



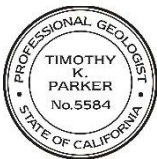
THE CALIFORNIA DEPARTMENT OF WATER RESOURCES' STATEWIDE AIRBORNE ELECTROMAGNETIC SURVEY PROJECT

DATA REPORT FOR SURVEY AREA 1 SALINAS VALLEY GROUNDWATER BASIN



**CALIFORNIA AIRBORNE ELECTROMAGNETIC SURVEYS
SALINAS VALLEY GROUNDWATER BASIN**

Project name California Airborne Electromagnetic Surveys for the Salinas Valley Groundwater Basin
Project no. 1690021880 – Work Order No. 1
Recipient California Department of Water Resources – Sustainable Groundwater Management Office
Document type Report
Version Final
Date May 27, 2022
Prepared by Ahmad-Ali Behroozmand, Chris Petersen, David Fairman, Ian Gottschalk, Julián Consoli, Kaylee Glenney, Max Halkjaer, Paul Thorn, Peter Thomsen
Checked by Timothy K. Parker
Approved by Timothy K. Parker, Max Halkjær
Description This is a data report describing the acquisition, processing, inversion and lithology transform for the AEM survey conducted in the Salinas Valley Basin. In addition, the report provides a description of the well data collected along the planned flight lines and the projects data management system.





Timothy K. Parker, PG

May 27, 2022
Date

TABLE OF CONTENTS

0.	Executive Summary	0-1
1.	Introduction	1
1.1	Overview of the California State-wide AEM Survey	1
1.2	Salinas Valley Groundwater Basin AEM Survey	6
1.3	Basin Geology	6
1.4	Report Contents and Appendices	7
2.	Hydrogeologic data acquisition and compilation	9
2.1	Well Lithology Logs	9
2.2	Well Resistivity Logs	10
2.3	Groundwater Occurrence	12
2.4	Total Dissolved Solids in Groundwater	13
3.	Airborne Electromagnetics Survey	15
3.1	Basin AEM Survey Methodology, Objectives and Flight Line Planning	15
3.2	Basin AEM Survey	20
4.	AEM Data Processing, Inversion, and Results	25
4.1	AEM Data Processing and Inversion	25
4.2	Selected Results	28
5.	Lithology Model	39
5.1	Introduction	39
5.2	Resistivity-to-Lithology Transform Methodology	40
5.3	Transform Results	42
5.4	Specific Cases	45
6.	Initial Hydrostratigraphic Model	48
6.1	Introduction	48
6.2	Methodology	48
6.3	Clustering Algorithm Implementation	50
6.4	Results	51
6.5	Perspectives on the Initial Hydrostratigraphic Model	53
7.	References	54

LIST OF APPENDICES

Appendix 1	Well Digitization and Data Management System
Appendix 2	Airborne Electromagnetic Survey Data
Appendix 3	AEM Processing and Inversion
Appendix 4	AEM Lithological Modeling
Appendix 5	Preliminary Hydrostratigraphic Model
Appendix 6	Profile atlas containing the smooth resistivity model and magnetic intensity
Appendix 7	Profile atlas containing the sharp inversion models and uncertainty
Appendix 8	Profile atlas showing the lithology model and lithology model uncertainty
Appendix 9	Profile atlas showing the initial hydrostratigraphic model results

Appendix 10	Resistivity maps for specific elevation intervals and as depth intervals
Appendix 11	Description of the deliverables.

LIST OF FIGURES

Figure 0-1 SGMA high and medium priority basins in California	0-1
Figure 0-2 Helicopter towing the hexagonal SkyTEM system	0-2
Figure 0-3 Outline of the Salinas Valley Groundwater Basin	0-3
Figure 0-4 Vertical resistivity section series from a AEM flight line	0-5
Figure 1-1 Map of California showing the SGMA medium- and high-priority basins	3
Figure 1-2 Map showing the flight lines flown	7
Figure 2-1 The location of wells and geophysical logs	11
Figure 2-2 A map showing the depths to groundwater in the basin	12
Figure 2-3 Map showing the groundwater quality, TDS and Conductivity	14
Figure 3-1 Figure showing the Airborne Electromagnetic Survey Schematic including the transmitter loop	16
Figure 3-2 An example of a single sounding of acquired AEM data	17
Figure 3-3 A map showing the planned flight lines (dark blue), the landing zones (light blue circle) and the surrounding land use	19
Figure 3-4 AEM Equipment and instrumentation configuration	21
Figure 3-5 Map showing the planned and flown flight lines	22
Figure 3-6 Photos of the AEM flights in the Salinas Valley Area	23
Figure 4-1 Resistivity along Section 103500	30
Figure 4-2 Resistivity along Section 103600	31
Figure 4-3 Resistivity along Section 100400	32
Figure 4-4 Resistivity along Section 101800	33
Figure 4-5 Example of illustration of the model uncertainties	34
Figure 4-5 Mean resistivity plan-view map in the depth interval 15-30 m	36
Figure 4-6 Mean resistivity plan-view map in the elevation interval 360-380 m	37
Figure 4-7 Mean resistivity plan-view map in the elevation interval -20 m to 0 m	38
Figure 5-1 Typical relationship between resistivity, lithology, and salinity	40
Figure 5-2 An example of a single fraction translator function	42
Figure 5-3 Lithology model along Section 102500	44
Figure 5-4 Schematic demonstrating the resistivity-to-lithology transform	46
Figure 6-1 The results of the clustering algorithm.	50
Figure 6-2 Initial hydrostratigraphic model	52

LIST OF ABBREVIATIONS AND ACRONYMS

ACT	Accumulated Clay Thickness
AEM	Airborne Electromagnetic
CF	Clay Fraction
DMS	Data Management System
DOI	Depth of Investigation
DWR	Department of Water Resources
EC	Electrical Conductivity
EM	Electromagnetics
GAMA	Groundwater Ambient Monitoring and Assessment
GIS	Geographic Information System
GPS	Global Positioning System
GSP	Groundwater Sustainability Plan
Km	Kilometer
L	Liter
M	Meter
mg	Milligrams
OSWCR	Online System for Well Completion Reports
PLSS	Public Land Survey System
QA	Quality Assurance
QC	Quality Control
SGMA	Sustainable Groundwater Management Act
SR	State Route
SWRCB	State Water Resources Control Board
TDS	Total Dissolved Solids
TEM	Time-domain (or Transient) Electromagnetics
USCS	Unified Soils Classification System

ACKNOWLEDGEMENTS

DWR would like to acknowledge the AEM Survey project partners including the Salinas Valley Basin Groundwater Sustainability Agency (GSA), Monterey County, Marina Coast Water District, County of San Luis Obispo, City of Paso Robles GSA, Shandon-San Juan Water District GSA, San Miguel CSD GSA, California Geologic Survey, California Department of Fish and Wildlife, California Department of Food and Agriculture, California State Water Resources Control Board, and United States Geologic Survey. This project was funded through the California Drought, Water, Parks, Climate, Coastal Protection and Outdoor for all Fund (Senate Bill 5, Proposition 68).

