March 15, 2018

MEMO TO THE MGA BOARD OF DIRECTORS

Subject: Agenda Item 5.1

Title: Presentation by Max Halkjær of Ramboll and Cameron Tana of Hydrometrics Regarding the Report Titled "*Hydrogeological Investigation Salt-Fresh Water Interface – Monterey*"

Attachments:

1. Report titled "*Hydrogeological Investigation Salt-Fresh Water Interface – Monterey*", by Max Halkjaer and others of Ramboll, dated February 2018

2. Technical Memorandum titled "*Management Implications of SkyTEM Seawater Intrusion Results*", from Cameron Tana of Hydrometrics, dated March 8, 2018

Background

The Santa Cruz Mid-County Groundwater Agency (MGA) invested in an innovative approach to try and determine the groundwater/ seawater intrusion interface in the aquifers offshore. This "SkyTEM" approach had only been tried a few times in parts of Europe and this was the first time this technology had been applied in the United States offshore. The effort was successful. One of the lead investigators and authors of the report (Max Halkjaer of Ramboll) and the MGA's consulting hydrologist (Cameron Tana of Hydrometrics) will present the findings and its groundwater resource implications at the March 15 meeting.

Hydrogeological Investigation Report

The report in Attachment 1 describes the SkyTEM investigation, including the survey design, data, and results. The data were processed to develop numerous very colorful images to help illustrate the findings. Figure 20 of the report encapsulates the findings showing the uppermost aquifers where seawater is observed along the coast.

Review of Report by Hydrometrics

Hydrometrics reviewed the SkyTEM report and provided context to as what the findings mean for managing the regions' groundwater resources (see Attachment 2).

Possible Board Actions:

1. By MOTION, accept the report and the hydrologist's review, OR

2. By MOTION, provide modifications to incorporate into the report and/or the hydrologist's review and then accept the documents with noted modifications, OR

3. Take no action.

By ______________________________

Ron Duncan
General Manager
Soquel Creek Water District

Intended for
Santa Cruz Mid-County Groundwater Agency (MGA)

Document type
Report

Date
February 2018

HYDROGEOLOGICAL INVESTIGATION
SALT-FRESH WATER INTERFACE – MONTEREY

rev

SALT-FRESH WATER INTERFACE – MONTEREY

Revision	**2**
Date	
Made by	**Max Halkjaer, Peter Thomsen and Paul Thorn**
Checked by	**Farid Achour (PG)**
Approved by	**Max Halkjaer**
Description	**SkyTEM survey, Processing, Inversion and interpretation**

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1. EXECUTIVE SUMMARY

Ramboll has been asked to map the interaction in between fresh and saline water in the coastal zone in the northern part of the Monterey Bay, California.

A Time Domain ElectroMagnetic (TDEM) survey based on a helicopter platform has surveyed a total of 320 line kilometres ~200 line miles. The system used has been the SkyTEM system.

The survey is flown as 15 flight lines with a spacing of approximately 100 m parallel to the coast line and 12 tie lines with a spacing from 1 to 2 km orientated perpendicular to the coastline. Two of the perpendicular lines in the southeastern part of the survey have been extended in-land.

The survey shows significant variations in the resistivity reflecting variations in salinity in the upper 100m (300ft) to a distance of approximately 1 km (3000ft) from the coastline.

The distribution of saline and fresh water is interpreted as being controlled by the geological layers, the flow of fresh water from in-land towards the coast and the volumes of pumped groundwater in the coastal area, near abstraction wells.

2. ABBRIVIATIONS

AEM	Airborne ElectroMagnetic
DOI	Depth of Investigation
DTM	Digital Terrain Model
ERT	Electrical Resistivity Tomography
F	Formation factor
Km	Kilometers
LCI	Laterally Constrained Inversion
M	Meter
MAG	Magnetic
m b.s.l	Meter below sea level
MLM	Multi-Layer Model
Ms	Milli seconds
Ohmm	Ohm meter
QA/QC	Quality Assurance/ Quality Control
Ro	The resistivity of the sediments filled with water
RTP	Reduced To Pole
RW	The resistivity of the water
SCI	Surface Constrained Inversion
TDEM	Time Domain Electro Magnetic
TDS	Total dissolved-solids
TMI	Total Magnetic Intensity
VD	Vertical Derivative

3. INTRODUCTION

The scope of work is to achieve an understanding of the interaction between the fresh and the saline water beneath the sea floor in the near coastal area along the northern part of the Monterey Bay area. See Figure 1.

The SkyTEM method measures lateral and vertical variations in the electrical resistivity due to varying geology and/or variations in the conductivity of the fluids. Thus the SkyTEM method is proven to be able to provide important information on the fresh water – saline water interaction in areas with shallow water. This is illustrated by a number of references /1/, /2/, /3/, /4/, /11/ including studies with specific to the hydrogeological settings in the Monterey Bay area /5/.

The terms resistivity and conductivity are used in the report. Electrical conductivity is the reciprocal of the electrical resistivity.

The report shall be seen as an extension to the data report provided by SkyTEM Surveys /6/.

Ramboll has made use of the initial processing provided by SkyTEM Surveys /6/. Based on processed data received from SkyTEM Surveys, Ramboll has reprocessed the data and done a quasi 3D inversion. The inversion results are together with other information used for a general hydrogeological interpretation.

As a secondary dataset the SkyTEM system recorded the total magnetic field providing information about the general geological structures and faults.

The report describes the data quality, processing of the data, modelling the data and finally the presentation and interpretation of the data. The chapter about presentation and interpretation can be read as a standalone chapter. The other chapters are of a more technical nature and thought as for documentation.

3.1 Partners

The following partners contributed to this project:

- SkyTEM Surveys: Responsible for the data collection of SkyTEM data;
- I-GIS: Entered some of the data in Geoscene3D and created animations;
- Ramboll Water: Lead company, planning, QA/QC, processing, inversion and interpretation.

3.2 Existing data

The following existing data has been used in the general interpretation framework:

- Borehole information (geophysical logs, lithology and salt content);
- Groundbased TDEM pilot study at the beach of Rio Del Mar;
- Electrical Resisitivity Survey (ERT) survey on the beach performed by Stanford University /8/;
- Existing conceptual model developed by Hydrometrics WRI /9/.

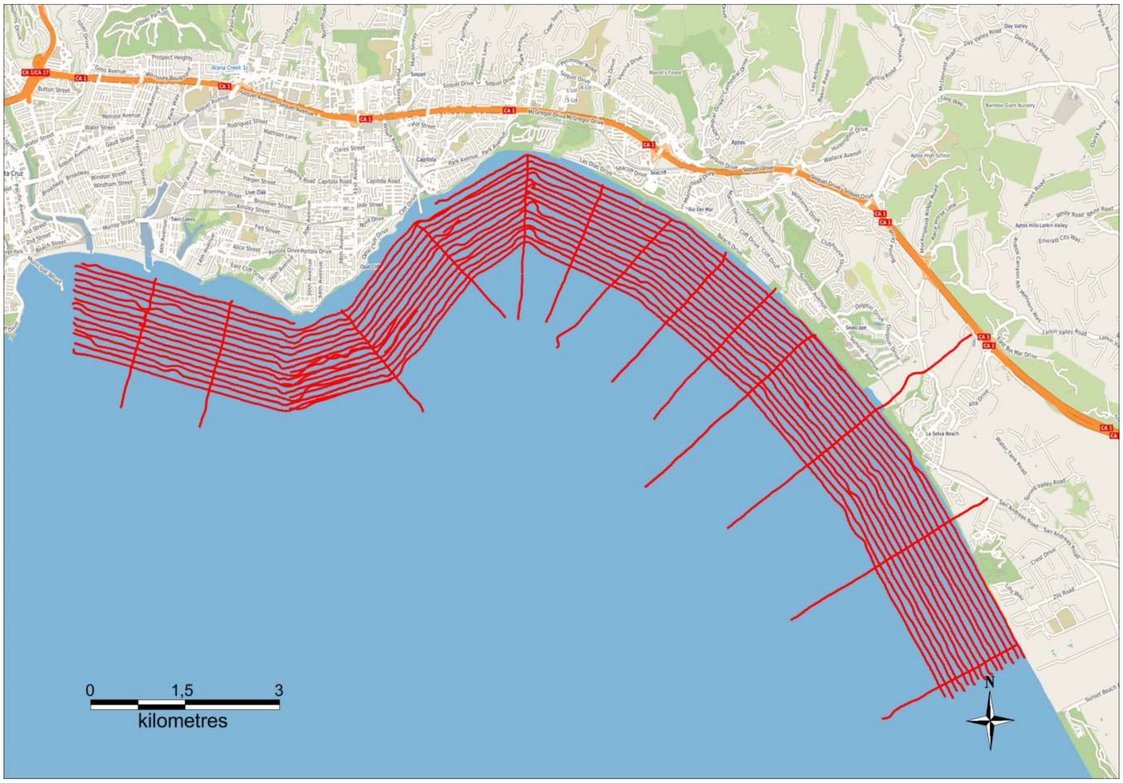


Figure 1. SkyTEM flight lines in the northern part of Monterey Bay.

4. SURVEY DESIGN

The design of the survey reflects the geological and hydrogeological settings as well as the possibilities and the limitations when using an electromagnetic method.

When the scope of work is to detect fresh water beneath seawater as well as sediments with saline water, the depth to water is a limiting factor. It is found that a depth to water can be a maximum of 15-20m /5/ in order to be able to detect fresh water beneath the sea bottom.

4.1 Depth of investigation

The SkyTEM system has been configured to achieve deepest penetration possible. This is needed, as the saline water in both the sea the sediments is very conductive, making the induced currents in the subsurface decay slowly. Therefore, it is desirable to obtain late time gates (10+ms) with the SkyTEM system in order to accommodate for the slower electromagnetic decays. For the actual survey, the center time for the last time gate has been set to 20 milliseconds.

4.2 Flight Lines

A total of 320-line km of SkyTEM data have been collected off-shore, along the coast line from the Santa Cruz Wharf to Port Watsonville in the northern part of Monterey Bay. An overview of the flight lines with production data is seen on Figure 1.

The survey is flown as 15 flight lines with a spacing of approximately 100 m parallel to the coast line and 12 tie lines with a spacing from 1 to 2 km orientated perpendicular to the coastline. Two of the perpendicular lines in the southeastern part of the survey have been extended in-land.

The main flight line direction parallel to the coast has been chosen to get data as close to beach as possible without disturbing people on the beach.

The line spacing of 100m provides detailed results and the ability to confirm the repeatability from line to line.

Figure 2 Leaving the local landing site for another mission along the coast towards north

5. DATA QUALITY

5.1 Field operation

May 23rd, 2017, SkyTEM Surveys ApS, collected a total of 320-line km in the survey area near Soquel Cove. The system setup is described in detail in the data report prepared by SkyTEM Surveys ApS /6/.

Figure 3 SkyTEM system towed 100 feet below the helicopter. Photo from another survey

5.2 QA/QC

Ramboll checked and approved the delivered data prior to demobilization of the SkyTEM field crew, helicopter and instrumentation.

The report provided by SkyTEM Surveys ApS has been checked and approved.

The quality check includes:

- Data from high altitude is checked with respect to instrumentation noise and the system response (bias). It is found that both the system response and the internal noise in the instrumentation are satisfactory.
- Review and check that there is consistency between the parameters given in the data report and parameters set in the accompanying setup files for inversion. This includes the used system setup geometry, timing and applied filters.
- The dataset is inspected and checked for compliance of minimum pitch and roll.
- Altitude and speed is reviewed and consistencies between laser altimeters are checked.

Filter width for filtering data and altitude is adjusted based on review of the collected data, and first time gate used for inversion has been determined.

Ramboll has requested additional processing of the initially provided magnetic data.

5.3 Data Quality

The TDEM data are characterized by a high signal to noise ratio. This is due to the fact that the conductive sea water and the saline water in the sub bottom sediments produces high signals.

The high signal to noise ratio has allowed the use of data until the very last time gate (20 ms). In that way we have obtained a maximum depth of investigation.

The quality of the magnetic data is acceptable taking into account that it is a secondary data set.

6. PROCESSING OF THE DATA

The processed data from SkyTEM Surveys /6/ have been further processed and inverted.

6.1 Automatic processing

First step processing step is the navigation data (GPS, altitude and inclinometer data). The second step is the electromagnetic data based on an automatic processing using settings defined through the review of the collected data.

Parameter set for automatic data processing includes setting filters that remove most coupling effects and data noise. The parameters for the filters are selected for the current data set. The purpose for automatic processing is to remove as many coupled and noisy data as possible, without removing useful data and to facilitate the manual processing. For the Soquel Creek data, coupling effects are limited and signal to noise level high due to the presence of conductive seawater.

The most important setting for the automatic data processing is data filtering through a specially defined filter, as illustrated in Figure 4. This filter ensures minimum filtering of data at earlier times, while data from later times has a wider filter width. The setup of this filter is very important in order to obtain the maximum benefit from the collected data. A too narrow filter results in poor data quality, while a too wide filter causes too much averaging, with the risk of loss of lateral solubility.

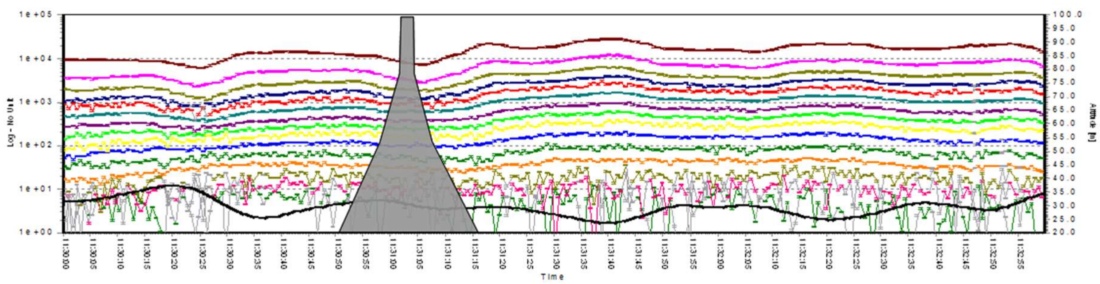


Figure 4 Sketch of applied filter for automatic data processing; narrow time centering at the top (early times) and wide time centering at the bottom (late times).

6.2 Processing of flight data

Prior to the manual data processing, processing of flight data has been performed, including DGPS, inclinometer and height. For altitude, an automatic processing is initially performed followed by manual processing. For the automatic height processing, an iterative polynomial is adjusted to the measured height data and the deviating height data points are automatically removed. A correction is also made for the transmitter and receiver coil angle relative to horizontal.

After the automatic height processing, a manual processing of height data is performed. During manual processing, the heights are adjusted in places where the automatic height processing has not successfully adjusted the measured height data. This often occurs along lines with very large variations in altitude or over forest. With the manual adjustments of the altitude height, the X and Y tilt are taken into account. In this regard, especially the X-tilt is important for the adjusted height. Since most of the Soquel Creek data are collected offshore, with a well-defined "topography", there has been no need for manual adjustment of the altitude in current dataset.

6.3 Processing of electromagnetic data

The electromagnetic data is initially processed automatically with the parameters selected based on the tests. After the automatic processing, manual data processing is performed. This is done by a visual review of data from both segments simultaneously, with manual adjustments made to the automatic processing. During manual processing, the locations of data points are plotted in GIS. Data noise, which was not removed during automatic processing, is subsequently removed, and data uncertainty is reviewed. The manual review has been done both along profiles, but also in GIS, since some observations cannot be recognized on the profile plot alone. For the current dataset, manual processing has been limited, since most data has a high signal to noise level due to the conductive saline seawater.

Figure 5 Flying along the coast in Monterey Bay

7. MODELLING OF SKYTEM DATA

The final processed data are modelled using the surface constrained inversion (SCI) method developed specifically for spatial inversion of AEM data like SkyTEM data /7/.

For the Soquel Creek dataset, a smooth model (a 30 layer – multi layer model) has been applied, resulting in a smooth distribution of the resistivity to a depth of 200 m below surface. Due to the very conductive sea water, the thickness of the first model layer is thin (0.5m). The following layers up to 30 layers have increasing thickness by depth.

7.1 A priori information

In the inversion process, all 30 layers are normally initiated with a resistivity of 50 ohmm. In this case it has been necessary to stabilize the inversion in the unusable high conductive environment. The resistivity of the top layers down to 10 m is set to 0.25 ohmm in the starting model in the inversion process. The remaining layers are all initiated with a resistivity of 50 ohmm. The 0.25 ohmm reflects the resistivity of sea water. The resistivity is still allowed to change in the inversion process.

The resistivity of the layers is constrained as the resistivity variations from layer to layer are moderately tied together, both horizontally and vertically in the inversion scheme.

No other priori information has been used in the modelling scheme.

7.2 Mean resistivity intervals

For visualization of the resulting models, mean resistivity has been calculated. The following intervals have been applied

From 0 m b.s.l. (sea level) to 10 m b.s.l. the thickness is 2 m
From 10 to 50 m b.s.l., the resistivity is presented in intervals of 5 m, and
From 50 to 160 m b.s.l. in 10 m intervals.

For the two in-land flight lines, the terrain is above sea level, however those data are only presented on vertical sections and not on mean resistivity maps.

The mean resistivity is calculated based on layer thickness and layer resistivity within the given interval.

Mean resistivity maps from sea level to 160 m b.s.l. are attached as Annex 1.01 to Annex 1.24 masked when the depth of investigation (DOI) is reached.

7.3 Sections

In annex 2.01 to 2.04, sections with inverted resistivity models are shown. Along each of the sections, the digital Terrain model (DTM) is plotted as a grey line.

At all sections, the DTM correlates with the boundary between the high conductive seawater and less conductive seabed.

Variation in resistivity below the seabed reflects variations related to either geology or changes in salinity.

8. MAGNETIC DATA

The total magnetic field has been measured during the TDEM off times by a magnetometer positioned in the front of the SkyTEM carrier frame. The magnetic field results from the magnetic properties of the underlying rocks.

Figure 6 Total Magnetic field sensor mounted in the front of the carrier frame and only measuring in the TDEM off-times.

SkyTEM Surveys has done the filtering and levelling of the data. The results are the total magnetic intensity and derivatives.

The magnetic anomalies can be due to dikes, faults, lava flows or other variations in the geological formations.

The magnetic data are used to support the geological interpretation. The reduced to pole magnetic data will show the deeper and more regional structures and the 1st vertical derivative the more surface near geology.

The magnetic data are presented in annex 3.01 to 3.03.

9. PRESENTATION AND INTERPRETATION

In this section, the Time Domain Electromagnetic data and the Magnetic data from the SkyTEM survey is compared with an existing conceptual model and near shore geological, water chemistry, geophysical logs and geomorphology results.

The results are presented as horizontal grids representing the mean resistivity in intervals from 2m in the upper part and 20m in the deeper part until a depth of 200 m b.s.l. The mean resistivity maps are shown in Annex 1.01 to Annex 1.24

The flight lines perpendicular to the coast are shown as vertical sections in annex 2.01 to 2.04. Borehole information is shown as lithology, resistivity logs, gamma-logs and salt content. In total there are 15 sections perpendicular to the coastline and a section following the flight lines closest to the shoreline. The location and the numbering of the sections are shown on the figure below.

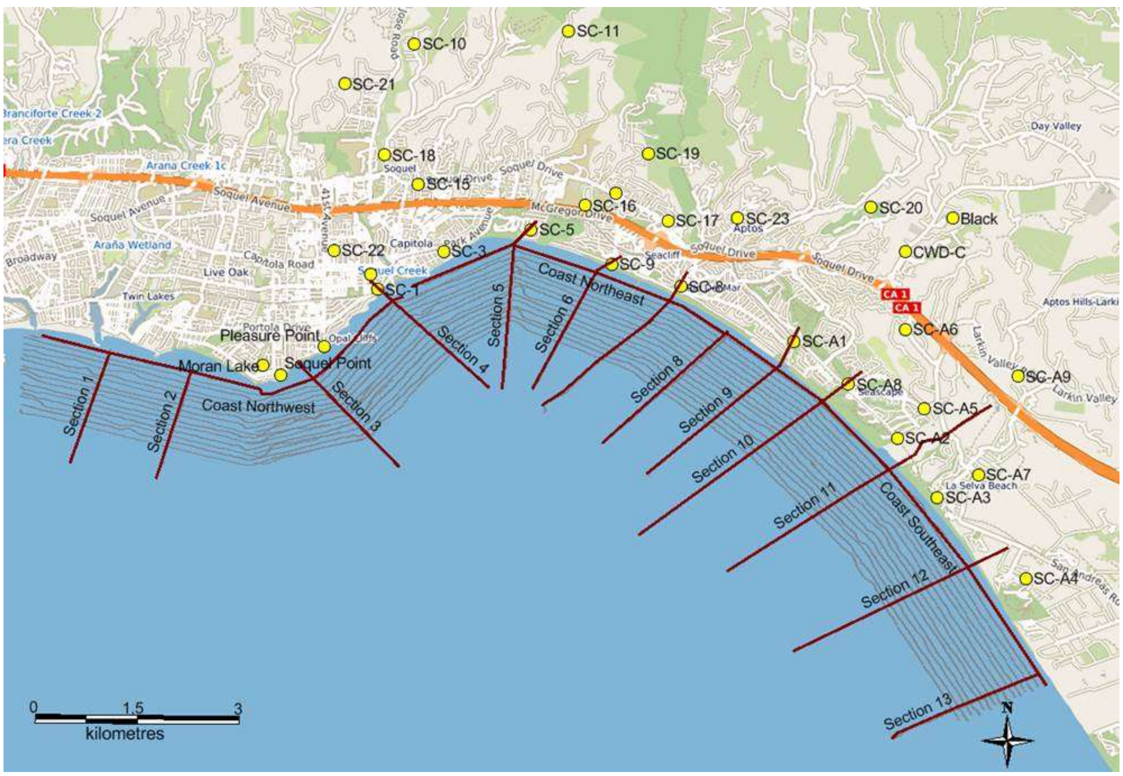


Figure 7 Location and naming of sections.

In general, the presentations are shown until a depth of 160 m b.s.l. In areas where the resistivity is low from the surface and downwards, the results from 120 m b.s.l. and deeper shall be expected to be uncertain.

9.1 Resistivity – hydrogeology relationship

Translating resistivities to lithology and hydrogeology is based on a general correlation. Figure 8 is shown a schematic form of the correlation, where sediments with saline water have low resistivity, and sand/gravel with a higher hydraulic conductivities results in higher resistivities.

This correlation is general assumption, and can vary from location to location. Therefore, correlation with ground truth etc. information from boreholes is crucial to obtain the most accurate description of the subsurface.

As for the specific survey we have sea water with resistivity of 0.25 ohmm and sea water below the sea floor in sandy sediments with a resistivity of 1 ohmm. This is under the assumption that the formation factor (F) can be described as F = Ro/RW where Ro is the resistivity of the sediments filled with water and RW is the resistivity of the water /12/. The sea water is considered to have a total dissolved-solids (TDS) content of 35,000 milligrams per liter.

The resistivity will within the survey area reflect geology and especially the salinity of the water filling the pore space in the sediments.

In Figure 8 a general and simplified relationship in between resistivity and hydrogeology is provided. The resistivity color scale is adjusted to fit the colors used in the plots in this report. The exact division of brackish water, sediments with salt water, clay/till and sand and gravel is to be considered as of more fundamental nature and not an outcome of the specific project. Note that there is overlap in the scale, where green colors can represent either brackish water in an aquifer or fresh water in clay units, or a combination of the two.

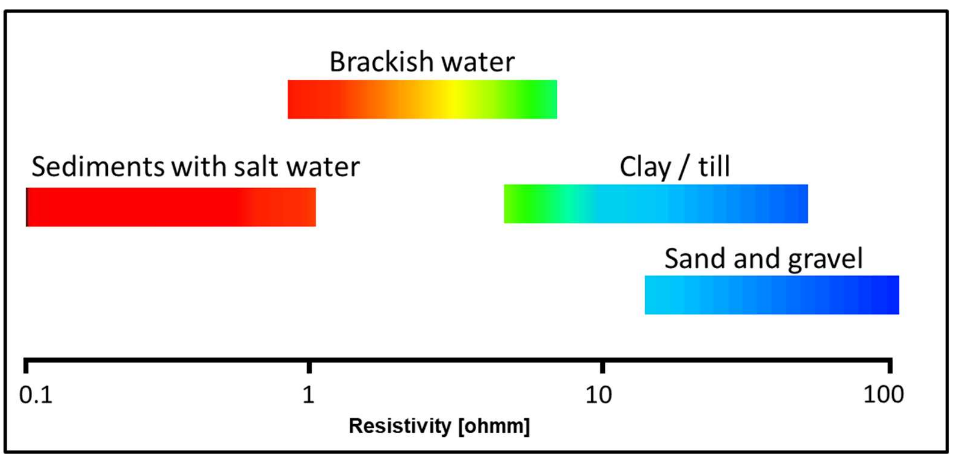


Figure 8 Simplified relationship in between resistivity and hydrogeology

In Figure 8 the resistivities below 1 ohmm have the same red color. This is done on purpose as the inversion scheme produced some very low resistivity structures close to the shore line. The structures are artifacts in an area with rapid laterally changes in the hydrogeology being impossible to model using the one-dimensional approximation.

9.2 General geological layers

The geological and hydrogeological interpretation is based on relatively few boreholes. To support the interpretation and for comparison, the conceptual model developed by HydroMetrics WRI /9/ has been used.

Table 1 Groundwater Model hydrostratigraphic units in the conceptual model /9/.

Unit Name (Geologic Unit)	Model Layer	Unit Type
Stream Alluvium	1-9[1]	Stream-associated water-bearing surficial alluvium
Terrace Deposits	1-9[1]	Alluvial terrace deposits near coast
Aromas Red Sands	2	Interbedded sand, silt, and clay deposits
Purisima TpDEF, TpF	3	Aquifer
Purisima TpD	4	Aquitard
Purisima TpBC	5	Aquifer
Purisima TpB	6	Aquitard
Purisima TpA	7	Aquifer
Purisima TpAA	8	Aquifer
Tu[2]	9	Aquifer

Table 1 shows the general units in the conceptual model developed for the Soquel-Aptos Groundwater Flow Model.

In the area, there are five main aquifers, where the three lower aquifers (layer 7, 8 and 9) are hydraulically connected.

A general interpretation of the SkyTEM results is that the distribution of fresh and saline water is controlled by the geological layers. With that in mind, it is evident that the existing hydrogeological model described above can be revised.

9.3 Evaluation of the depth of investigation

The very conductive sea water and saline formation fluid is the limiting factor for the depth of investigation (DOI). The DOI was carefully evaluated during the proposal phase and was found to be in the range 100-150 m close to coast.

Based on the actual acquired data the DOI reaches 200m close to the coast where more resistive layers are found. The data collected in areas with water depths of 15-20m is found to be at around 60-70m.

The mean resistivity intervals are masked in the depth when the DOI is reached. On the vertical sections the DOI is shown as a black line.

9.4 Mean resistivity intervals

The mean resistivity maps are shown in Annex 1.01 to Annex 1.24.

The presence of seawater results in low resistivity (approx. 0.25 ohmm) in the top layer. Close to the beach, the seafloor is reached in the interval 0-2 m b.s.l. The flight lines far from the coast show water depth to be at around 15m. The boundary between seawater and the seabed is clearly identified by increasing resistivity.

The mean resistivity maps can be viewed by stepping down from page to page which creates a semi 3D animation giving the reader the ability to go back and forth and follow the development of specific structures in the dataset.

9.5 Sections

Vertical sections are shown in annex 2.01 to 2.04 for all perpendicular flight lines and the flight closest to the shoreline. The sections are extended inland to show the location of boreholes. The boreholes are presented with lithology, gamma-log, electrical logs and salt concentrations.

Figure 9 shows cross section 5, orientated South-North. On the top profile, results from the SkyTEM survey are shown, where red colors show lower resistivities and blue colors show higher resistivities.

The lower profile on Figure 9 shows the hydrostratigraphic units as interpreted in reference /9/. Layer boundaries are also drawn on the top profile showing resistivity. By comparing the two sections, a good correlation between areas with high resistivity based on the SkyTEM survey and the aquifer unit BC can be seen.

Resistivity above 10 ohmm in aquifer unit BC indicate the presence of fresh water entering the aquifer. If this aquifer was saturated with seawater, the resisitivity would have been ~ 1 ohmm under the assumption that the aquifer can be characterized by a formation factor of 4. The resistivity and thickness is highest close to the coast, while the resistivity and thickness decreases towards the south. This can be interpreted as a fresh water lens with lower salinity extending from the coast under Monterey Bay is being diluted as the distance to the coast increases.

In the deeper part very close to the coast, the resitivities are atypically low (less than1 ohmm). This is interpreted as an artifact caused by the inversion scheme where the hydrogeology changes vary rapidly for what reason the one-dimensional approximation used in the inversion scheme is not valid. Professor Esben Auken at Aarhus University has confirmed that they recently have seen the exact same problem on another project. Even though the resistivities in the deeper part are still considered to be low, it still reflects a high salt content in the pore water.

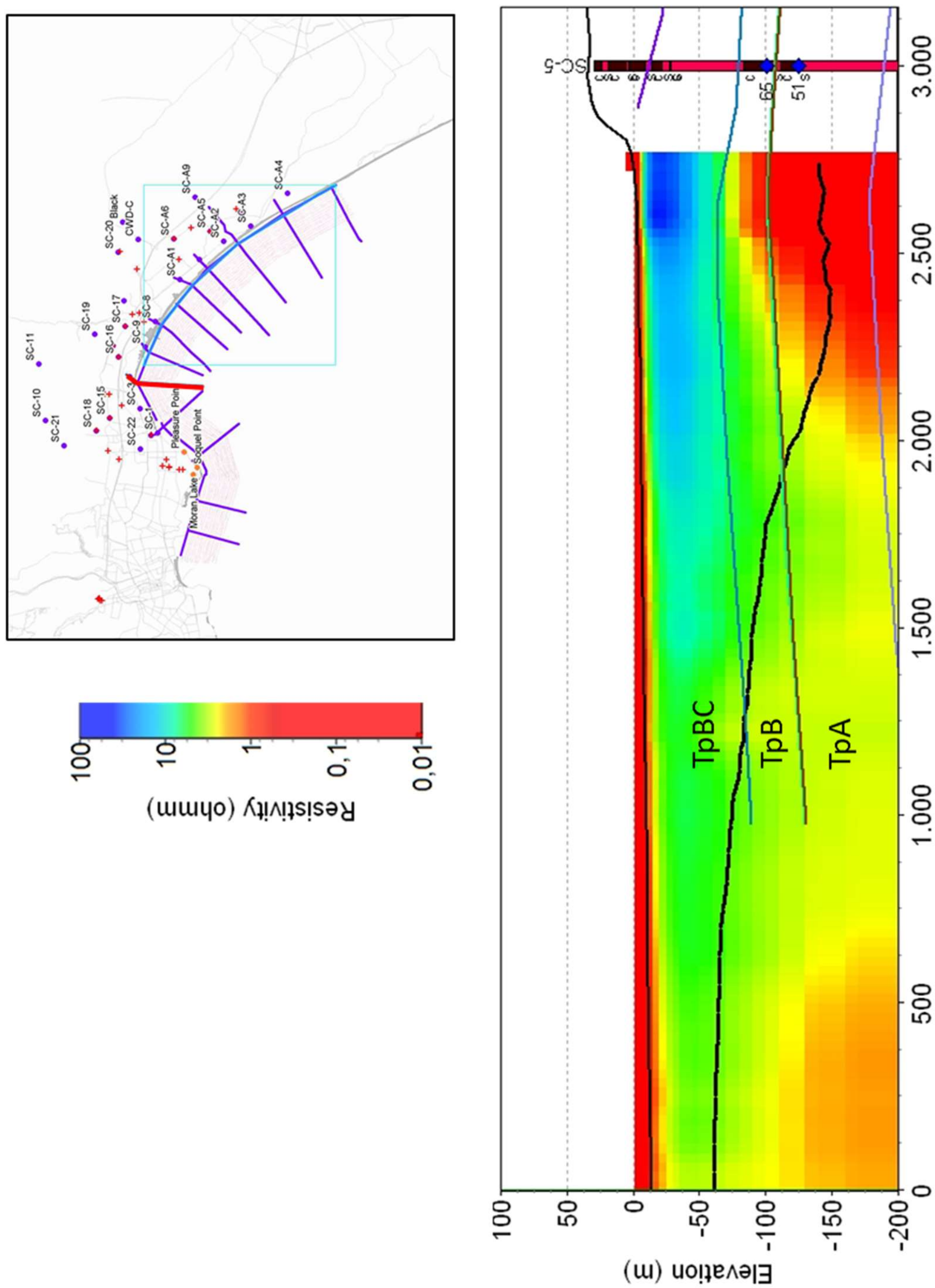


Figure 9 Cross section 5, located in the northern part of Monterey Bay, and is orientated from south to north (marked with a red line on the map). Elevation is given in meters above mean sea level and distance is given in meters. The thick black line is the depth of investigation (DOI).

