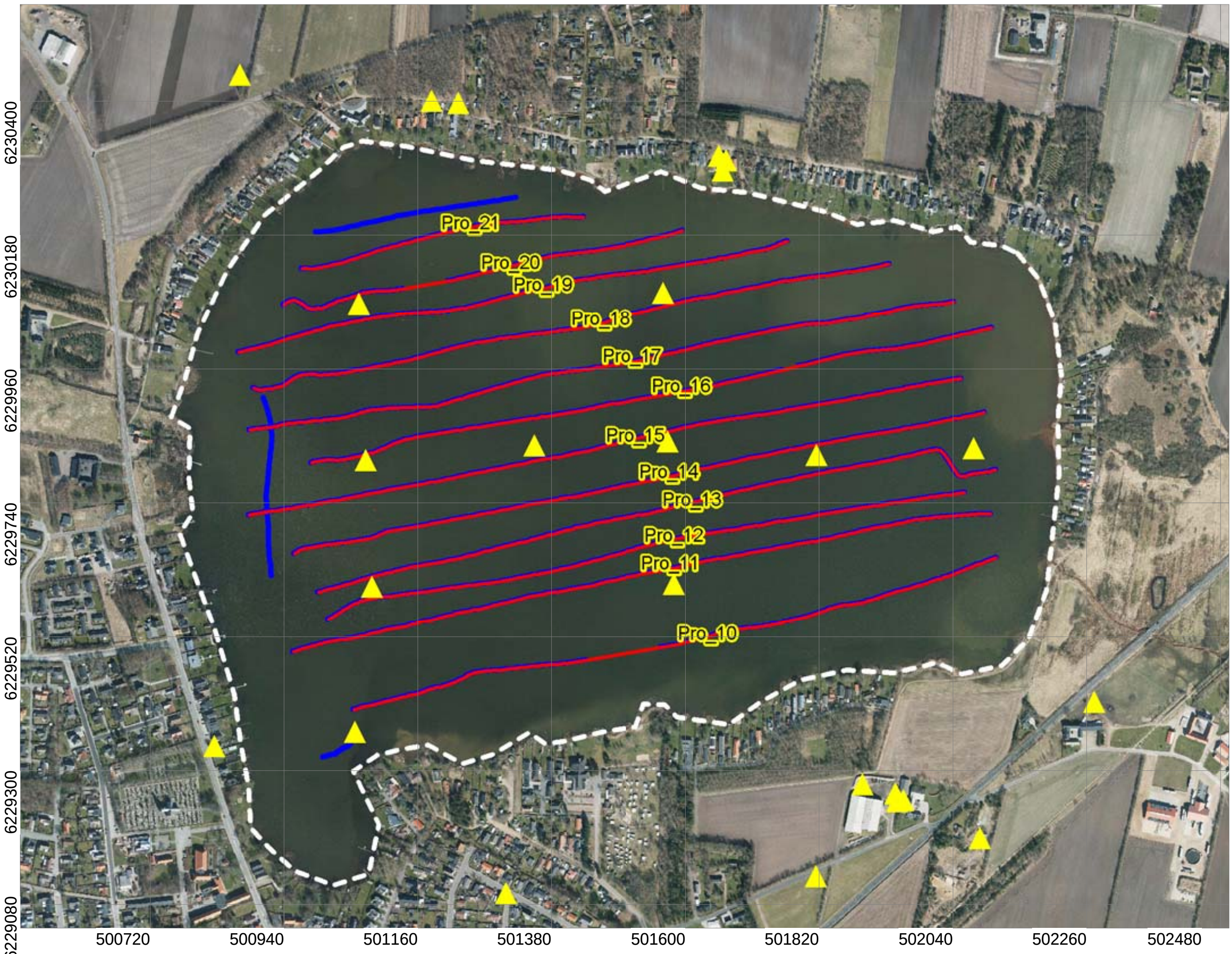
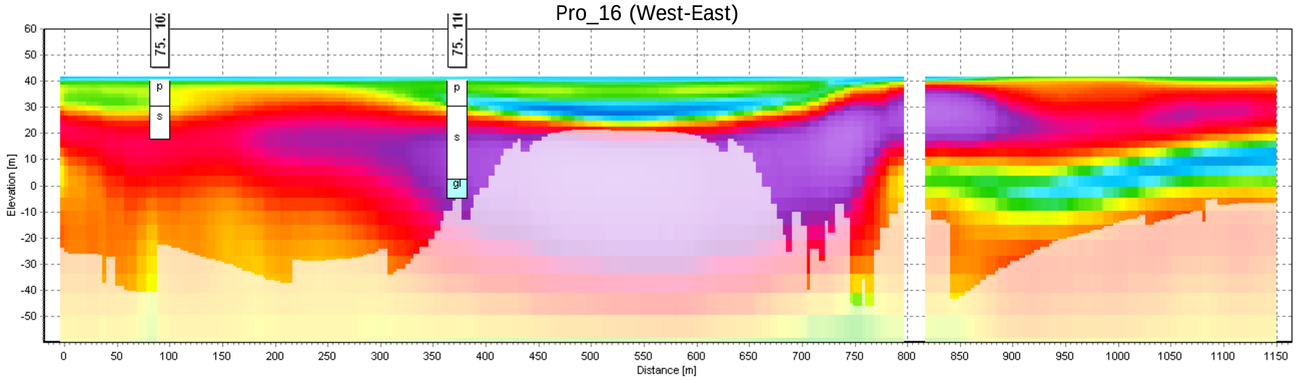
Resistivity Profiles (ohm-m)

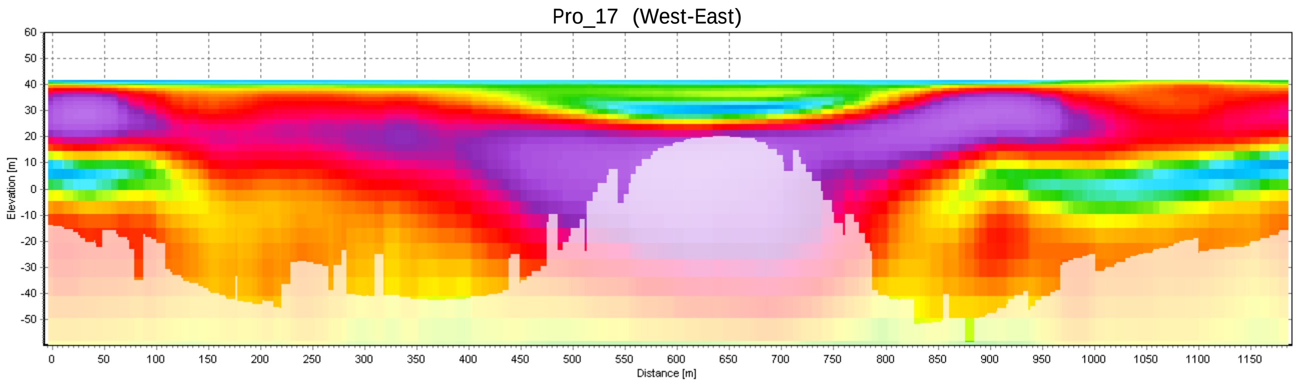
Smooth SCI Model

1 10 100 1,000
[Ohmm]

The profiles display model bars from the smooth inversion results
Models have been blanked by 75% below the DOI Standard.