PROJECT TEAM

The project team for the AEM Survey covering the Salinas Valley Groundwater Basin includes:

Ramboll – responsible for coordination of the contractors, onsite geophysicist during data acquisition, data processing and inversion, lithology model, initial hydrostratigraphic model, reporting and quality control of deliverables.

GEI – collected and compiled well data into the data management system and assisted in report preparation.

SkyTEM – coordinated the AEM surveys field operation, providing the AEM equipment and leading the field work.

Sinton Helicopters – provide helicopter, pilots, AEM instrumentation and flew the AEM survey.

AECOM – assisted DWR with outreach to the local GSA's and authorities, plan the location of the flight lines, assisting with the initial collection of well data from the GSA's.

Eclogite – digitized well lithology and geophysical logs.

Regional Aquifer Services – provided additional geophysical logs in digital format.

Aarhus University, Denmark – assisted with the lithology model and the initial hydrostratigraphic model.

AEM Data Report and Use Disclaimer

This Data Report was prepared by the Project Team for the California Department of Water Resources (DWR). DWR makes no warranties, representations or guarantees, either expressed or implied, as to the accuracy, completeness, correctness, or timeliness of the information provided in this report or related datasets that are accessible through the California Open Data Portal, nor accepts or assumes any liability arising from use of the AEM data or reports. Neither the Department nor any of the sources of the information utilized by the contractor to develop the report and datasets shall be responsible for any errors or omissions, or for the use or results obtained from the use of this information. Classifications and boundaries shown in this report are graphical representations only, and do not establish legal rights or define legal boundaries. A Groundwater Sustainability Agency is not required to use the AEM report and underlying data, and their use does not guarantee the adequacy of a Groundwater Sustainability Plan that relies on such data.

0. EXECUTIVE SUMMARY

Regional airborne geophysical surveys are being conducted by the California Department of Water Resources (DWR) and its contractors in all of the state's high- and medium-priority groundwater basins to collect data on the geometry and geologic properties of the underlying aquifer systems that provide groundwater to local communities (Figure 0-1). The focus of this report is the Salinas Valley Groundwater Basin geophysical survey (Figure 0-1). The regional geophysical surveys, which use the airborne electromagnetics (AEM) technique, have been compared to an MRI to see beneath the ground surface. The AEM data and products from the surveys are being provided to assist local water managers and the state as they implement the Sustainable Groundwater Management Act (SGMA) to manage groundwater for long term sustainability. The AEM surveys are funded by voter-approved Proposition 68, and all the data from the surveys are being made publicly available online.



Figure 0-1 SGMA high and medium priority basins in California. The Salinas Valley Groundwater Basin is marked in red.

The AEM survey technique utilizes a helicopter flying approximately 80 kilometers per hour (50 miles per hour), with the geophysical equipment suspended below, mounted on a large hexagonal frame about 30 meters (100 feet) above the ground surface (Figure 0-2). The AEM equipment sends a pulsating weak electromagnetic signal into the ground and measures the response, which provides an electrical resistivity profile of the earth's geological layers and structures down to depths of as much as 300 meters (1,000 feet). Aquifer systems consist of (1) aquifers typically composed of sands and gravels that have high resistivities, and (2) aquitards composed of silt and clays that have low resistivities, so the resistivity profiles help in mapping the overall aquifer systems dimensions and extent. The AEM survey data are analyzed in detail, correlated with data from nearby wells, and modeled to produce subsurface maps of the resistivity, lithology, and an initial hydrostratigraphic model.



Figure 0-2 Helicopter towing the hexagonal SkyTEM system while collecting AEM data during the survey.

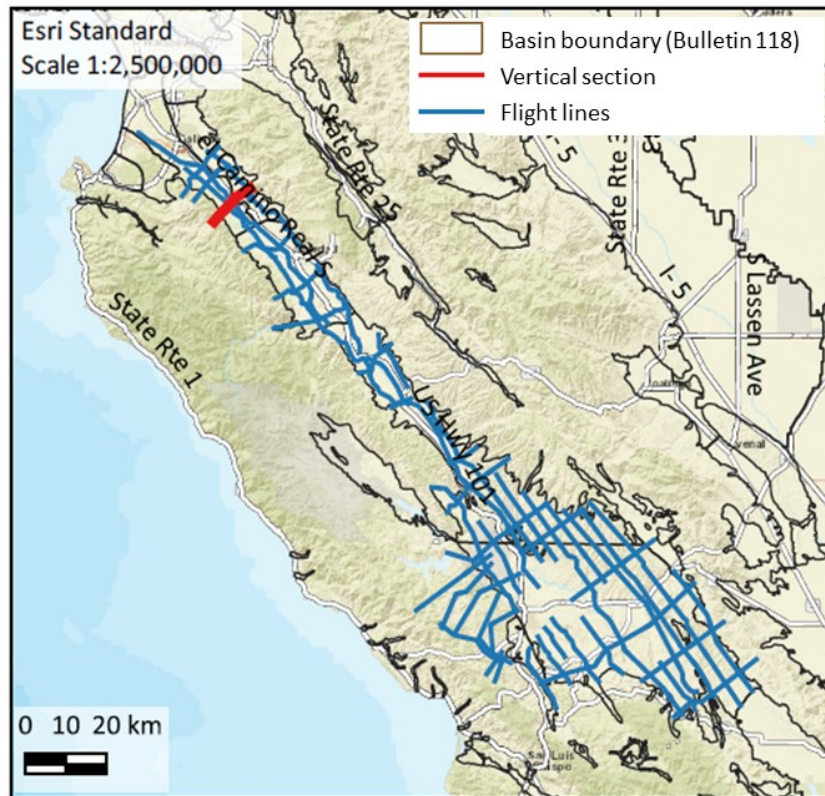


Figure 0-3 Outline of the Salinas Valley Groundwater Basin and the flight lines showing where the AEM survey was flown. The red line shows the location of the vertical profile shown in Figure 0-3.