Figure 10 shows a section parallel to the coast. At this section it is more difficult to identify the units in the conceptual model from the SkyTEM survey.

The resistivity model is highly affected by changes in salinity. Considering the structures mapped by SkyTEM, the southeast dipping units from the hydrostratigraphic model can be recognized. However there is an off-set between the boundaries in the hydrostratigraphic conceptual model and the boundaries seen in the SkyTEM resistivities. In addition, it appears that the Aromas formation has multiple southeasterly dipping geological layers with alternating relatively fresh and relatively saline groundwater.

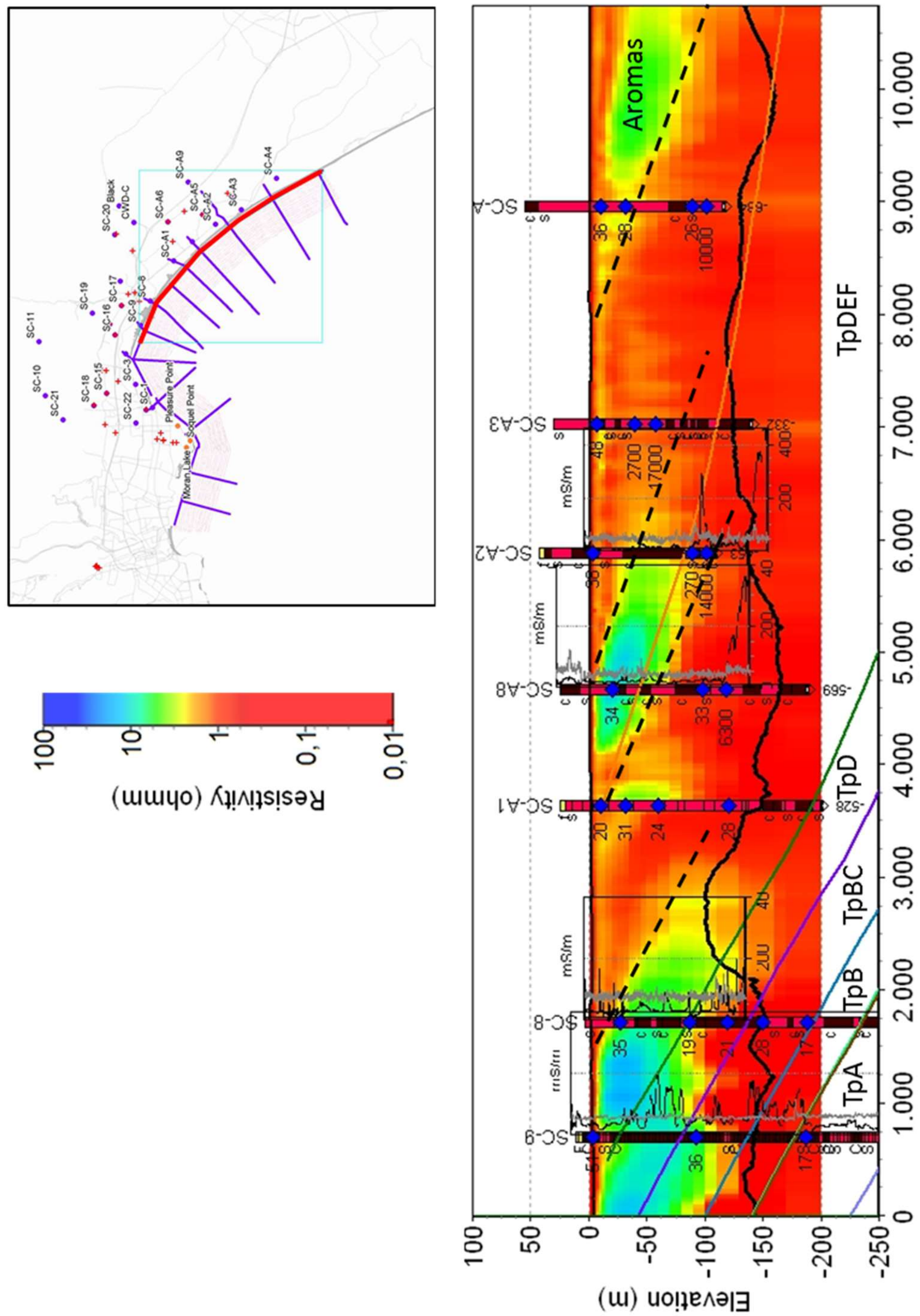


Figure 10 Coastline section from monitoring well SC-9 to SC-A4, presented from northwest to southeast and marked with a red line on the map. The black dashed lines show the possible geological boundaries as seen in the SkyTEM data. Note: the wells are between 300 and 700 m to the NE of the section line; the actual offset is shown (in m) at the bottom of each well. Distance is given in meters and elevation in meters over mean sea level. The thick black line is the depth of investigation (DOI).

Figure 11 shows the resistivity in the interval 20 to 25 m b.s.l. Six areas with relatively high resistivity stand out. They are marked 1 to 6 on the figure.

Area 1 and 2 are areas were high resistivity is interpreted as a freshwater propagating from inland under Monterey Bay. Between area 1 and 2, just northwest of area 2, the freshwater lens is missing and saline seawater is mapped close to the coast.

The smaller areas, 3, 4, 5 and 6, are all located close to where freshwater streams or rivers reach the ocean. High resistivity in these areas is interpreted to originate from permeable sediments below the creeks and rivers channeling water towards the sea.

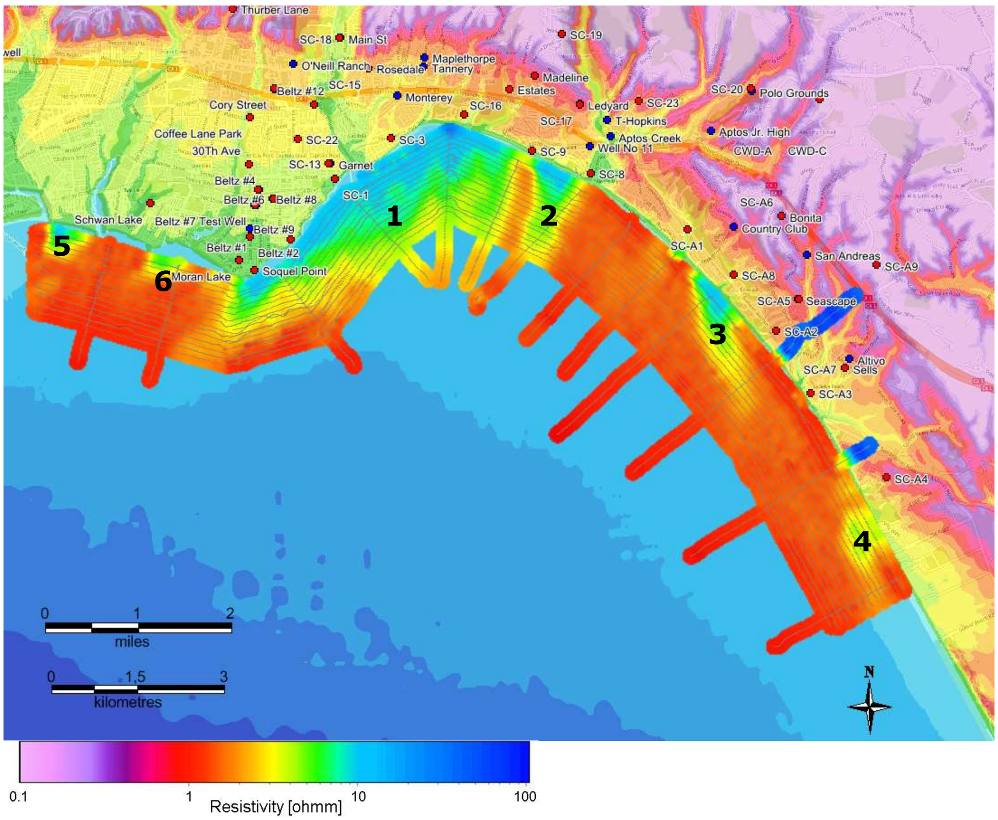


Figure 11 Resistivity interval 20 to 25 m b.s.l. Red and blue dots represent boreholes. Areas characterized by high resistivity are named area 1 to 6

9.6 Magnetic structures

Based on an evaluation of both the reduced to pole magnetic data and the 1st vertical derivative, some lineaments have been identified, see Figure 12. As for comparison, faults identified by the USGS are shown as grey dashed lines on Figure 12.

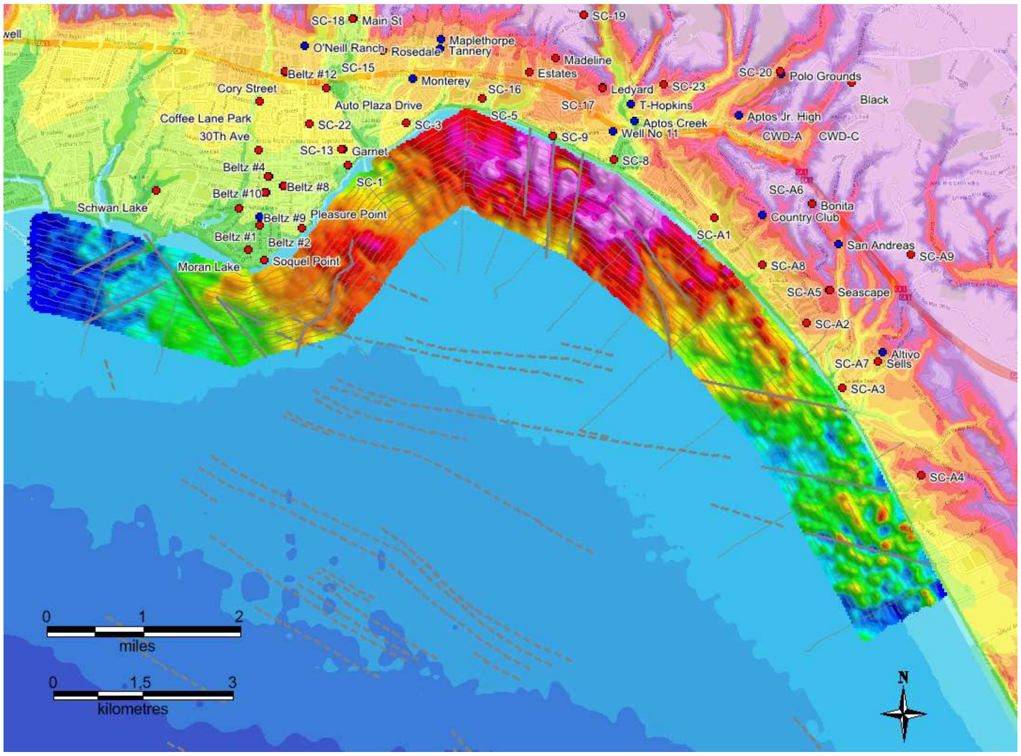


Figure 12 Interpreted structures as grey lines based on RTP and 1st VD grids.

9.7 Comparison of SkyTEM, MAG, known faults and geomorphology

A comparison of the structures found in the magnetic data with the SkyTEM resistivity in the interval 30-35 m b.s.l. and known fault lines in the area is shown on Figure 13.

It is seen that the north south striking low resistive anomaly (A) shows a good correlation with the magnetic structures. When compared with resistivities in the deeper levels, the structure has an offset towards east, indicating a dipping structure.

Some of the structures identified in the magnetic data (B and C) follow nicely the known off shore faults, as well as features in the digital terrain model onshore.

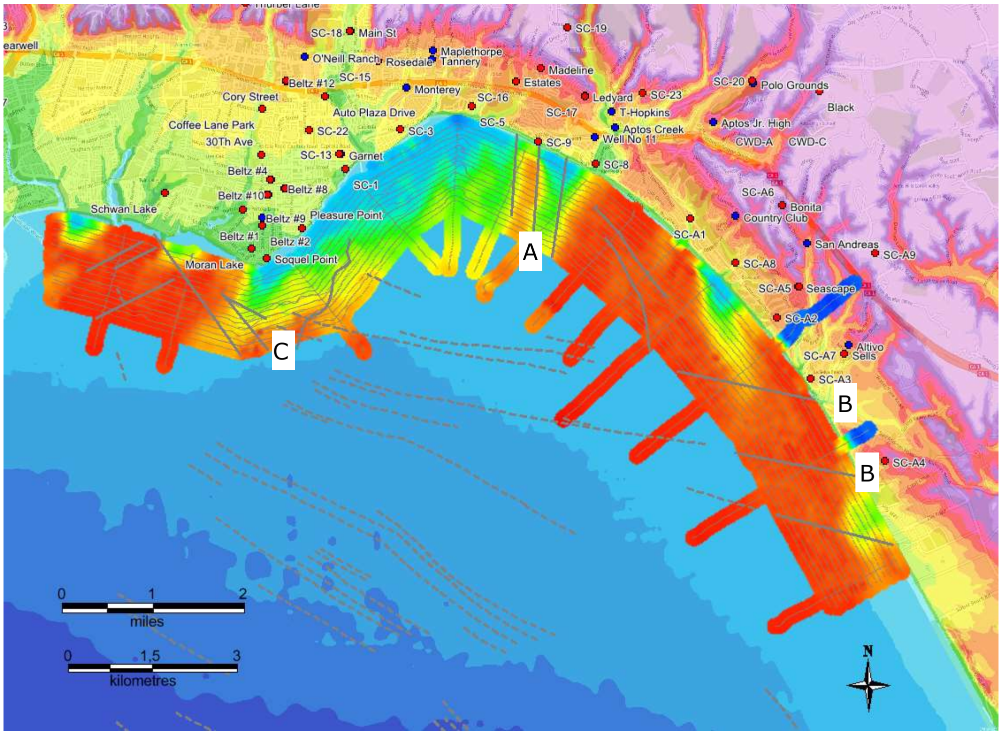


Figure 13 Magnetic structures (grey lines) compared with resistivities in the interval 30-35 m b.s.l. Dashed lines are USGS identified faults.

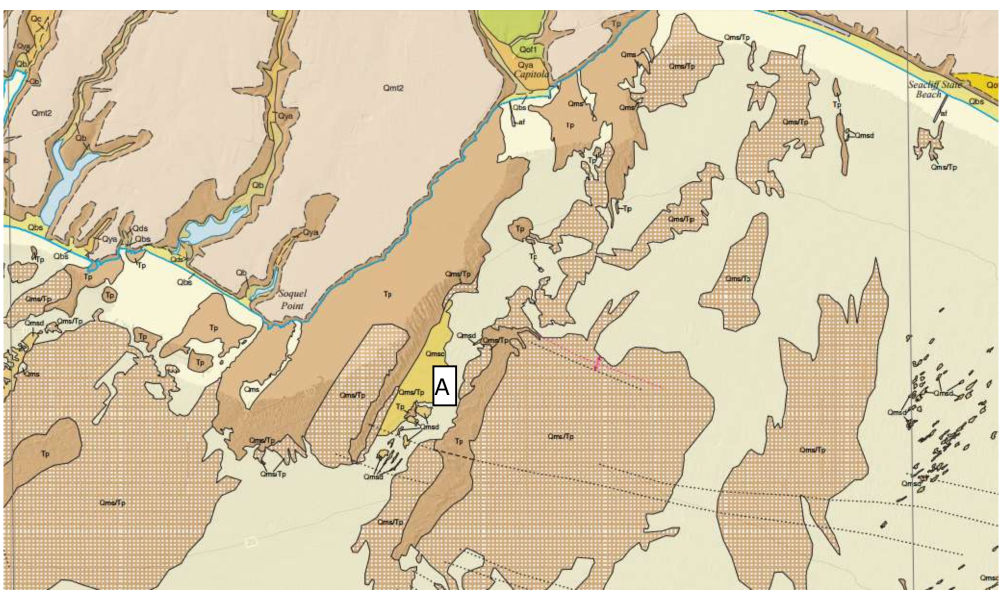


Figure 14 Offshore and Onshore Geology and Geomorphology, Offshore of Aptos Map Area, USGS /10/, Tp: Purisima Formation (Pliocene and late Miocene)—Predominantly gray and greenish-gray to buff, fine-grained marine sandstone, siltstone, and mudstone. Qms: Marine nearshore and shelf deposits (late Holocene)—Mostly sand.

A channel structure marked with an 'A' on Figure 14 and Figure 15 coincide with a meandering structure in the magnetic data. The channel is not seen in the SkyTEM data. Structure marked with a 'B' is seen both in the magnetic data and in the SkyTEM data. It is interpreted as sand with saline water, hence the low resistivities.

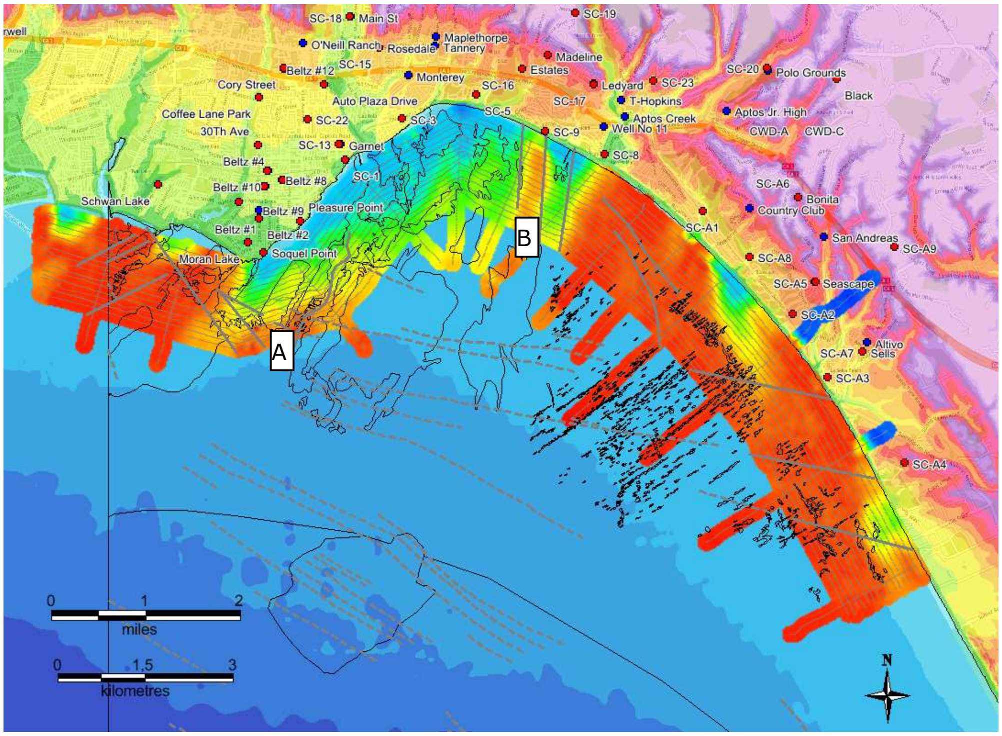


Figure 15 Resistivity found in the interval from 30-35 m.b.s.l. with structures found in the magnetic data and known faults and offshore geomorphology in the bay area

9.8 Bathymetry

The model results demonstrate a very good agreement in between the known bathymetry and the thickness of the shallow conductor representing sea water. An example is shown on Figure 16. The resistivity of seawater at 0,25 ohmm is in good agreement with the value to be expected from a theoretical point of view (salt concentration of 33,5 BAC). This is a good indicator that the SkyTEM system is well calibrated.

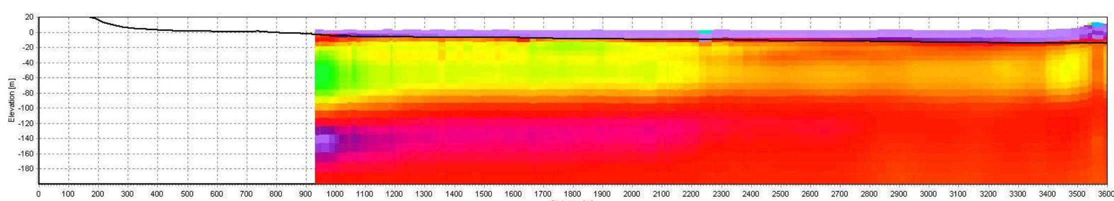


Figure 16 Section 7. The black line is the bathymetry. The purple colors represents resistivities in the range of 0.25 ohmm. Note – the color scale has been changed in the interval from 0.1 to 1 ohmm (purple and red colors) to enhance the boundary in between sea water and the sea floor.

9.9 Seawater intrusion

The interaction between saline groundwater and fresh groundwater can be clearly seen in the results from the SkyTEM survey. Figure 17 shows the mean resistivity between 20 m and 25 m below mean sea level, where the blue colors show freshwater, whereas green and yellow indicate brackish water with increasing salinities. From the map, freshwater discharge into Monterey Bay can be divided into three separate zones: the area west of Soquel Point, between Soquel Point and monitoring well SC-8 and south of SC-8.

In the area west of Soquel Point, saline groundwater is observed all the way to seafloor surface, where there are only two small pockets where brackish water is observed in the SkyTEM data.

The Tu aquifer has relatively high salinities all the way to the coastline. We can see two areas with a limited amount of brackish water extending under the bay, as shown by the yellow and green colors west of Soquel Point on Figure 14. Section 2 in Annex 2 shows that this tongue of brackish water is restricted to the TpAA aquifer and extends about 200 m (650 feet) from the coastline.

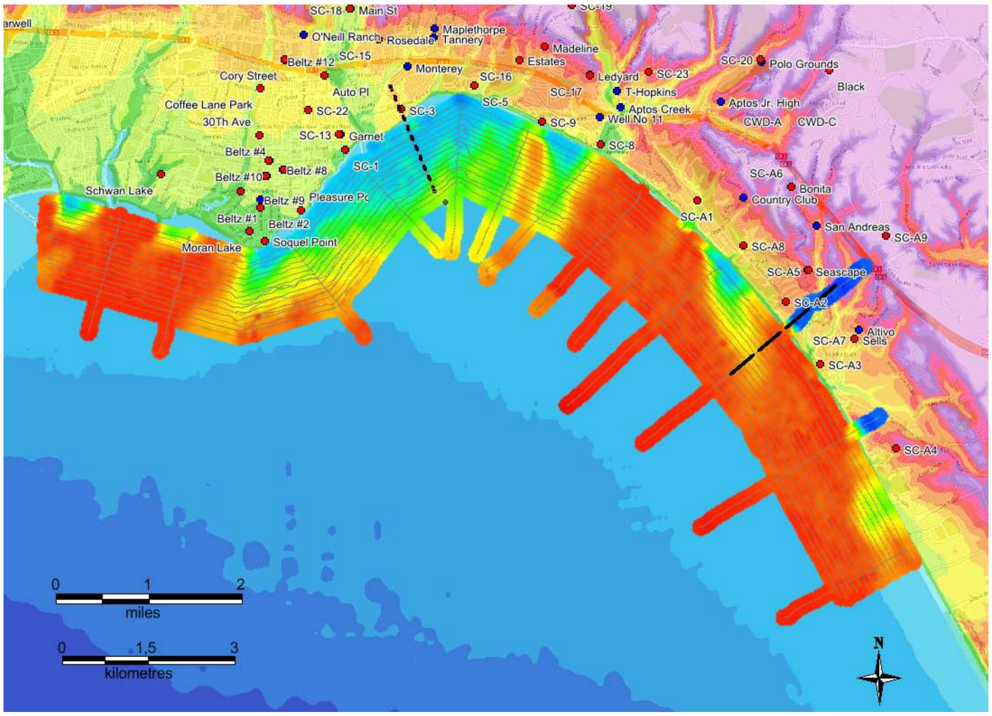


Figure 17 Map of the SkyTEM resistivity from 20 to 25 m below mean sea level. The dotted line shows the location of the profile in Figure 18 and the dashed line shows the profile in Figure 19.

In the area between Soquel Point and monitoring well SC-8, the SkyTEM resistivities indicate that fresh water in the aquifers extends well underneath the bay. The profile in Figure 18 shows this interaction of freshwater and seawater along the coast. In this profile, freshwater is observed in TpBC aquifer as much as 1000 m (3280 feet) from the coastline. However, in the aquifer TpA, brackish waters (shown by green and yellow colors) are observed all the way to the coastline. Chloride levels measured in monitoring well SC-3, approximately 200 m (660 feet) from the coast, show that that the groundwater in the TpA aquifer is still fresh, but the SkyTEM data indicates that brackish water extends all the way to the coastline (Fig. 18). Thus, heavier pumping from the TpA aquifer could cause the brackish water to intrude inland. The same pattern can be seen in sections 4 – 7 in Annex 2, where freshwater is observed in the upper 50 m of the aquifers, brackish and saline groundwater remain deeper. The Soquel Point monitoring well, where brackish water (indicated by Cl concentration of 1200 mg/l) underscores the observation of brackish water intruding at deeper levels.

Southeast of SC-8, freshwater is generally not observed in the aquifers under the bay, apart from one area just off shore from monitoring well SC-A8. The pocket of freshwater can be seen in sections 9 and 10 in Annex 2, where the freshwater is limited to the Aromas Red Sands and discharging into the bay 200 – 300 m (650 to 980 feet) offshore. Below this limited pocket of freshwater, in the TpDEF aquifer, the SkyTEM shows that the water is saline. This corresponds well with the observations in well SC-A8. Further south, along the monitoring wells SC-A2 and SC-A5, even the Aromas Sands have brackish water reaching the coast (Fig. 19). However, in the profile shown in Figure 19, it is apparent that there is active seawater intrusion extending into the TpDEF aquifer. This is confirmed by the observations seen in both monitoring wells. The SkyTEM data shows this intrusion extending at least 1600 m (1 mile) inland, if not further.

The SkyTEM survey shows that the risk of seawater intrusion into the production wells is dependent upon both the geographical location and which aquifer groundwater abstraction is coming from. In the northern part of the bay, freshwater in the aquifer TpBC extends out into the bay, where as a little deeper in aquifer TpA, brackish water extends all the way to the coastline. In the eastern part of the bay, the salinity appears to follow the Ghyben-Herzberg relationship, whereas there is intrusion occurring within the TpDEF aquifer. The areas are marked on Figure 20 outlining the upper aquifer where a higher risk of seawater intrusion, as indicated by the SkyTEM results.

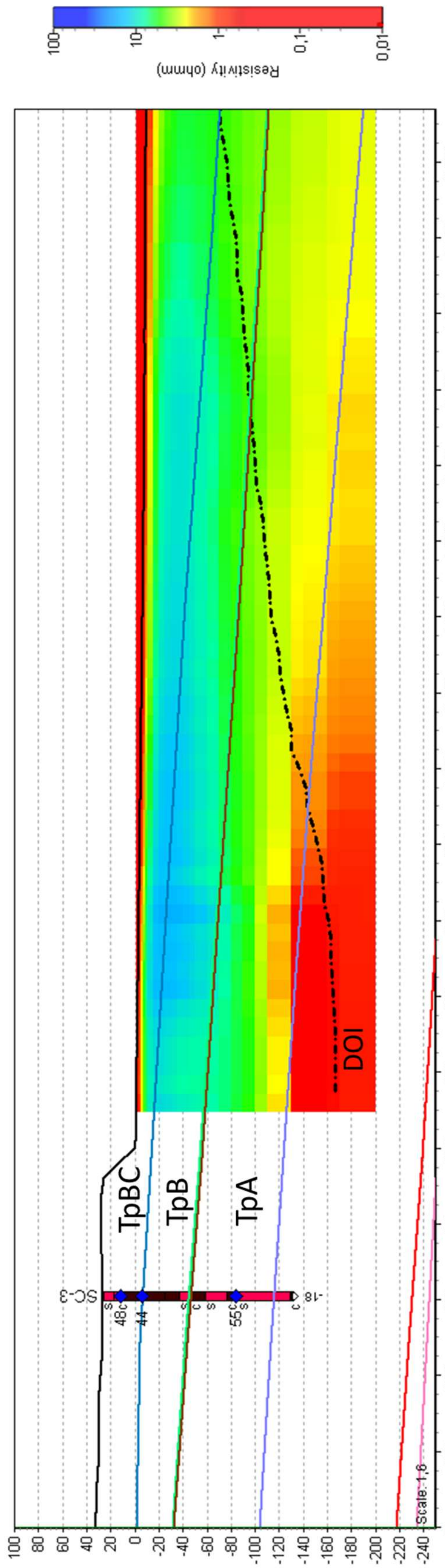


Figure 18 Section, oriented north to south, showing resistivity compared with measured chloride concentrations (mg/l) in monitoring well SC-3. The dark blue diamonds show the depth in the well from which the chloride measurements were taken. The dashed line shows the depth of investigation (DOI) of the resistivity survey. The location of the section is shown on Figure 17. The thick black dashed line is the depth of investigation (DOI).