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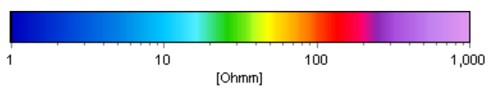
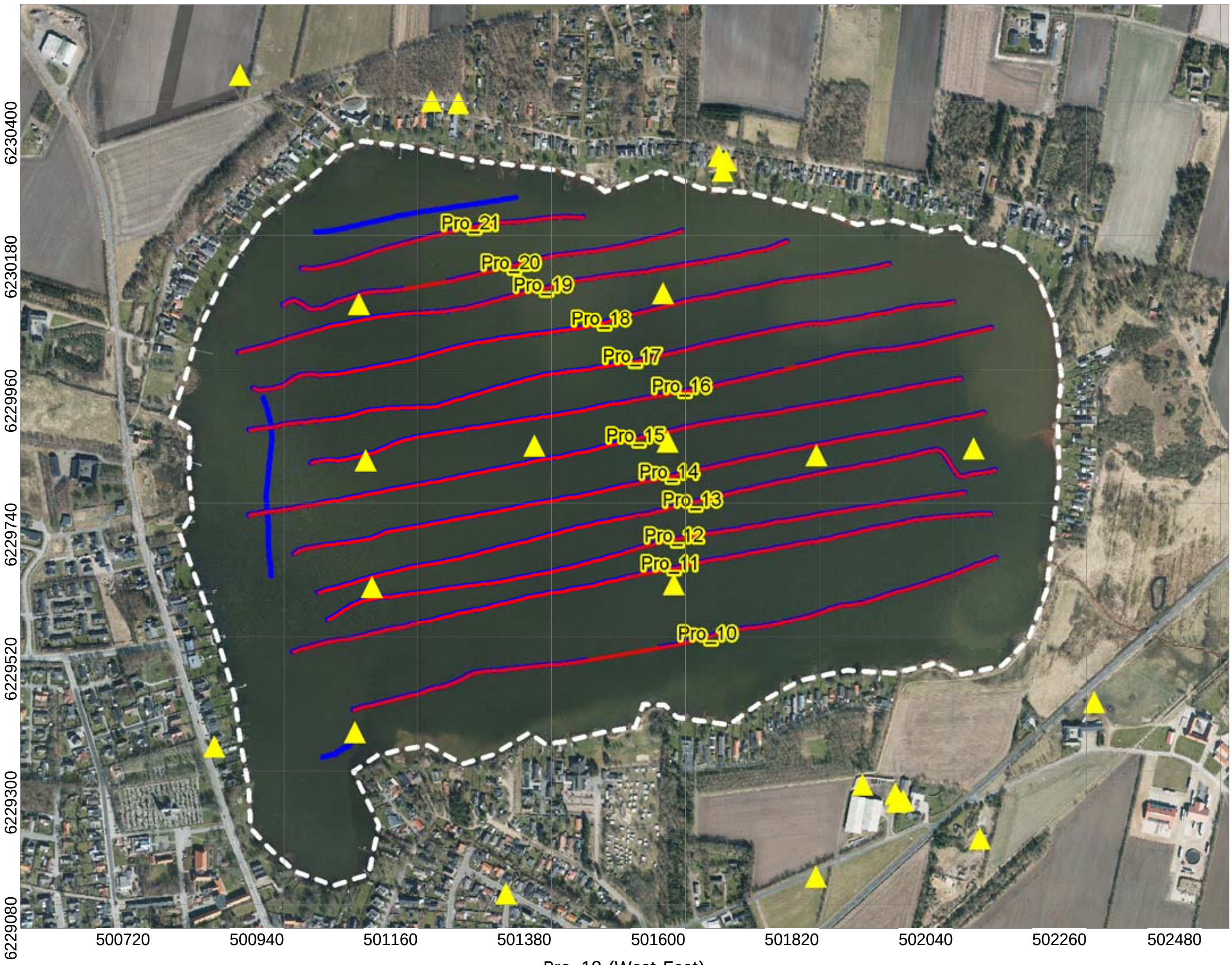
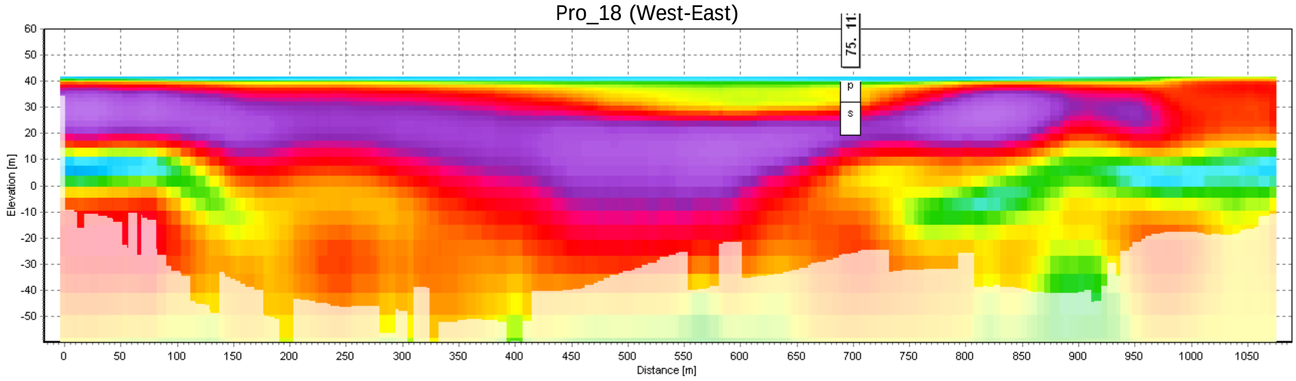


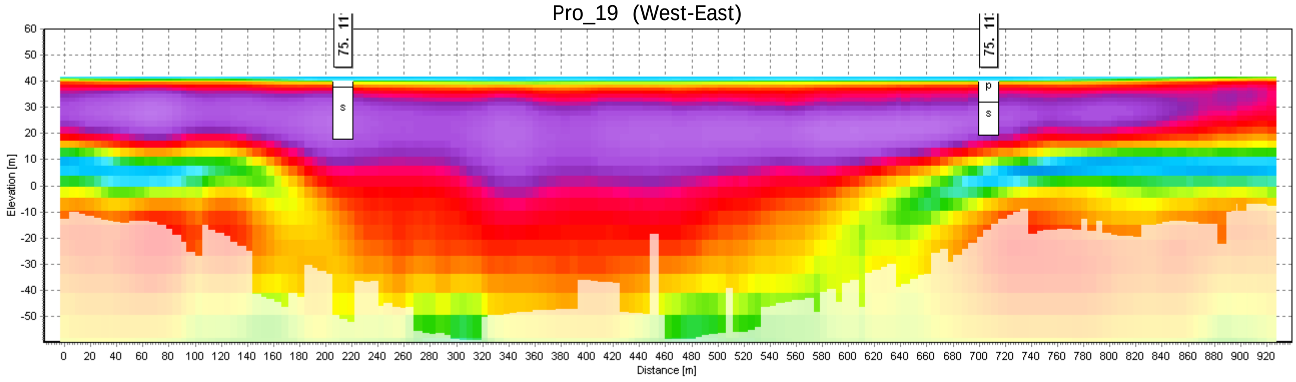
Resistivity Profiles (ohm-m)

Smooth SCI Model

The profiles display model bars from the smooth inversion results
Models have been blanked by 75% below the DOI Standard.