Salinas Valley Groundwater Basin AEM Survey

The Salinas Valley Groundwater Basin survey was conducted in August 2021, totaling 1,274 linear kilometers (796 miles). Prior to the survey, public outreach was conducted, providing information on the survey to local residents, media and law enforcement agencies. Both during and after AEM data acquisition, measures were taken to ensure acceptable data quality. This included daily AEM system tests, evaluation of the unprocessed AEM data, and conducting repeat AEM lines to ensure the reproducibility of the collected data.

Well lithology and oil and gas geophysical logs located along the AEM flight lines were compiled to provide additional data to support and ground-truth the surveys, with the objective of obtaining two high quality lithology logs in each of the Public Land Survey System one-mile square sections that the flight lines cross. High quality lithology logs are defined as having a verified location accuracy of less than 50 meters (164 feet), wells that are at least 30 meters (98 feet) deep and have an average description interval of less than 30 meters (98 feet). In total, there were 1,031 high quality lithology

logs and 95 geophysical logs compiled. Groundwater levels and water quality data (as total dissolved solids [TDS]), both of which can affect the subsurface resistivity, were also compiled.

The AEM data was then processed to filter out potential noise in the data and, if necessary, remove the data where interference is too great to effectively filter. Potential sources for noise in the data includes electric power transmission lines, railroads, pipelines, and any significant metallic objects. Subsequent to AEM data processing, resistivity models were produced that in general, provide profiles indicative of coarse-grained (sands and gravels) and fine-grained (silts and clays), represented by higher and lower resistivities, respectively. Two types of models were produced: a smooth resistivity model, showing the gradual resistivity transition with depth, and sharp resistivity model, where subsurface boundaries are inferred from the AEM data. Figure 0-4 shows a vertical resistivity section with the smooth resistivity model (top section) and with the sharp model (second section).

The AEM modeled resistivity was then processed, combining the detailed high quality well lithologic data with information on the spatial heterogeneity from the resistivity to provide an interpretation of lithology. In the first step of the process, the well lithology data descriptions were aggregated into either (1) coarse or (2) fine material classifications. Then computer-based numerical calculations using an inversion algorithm were performed to iteratively compare the modeled resistivity with the simplified lithology from the lithology log data to produce a model of the coarse fraction thickness consistent with the lithology log coarse fraction thickness. The third section on Figure 0-4 shows the interpretation of the coarse fraction thickness along the AEM flight line.

The resistivity and coarse fraction data were combined to produce an initial hydrostratigraphic model for the basin, designating areas or layers of the subsurface having similar properties related to groundwater flow. This was done utilizing a clustering algorithm, where the relationship between resistivity and coarse fraction were divided into groups with similar properties. As resistivity and coarse fraction is inherently related to the earth's hydrogeological properties, each group of datapoints represents an individual hydrostratigraphic unit. The datapoints were then plotted on the profiles to produce an initial hydrostratigraphic model for the basin (Figure 0-4, bottom profile). For the Salinas Valley Groundwater Basin, the initial model contained 5 separate groups based on the resistivity and coarse fraction along the flight line.

The resistivity, lithology profiles and initial hydrostratigraphic model will be useful for local groundwater management agencies to help refine hydrogeologic conceptual models and groundwater flow models, and may also assist in the identification of recharge areas and interconnected surface water.

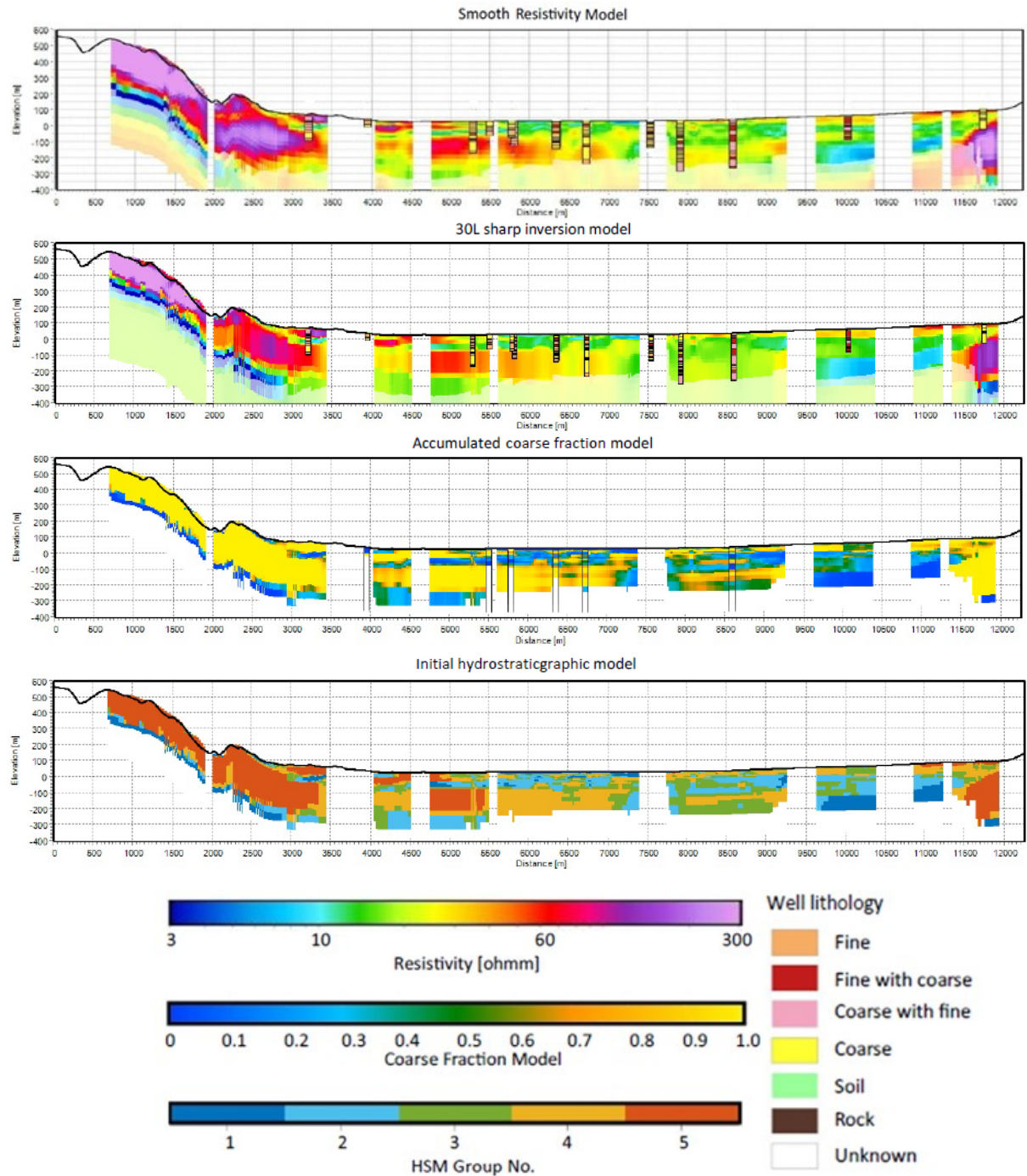


Figure 0-4 Vertical resistivity section series from a AEM flight line in the Salinas Valley Groundwater Basin. The top section shows the smooth resistivity model, the second section shows the 30-layer sharp resistivity model, the third section shows the accumulated coarse fraction model and the bottom section shows the initial hydrostratigraphic model. The location of the section is shown on Figure 0-3.