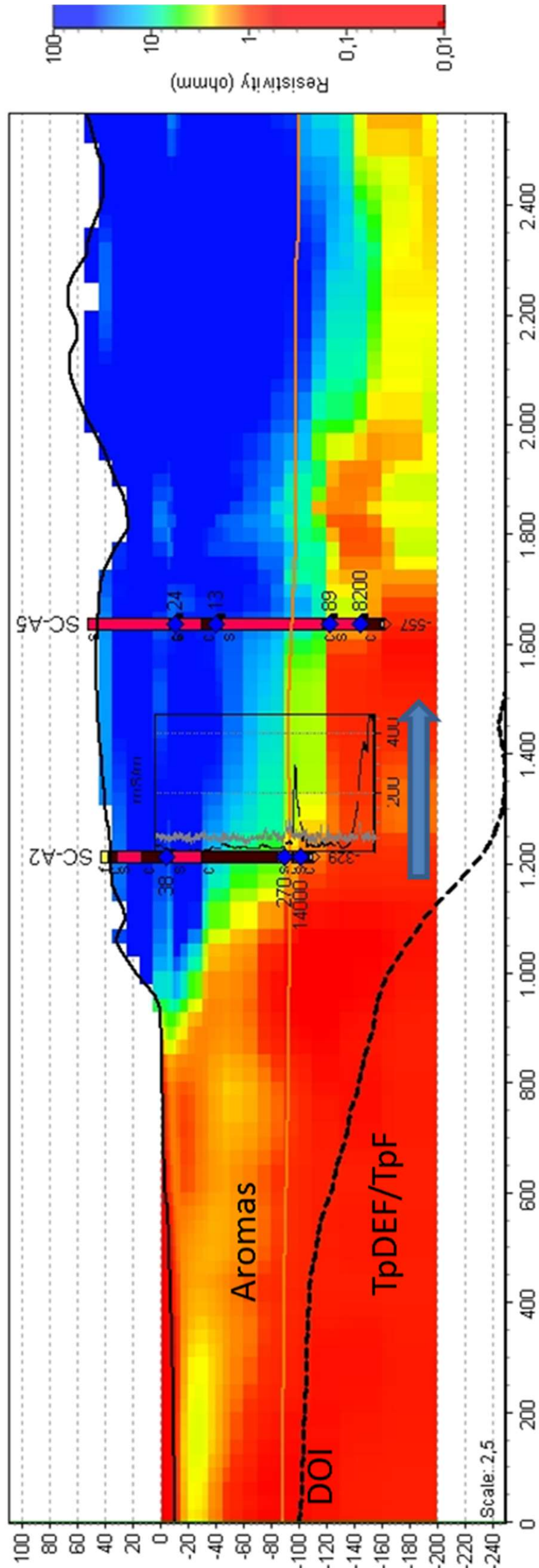


Figure 19 Section, oriented west to east, showing resistivity compared with measured chloride concentrations (mg/l) in monitoring wells SC-A2 and SC-A5. The dark blue diamonds show the depth in the well from which the chloride measurements were taken. The blue arrow shows the direction of seawater intrusion in the TpDEF aquifer. The dashed line shows the depth of investigation (DOI) of the resistivity survey. The location of the section is shown on Figure 17. The thick black dashed line is the depth of investigation (DOI).

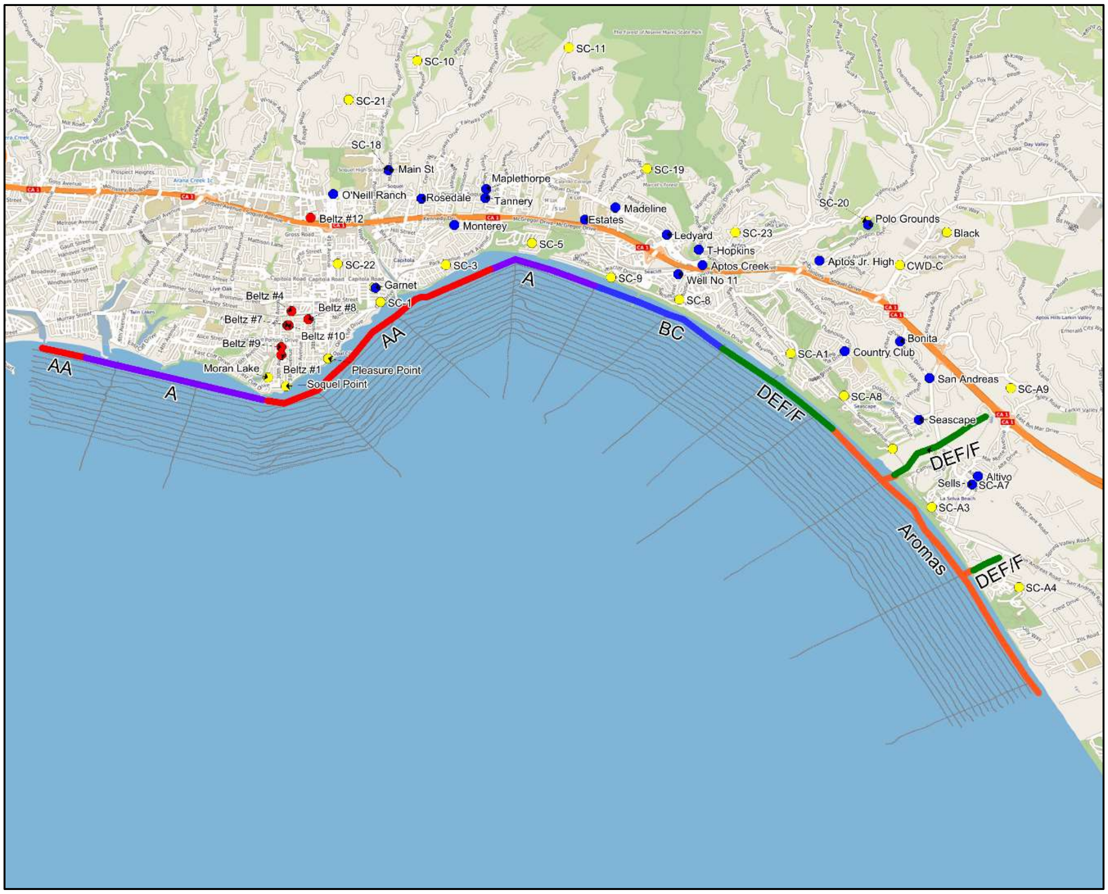


Figure 20 Map showing the uppermost aquifer where saltwater intrusion is observed, as indicated by the color scheme along the near-coast SkyTEM survey and line segment of the two surveys conducted inland. The red line indicates where the uppermost aquifer with saltwater is TpAA, the purple line TpA, the blue line TpBC, the green line TpDEF/TpF, and the orange line Aromas.

9.10 Geoscene3D

The results are provided as a Geoscene3D workspace. A free Geoscene3D viewer is available from I-GIS.

Figure 21 and Figure 22 show two examples of the visualization from Geoscene3D. Figure 21 shows a visualization of the surface where resistivities change from saline water to more fresh/brackish waters. The freshwater lenses infiltrating in from the coast can be seen in the visualization.

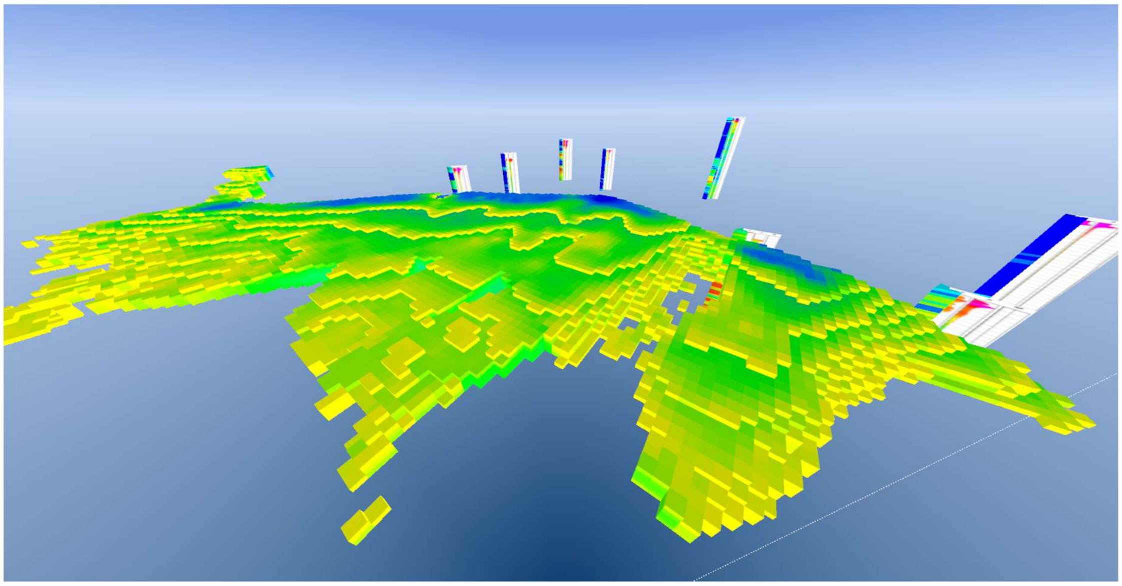


Figure 21. A 3D visualization in Geoscene3D of the surface, where resistivities are higher than 4 ohmm.

Figure 22 shows a combination of the reisistivity in a net of cross-sections across the study area combined with the resistivities at a depth of 35 m b.s.l. The freshwater lenses can be seen on the surface map, whereas the cross-sections allow a visualization of the resistivities above 35 m.b.s.l. The seafloor can clearly be seen in the red and purple colors on the cross-sections.

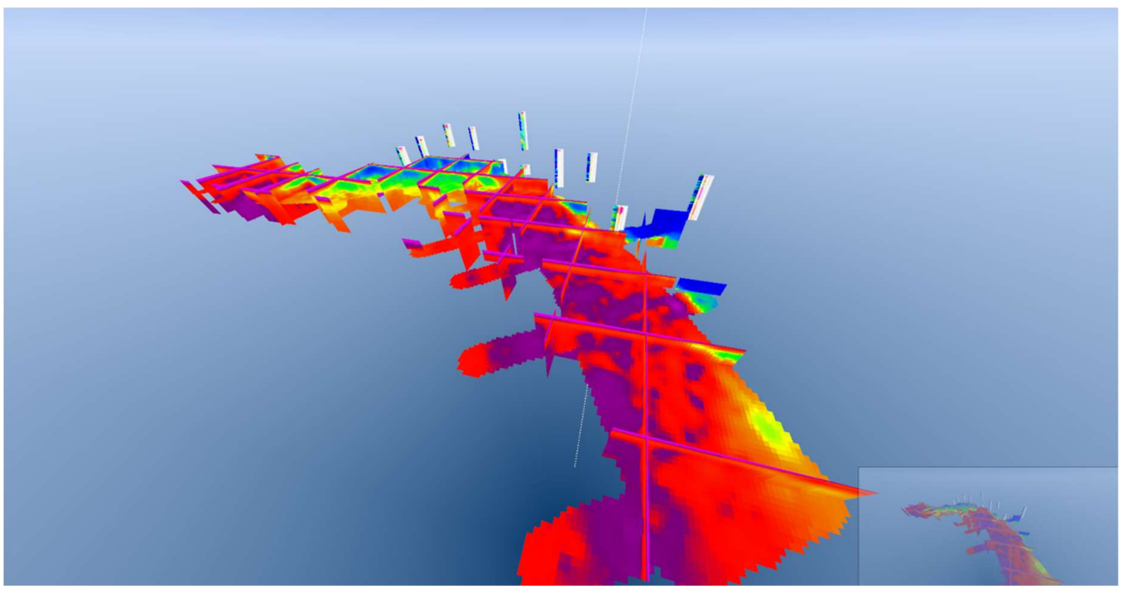


Figure 22. A visualization in Geoscene 3D of the reisistivities along selected cross-sections and at a depth of 35 m b.s.l.

10. CONCLUSION

A total of 320 line km of off-shore SkyTEM data (airborne electromagnetic) has been collected in the northern part of Monterey Bay, along the coast line from the Santa Cruz Wharf to Watsonville. The SkyTEM survey is flown as 15 flight lines with a spacing of approximately 100 m parallel to the coast line and 12 tie lines with spacing from 1 to 2 km, orientated perpendicular to the coastline.

The geophysical results have been visualized in combination with available information from boreholes, geological and geomorphological information developed by USGS /10/ and a conceptual model developed by HydroMetrics WRI /9/.

The main purpose has been to achieve insight in the interaction in between fresh and saline water in the near shore coastal zone. The results from the SkyTEM data have identified six different fresh water lenses in the aquifers underneath Monterey Bay, as seen in Figure 11.

In the northern part of the bay, SkyTEM results show that the near surface aquifer (TpBC) still contains fresh groundwater, whereas the deeper aquifer (TpA) contains brackish water all the way to the flight line just off the coast, as seen in Figure 18.

On the eastern part of the coast, around monitoring well SC-A8, SkyTEM results show freshwater extending down to a depth of -50 m in the Aromas Formation, whereas in the aquifer below (TpDEF/TpF) is dominated by saline water. However, just 600 m south from well SC-A8, the Aromas becomes brackish and salinity continues to increase southward. This is confirmed by the increased salinity observed in the monitoring wells SC-A2 and SC-A5, as seen in Figure 19.

The interaction between fresh and saline water along the coast, as seen and mapped by SkyTEM, is interpreted to be controlled by both the geological stratigraphy as well as past and current groundwater abstraction near the coast.

11. DELIVERABLES

As part of the report the following digital data is provided:

- SkyTEM results:
  - Raw data as described in reference /6/;
  - Database with raw data, processed data and inversion results (GERDA format);
- GIS themes;
- Geoscene3D workspace;
- Animations made in Geoscene3D;
- Report in PDF format.

12. REFERENCES

/1/ Meredith Goebela, Adam Pidliseckyb, Rosemary Knight, February 2017, Journal of Hydrology, Resistivity imaging reveals complex pattern of saltwater intrusion along Monterey coast.

/2/ Auken et al., 2010, SWIM21 - 21st Salt Water Intrusion Meeting, The use of airborne electromagnetic for efficient mapping of salt water intrusion and outflow to the sea

/3/ Kok et al., SWIM21 - 21st Salt Water Intrusion Meeting, Using ground based geophysics and airborne transient electromagnetic measurements (SkyTEM) to map salinity distribution and calibrate a groundwater model for the island of Terschelling – The Netherlands

/4/ Kirkegaard et al., 2011, Salinity Distribution in Heterogeneous Coastal Aquifers Mapped by Airborne Electromagnetics

/5/ Ramboll, 2017-05-15, Proposal, Mapping Salt-Fresh Water Interface – Geophysical Survey, Santa Cruz Mid-County Groundwater Agency (MGA)

/6/ SkyTEM Survey, June 2017, Soquel Creek Water District areas, California

/7/ Viezzoli, A., A. V. Christiansen, E. Auken, and K. I. Sørensen, 2008, Quasi-3D modeling of airborne TEM data by Spatially Constrained Inversion, Geophysics, 73, 3, F105-F113.

/8/ Meredith Goebel, Adam Pidlisecky, Rosemary Knight, 2017, Resistivity imaging reveals complex pattern of saltwater intrusion along Monterey coast

/9/ HydroMetrics WRI, November 2015, Soquel-Aptos Groundwater Flow Model: Subsurface Model Construction (Task 3), Technical Memorandum

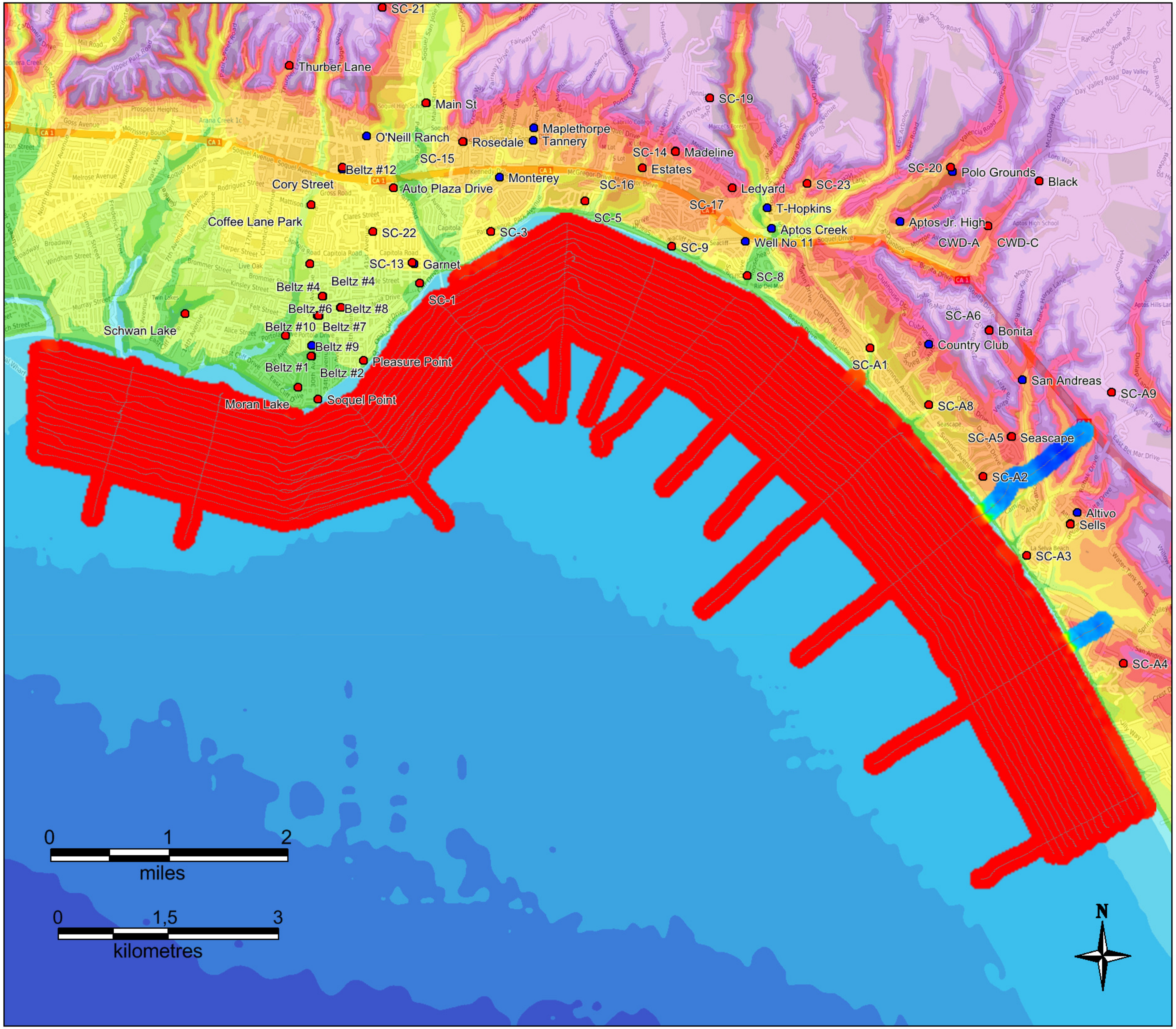
/10/ USGS, Samuel Y. Johnson, Stephen R. Hartwell, Clifton W. Davenport, and Katherine L. Maier, 2016, Offshore and Onshore Geology and Geomorphology, Offshore of Aptos Map Area, California, https://pubs.usgs.gov/of/2016/1025/ofr20161025_sheet10.pdf

/11/ Pedersen et al., August 2017, Mapping the fresh-saltwater interface in the coastal zone using high-resolution airborne electromagnetics, First Break, Volume 35, p57-61

/12/ W.O. Winsauer, H.M. Shearin, Jr., P.H. Masson, and M. Williams, 1952, AAPG, Resistivity of Brine Saturated Sands in Relation of Pore Geometry

APPENDIX 1
MEAN RESISTIVITY MAPS

Santa Cruz Mid-County Groundwater Agency



Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

Rev.: 03
Date: 2018-02-06
By: PRT
QC: MAXH
Project: 1100028721

Annex 1.01

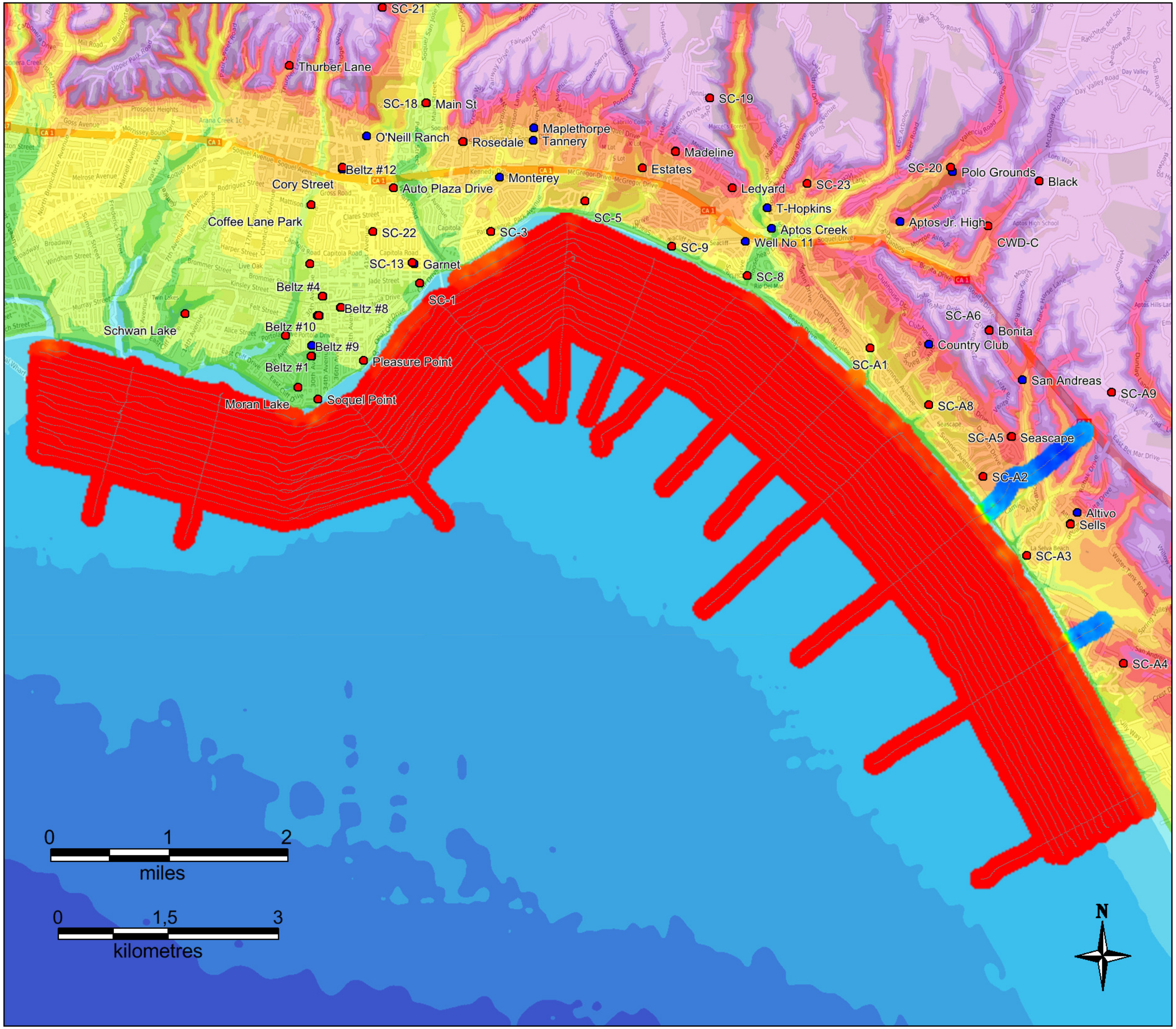
Mean resisitivity 0 to 2 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
Aarhus N

Santa Cruz Mid-County Groundwater Agency



Legend

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- SCWD production wells

Gridding parameters
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- Kriging

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Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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Annex 1.02

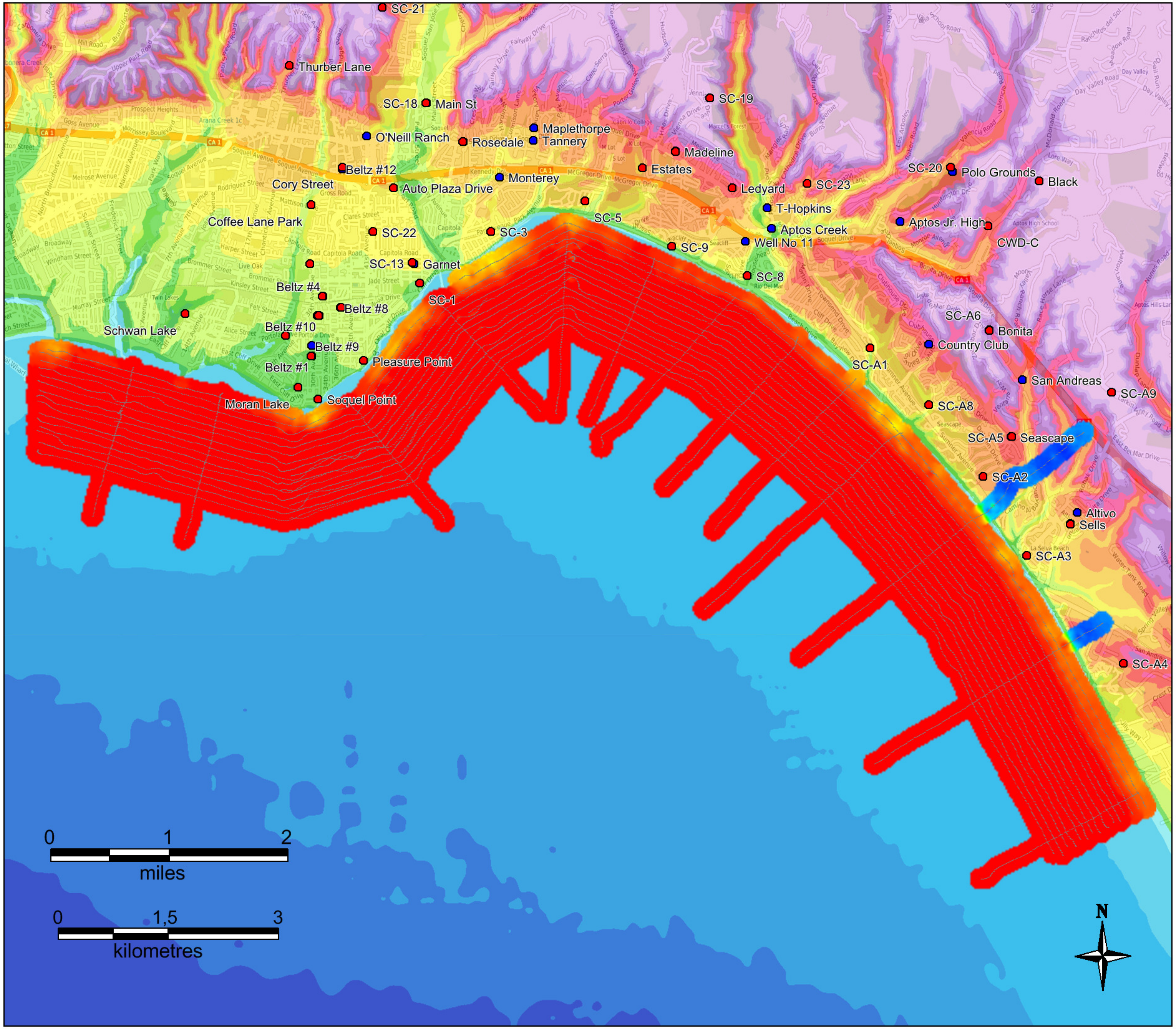
Mean resisitivity 2 to 4 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N

Santa Cruz Mid-County
Groundwater Agency



Legend

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- SCWD production wells

Gridding parameters
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Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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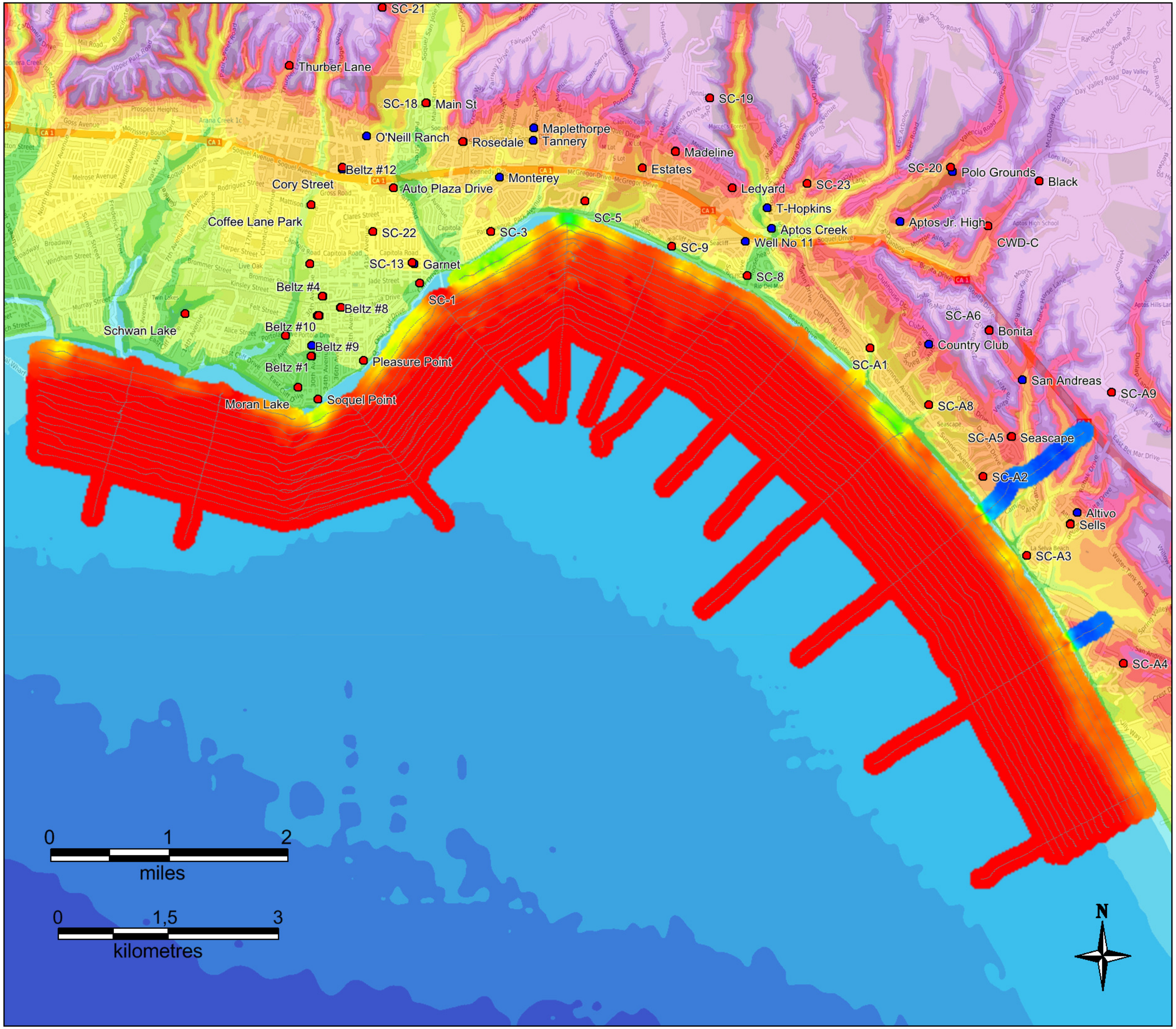
Annex 1.03

Mean resisitivity 4 to 6 mbsl.