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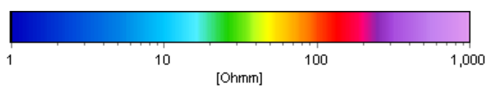
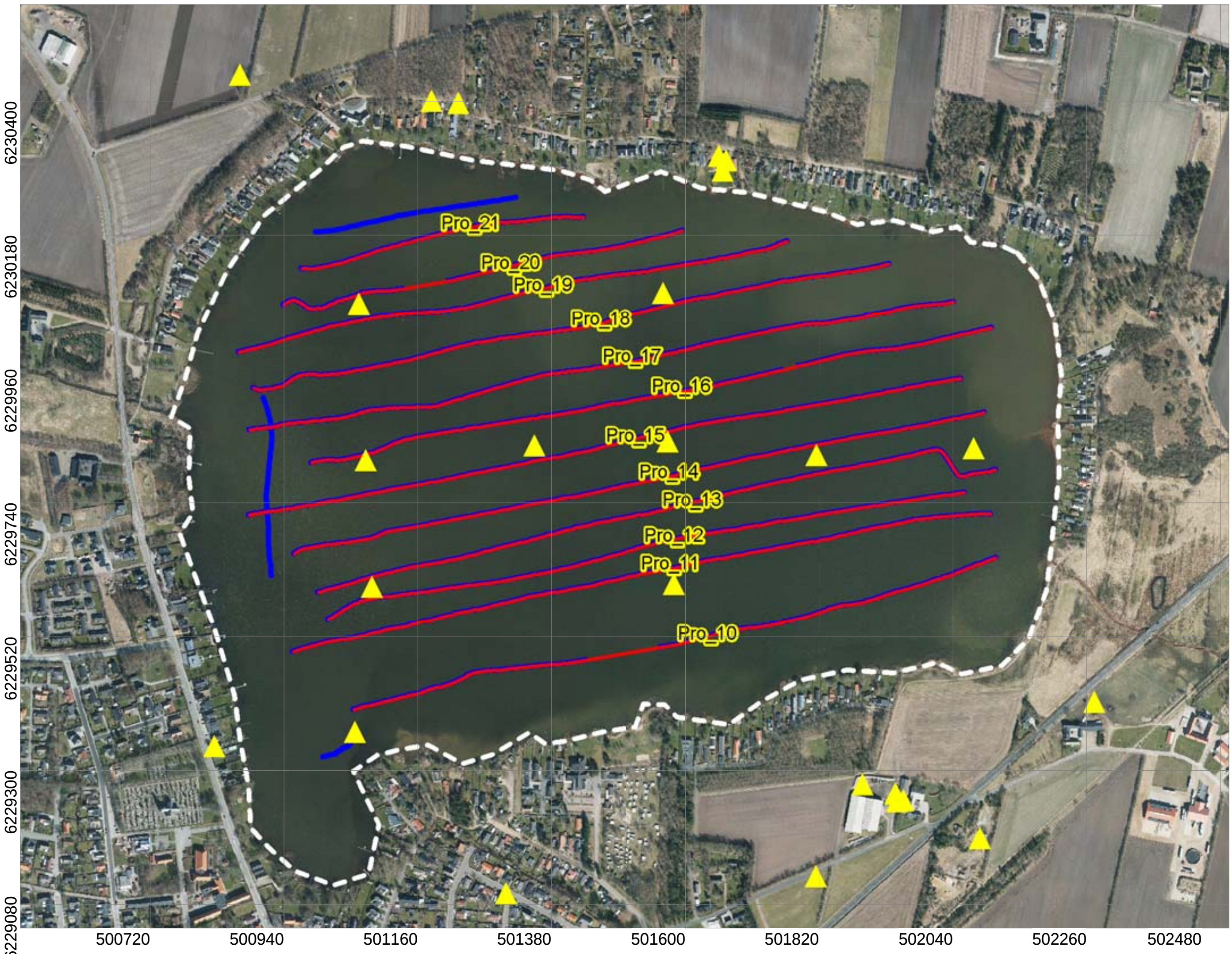
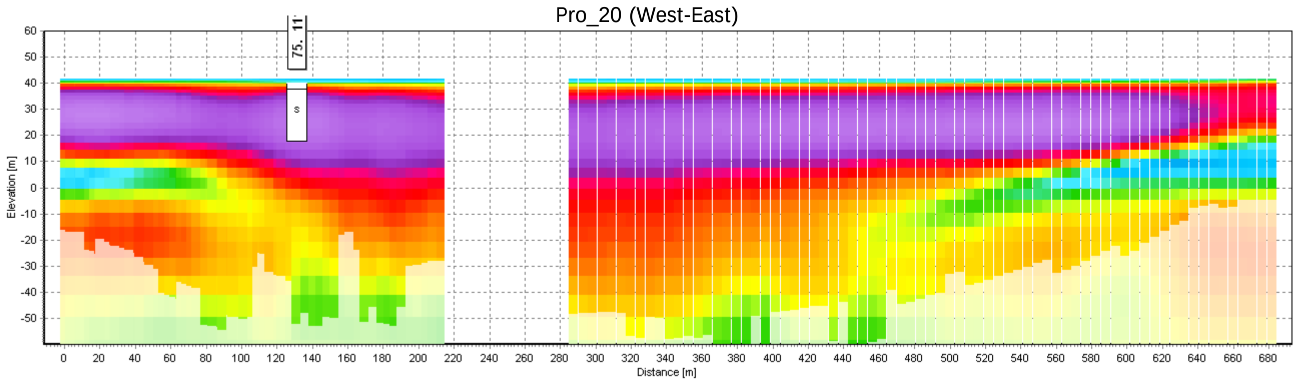


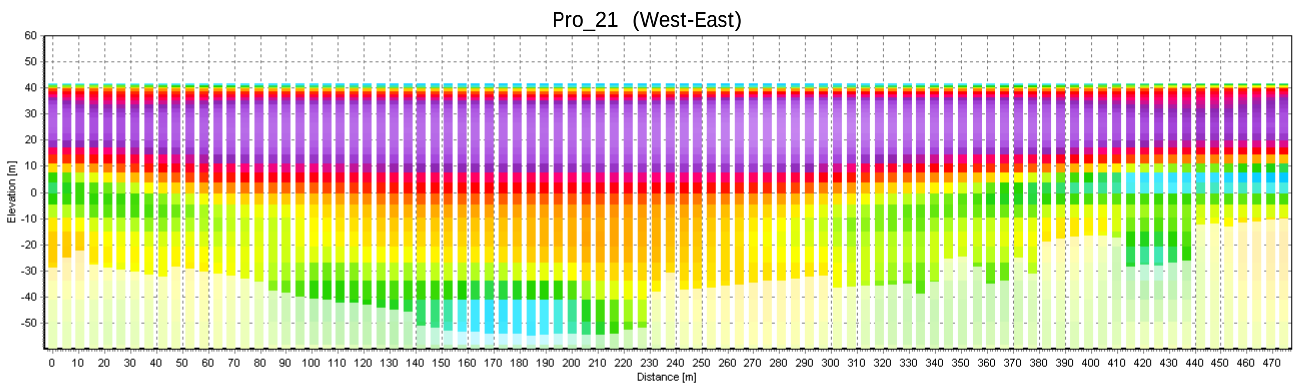
Resistivity Profiles (ohm-m)

Smooth SCI Model

The profiles display model bars from the smooth inversion results
Models have been blanked by 75% below the DOI Standard.







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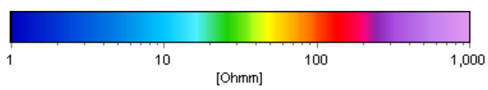
Resistivity Profiles (ohm-m)

Smooth SCI Model



The profiles display model bars from the smooth inversion results
Models have been blanked by 75% below the DOI Standard.

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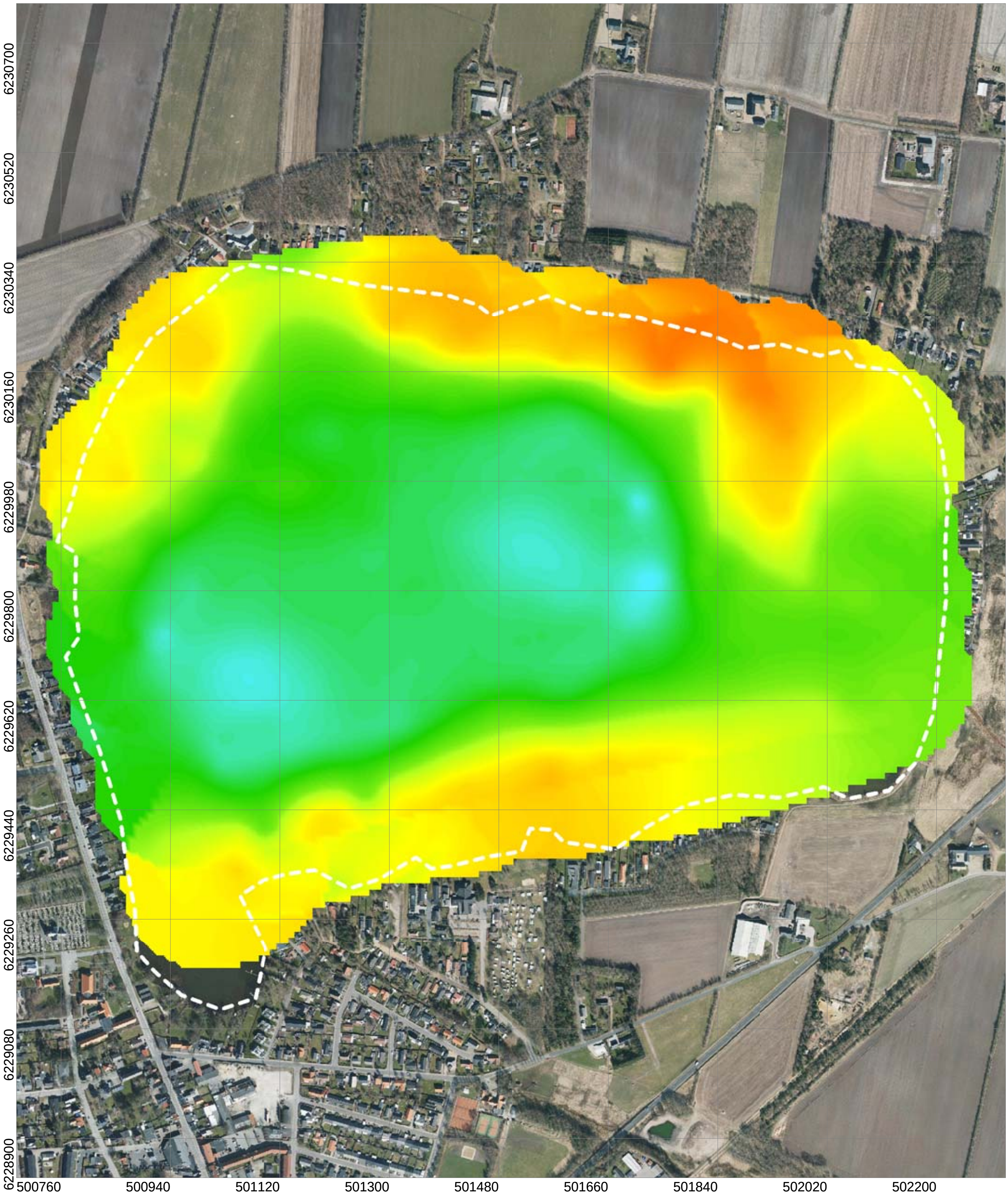
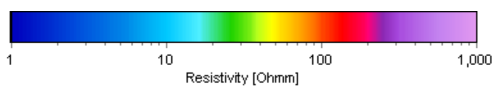
APPENDIX III: MEAN RESISTIVITY MAPS

This appendix includes mean resistivity maps generated from the smooth model inversion result in 5 m depth intervals from 0 to 30 m, and in 10 m intervals from 30 to 80 m. The resistivity models have been blanked at the DOI standard value prior to the interpolation to regular mean resistivity grids.