1. INTRODUCTION

The California Department of Water Resources (DWR) is currently conducting airborne electromagnetic (AEM) surveys in California's high- and medium-priority groundwater basins. The data from the surveys are collected in order to assist local water managers as they implement their respective GSPs to comply with the Sustainable Groundwater Management Act (SGMA) to sustainably manage groundwater.

An electromagnetic (EM) survey is a geophysical technique conducted from the land surface or the air that measures the electrical properties of the earth's subsurface materials. AEM is an airborne EM technique that includes a large hexagonal frame containing the geophysical equipment suspended by cable beneath a helicopter about 100 feet above the ground surface along a defined flight path. During the survey, the system sends a weak pulsating electromagnetic signal that penetrates up to around 300 meters (1,000 feet) into the earth. The returning signal pulse is picked up by receivers in the frame. The data collected provides a measurement of the electrical resistivity of the different geological strata, providing information on the distribution of coarse-grained and fined-grained materials in the subsurface as well as groundwater salinity.

This report presents information on the AEM survey conducted in the Salinas Valley Groundwater Basin including the 180/400 Foot Aquifer, East Side Aquifer, Forebay Aquifer, Upper Valley Aquifer and the Paso Robles Area groundwater subbasins. The Salinas Valley is located within the Central Coast Ranges, and the subbasins within are designated either high- or medium priority by the state (Figure 1-1). The report provides full documentation of the data collection, processing and analysis, including the methods used, results, uncertainty and quality control.

1.1 Overview of the California State-wide AEM Survey

The DWR has a long history of data collection, monitoring, and reporting to support characterizing California's groundwater basins. *California's Groundwater*, DWR Bulletin 118, Update 2020 (DWR 2020) is the State's official publication on the occurrence and nature of groundwater in California. The publication defines the groundwater basin boundaries and features current knowledge of groundwater resources including information on the location, characteristics, use, management status, and conditions for each of the State's 10 hydrologic regions. With the passage of SGMA in 2014, there is an increased need for local and state agencies and the public to better understand groundwater basin characteristics in order to make informed management decisions to achieve sustainability in the next two decades.

The objective of the Proposition 68 funded AEM survey program is to support the State's continued effort to improve groundwater basin characterization and to provide

groundwater sustainability agencies (GSAs) and interested parties with a regional and statewide dataset, which GSAs can utilize as one way to support the technical requirements of DWR's Groundwater Sustainability Plan (GSP) Regulations and SGMA. The data collection effort will provide essential information about subsurface hydrogeologic characteristics of groundwater basins that will reduce uncertainty and could improve the potential for successful implementation of GSPs and groundwater recharge projects. The focus of the AEM surveys is all of California's high- and medium-priority groundwater basins (Figure 1-1) where data collection is feasible, as these are the groundwater basins that are required to develop GSPs and achieve long-term sustainability within 20 years under SGMA.

1.1.1 DWR AEM Survey Flight Line Planning

DWR conducts the AEM survey flight line planning with input from local, state and federal agencies and then transmits the flight line plan to Ramboll for execution. The AEM survey flight lines are developed with the goal of collecting high-quality data that are beneficial to local, state, and federal agencies by supporting basin characterization and the implementation of SGMA. The steps to developing the survey flight lines are described below.

Step 1: An approximate 2-mile by 8-mile grid was first oriented to capture large-scale hydrogeologic features within the surveyed area, with input from DWR's Region Office staff. Large-scale hydrogeologic features that were considered included aquifer structures, geologic bedding and buried feature orientations, faults, and presence of brackish to saline groundwater.

Step 2: For a combination of safety considerations and potential for noise in the collected data, flight lines were modified to avoid, or minimize the interaction with, the following:

- Urban areas
- Structures containing people or confined livestock
- Oil and gas well fields
- Highways
- Transmission lines
- Railroads
- Pipelines
- Vineyards (most vines are supported by metal posts)

Step 3: Flight lines were modified to incorporate important areas identified by GSAs and state and federal agencies.

Step 4: The flight lines were finally modified to be co-located with existing high-quality lithology or geophysical data gathered from public databases or provided from the GSAs.