Soquel creek - SkyTEM

RAMBØLL

Olof Palmes Allé 22
DK-8200 Aarhus N



Santa Cruz Mid-County
Groundwater Agency

Legend

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- SCWD production wells

Gridding parameters
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Elevation [masl]

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Resistivity [ohmm]

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Annex 1.04

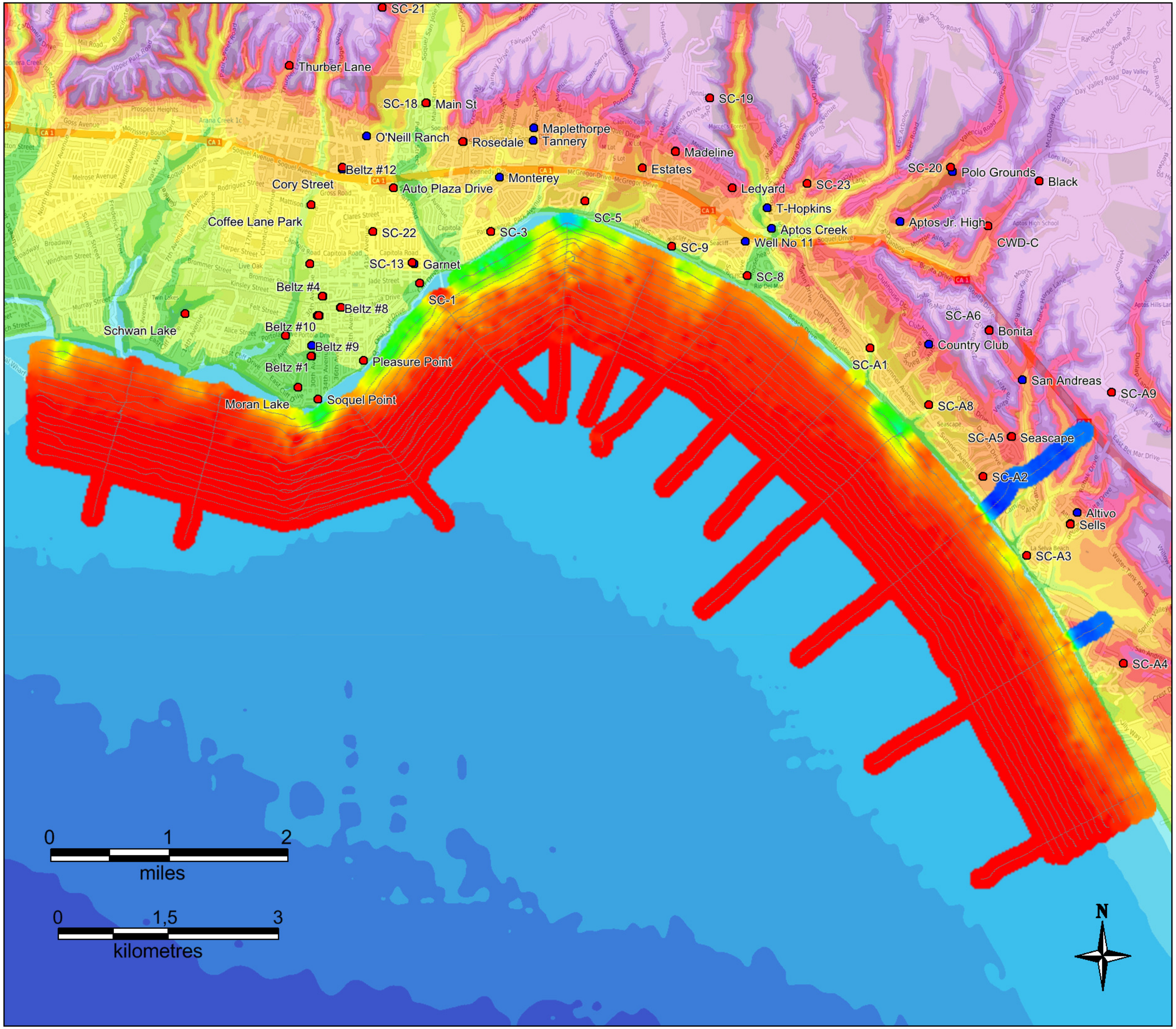
Mean resisitivity 6 to 8 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
Aarhus N

Santa Cruz Mid-County
Groundwater Agency



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Resistivity [ohmm]

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Annex 1.05

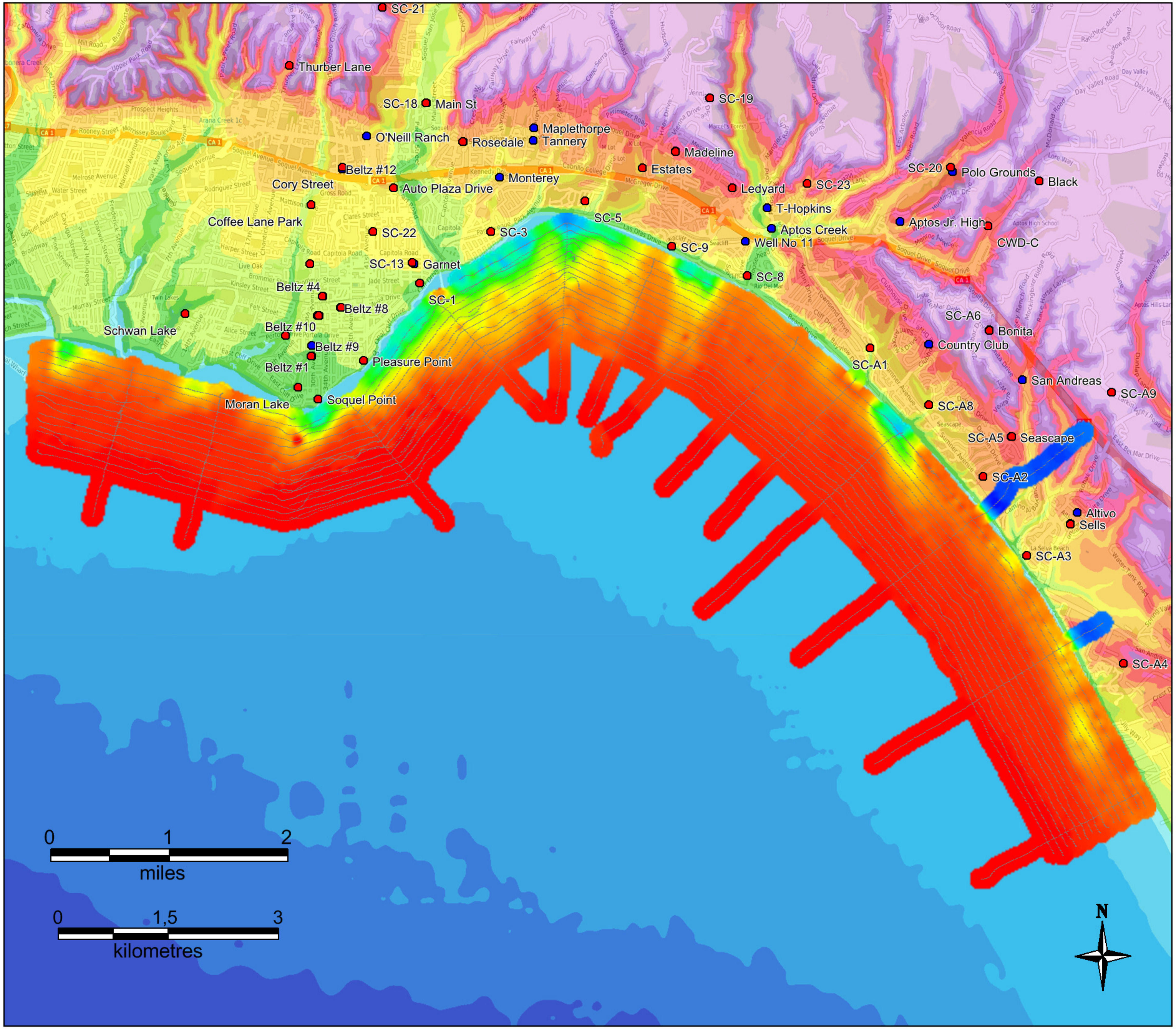
Mean resisitivity 8 to 10 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
DK-8200 Aarhus N

Santa Cruz Mid-County
Groundwater Agency



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Gridding parameters
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Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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Annex 1.06

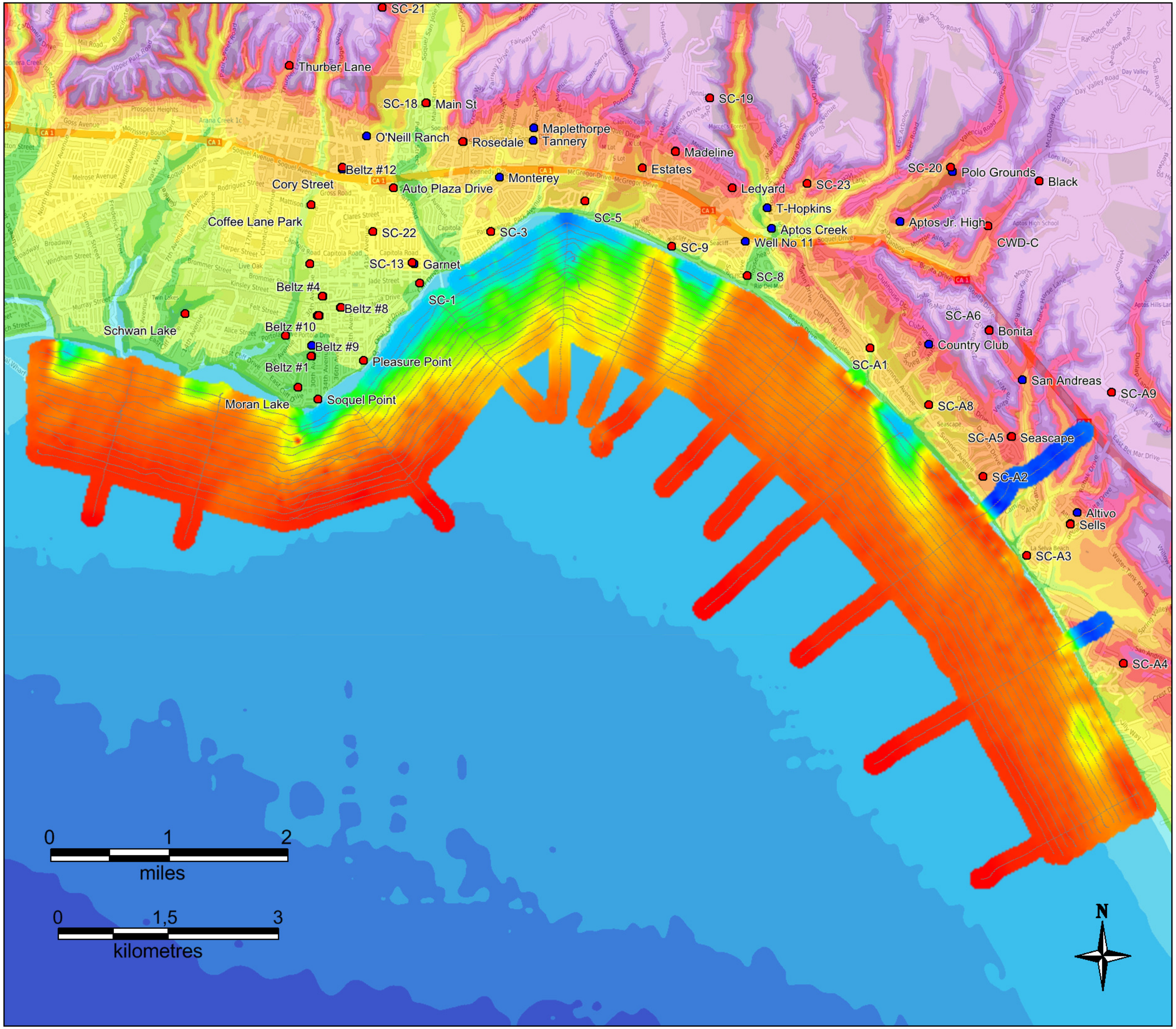
Mean resisitivity 10 to 15 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
DK-8200 Aarhus N

Santa Cruz Mid-County Groundwater Agency



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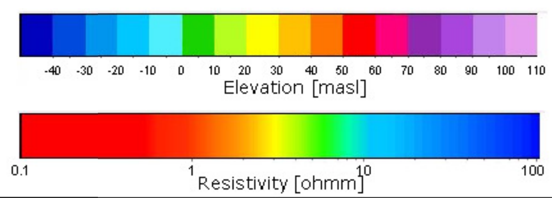

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Project:	1100028721

Annex 1.07

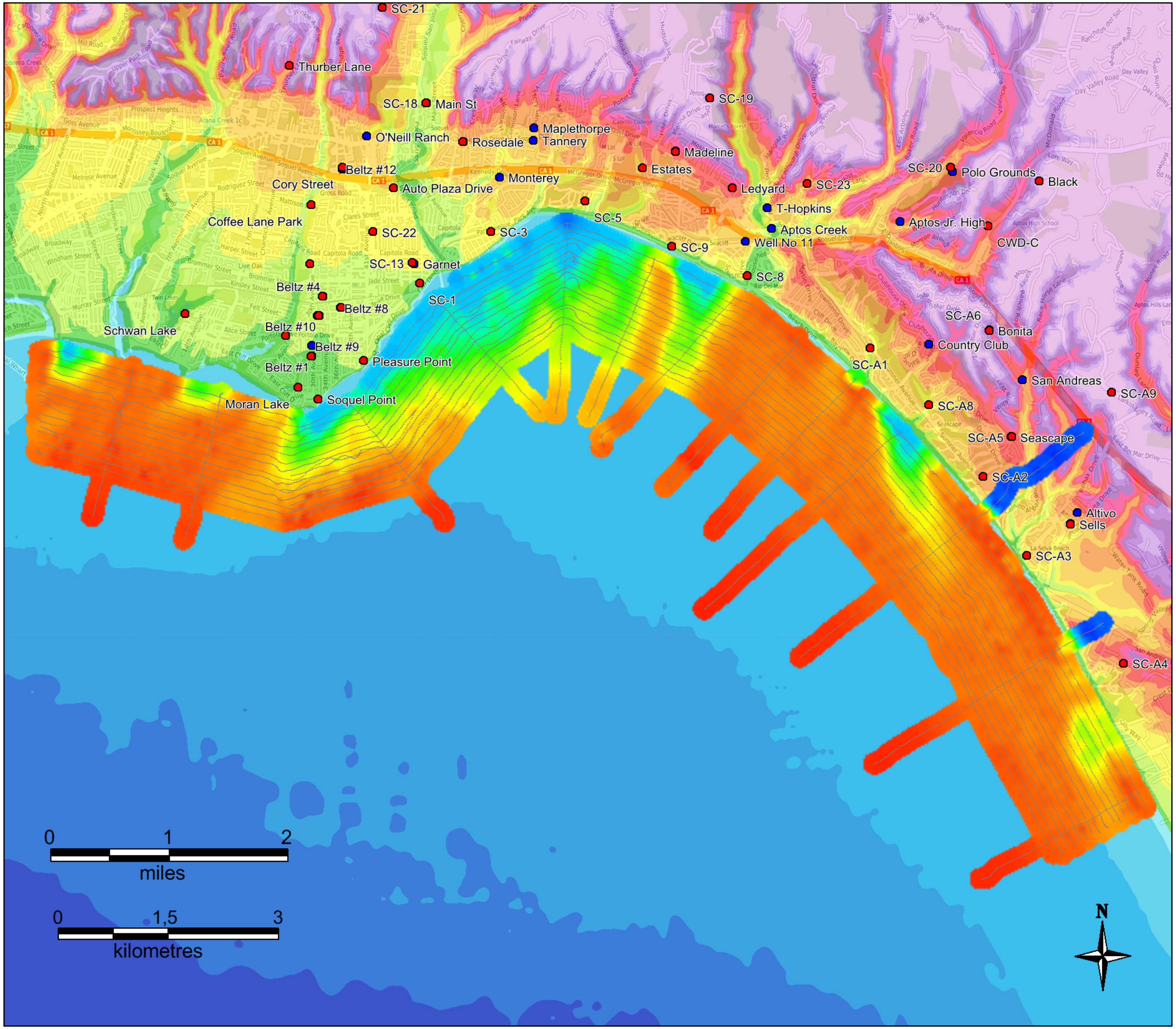
Mean resisitivity 15 to 20 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N

Santa Cruz Mid-County Groundwater Agency



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Gridding parameters
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Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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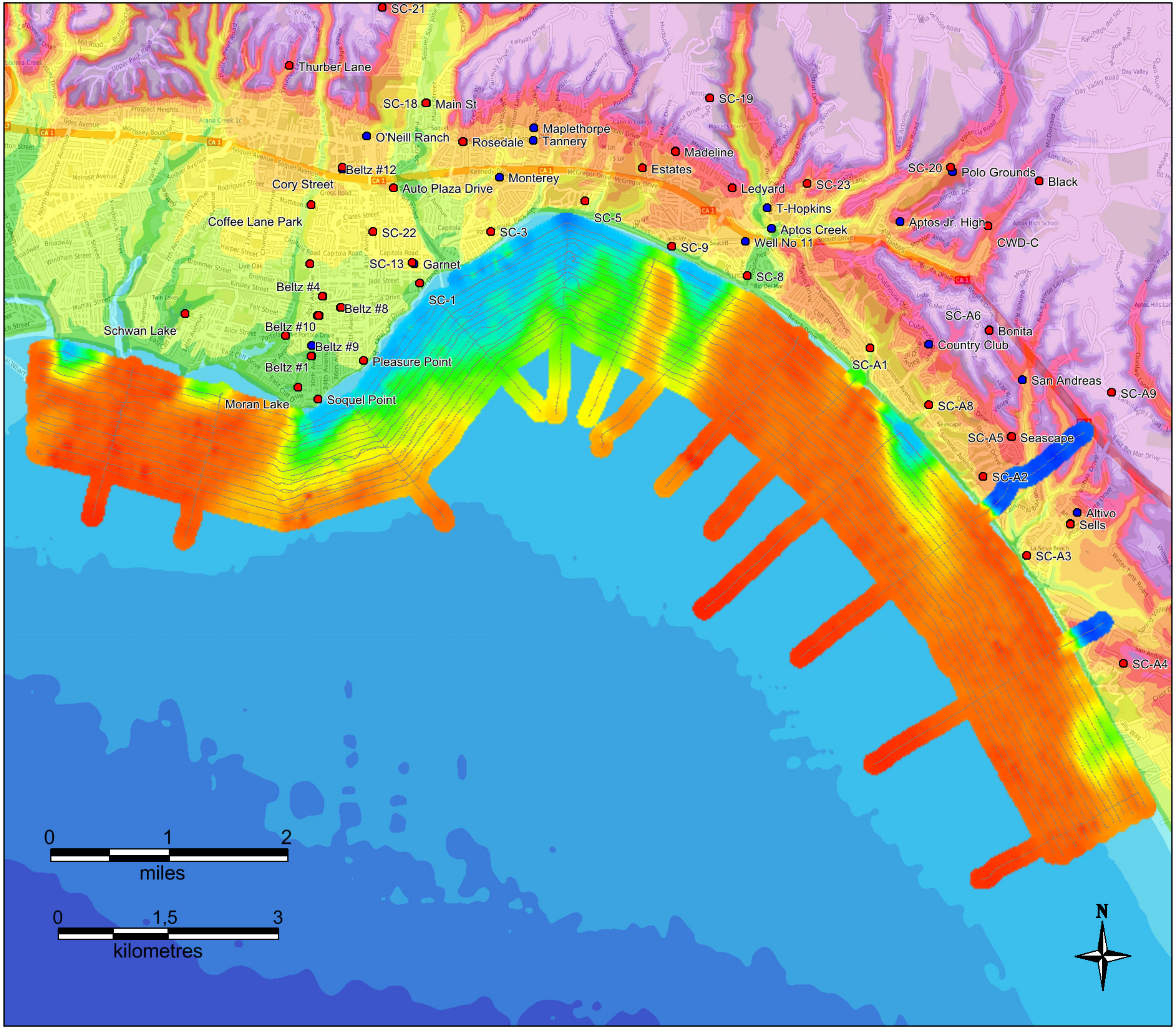
Annex 1.08

Mean resisitivity 20 to 25 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N



Santa Cruz Mid-County Groundwater Agency

Legend

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- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
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- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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Project: 1100028721

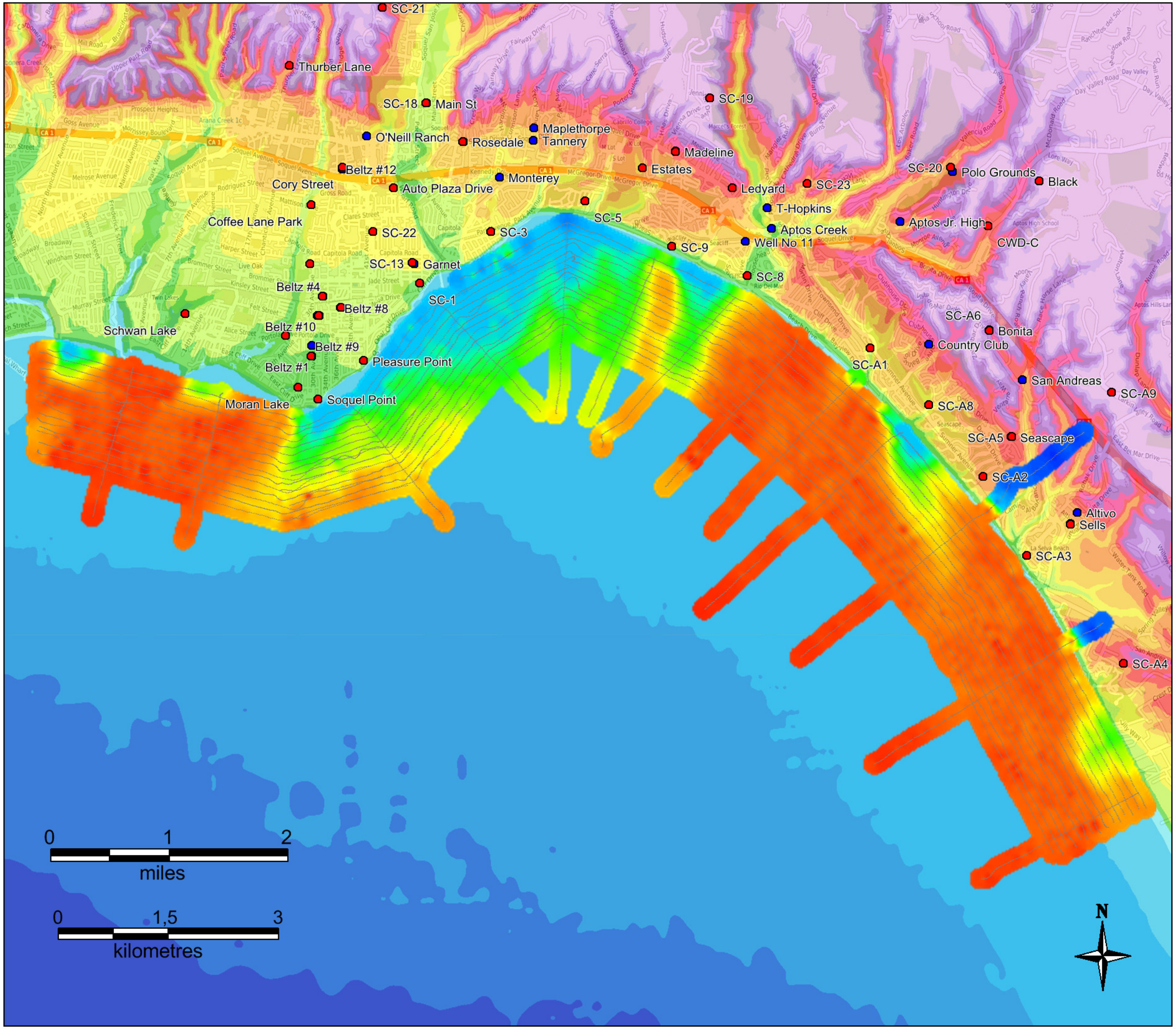
Annex 1.09

Mean resisitivity 25 to 30 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N



Santa Cruz Mid-County Groundwater Agency

Legend
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- SC production wells
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- SCWD production wells

Gridding parameters
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- Cell size 25 m
- Kriging

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Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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Annex 1.10

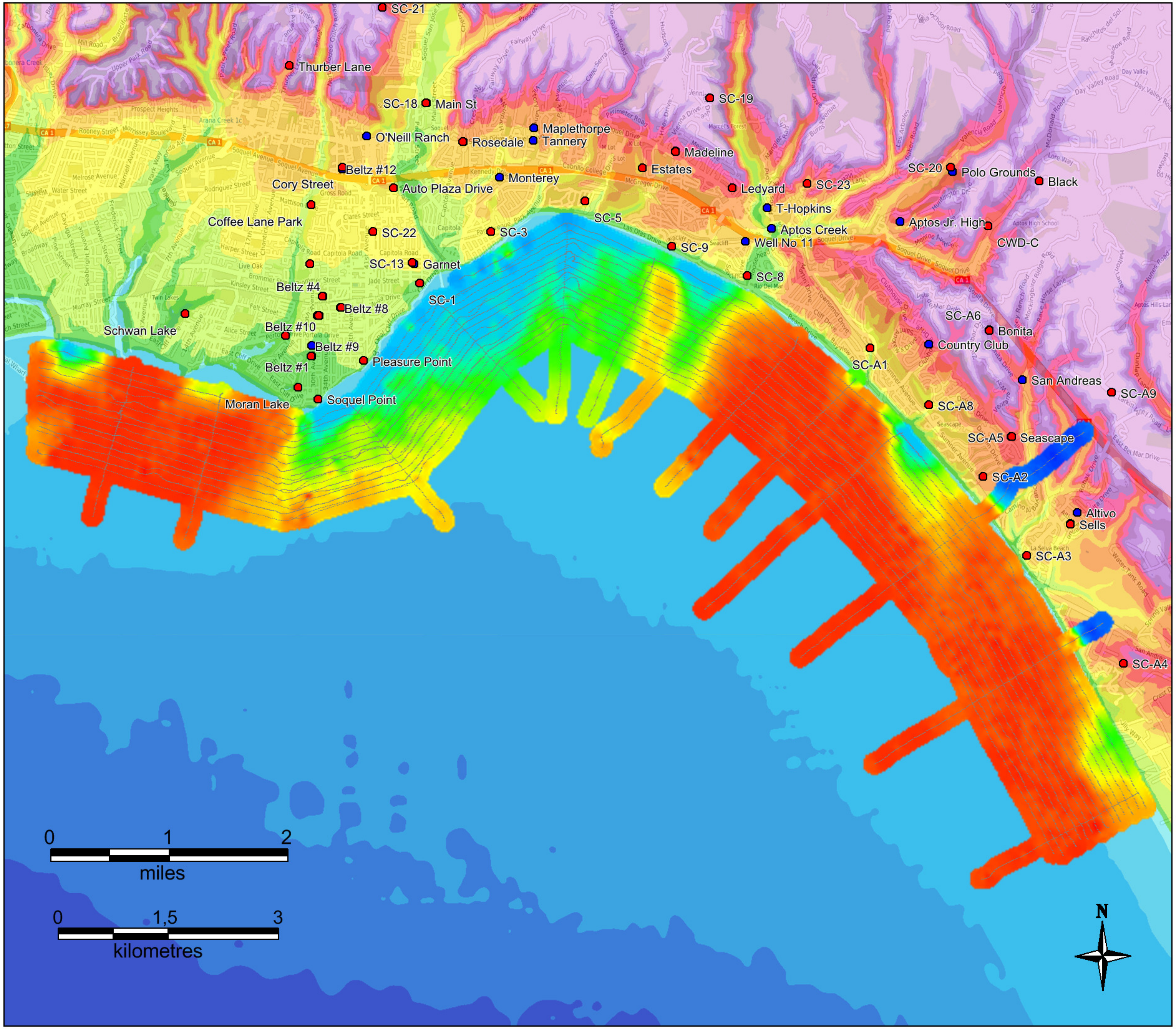
Mean resisitivity 30 to 35 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
DK-8200 Aarhus N

Santa Cruz Mid-County Groundwater Agency



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- SCWD production wells

Gridding parameters
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- Cell size 25 m
- Kriging

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Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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Project:	1100028721

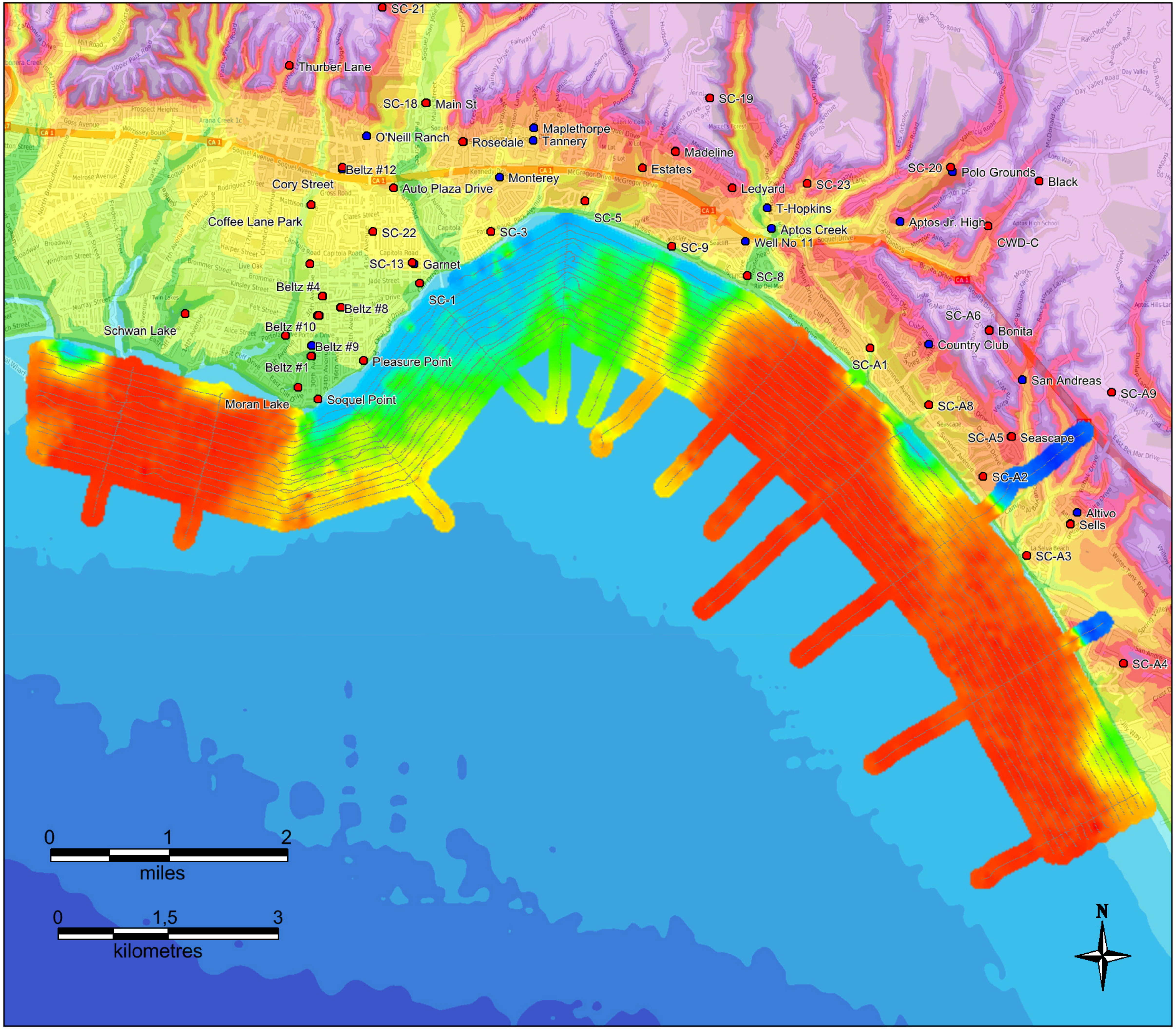
Annex 1.11

Mean resisitivity 35 to 40 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N