The interpolation of the mean resistivity values is performed by kriging interpolation, with a node spacing of 5 m, a search radius of 150 m, and with additional pixel smoothing.





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Mean Resistivity - Depth 0 - 5 m (ohmm)

SCI Smooth Model - Kriging with search radius 150 m

UTM 32N WGS84

0.5 km

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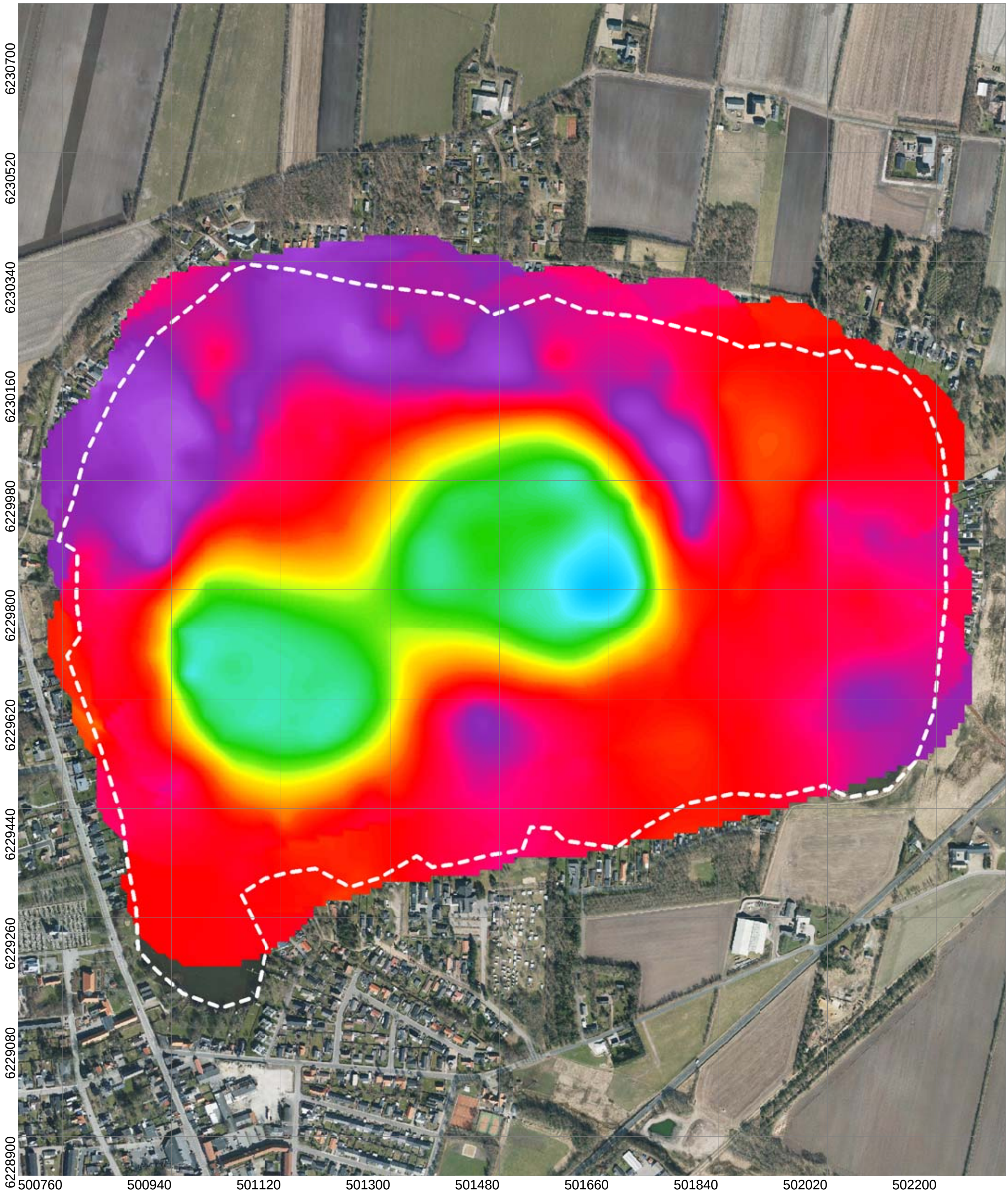

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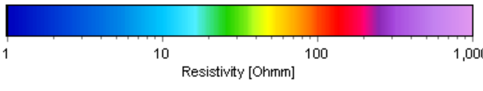
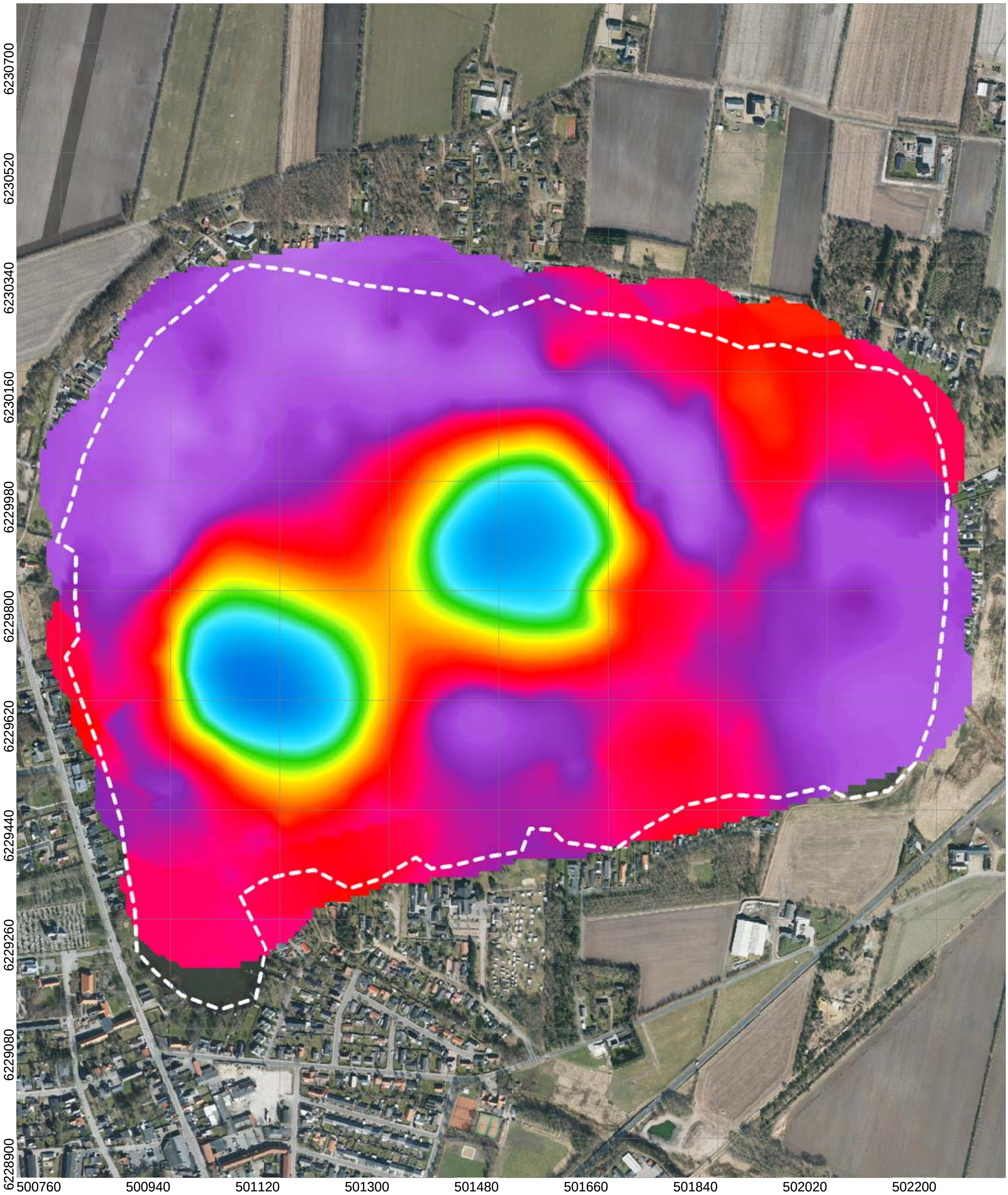