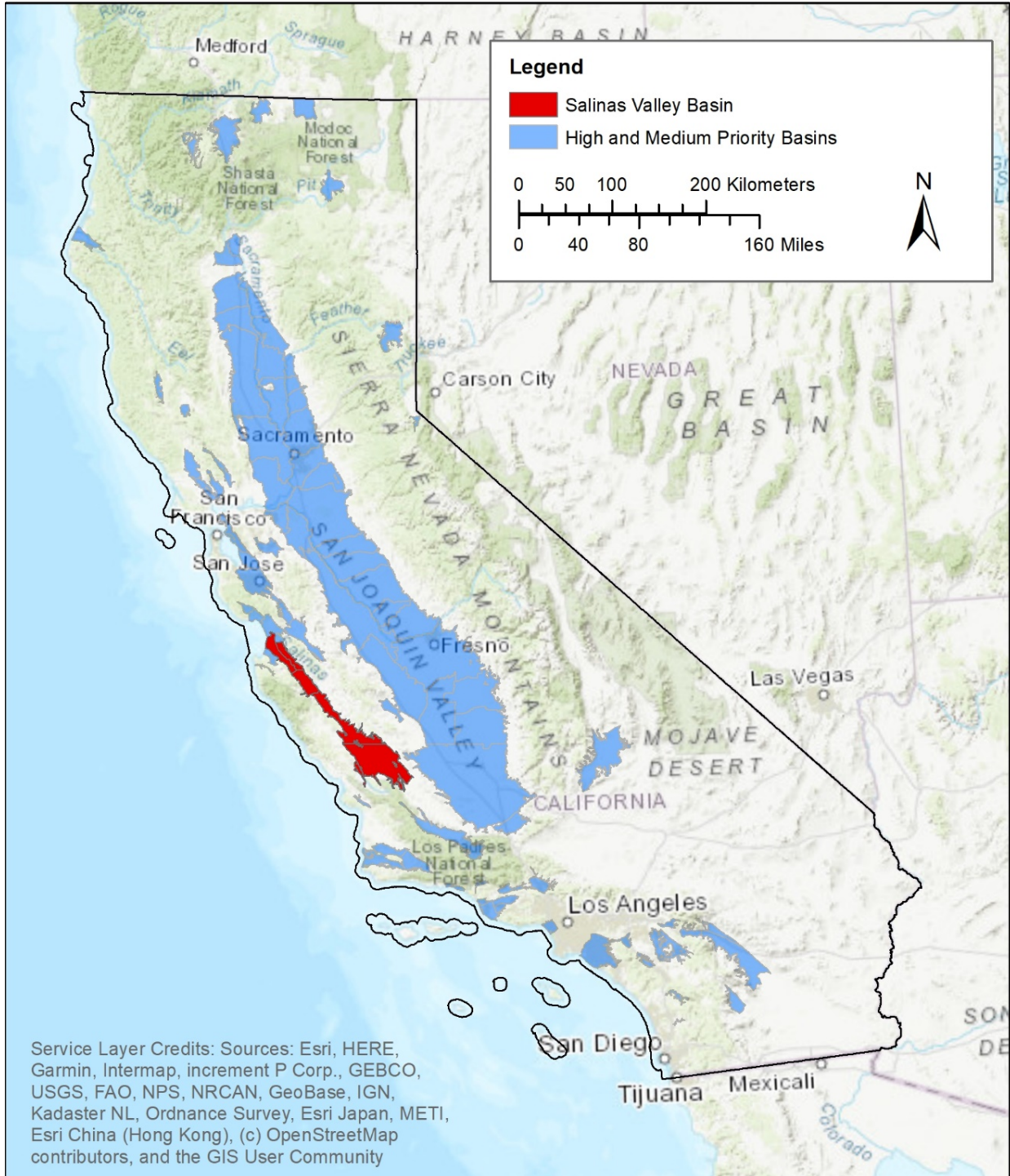


Figure 1-1 Map of California showing the SGMA medium- and high-priority basins, highlighted in blue. The Salinas Valley Groundwater Basin, the subject of this report, is highlighted in red.

Step 5: The flight lines were transmitted to the consultant team, where they are further examined by SkyTEM and Ramboll to adjust for potential infrastructure interference and safety considerations.

All flight line planning was conducted using ArcGIS, and publicly available data were utilized when available.

1.1.2 Statewide AEM Survey Planning and Coordination

Coordination and engagement with a wide range of organizations helps to ensure that the end use of the high-value AEM data are optimized to support sustainable groundwater management activities, in addition to providing benefits to a range of state, federal, and Tribal government hydrogeologic and geologic related projects. For each priority groundwater basin to be surveyed, DWR coordinates and engages with local, state, federal agencies, and Tribal governments (where present) to develop the survey design to meet a broad number of objectives. DWR also provides ongoing coordination, communication and public outreach throughout the process to support the AEM project logistics and to ensure the community is informed of the activities, as outlined below.

Local Coordination

DWR coordinates with local GSAs within each groundwater basin planned for an AEM survey to identify important areas within their basin where they want to ensure that AEM data is collected. For many GSAs, these include areas of known data gaps, areas being considered for groundwater recharge or other projects, or areas critical to GSP implementation.

Local Data Request

DWR also requests that the local basin GSAs share high-quality, digitized lithology or geophysical logs (that are not currently available in state databases) with DWR to support the AEM data interpretation. Integration of existing lithology and geophysical logs supports and reduces the uncertainty in the interpretation of the AEM data and is incorporated into the groundwater basin flight line planning process (described in Section 3.1)

State and Federal Agency Coordination

DWR is collaborating and coordinating with state and federal agencies listed below that may benefit from the AEM data to support other state- and federal-related interests, such as fault and seismic hazard mapping, canal and aqueduct maintenance, land subsidence, managed aquifer recharge, and groundwater modeling. DWR solicits input on flight line planning, requests area maps and descriptions and provides updates on the AEM survey program status and schedule.

State Agencies

- California Department of Fish and Wildlife

- California Department of Food and Agriculture
- California Department of Water Resources
- California Geological Survey
- State Water Resources Control Board

Federal Agencies

- United States Bureau of Reclamation
- United States Geological Survey

Tribal Government Engagement

DWR elected not to survey Tribal Trust Lands (as defined by the United States Bureau of Indian Affairs) unless the Tribe within the surveyed basin indicates that data collection and publication is acceptable.

DWR engages with Tribes within the surveyed basin through meetings and letters to Tribal leaders with information about the AEM project and an invitation to elect to join the surveys. DWR will only survey Tribal Trust Lands (as defined by the United States Bureau of Indian Affairs) if the specific Tribe(s) within the basin to be surveyed indicates that data collection and publication is acceptable. Notifications of surveys are provided in lieu of invitations if data collection over the Tribal Trust Land is not possible due to technical limitations. Technical limitations can be caused by the proximity of a potential survey area to urban areas, buildings, or electromagnetic noise sources, like infrastructure and other metallic features.

The AEM Survey Schedule webpage (<https://gis.water.ca.gov/app/AEM-schedule>) provides a map showing the AEM survey progress and locations of federally recognized Tribal Trust Lands and the surveyed basins.

1.1.3 AEM Survey Public Outreach

Prior to initiating the surveys within a groundwater basin, DWR conducts outreach to the public to provide an overview of the project and to notify interested parties of the upcoming work. Conducting outreach is a priority for DWR to ensure that the public is comfortable with the low-flying helicopter and is aware of the importance of the project. DWR's public outreach plan in each survey area includes the following activities:

- Posting a social media announcement on DWR's LinkedIn and Twitter pages and sharing with local GSAs to be re-posted on their social media websites.
- Providing a press release to local media outlets to be shared with their subscribers; interviews were also conducted by DWR staff when requested.
- Sending notification letters (in English and Spanish) via United States Postal Services to parcel owners within a 500-meter buffer beneath the planned flight path.

These public outreach activities were conducted within one month prior to the start of the AEM survey in the Salinas Valley groundwater basin.