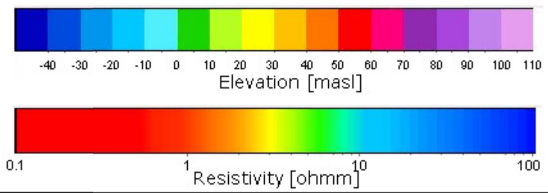


Santa Cruz Mid-County
Groundwater Agency

Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging



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Project:	1100028721

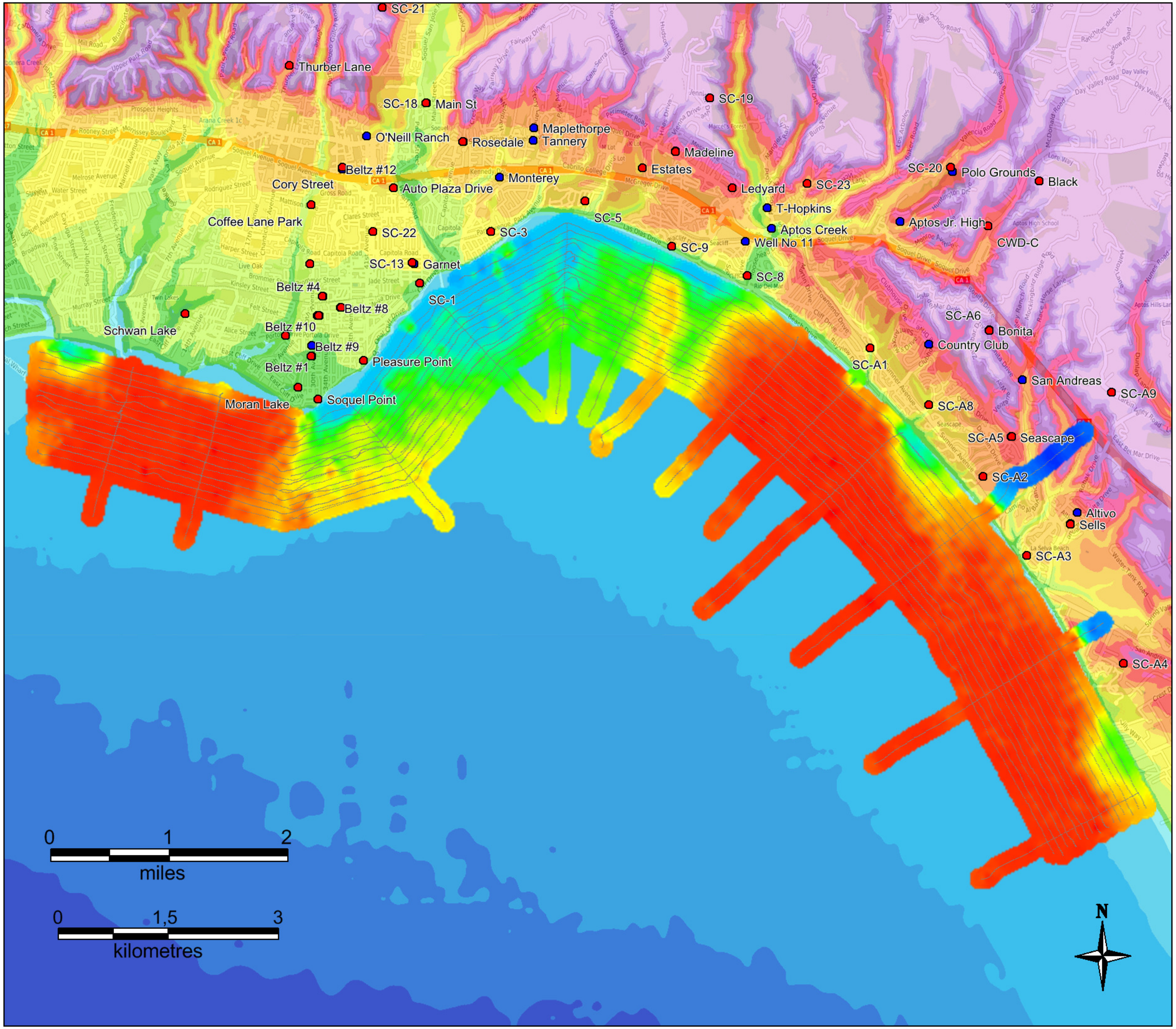
Annex 1.12

Mean resisitivity 40 to 45 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N



Santa Cruz Mid-County Groundwater Agency

Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
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- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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Date: 2018-02-05
By: PRT
QC: MAXH
Project: 1100028721

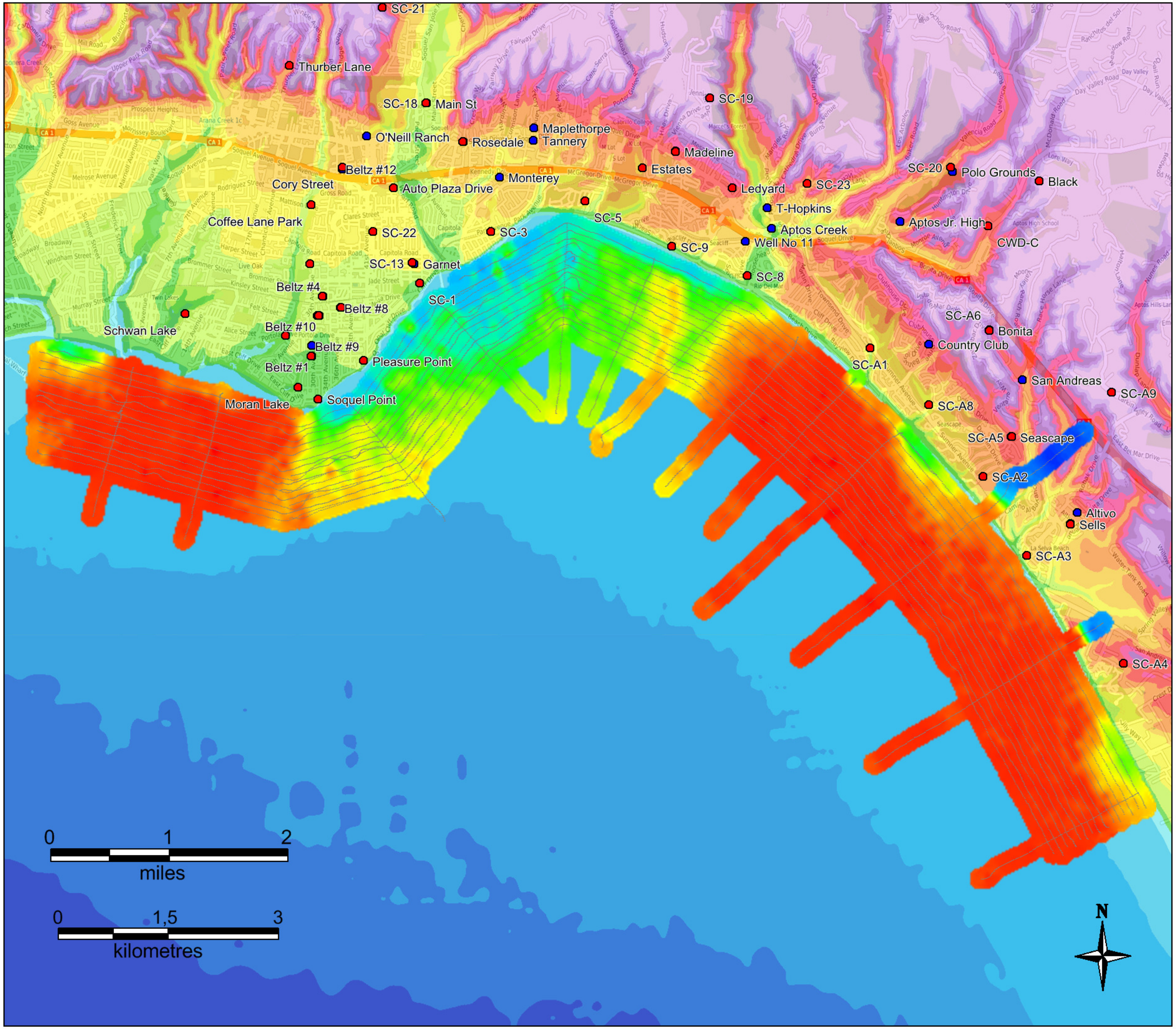
Annex 1.13

Mean resisitivity 45 to 50 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
DK-8200 Aarhus N



Santa Cruz Mid-County Groundwater Agency

Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
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- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110

Elevation [masl]

0.1 1 10 100

Resistivity [ohmm]

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Project: 1100028721

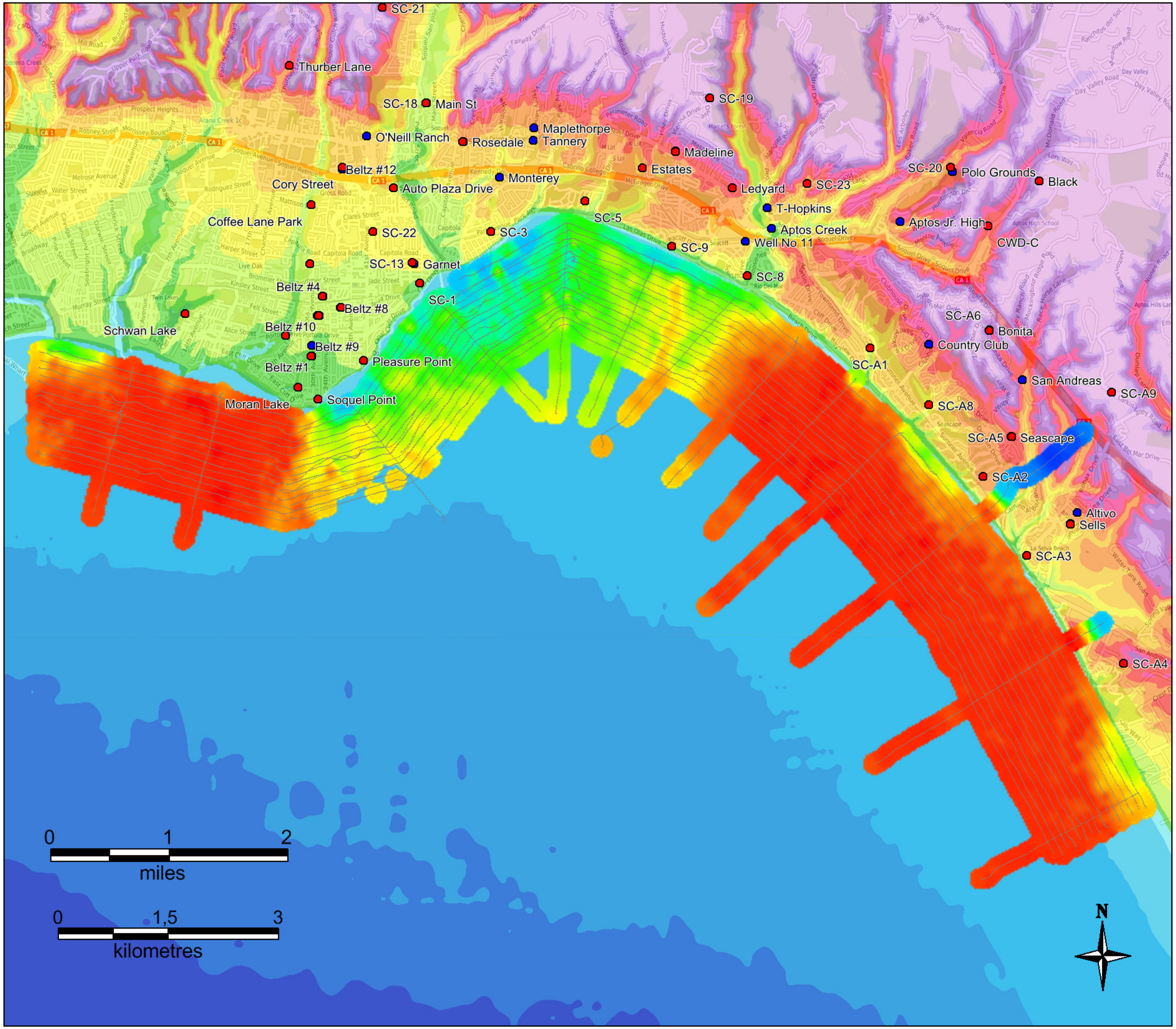
Annex 1.14

Mean resisitivity 50 to 60 mbsl.

Soquel creek - SkyTEM

RAMBØLL

Olof Palmes Allé 22
8000 Aarhus N



Santa Cruz Mid-County Groundwater Agency

Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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Date: 2018-02-05
By: PRT
QC: MAXH
Project: 1100028721

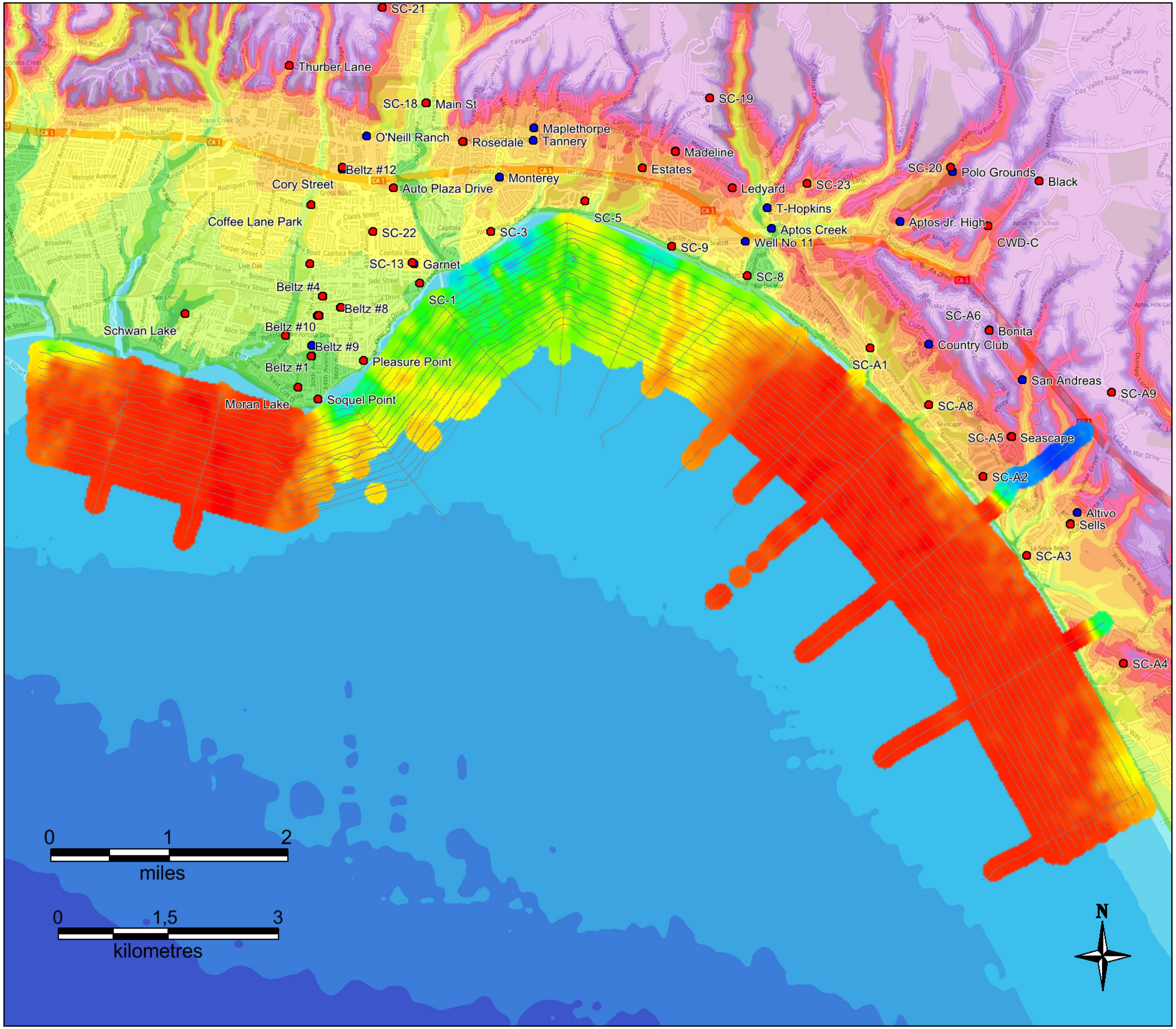
Annex 1.15

Mean resisitivity 60 to 70 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
DK-8200 Aarhus N



Santa Cruz Mid-County
Groundwater Agency

Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

Rev.: 03
Date: 2018-02-06
By: PRT
QC: MAXH
Project: 1100028721

Annex 1.16

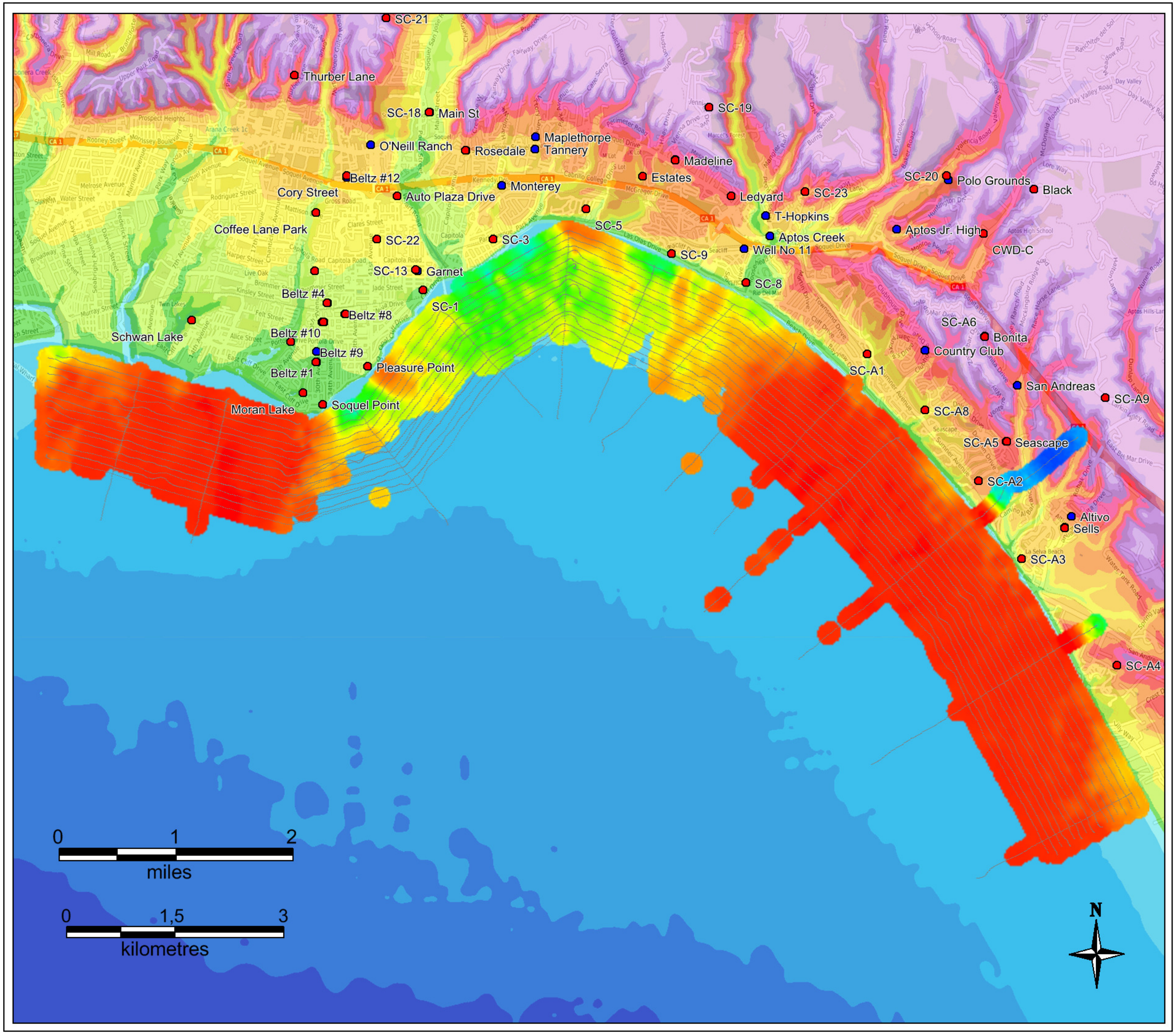
Mean resisitivity 70 to 80 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N

Santa Cruz Mid-County Groundwater Agency



Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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By: PRT
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Project: 1100028721

Annex 1.17

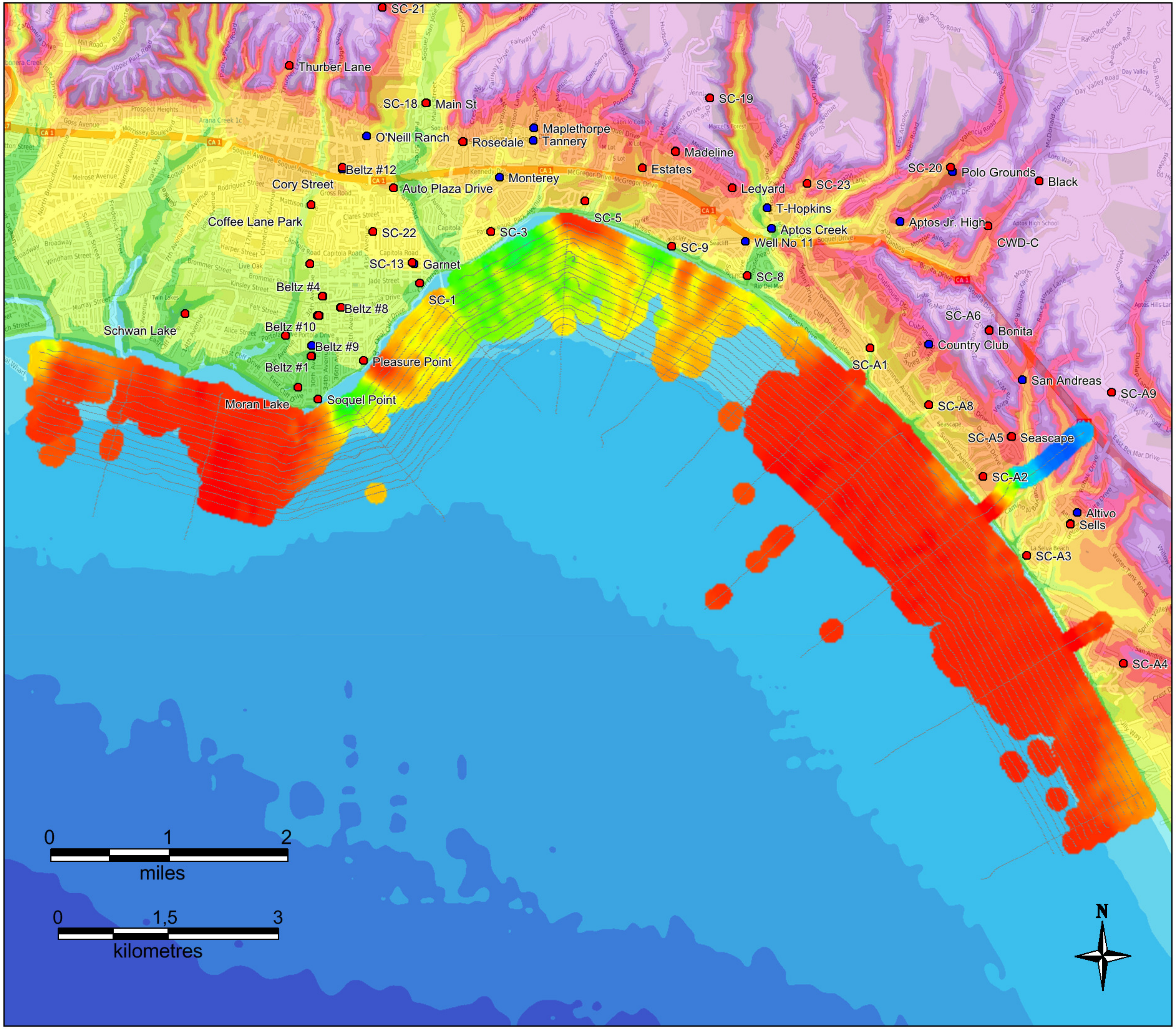
Mean resisitivity 80 to 90 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
DK-8200 Aarhus N

Santa Cruz Mid-County Groundwater Agency



Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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By: PRT
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Project: 1100028721

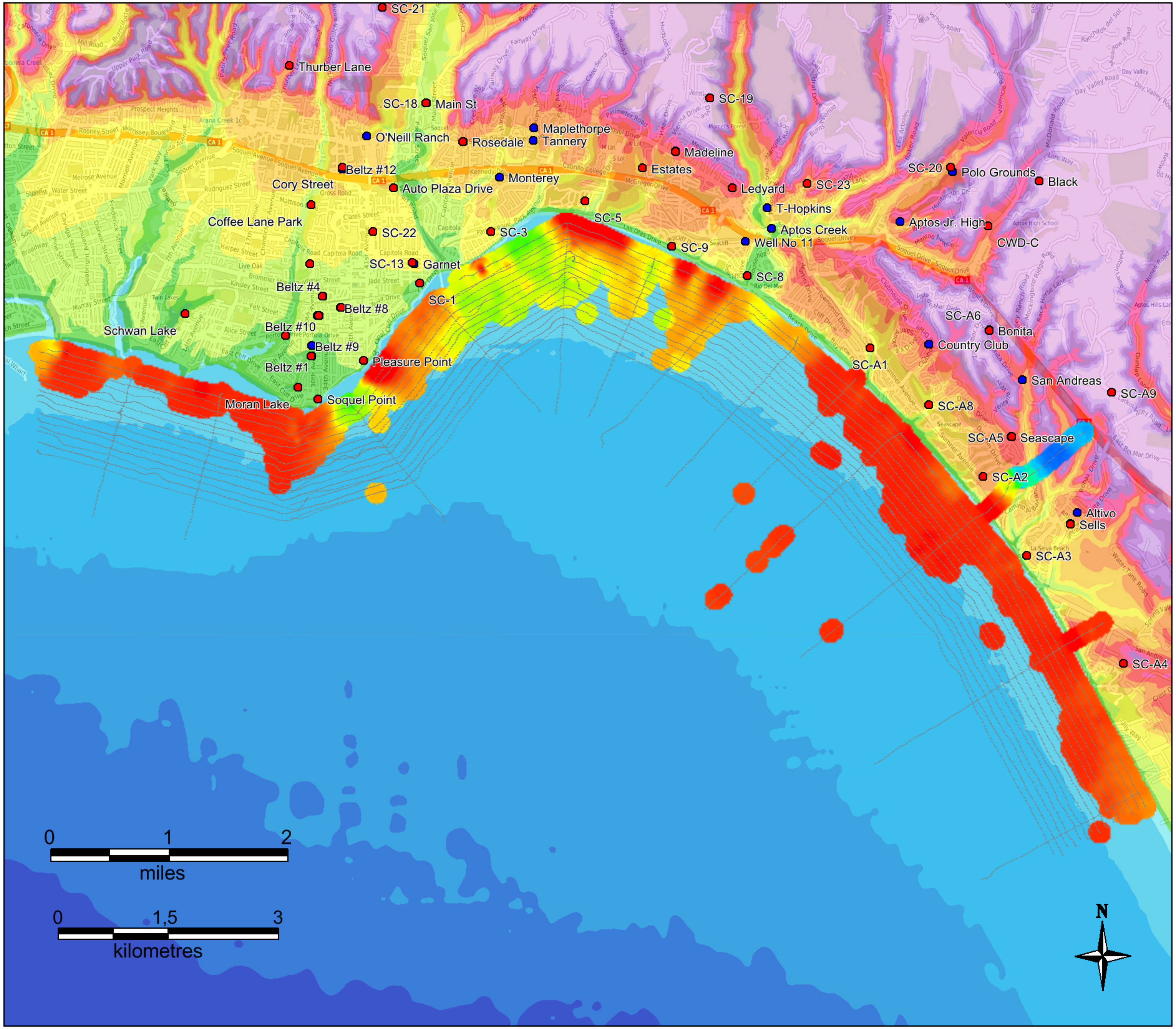
Annex 1.18

Mean resisitivity 90 to 100 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N



Santa Cruz Mid-County Groundwater Agency

Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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By: PRT
QC: MAXH
Project: 1100028721

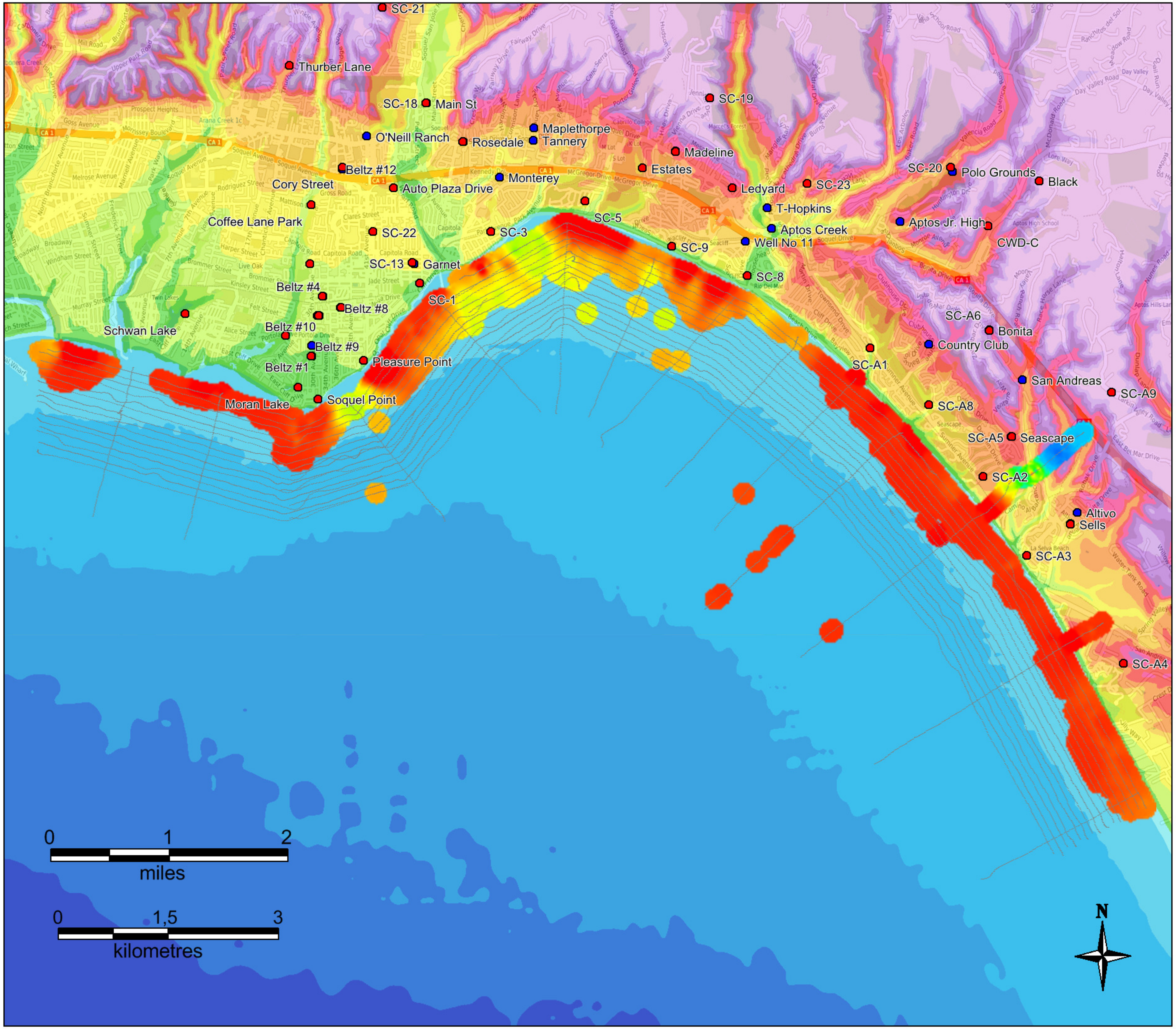
Annex 1.19

Mean resisitivity 100 to 110 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
Aarhus N