Mean Resistivity - Depth 5 - 10 m (ohmm)

SCI Smooth Model - Kriging with search radius 150 m

UTM 32N WGS84

0.5 km



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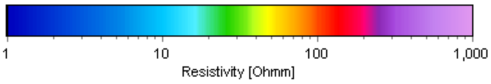
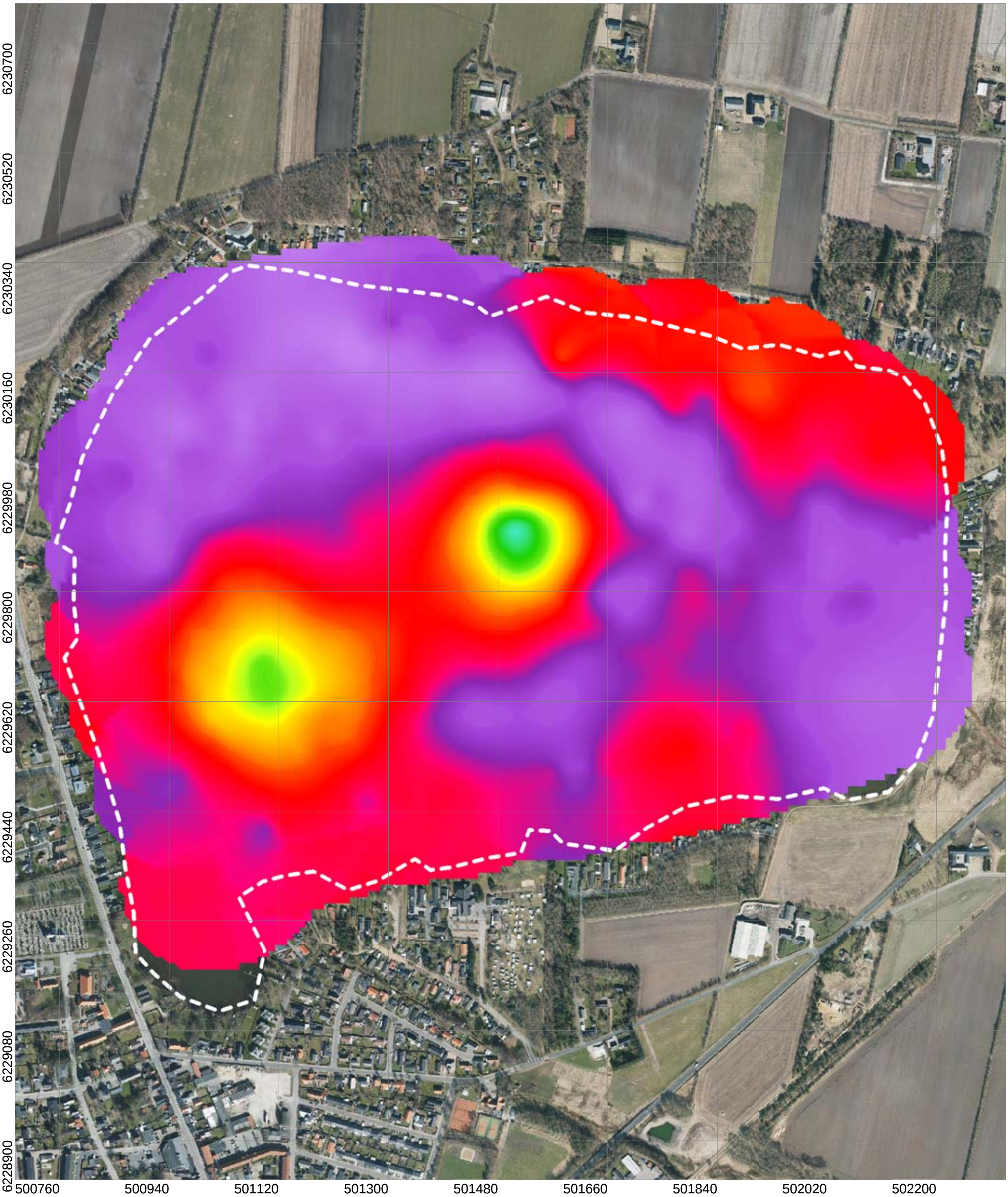
Mean Resistivity - Depth 10 - 15 m (ohmm)

SCI Smooth Model - Kriging with search radius 150 m



UTM 32N WGS84

0.5 km



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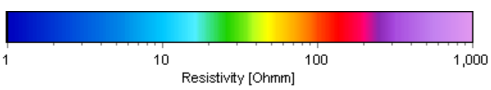
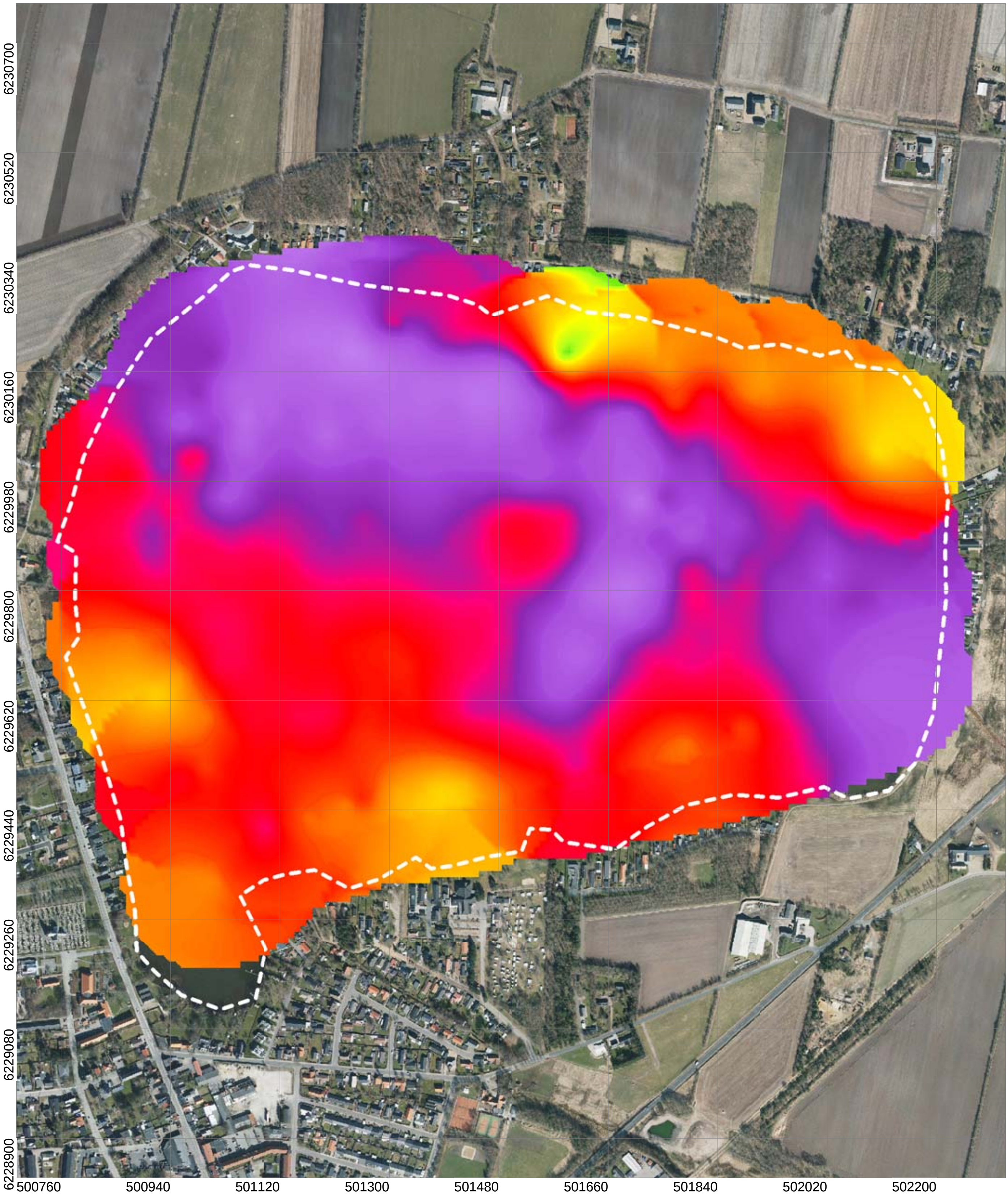
Mean Resistivity - Depth 15 - 20 m (ohmm)