Ramboll, SkyTEM, and Sinton Helicopters conducted outreach to county law enforcement to notify them of the AEM surveys and to provide background information about the project. Prior to the surveying the following sheriff offices were contacted via mail and telephone:

- Monterey County Sheriff
- San Luis Obispo County Sheriff

1.2 Salinas Valley Groundwater Basin AEM Survey

For the Salinas Valley survey, shown on Figure 1-2, a total of 1,274 line kilometers (796 miles) was flown and data acquired between July 29 and August 12, 2021. During the survey, the acquired AEM survey data were downloaded from the AEM instrumentation, initially checked for quality, and uploaded to a secure server for storage and subsequent analysis on a daily basis.

Parallel to the collection and processing of the AEM data, well information along the flight lines was gathered and compiled in a project data management system. The well data collected includes lithology, geophysical logs, water level measurements and water quality (TDS) measurements. The processed and inverted AEM resistivity data was then analyzed in combination with the well data, providing information on how resistivity relates to lithology. This report provides a summary and documentation of the listed tasks, including the methods used, results, uncertainty, and quality control.

1.3 Basin Geology

This report has a focus on the AEM data collected in the Salinas Valley Groundwater Basin. However, the basin's hydrogeology will affect the inversion of the AEM data as well as the lithology model and initial hydrostratigraphic model generated in this report. Therefore, a very basic hydrogeological description of the Salinas Valley Groundwater Basin is provided in this section, providing the basic background for this section. For more information please see the descriptions in Bulletin 118 (<https://water.ca.gov/programs/groundwater-management/bulletin-118>) as well as the GSP submitted for the basin (<https://sgma.water.ca.gov/portal/gsp/status>).

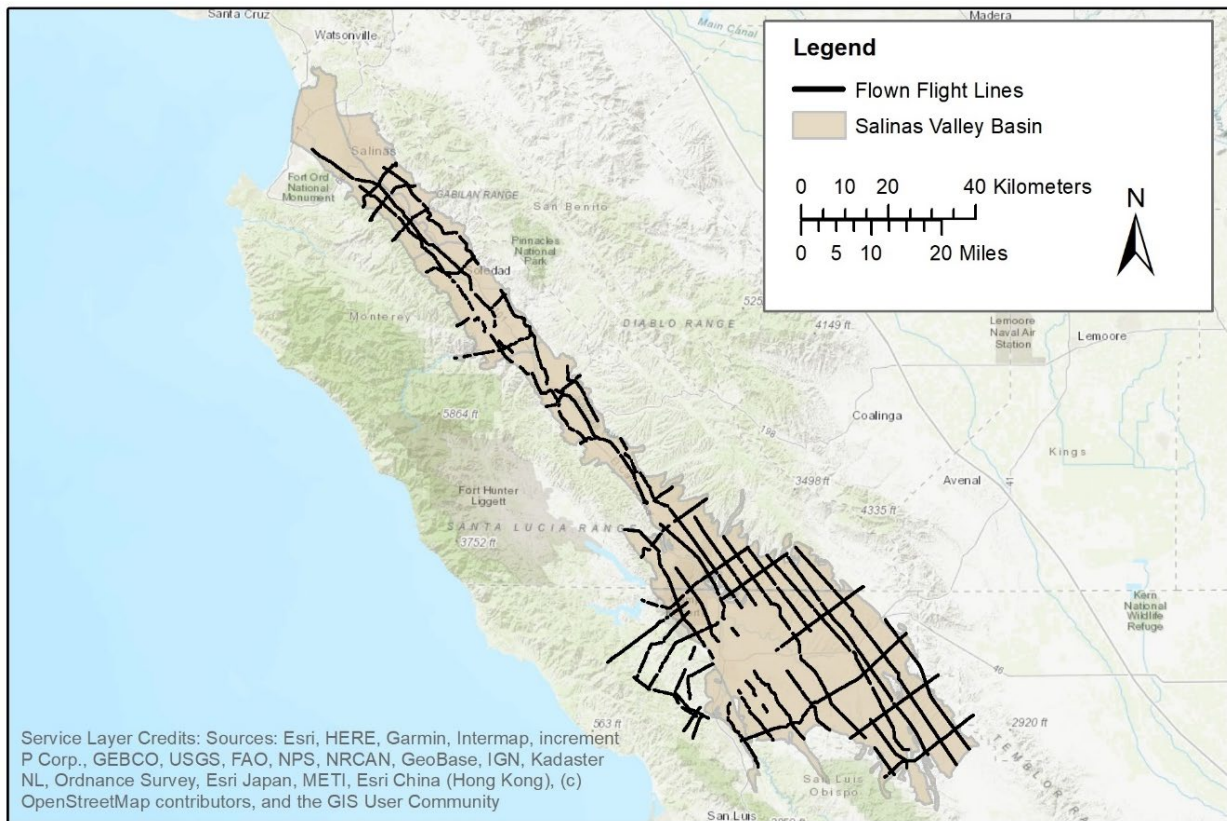


Figure 1-2 Map showing the flight lines flown in the Salinas Valley Groundwater Basin. The part of the basin that was surveyed is shown in brown.

The Salinas Valley Basin is a structural northwest-trending trough filled with sediments that have been folded and faulted by regional tectonics. The Basin is bordered by the King's City and Rinconada faults to the west and portions of the Basin are bordered by the San Andreas fault zone on the east. The majority of the Lower Salinas Basin's surficial geology consists of Quaternary (Pleistocene to Holocene) alluvium deposited by the Salinas River, as well as lake, playa, and terrace deposits. Portions of the valley margins include Pliocene to Pleistocene sandstone, shale, and gravel deposits. The Upper Salinas Valley (Paso Robles Area Subbasin) is primarily composed of the Pliocene to Pleistocene deposits, locally known as the Paso Robles Formation, with lesser portions of the Subbasin composed of the Quaternary alluvium around the Salinas River and its tributaries. Basement rocks include Mesozoic plutonic, metasedimentary, and metavolcanic lithologies including granite, slate, quartzite, chert, and gneiss (CGS 2010).

1.4 Report Contents and Appendices

The data report for the Salinas Valley Groundwater Basin survey is divided up into a main body and 11 appendices. The purpose of the main report is to provide a general

overview of the activities conducted and a basic description of the methodology and results. The main report is divided into six sections. The first section includes an introduction to the California statewide AEM survey and the specific survey for the Salinas Valley. Section 2 gives a brief description of the Salinas Valley Groundwater Basin geography and hydrogeology. Section 3 provides a description of the data collection, including the acquisition of the AEM data as well as the gathering of well data along the planned flight lines. Section 4 presents the AEM processing and inversion methods, results, and uncertainty. Section 5 includes the methodology and results for the lithology transform. Finally, Section 6 provides a list and description of the digital data delivered to DWR from the Salinas Valley survey.