Santa Cruz Mid-County Groundwater Agency

Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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Date: 2018-02-06
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Project: 1100028721

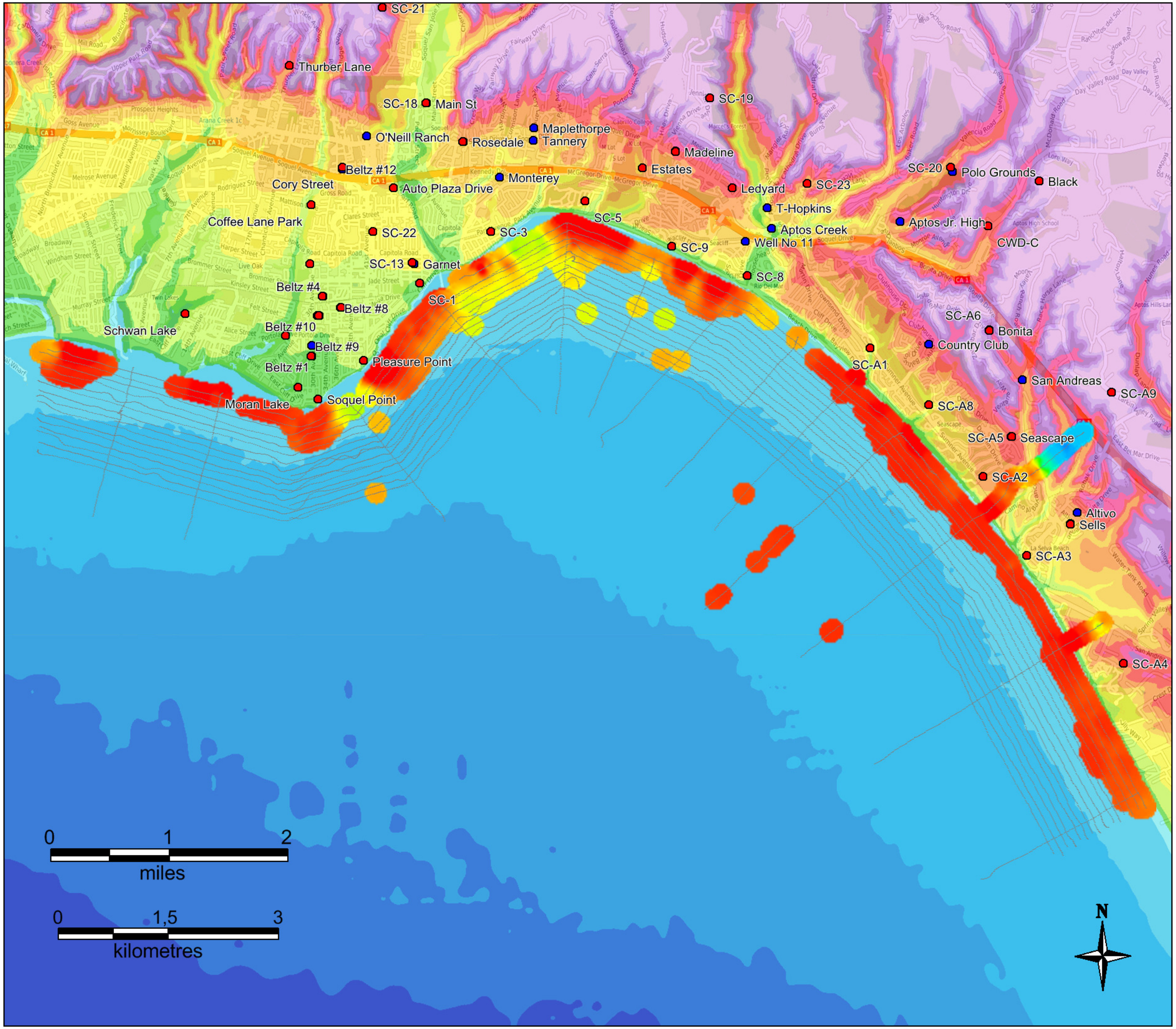
Annex 1.20

Mean resisitivity 110 to 120 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
DK-8200 Aarhus N



Santa Cruz Mid-County Groundwater Agency

Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

Rev.: 03
Date: 2018-02-06
By: PRT
QC: MAXH
Project: 1100028721

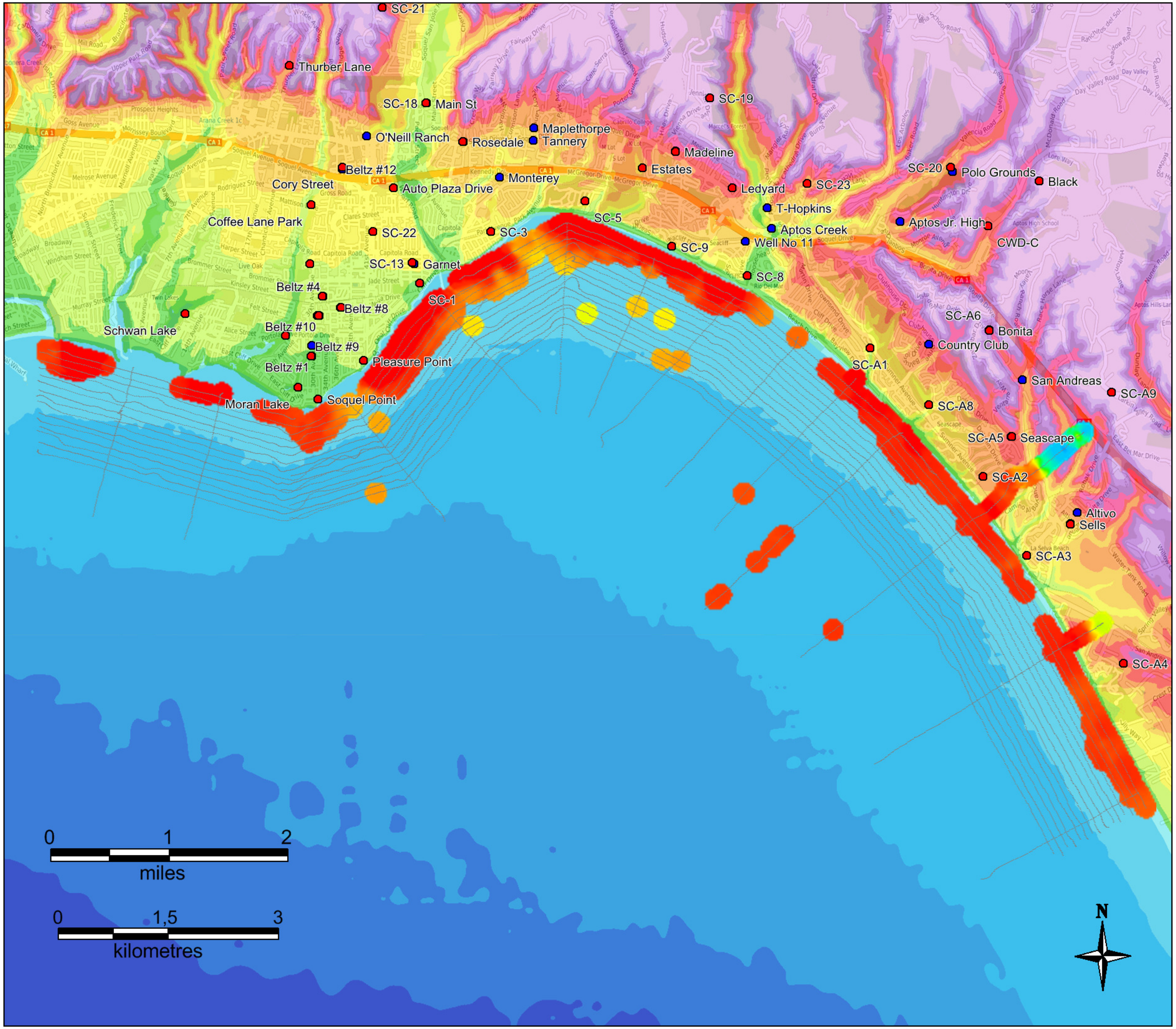
Annex 1.21

Mean resisitivity 120 to 130 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N



Santa Cruz Mid-County
Groundwater Agency

Legend
- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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Date: 2018-02-06
By: PRT
QC: MAXH
Project: 1100028721

Annex 1.22

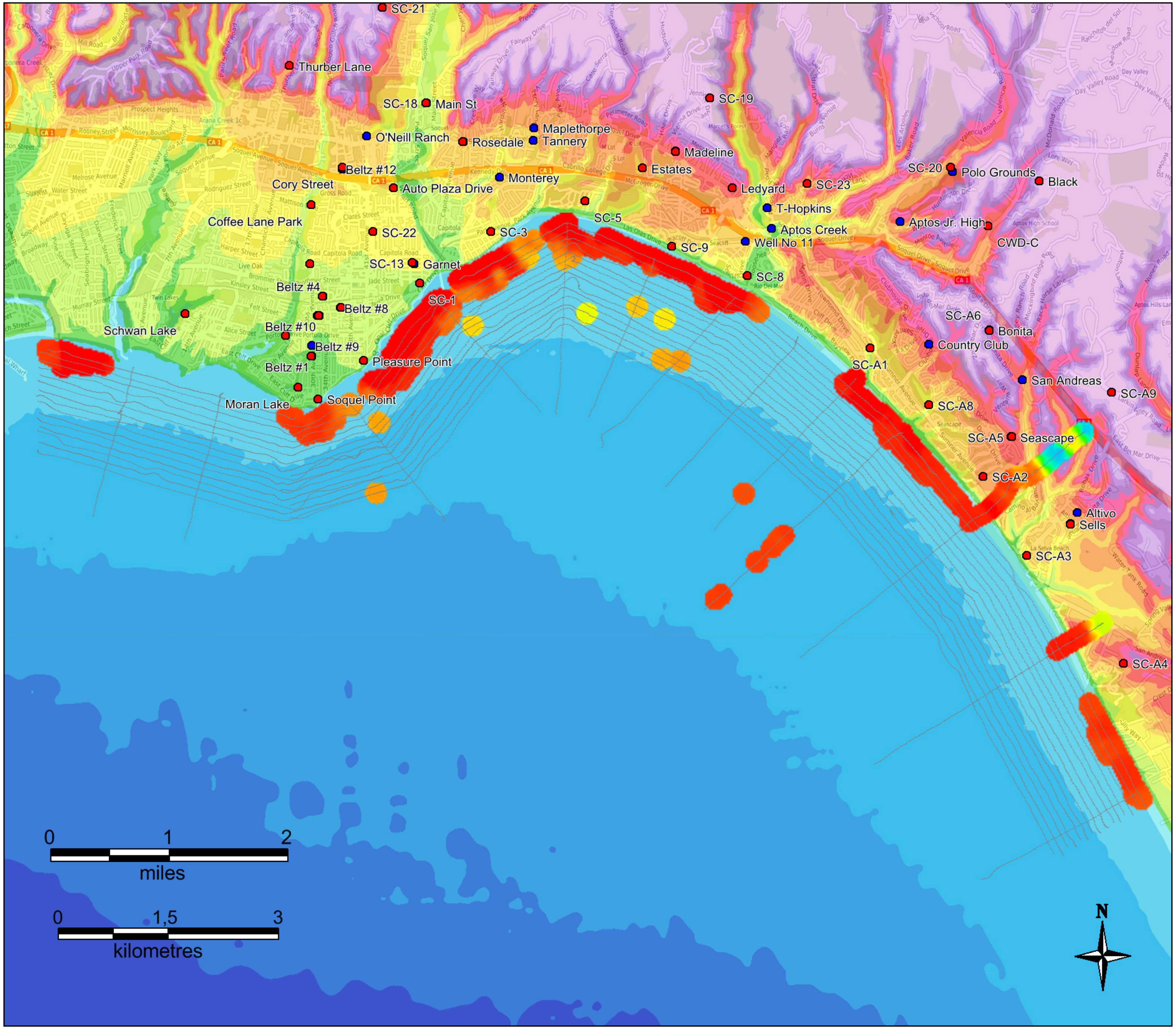
Mean resisitivity 130 to 140 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N

Santa Cruz Mid-County Groundwater Agency



Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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QC:	MAXH
Project:	1100028721

Annex 1.23

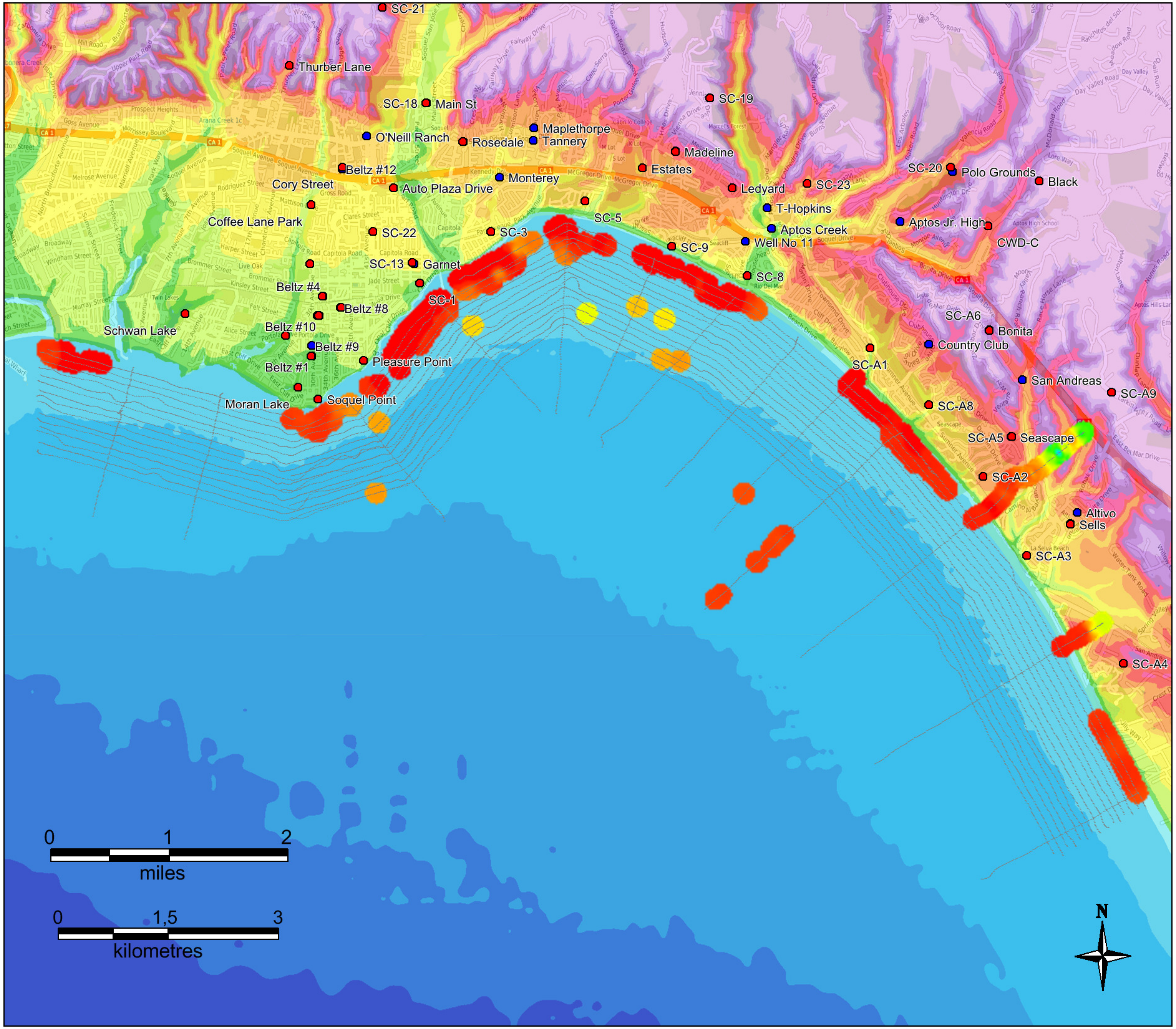
Mean resisitivity 140 to 150 mbsl.

Soquel creek - SkyTEM

RAMBOLL

Olof Palmes Allé 22
Aarhus N

Santa Cruz Mid-County Groundwater Agency



Legend

- SC monitoring wells
- SC production wells
- SCWD monitoring wells
- SCWD production wells

Gridding parameters
- Search radius 150 m
- Cell size 25 m
- Kriging

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110
Elevation [masl]

0.1 1 10 100
Resistivity [ohmm]

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Date: 2018-02-06
By: PRT
QC: MAXH
Project: 1100028721

Annex 1.24

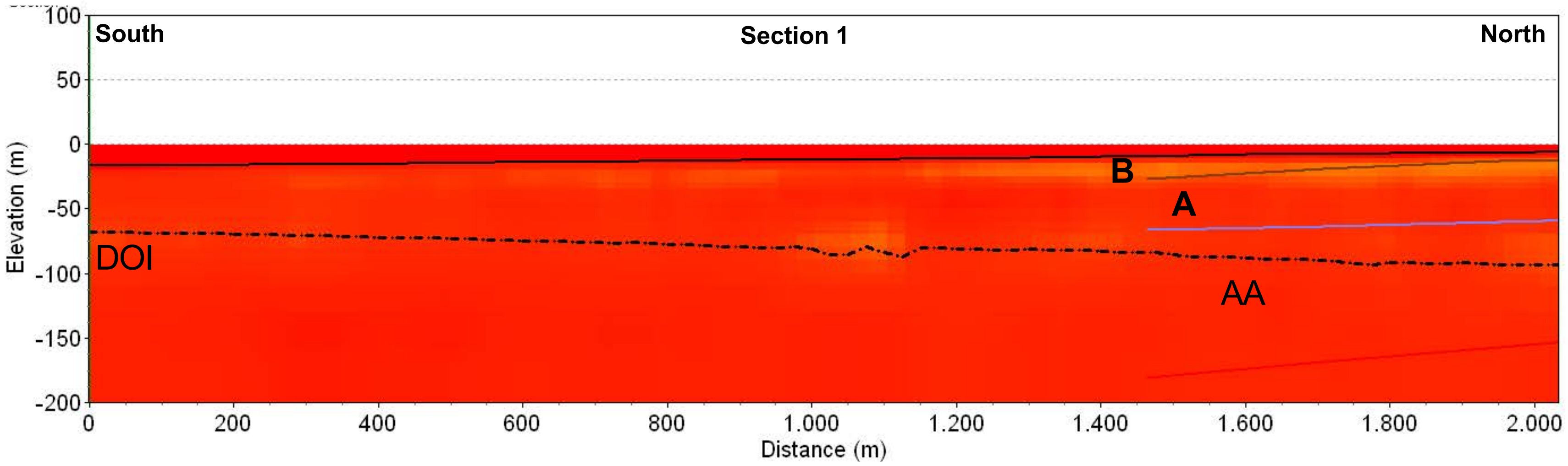
Mean resisitivity 150 to 160 mbsl.

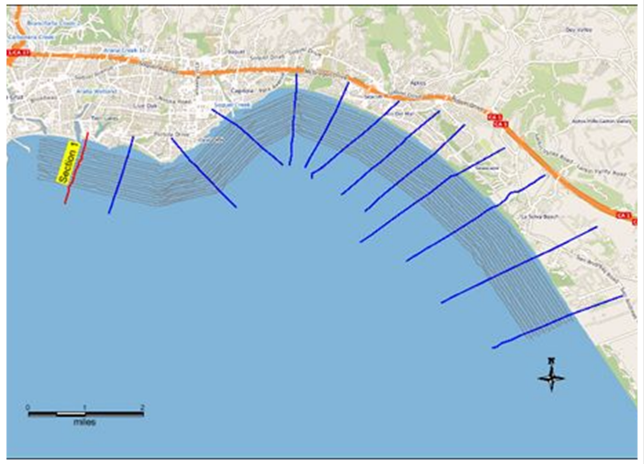
Soquel creek - SkyTEM

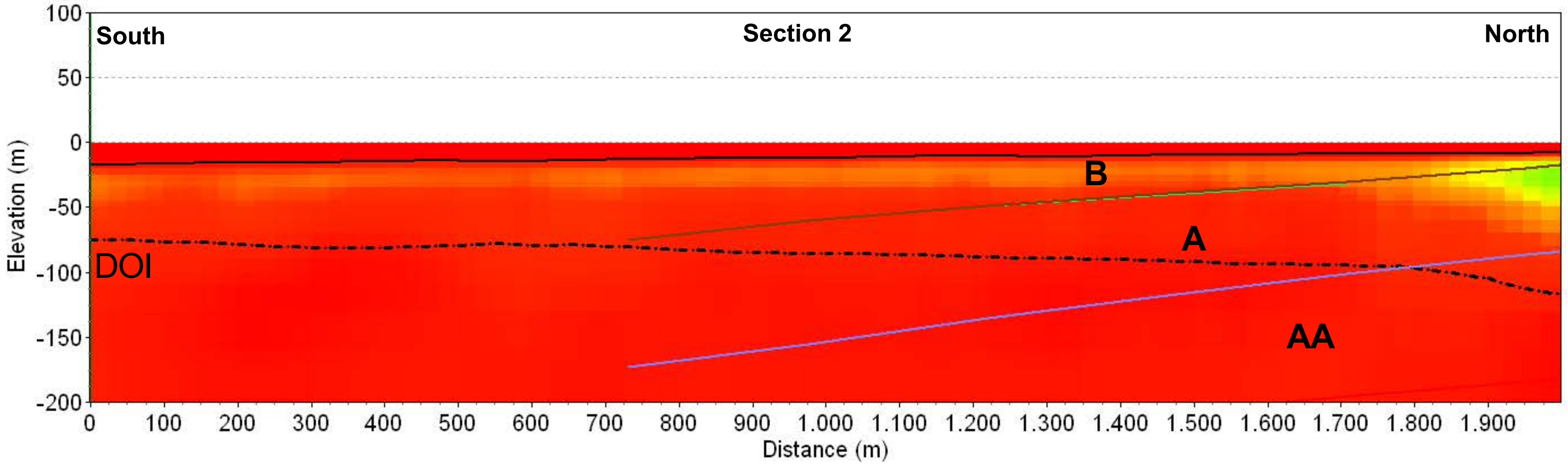
RAMBOLL

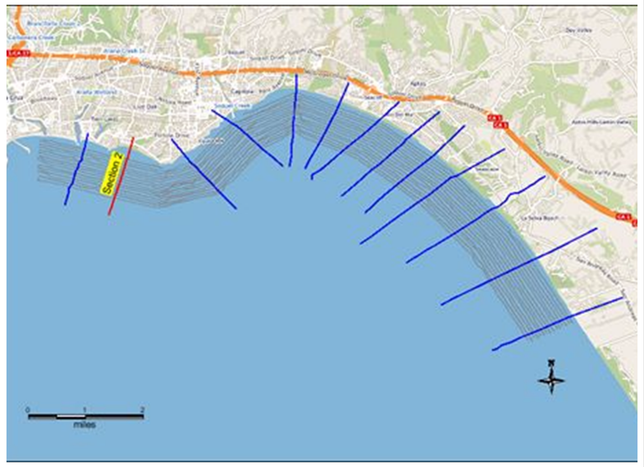
Olof Palmes Allé 22
8200 Aarhus N

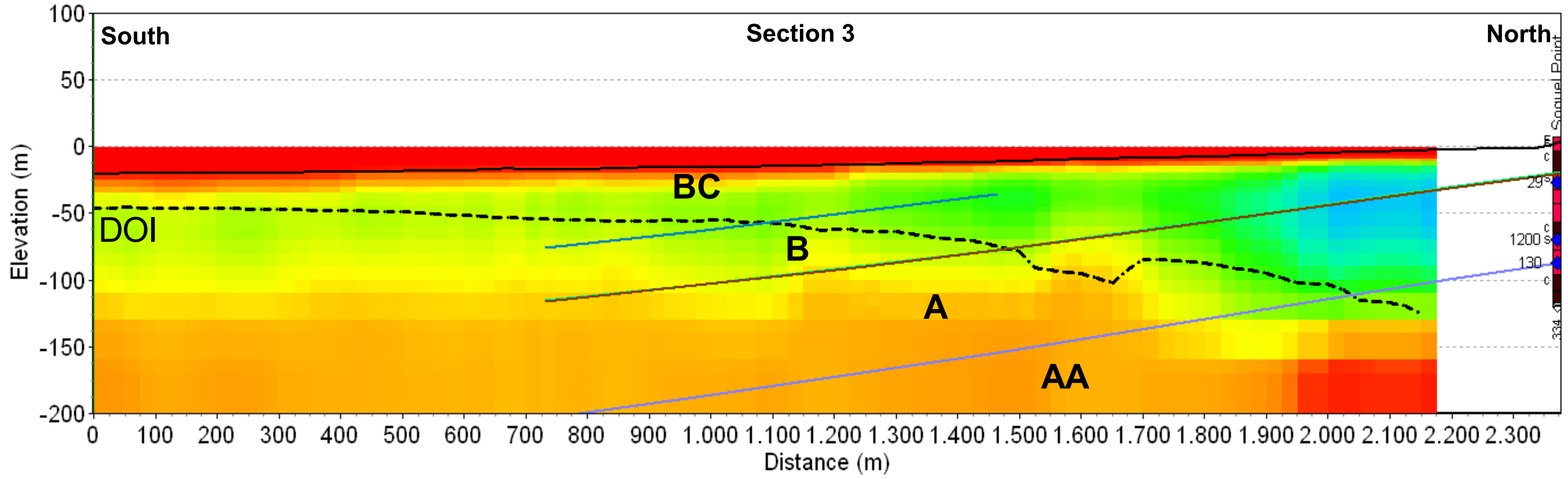
APPENDIX 2
VERTICAL SECTIONS

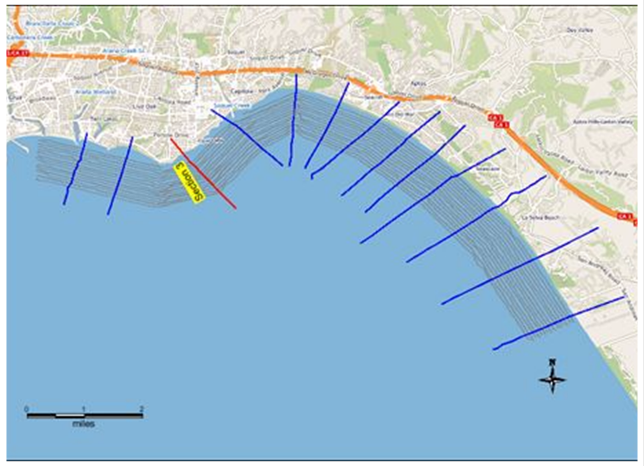


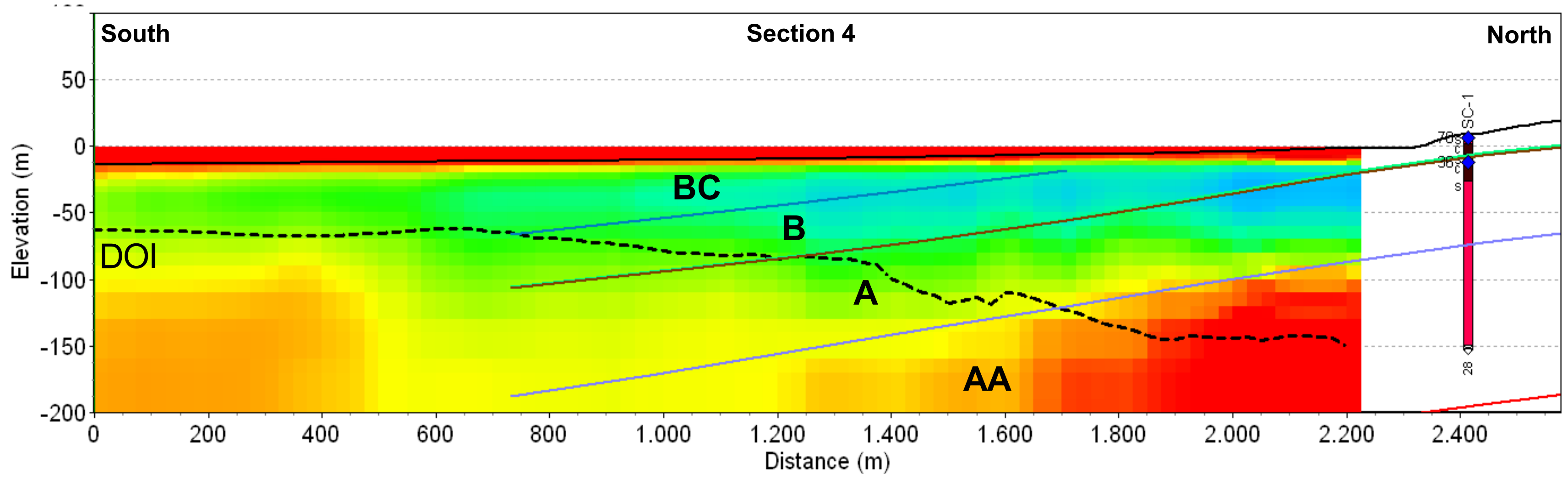












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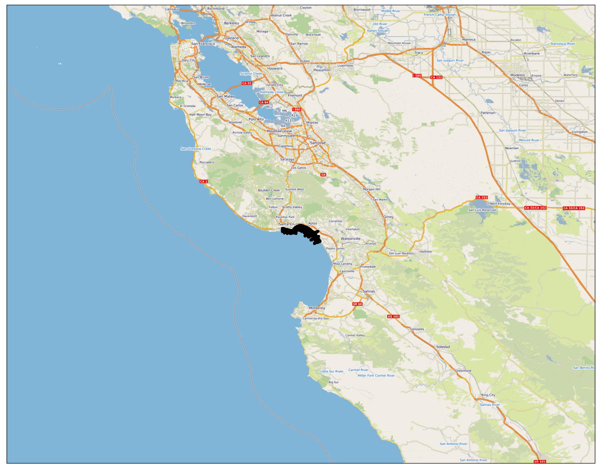
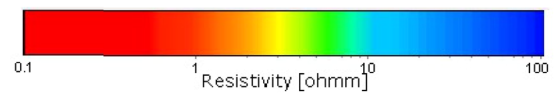
Groundwater Agency





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Date: 2017-10-10
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Project: 1100028721