SCI Smooth Model - Kriging with search radius 150 m



UTM 32N WGS84

0.5 km



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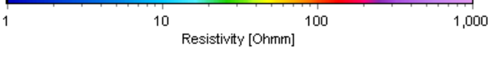
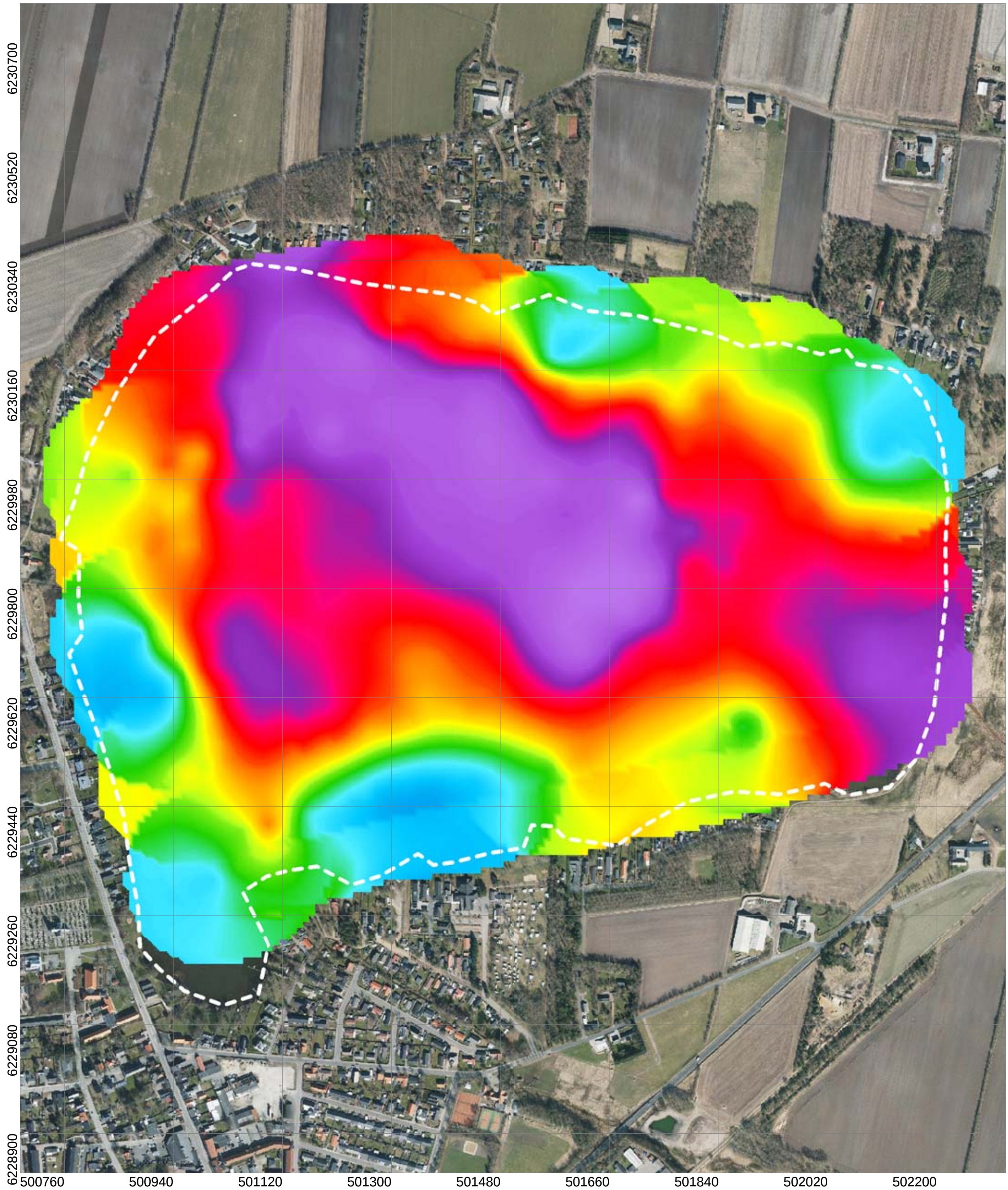
Mean Resistivity - Depth 20 - 25 m (ohmm)

SCI Smooth Model - Kriging with search radius 150 m



UTM 32N WGS84

0.5 km



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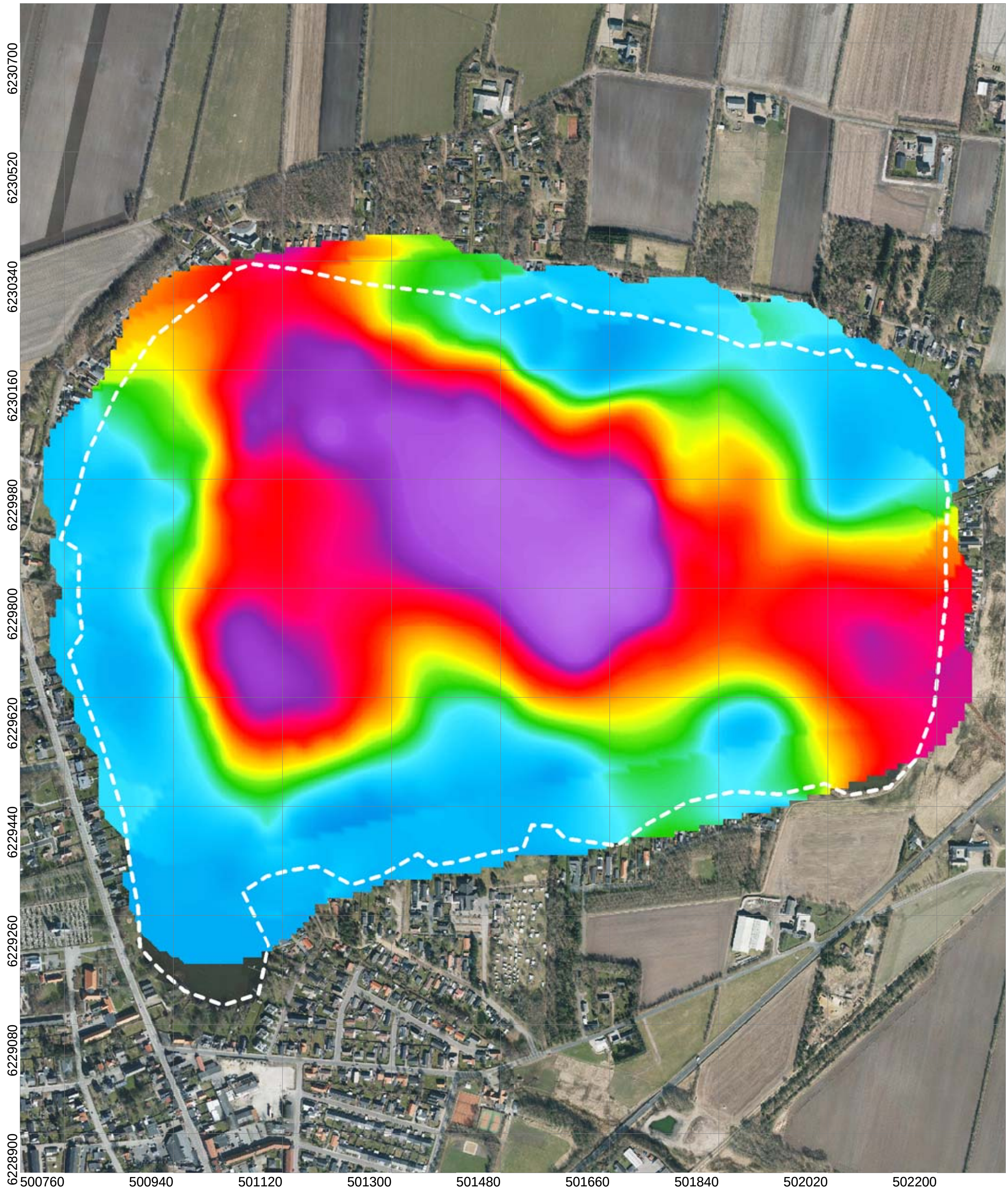
Mean Resistivity - Depth 25 - 30 m (ohmm)