The report appendices provide detailed technical documentation of all the activities conducted including survey methodology, results and quality control measures undertaken before, during, and upon completion of the AEM surveys, and include:

- Appendix 1 - Detailed description and presentation of the well data gathered along the planned flight lines, a description of the data management system, and the quality control checks of the collected well data included in the data management system.
- Appendix 2 - Technical details on the acquisition and quality control of the AEM data.
- Appendix 3 - Technical details of the processing and inversion of the AEM data, including methodology, results, uncertainty and quality control.
- Appendix 4 - Technical details of lithology model.
- Appendix 5 – Technical details of the development of the initial hydrostratigraphic model.
- Appendix 6 – Profile atlas containing the smooth resistivity model and the total magnetic intensity.
- Appendix 7 – Profile atlas containing the 30-layer sharp inversion model, the 4-layer model and the resistivity uncertainty analysis.
- Appendix 8 – Profile atlas showing the lithology model results and lithology model uncertainty.
- Appendix 9 – Profile atlas showing the initial hydrostratigraphic model results and cluster model uncertainty index.
- Appendix 10 - Resistivity maps, broken out for specific elevation intervals and as depth intervals.
- Appendix 11 - Description of the deliverables.

2. HYDROGEOLOGIC DATA ACQUISITION AND COMPILATION

Lithologic data, resistivity logs, water level measurements, and water quality (TDS) measurements from wells were assembled for the Salinas Valley Groundwater Basin. The data were compiled along the planned flight lines before they were flown. This data was then quality control checked and assembled into a data management system (DMS) for this project. This section provides a brief description of the results for the collection of the well data. A detailed description of the data compilation process and results is presented in Appendix 1.

2.1 Well Lithology Logs

For the project, the contractual objective is to obtain a minimum of two “best available” lithology logs from available well completion reports for each Public Land Survey System (PLSS) one-mile square section the flight lines cross. Best available lithology logs are defined as logs which can be accurately located within 50 meters (165 feet), and that contain high quality lithologic descriptions based on the detail in both the description and discretization. A lithology log is considered to be high quality if the log’s descriptions extend more than 30 meters (100 feet) below ground surface, and the average description interval is less than 30 meters (100 feet) (i.e. there are at least one lithologic description for every 30 meters on average); otherwise, it is considered to be a low quality lithology log.

In total, the planned flight lines cross 943 PLSS sections, as shown on Figure 2-1. There is a total of 1,031 high quality lithology logs distributed across 369 PLSS sections that the flight lines cross. There are 59 sections which only contain low quality lithology logs. In total, there are 563 sections that do not contain any lithology logs. Of the 1,031 high quality lithology logs, 648 were obtained directly from the local agencies, 182 were digitally available from the Online System for Well Completion Reports (OSWCR) database, and 201 were digitized for this project (as described in Appendix 1).

The well lithology log data were added to the project DMS. The lithologic descriptions in the DMS were then standardized with regards to their different descriptors to generally conform with the Unified Soils Classification System (USCS). These were then simplified into three basic textures: fine, coarse and rock. The data entered into the DMS were quality control checked with regards to the well placement, transcription, and other well construction information such as well screen interval. All wells digitized by the project team were quality control checked, whereas a random control check of 10% of the wells provided by local agencies and from the OSWCR database was conducted.

2.2 Well Resistivity Logs

For the project, high quality electrical resistivity logs were compiled from wells from the CalGEM database that are within the PLSS sections in which the flight lines cross. High quality electrical resistivity logs are defined as being located with an accuracy of 50 meters (165 feet), with measurements over the interval of 0 to 300 meters (1,000 feet) below ground surface, and that have a hard copy log image of sufficient quality to be digitized. However, logs that were more than 40-years old or within an oil field were not included because the changing hydrological conditions in the basin over time (potential changes in water levels and groundwater salinity), or due to the metal infrastructure within oil fields that interfere with the AEM survey signal. In the Salinas Valley, there were resistivity logs in the CalGEM database from 29 wells within the sections which met the criteria.