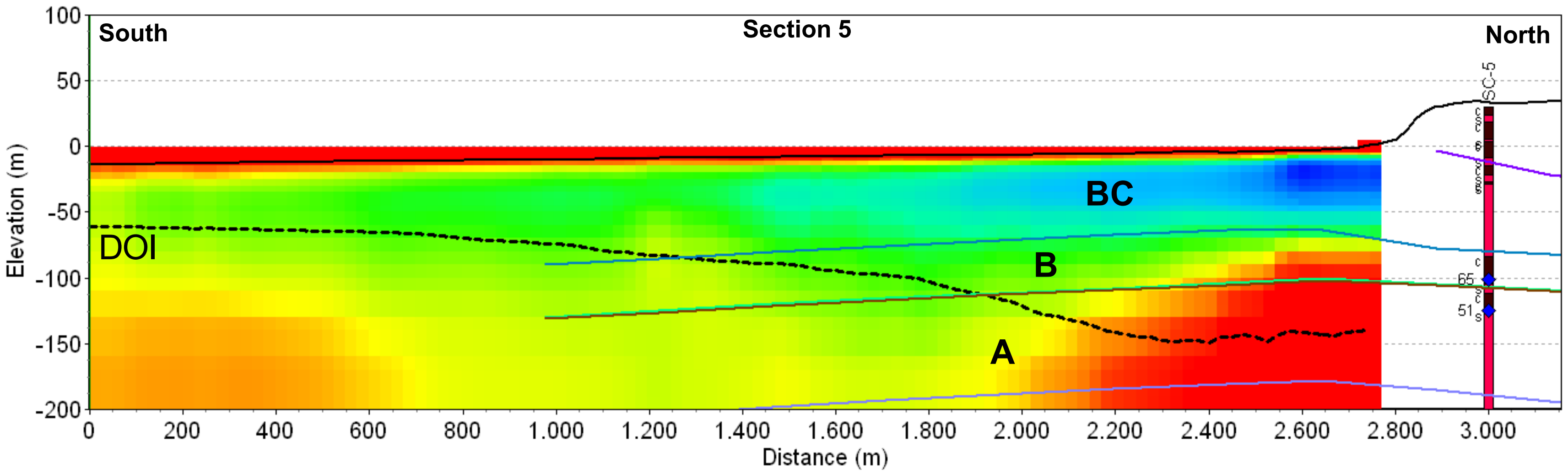
Annex 2.01

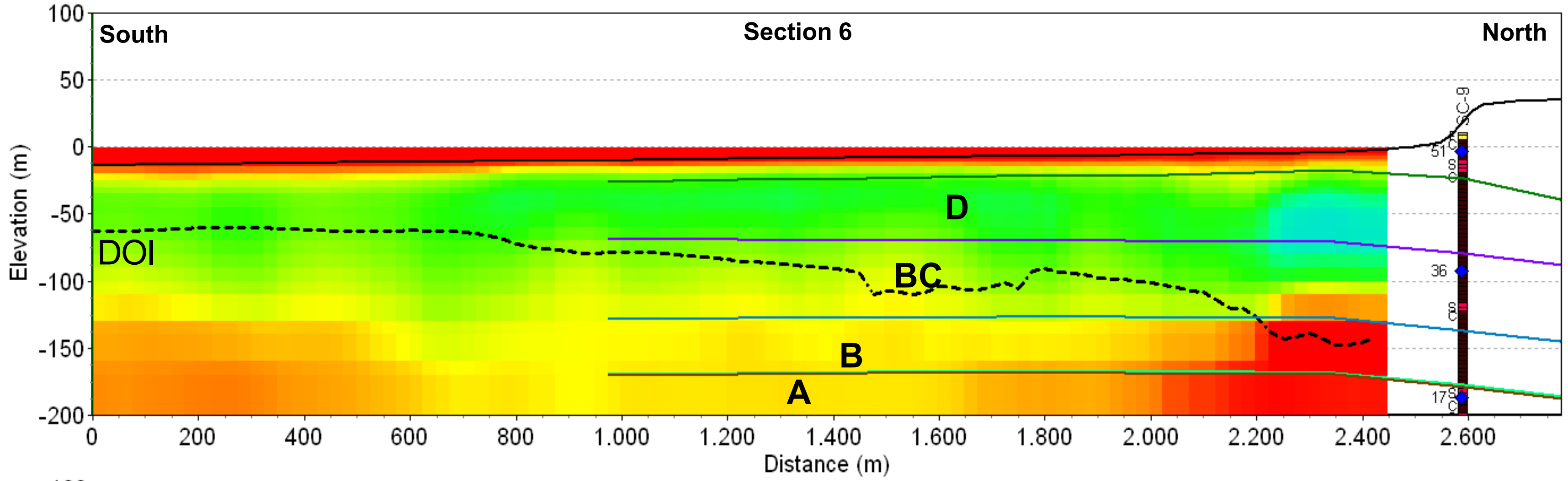
Model sections and hydrostratigraphic units

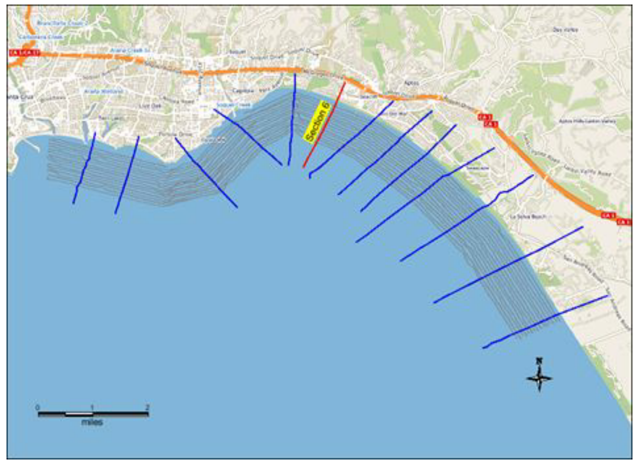
Soquel creek

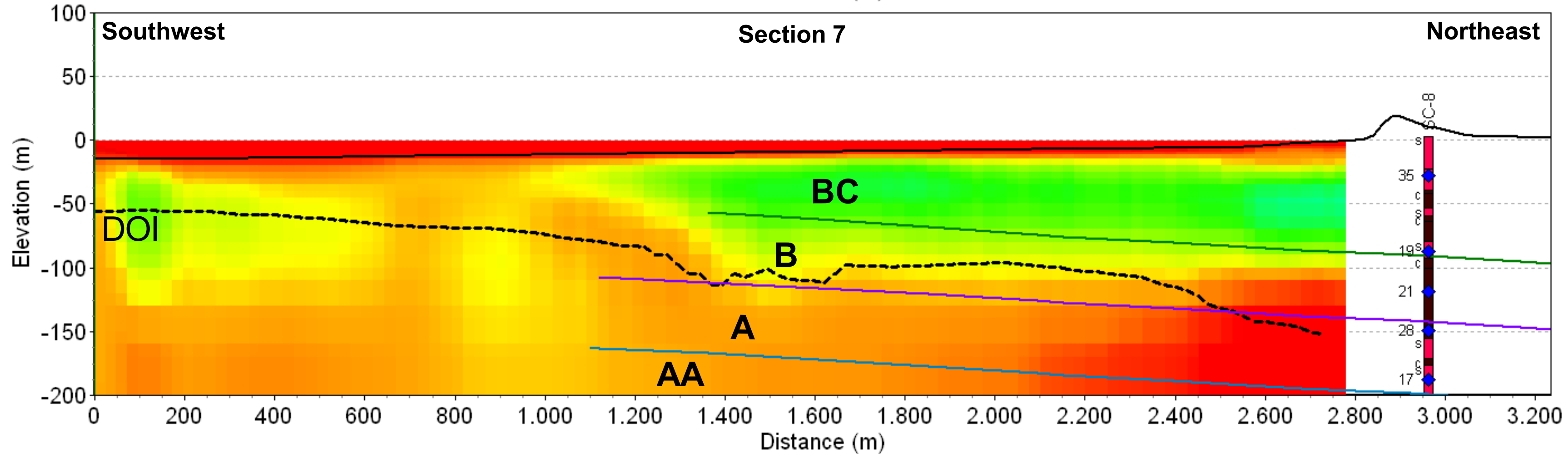
RAMBOLL

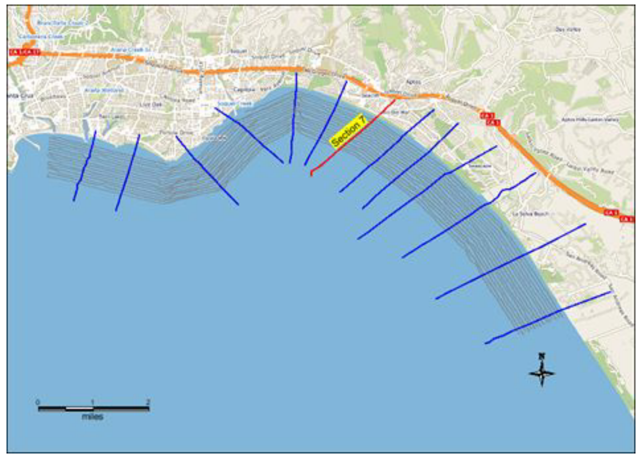
Olof Palmes Allé 22
DK-8200 Aarhus N

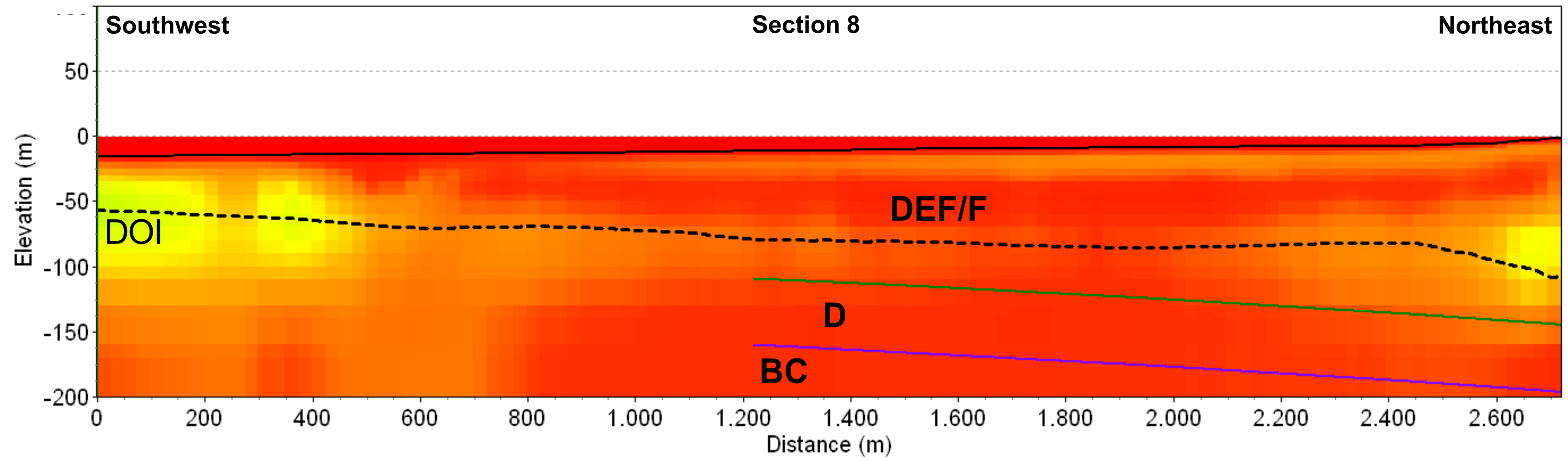


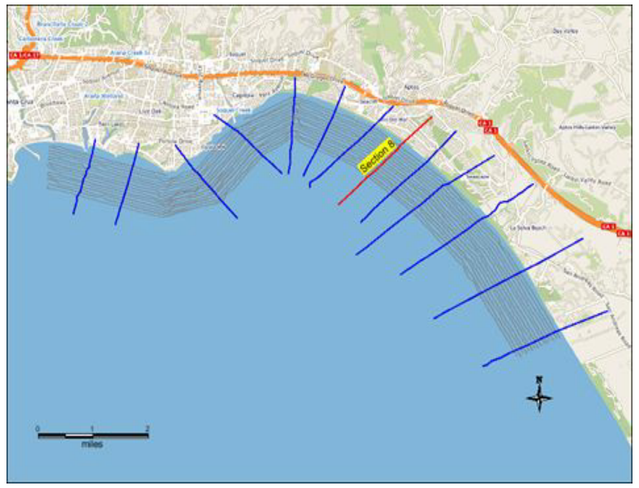




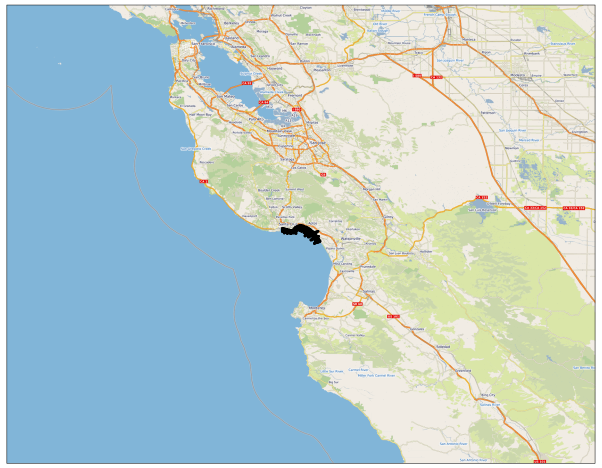


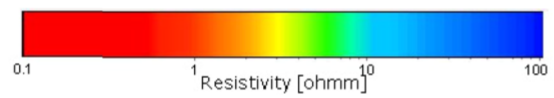






Santa Cruz Mid-County Groundwater Agency





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Project: 1100028721

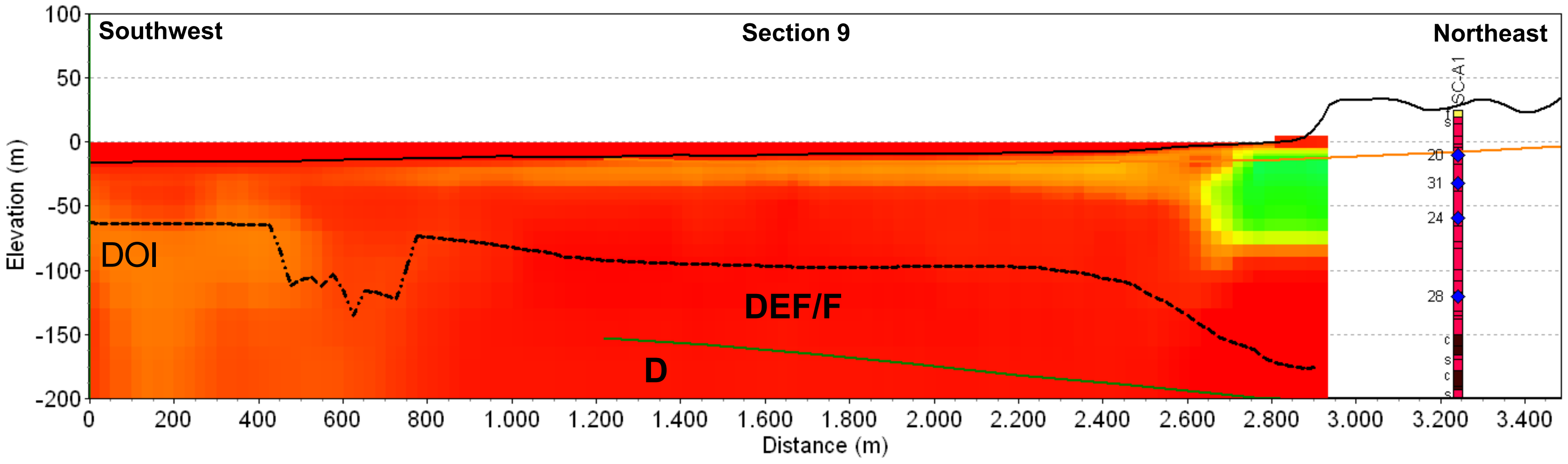
Annex 2.02

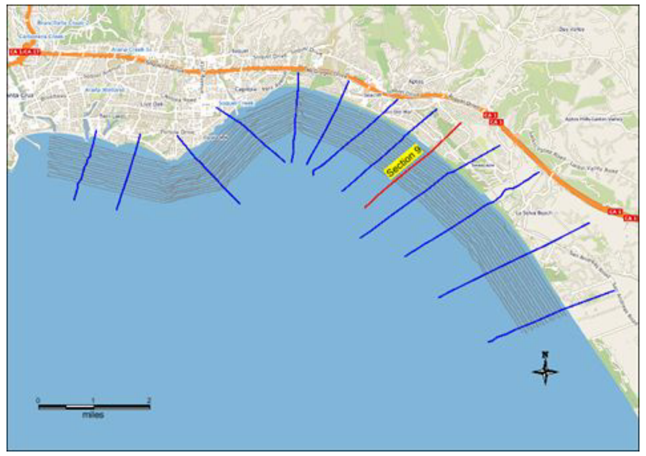
Model sections and hydrostratigraphic units

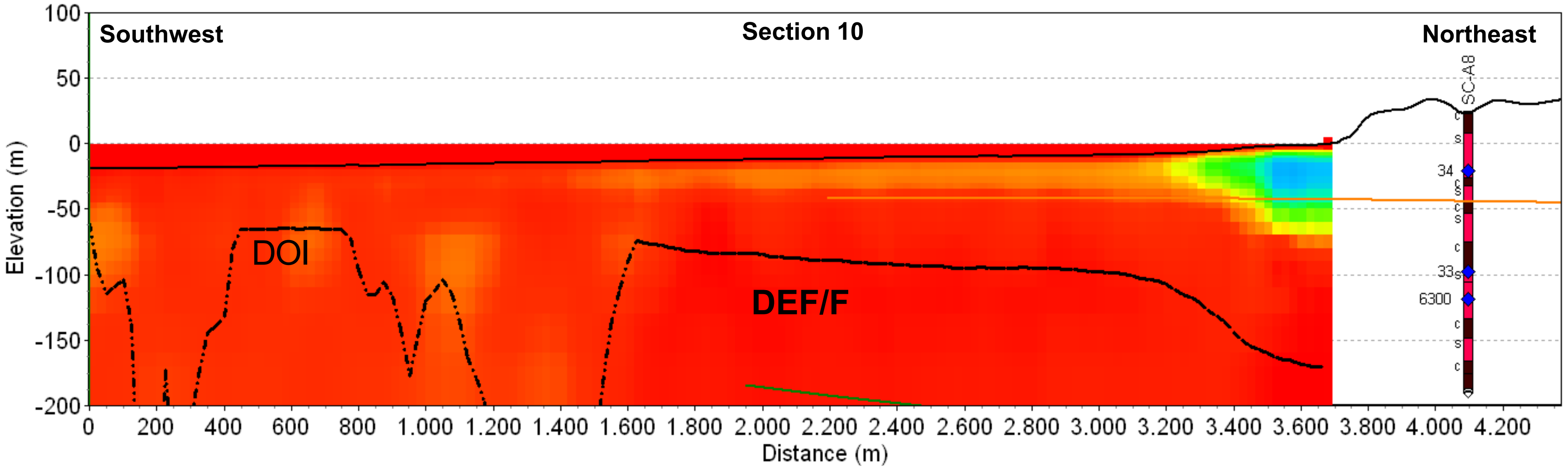
Soquel creek

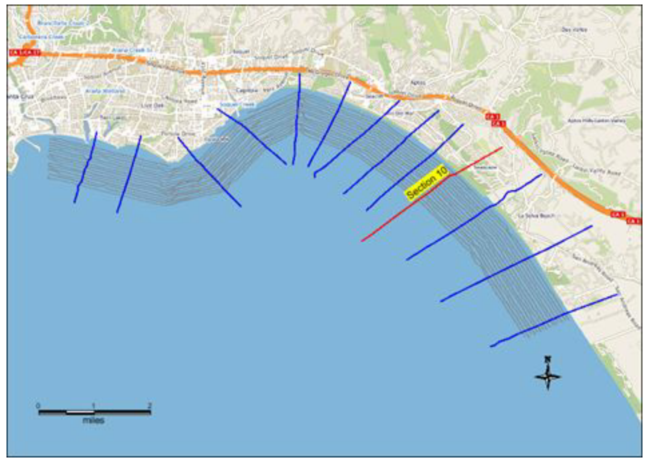
RAMBOLL

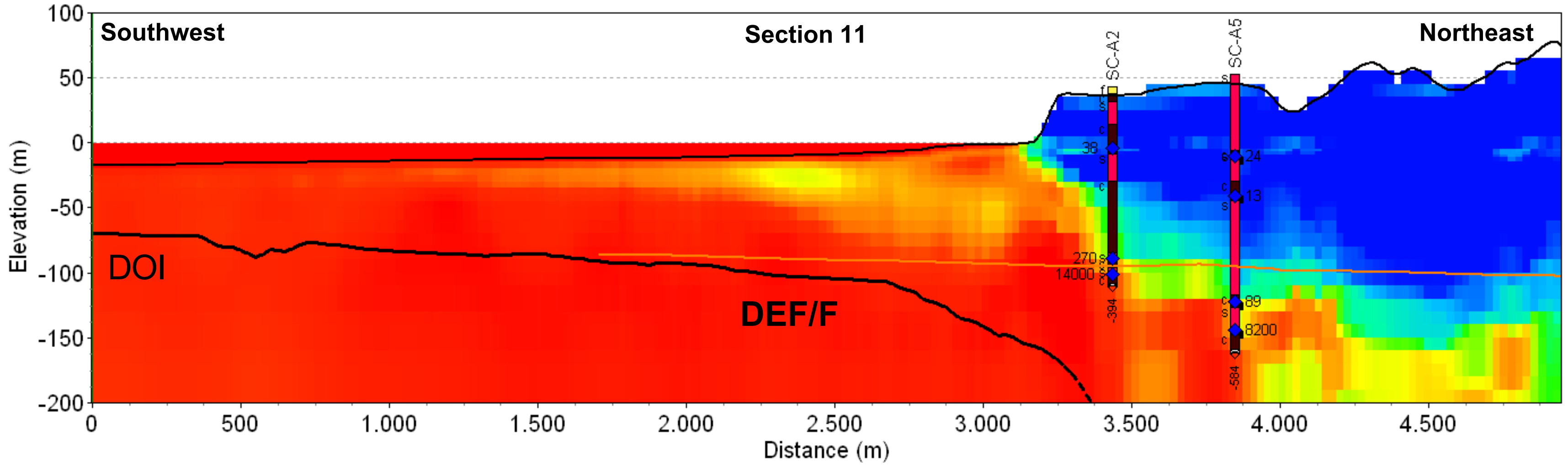
Olof Palmes Allé 22
8200 Aarhus N

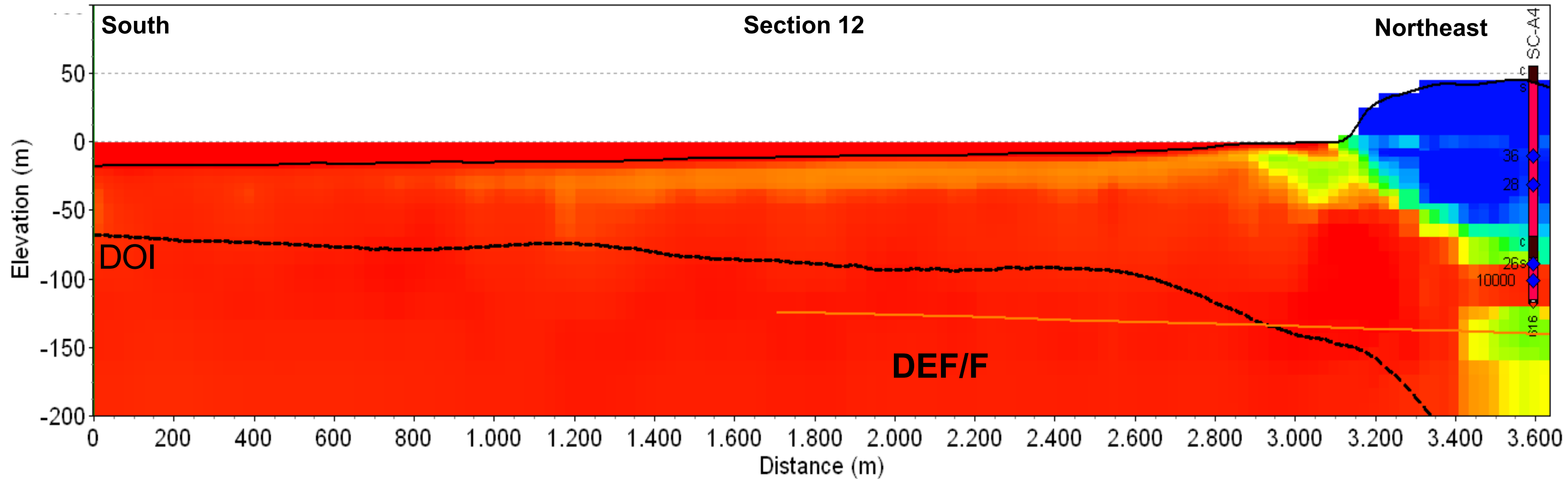


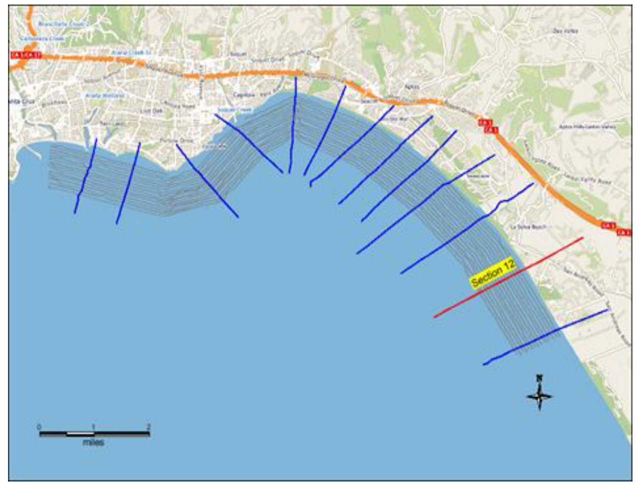


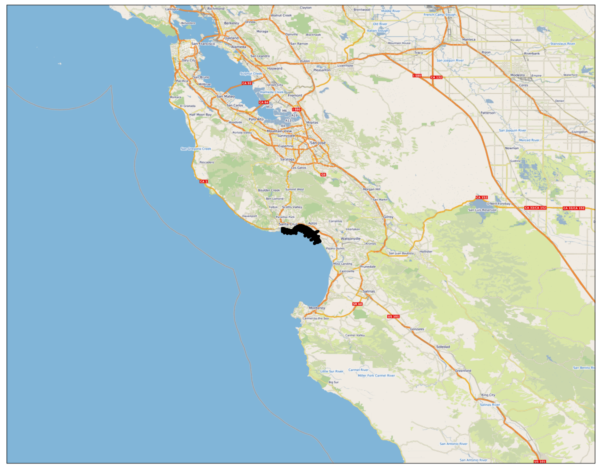


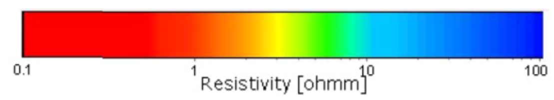












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Date: 2017-10-10
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Project: 1100028721

Annex 2.03

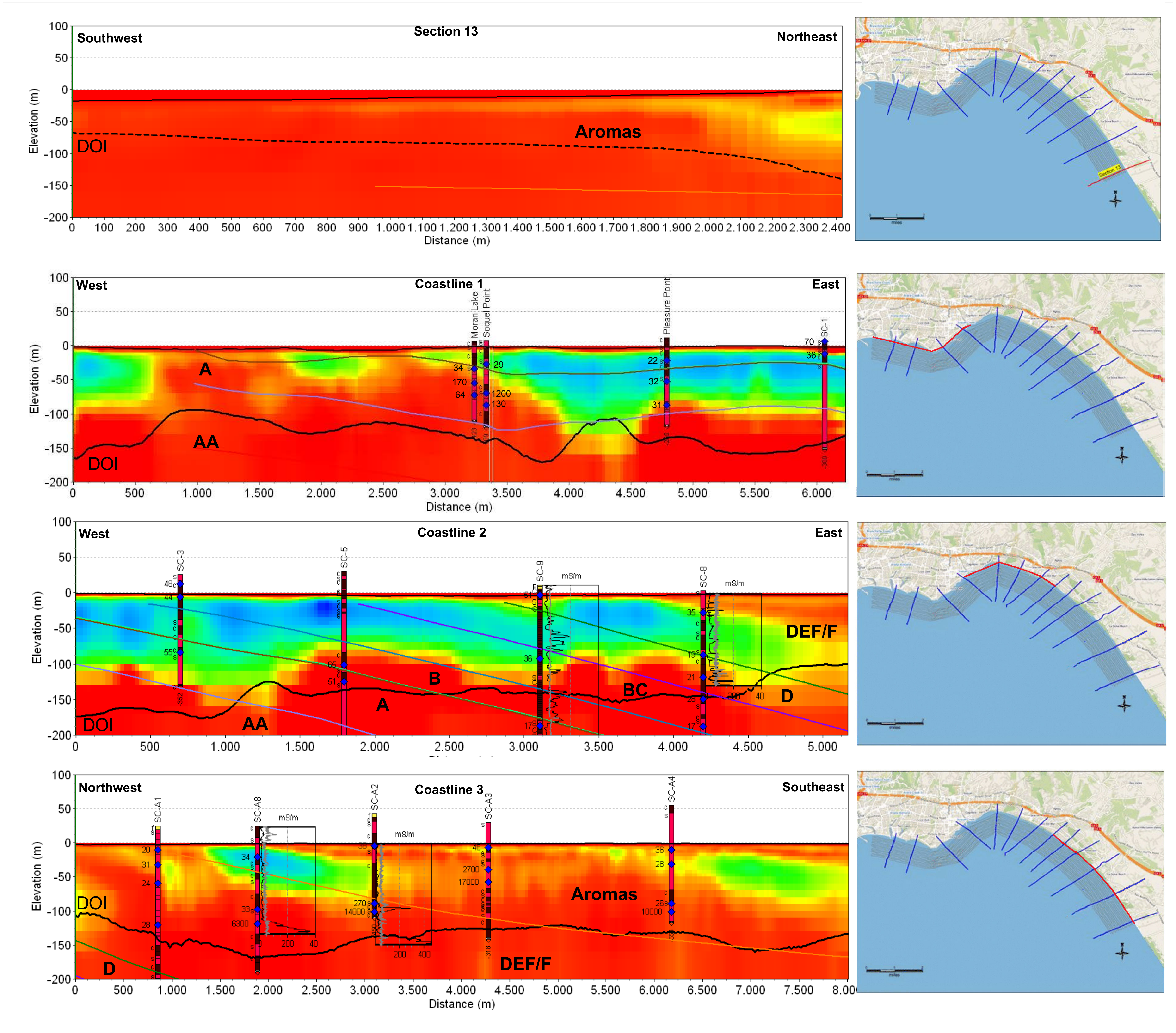
Model sections and hydrostratigraphic units

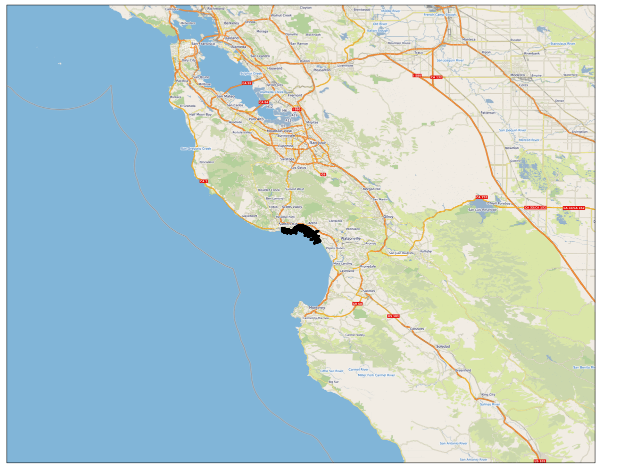
Soquel creek

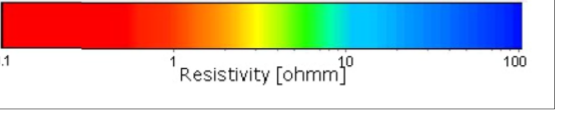
RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N

Santa Cruz Mid-County Groundwater Agency







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Date: 2017-10-10
By: PRT
QC: MAXH
Project: 1100028721