SCI Smooth Model - Kriging with search radius 150 m

UTM 32N WGS84

0.5 km



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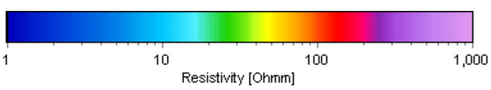
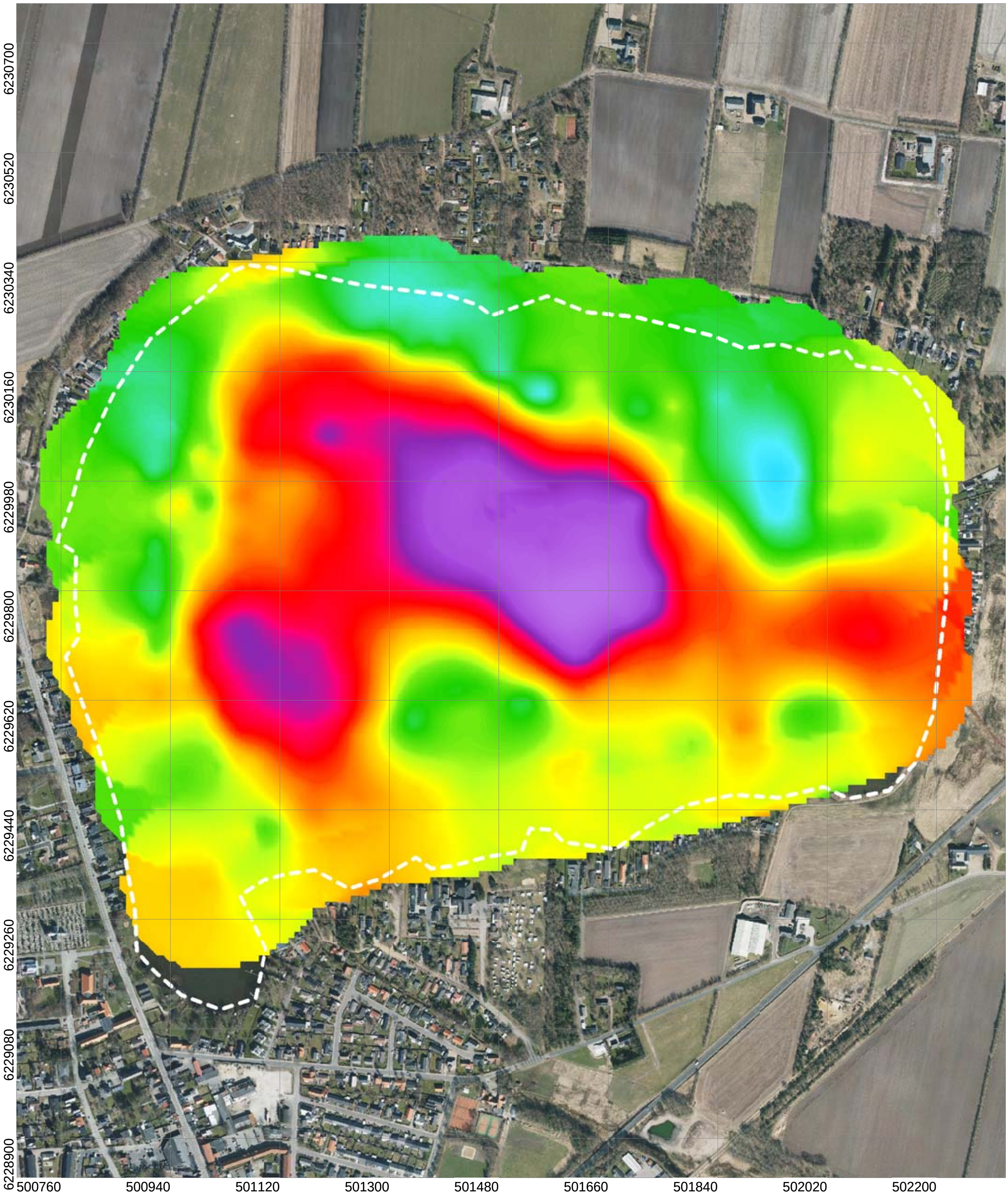
Mean Resistivity - Depth 30 - 40 m (ohmm)

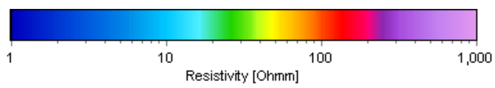
SCI Smooth Model - Kriging with search radius 150 m



UTM 32N WGS84

0.5 km





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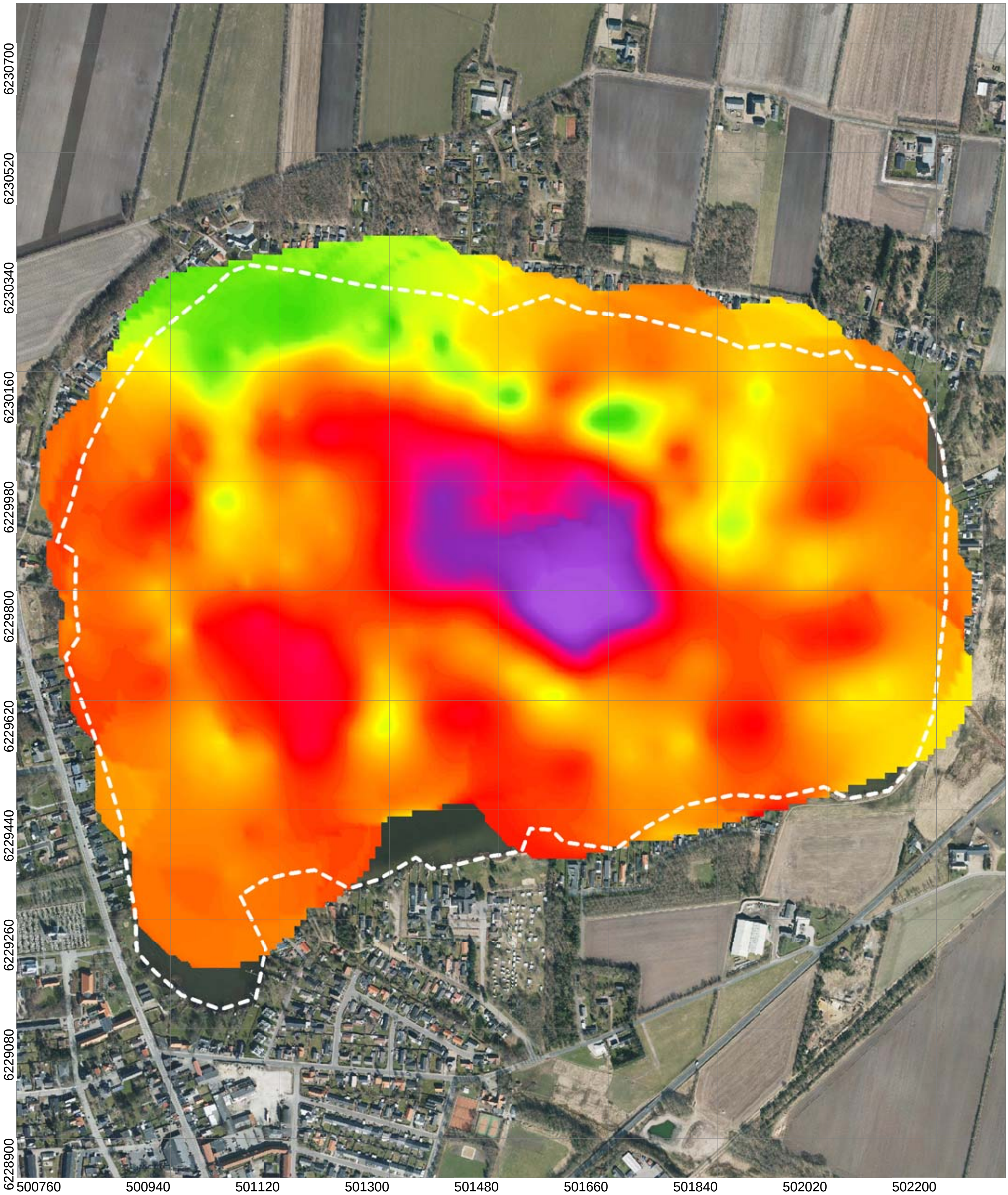
Mean Resistivity - Depth 40 - 50 m (ohmm)