Annex 2.04

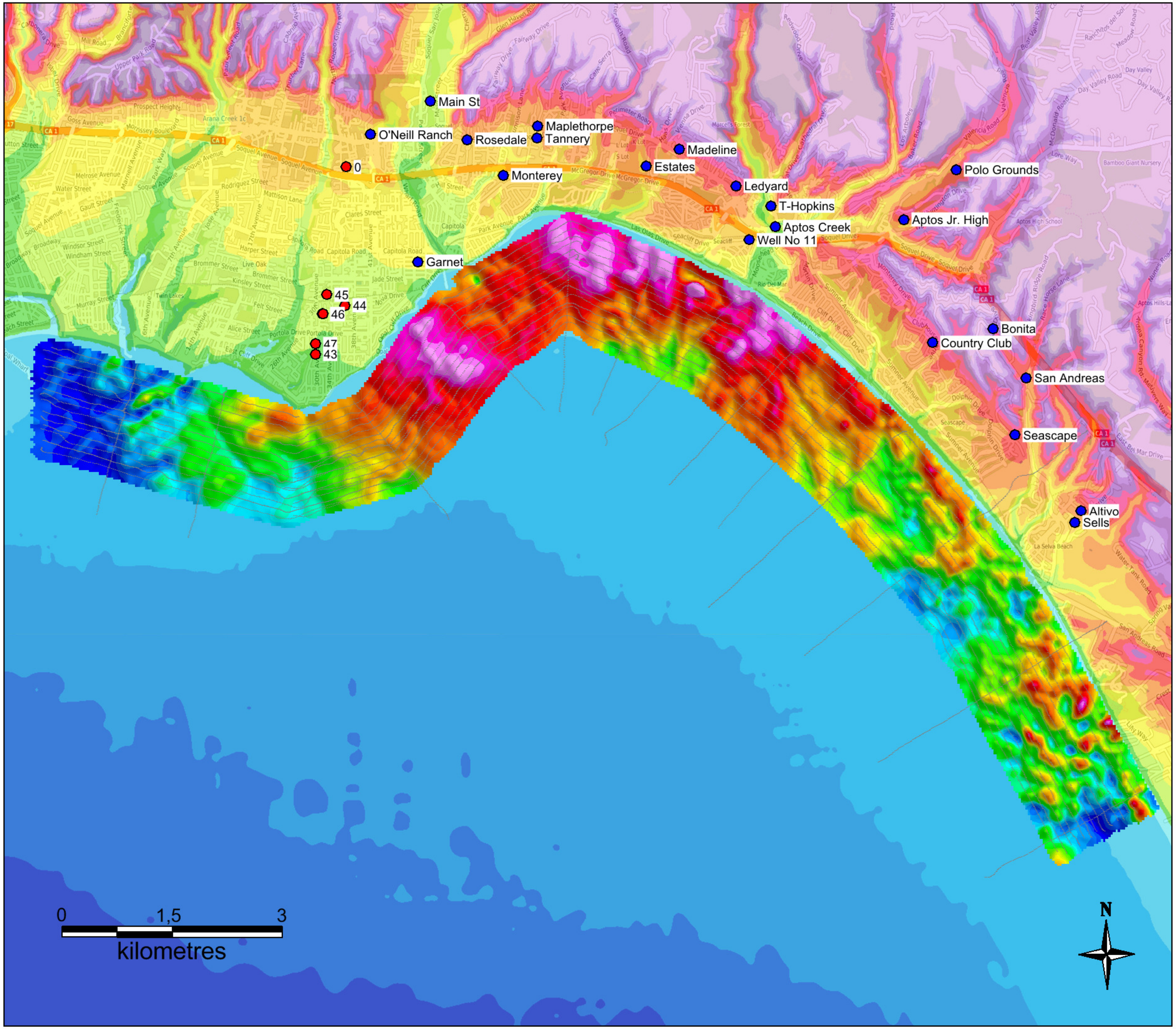
Model sections and hydrostratigraphic units

Soquel creek

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N

APPENDIX 3
MAGNETIC DATA



Santa Cruz Mid-County
Groundwater Agency

Legend

- Santa Cruz Production wells
- Soquel Creek Water District Production wells

Transparent

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110

Elevation [masl]

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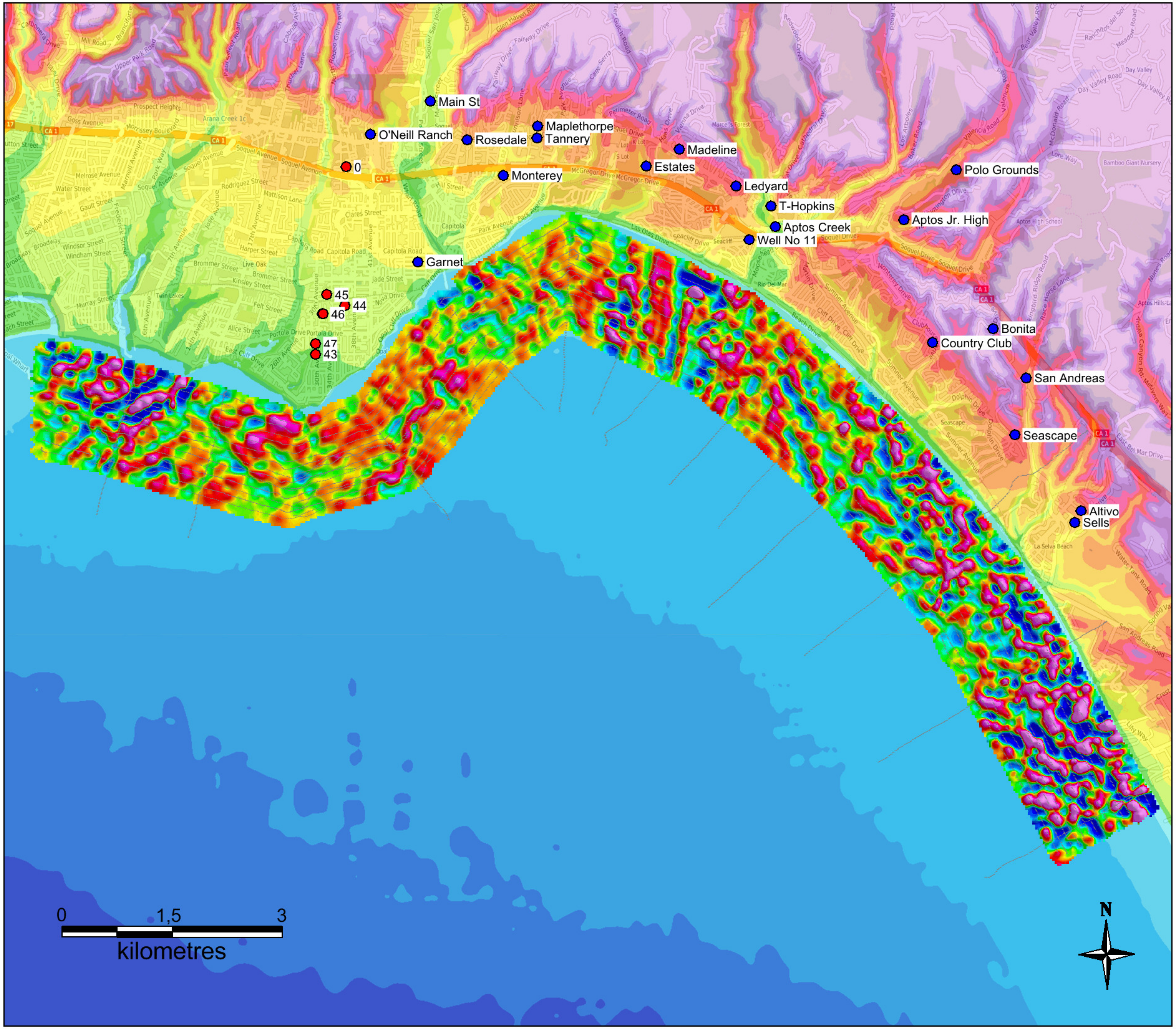
Date: 2017-10-10
By: PRT
QC: MAXH
Project: 1100028721

Annex 3.02

Mag - Reduction to pole

Soquel creek

Olof Palmes Allé 22
8200 Aarhus N



Santa Cruz Mid-County
Groundwater Agency

Legend

- Santa Cruz Production wells
- Soquel Creek Water District Production wells

Transparent

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110

Elevation [masl]

Rev.: 01
Date: 2017-10-10
By: PRT
QC: MAXH
Project: 1100028721

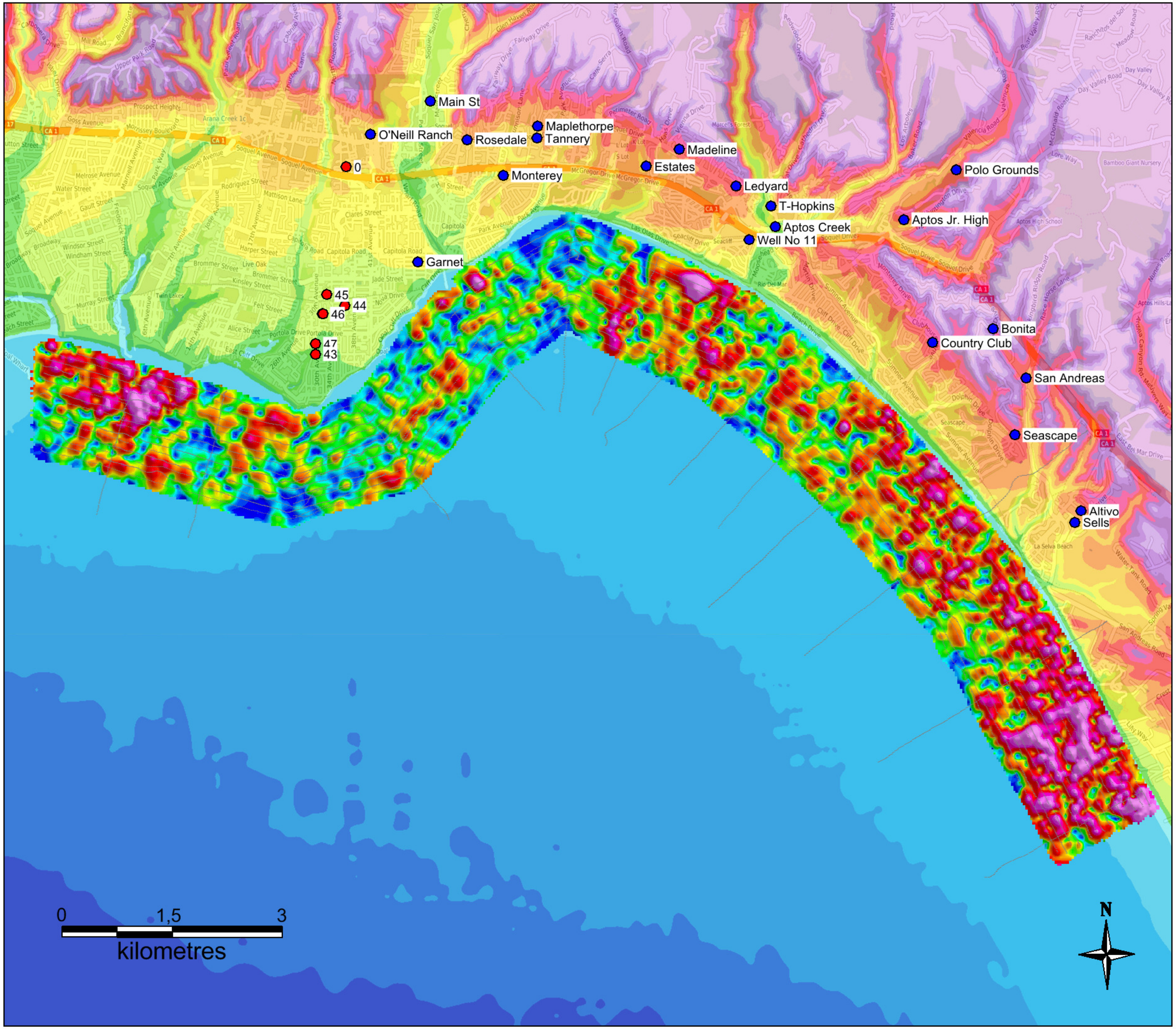
Annex 3.01

Mag - 1st Vertical Derivative

Soquel creek

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N



Santa Cruz Mid-County
Groundwater Agency

Legend

- Santa Cruz Production wells
- Soquel Creek Water District Production wells

Transparent

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110

Elevation [masl]

Rev.: 01
Date: 2017-10-10
By: PRT
QC: MAXH
Project: 1100028721

Annex 3.03

Mag - Analytical Signal

Soquel creek

RAMBOLL

Olof Palmes Allé 22
8200 Aarhus N

HydroMetrics WRI
1814 Franklin St, Suite 501
Oakland, CA 94612

TECHNICAL MEMORANDUM

To: Ron Duncan
For Santa Cruz Mid-County Groundwater Agency Executive Staff

From: Cameron Tana

Date: March 8, 2018

Subject: Management Implications of SkyTEM Seawater Intrusion Results

---

This memorandum describes the groundwater management implications of Ramboll's SkyTEM seawater intrusion results. The SkyTEM data provide new information regarding the location of seawater intrusion in the groundwater aquifers offshore. We are not experts in interpreting geophysical data but Ramboll's description of its analysis is reasonable and we accept the interpretation of the geophysical data as presented in the February 2018 report *Hydrogeological Investigation Salt-Fresh Water Interface – Monterey*. There are a few aspects of the results that guide our understanding of groundwater management implications:

1. Areas that Ramboll confidently identifies as brackish groundwater should be considered along with areas identified as full strength seawater.
2. Ramboll identifies salty water just offshore in aquifer units where low salt concentrations measured in coastal monitoring wells indicate freshwater onshore.
3. Ramboll identifies salty water just offshore in areas of aquifer units where high salt concentrations measured in coastal monitoring wells confirming seawater intrusion occurring in those areas.
4. In one portion along the coast, Ramboll identifies salty water offshore in aquifer units below aquifer units that are pumped in those coastal areas, which still allows the pumped aquifer units to be protected from seawater intrusion.
5. Along most of the coast, Ramboll identifies salty water offshore in aquifer units where those aquifer units are pumped including areas where coastal groundwater levels remain below protective elevations.

1. Identifying Brackish Groundwater

Brackish groundwater will result in undesirable groundwater quality of the water supply. For example, the drinking water standard for chloride is 250 milligrams per liter (mg/L) while full strength seawater is 19,000 mg/L so there is a large range of chloride concentrations that are considered brackish. According to Ramboll's Figure 8, resistivities just above 1 ohm identified with orange and yellow colors are identified as brackish. Resistivities just below 10 ohms identified with a green color may be brackish but may also represent finer-grained sediments. Ramboll's Figure 19 shows a flight line inland that passes monitoring wells where measured chloride concentrations below the drinking water standard occur at depths identified with resistivities represented as green. Therefore, we focus on the red, orange, and yellow colors on Ramboll's figures to identify salty water of undesirable quality for water supply.

We do not focus on the identification of areas of freshwater offshore as shown in Ramboll's Figure 11 and Figure 17. This freshwater occurs in aquifer units shallower than what is pumped in those units. Some freshwater outflow is likely necessary in shallow units to prevent deeper seawater intrusion.

2. Salty Water Offshore of Coastal Monitoring Wells with Low Salt Concentrations

Ramboll identifies salty water in the flight line closest to the coastline in aquifer units where low salt concentrations below the drinking water standard measured in coastal monitoring wells indicate groundwater is fresh. Ramboll's Figure 20 shows the shallowest aquifer unit where SkyTEM data indicate salty water in the flight line closest to the coastline as well as the inland flight lines. Figure 1 overlays this identification of the shallowest aquifer unit with salty water just offshore on a map of measured chloride concentrations in wells screened in the deepest aquifer unit pumped in the area of the wells. Figure 1 does include a revision of the identification of the Purisima A unit as the shallowest aquifer with salty water near Soquel Point to be consistent with Ramboll's results shown for Coastline 1 on Ramboll's Annex 2.04.

Coastal monitoring wells SC-5, SC-9, SC-8, and SC-A1 have low chloride concentrations in the aquifer units where SkyTEM data show salty water just offshore. At SC-9 and SC-8, deeper aquifer units also have measured low chloride concentrations. The distances of 150-300 meters between the first flight line offshore and the coastal monitoring wells are a plausible reason for these differences. Salty water is as close to these coastal monitoring wells as SkyTEM can detect.

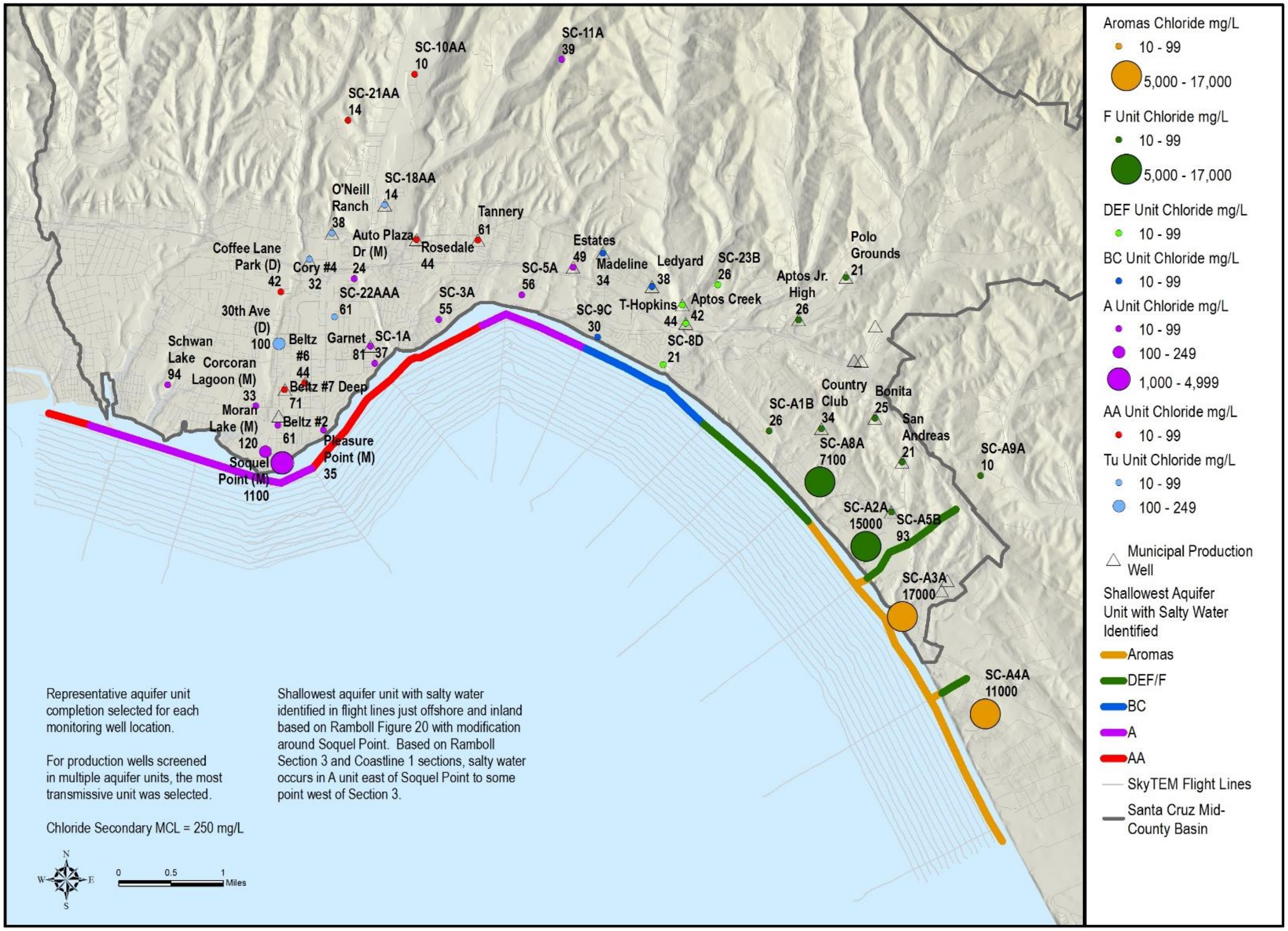


Figure 1. Water Year 2016 Chloride Concentrations in Onshore Wells and Shallowest Aquifer Unit with Salty Water Just Offshore

3. Salty Water Offshore of Coastal Monitoring Wells with High Salt Concentrations

SkyTEM data show areas with previously measured high salt concentrations above the drinking water standard in wells onshore have salty water offshore. These include the Moran Lake and Soquel Point wells in the western area of the Purisima A unit and the Aromas area where the Purisima F unit and Aromas Red Sands Formation is pumped. This provides strong evidence supporting the prior assumption that salty water measured onshore is a result of seawater intrusion.

SkyTEM data confirm salty water in the Purisima A aquifer unit just offshore of the Moran Lake and Soquel Point wells where high concentrations have been detected in the Medium completions of those wells in the Purisima A unit. However, the data do not explain why high concentrations have only been detected in the Medium completions of those wells and not the Deep completions. The City of Santa Cruz's protective elevations are set to prevent seawater intrusion in the Medium completions in the Purisima A unit[1] that is the primary pumped aquifer in the area, but SkyTEM data reveal there is also salty water offshore in the Purisima AA unit at the depths of the Deep completions. It appears that A unit pumping has previously pulled in salty water from offshore in the A unit only.

The Aromas area where the Purisima F unit and Aromas Red Sands Formation also has onshore seawater intrusion as indicated by high salt concentrations measured in monitoring wells such as SC-A8, SC-A2, SC-A3, and SC-A4 along the coast. The information about the depths where salty water occurs offshore will allow for estimates about how the interface extends from the coast onshore even where inland flight lines do not exist. Soquel Creek Water District established its protective groundwater elevations for these coastal monitoring wells[2] to prevent the interface from moving farther inland and these data better define the current interface.

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[1] The City of Santa Cruz established protective elevations for its coastal monitoring wells Moran Lake, Soquel Point, and Pleasure Point based on the Ghyben-Herzberg calculation to prevent seawater intrusion at the Medium completions screened in the Purisima A unit. Protective elevations are quantified relative to mean sea level and would also be relative to rising sea levels.

[2] The District established protective elevations for its coastal monitoring wells SC-A1B, SC-A8A, SC-A2A, SC-A3A, and SC-A4A to prevent further advancement of seawater intrusion observed onshore in the Purisima F unit and Aromas Red Sands Formation. The District's protective elevations were set at a 70% probability of preventing seawater intrusion (less than 30% risk level) but the model results are also used.

4. Salty Water in Aquifer Units Below Pumped Aquifer Units is Allowable for Protecting Groundwater Supply

Ramboll's Figure 20 shows an area where the shallowest aquifer unit with salty water just offshore is the Purisima AA unit. Pumping in this area has mostly occurred from the Purisima A unit above the AA unit. Therefore, the City of Santa Cruz[1] and Soquel Creek Water District[3] have established protective elevations for the Pleasure Point, SC-1, and SC-3 coastal monitoring wells to protect the Purisima A unit. By establishing protective elevations for the Purisima A unit, it is implied that salty water occurring underneath the Purisima A unit is acceptable. Therefore, salty water identified in the Purisima AA unit just offshore would be considered an acceptable condition at the coastal monitoring wells onshore.

Groundwater levels at the Pleasure Point, SC-1, and SC-3 coastal monitoring wells have been above established protective elevations for at least two years. If these groundwater levels are maintained over the long-term, the Purisima A unit should continue to be protected from seawater intrusion as observed both onshore and out to over 200 meters offshore according to the flight line from SC-1 (Section 4 on Ramboll Annex 2.01) where brackish water is detected near the bottom of the A unit. Figure 2 shows the risk levels of eventual seawater intrusion for protected aquifers based on Water Year 2017 groundwater level averages with smaller circles representing lower risk of seawater intrusion. The reduced risk of seawater intrusion in this area is a result of an increasing groundwater level trend over multiple years related to reduced pumping in the area.

Figure 2 also shows the deepest aquifer units pumped. Although most of the pumping in this area is from the Purisima A unit, there is some pumping from the deeper Purisima AA unit and Tu unit. Sustainability management criteria to prevent seawater intrusion in these deeper units should be considered for the Groundwater Sustainability Plan.

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to assess prevention probabilities or risk levels based on measured groundwater levels. Protective elevations are quantified relative to mean sea level and would also be relative to rising sea levels.

[3] Soquel Creek Water District established protective elevations for its coastal monitoring wells SC-1A, SC-3A, SC-5A, SC-9C, and SC-8D based on cross-sectional models to protect Purisima A, BC, and DEF units at the coastline in the areas those units are pumped. The District's protective elevations were set at a 70% probability of preventing seawater intrusion (less than 30% risk level) but the model results are also used to assess prevention probabilities or risk levels based on measured groundwater levels. Protective elevations are quantified relative to mean sea level and would also be relative to rising sea levels.

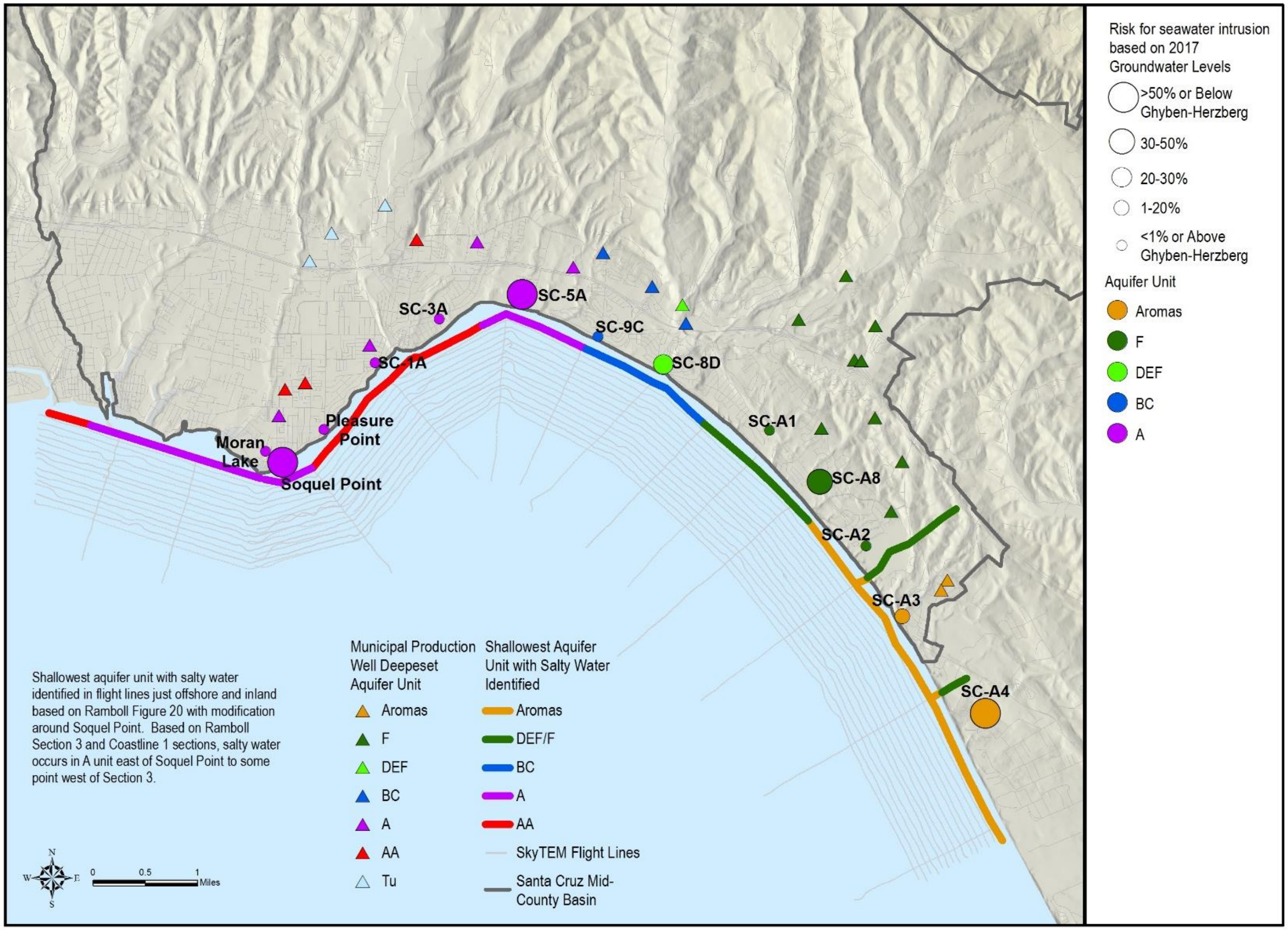

Figure 2: Pumped Aquifer Units, Risk for Seawater Intrusion Based on Water Year 2017 Groundwater Levels and Shallowest Aquifer Unit with Salty Water Just Offshore

5. Salty Water Offshore Occurs in Pumped Aquifer Units where Coastal Groundwater Levels Remain Below Protective Elevations

Figure 2 show that salty water occurs in pumped aquifer units just offshore of much of the coast. As a result of reduced pumping in the Basin, groundwater levels have risen in recent years and reduced the risk of seawater intrusion coming onshore or advancing farther onshore. However, in each the aquifer units where salty water occurs just offshore, at least one coastal monitoring well continues to have groundwater levels below protective elevations[3] established for preventing seawater intrusion onshore or farther onshore in pumped aquifer units.

- Groundwater levels at the Soquel Point Medium well are below protective elevations where salty water is identified just offshore in the Purisima A unit in addition to previously measured salty water in the well.
- Groundwater levels at the SC-5A well are below protective elevations where salty water is identified just offshore in the Purisima A unit.
- Groundwater levels at the SC-9C well had been below protective elevations until Water Year 2017 where salty water is identified just offshore in the Purisima BC unit.
- Groundwater levels at the SC-A8A well are below protective elevations where salty water is identified just offshore in the Purisima DEF/F units in addition to previously observed onshore seawater intrusion in the Purisima F unit.
- Groundwater levels at the SC-A4A well are below protective elevations where salty water is identified just offshore in the Aromas Red Sands Formation in addition to previously observed onshore seawater intrusion in the Aromas Red Sands. However, this area is outside of the Santa Cruz Mid-County Basin.

In general, groundwater levels at the coastal monitoring wells were the highest they have been since most of the wells were installed around 1984. As a result, the above wells represent the fewest number with groundwater levels below protective elevations. Lowering groundwater levels to levels from just a few years ago would increase risk of seawater intrusion along more of the coast. Also, what is considered protective may change as the Mid-County Groundwater Agency may develop sustainability management criteria for seawater intrusion that have a different level of acceptable risk or change which aquifer units should be protected from what City of Santa Cruz and Soquel Creek Water District used to establish protective elevations.

6. Groundwater Management Implications and Uses

The main new information provided by the SkyTEM data is identification of salty water just offshore in pumped Purisima Formation aquifer units where high salt concentrations have not been measured onshore. Although the data do not show how fast the saltwater interface is moving, the close proximity of the interface emphasizes the need to develop and implement a Groundwater Sustainability Plan that will recover groundwater levels to elevations and maintains those levels over the long-term that prevent seawater intrusion from coming onshore. The close proximity of the interface also provides a reason to set a goal to recover the groundwater levels sooner than the 2040 deadline to achieve sustainability required by the Sustainable Groundwater Management Act.

It is also planned that information about interface location throughout the Basin will be used to establish an initial condition in the seawater interface package to be used with the Basin groundwater model to evaluate what happens with the interface under different groundwater management alternatives that are simulated.