SCI Smooth Model - Kriging with search radius 150 m

UTM 32N WGS84

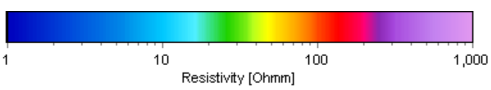
0.5 km



FloaTEM Sunds 2018

Mean Resistivity - Depth 50 - 60 m (ohmm)

SCI Smooth Model - Kriging with search radius 150 m



UTM 32N WGS84

0.5 km

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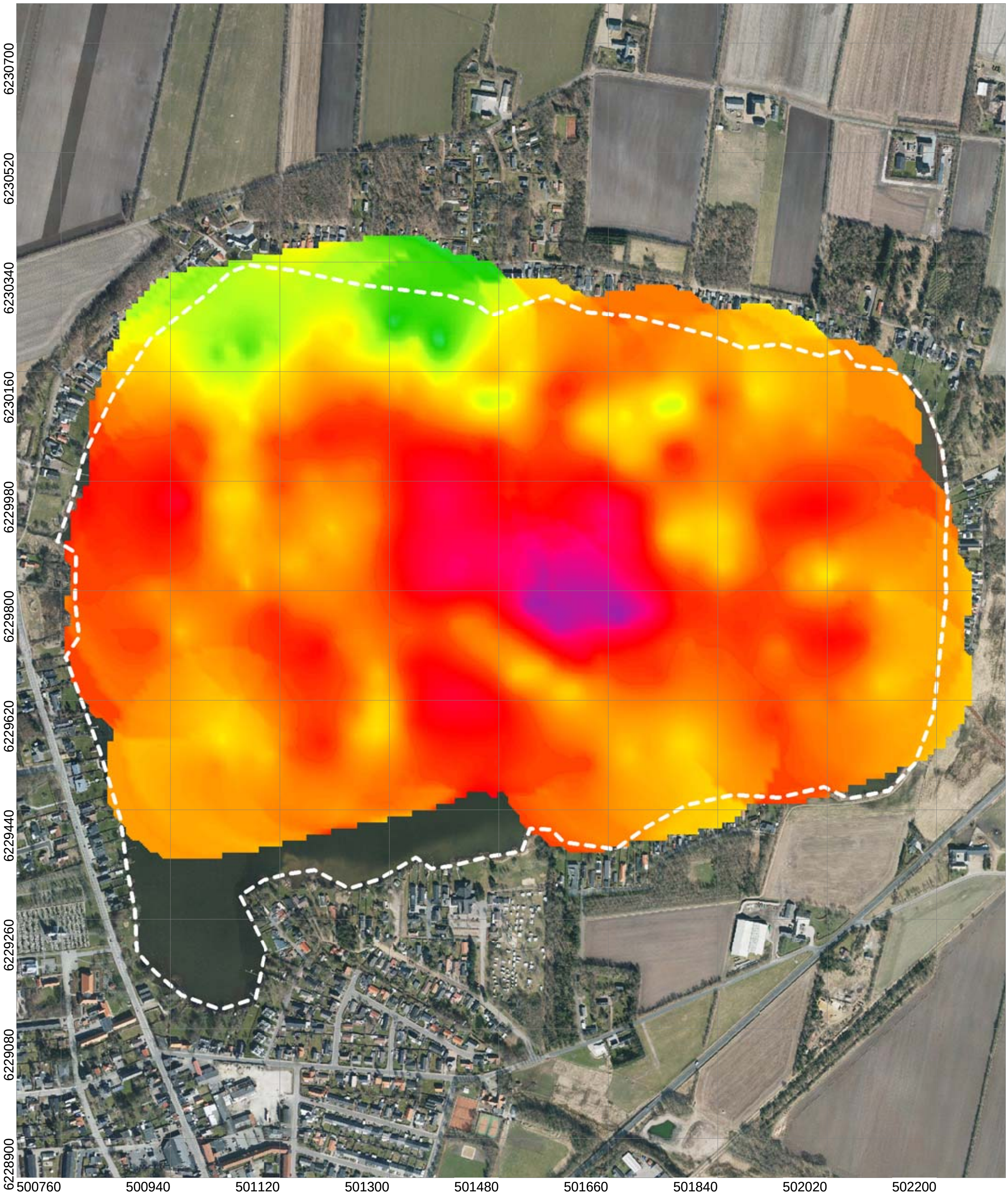

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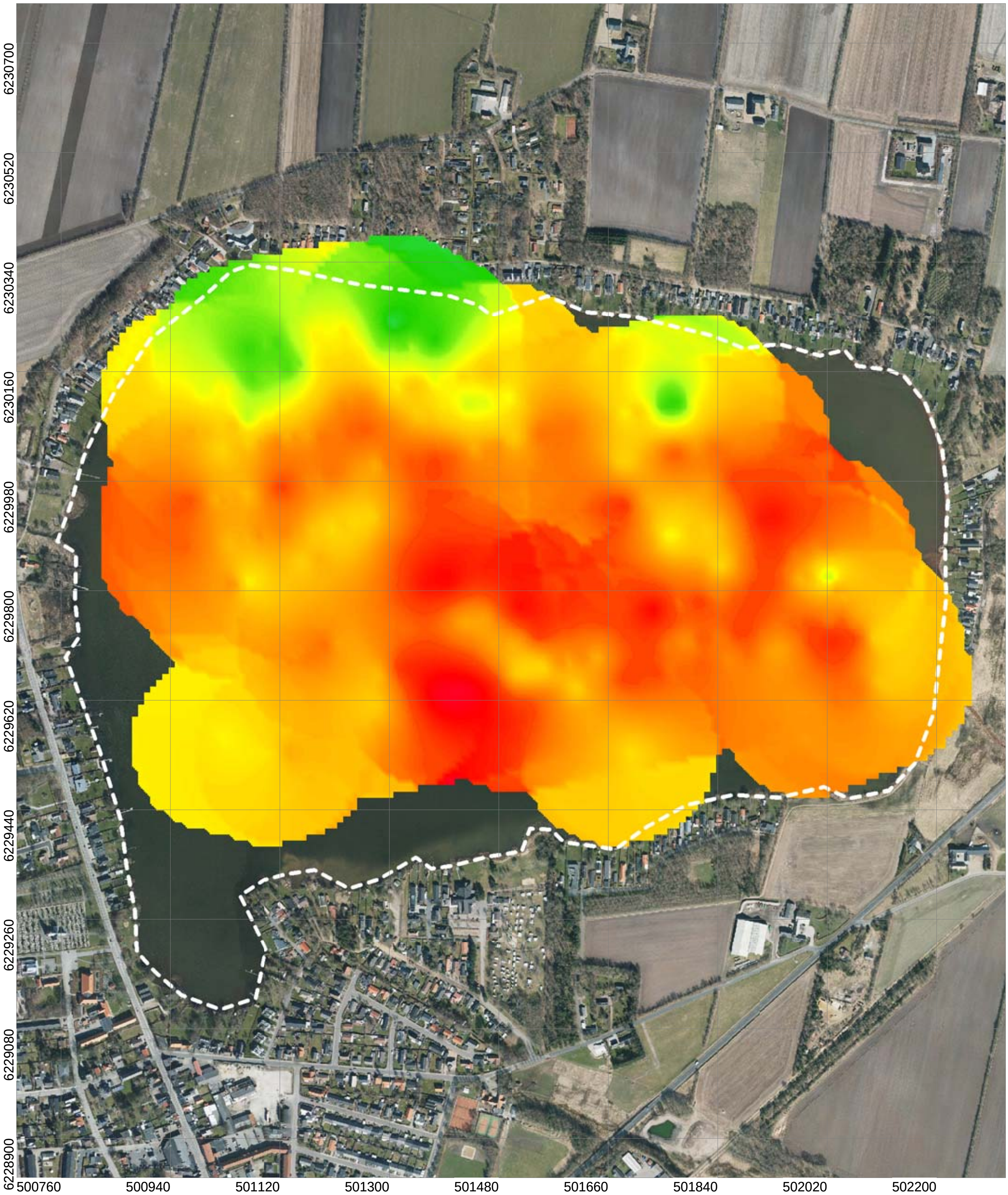
Mean Resistivity - Depth 60 - 70 m (ohmm)

SCI Smooth Model - Kriging with search radius 150 m

1 10 100 1,000
Resistivity [Ohmm]

UTM 32N WGS84

0.5 km



FloaTEM Sunds 2018

Mean Resistivity - Depth 70 - 80 m (ohmm)

SCI Smooth Model - Kriging with search radius 150 m

1 10 100 1,000
Resistivity [Ohmm]

UTM 32N WGS84

0.5 km

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