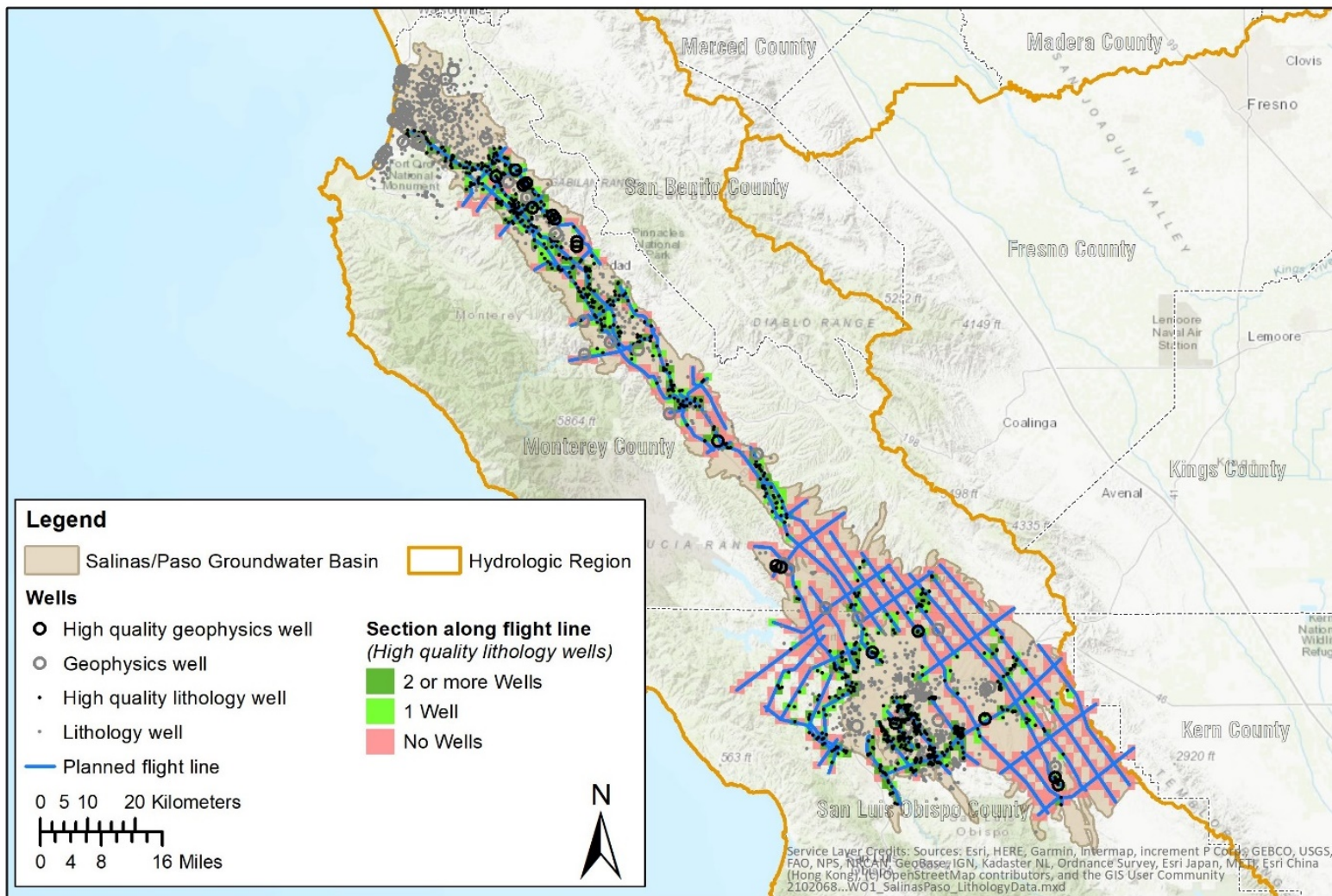


Figure 2-1 The location of wells and geophysical logs within the Salinas Valley Groundwater Basin used in the AEM survey. The map shows the flight lines in blue and the wells within the PLSS sections that the flight lines cross. The sections with 2 or more high quality wells are shown in dark green, sections with 1 high quality well in light green and with now wells as light red.

2.3 Groundwater Occurrence

Information on the depth to groundwater is important in the interpretation of geophysical data because the electrical resistivity of subsurface lithologies differs between unsaturated and saturated conditions. Understanding the depth to groundwater supports both the AEM data inversion process as well as the development of the initial hydrostratigraphic model. Figure 2-2 shows depths to groundwater for select wells in the Salinas Valley Groundwater Basin. For more detailed information on groundwater occurrence see the GSP for the basin.

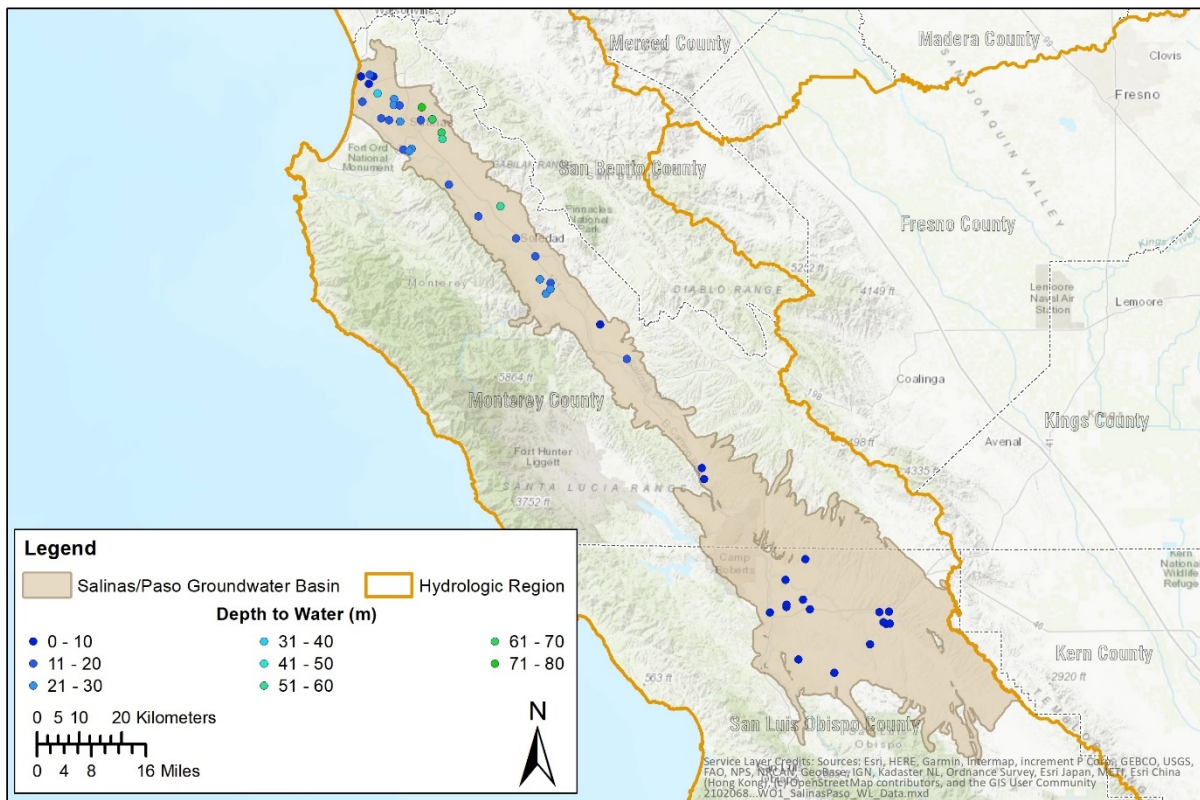


Figure 2-2 A map showing the depths to groundwater in the basin for select wells collected between 2008 and 2021. Shallow depths to water (< 30 m) are shown in blue, depths to water between 30 and 60 m are in blue-green, and deeper depths to water (60-80 m) are in green.

2.4 Total Dissolved Solids in Groundwater

Groundwater quality is important to geophysical interpretation because electrical conductivity varies depending on the dissolved constituents in groundwater which can vary by depth, aquifer, and geographic location within a groundwater basin. A measure of the amount of dissolved constituents is recorded in total dissolved solids (TDS) concentrations. In addition to TDS measurements, electrical conductivity (EC) is often measured directly. TDS and EC vary proportionally to one another and both measurements were assembled from the State Water Resources Control Board's (SWRCB) Groundwater Ambient Monitoring and Assessment (GAMA) system. The GAMA system is the most comprehensive, readily-available, and reliable water quality dataset and includes data collected from various federal, state, and local programs. This dataset is being updated by the state as new water quality data are reported to the state for compliance monitoring.

Figure 2-3 shows available water quality data throughout the study area. For sites with concurrent TDS and EC measurements, TDS was used. TDS and EC vary proportionally to each other, but the conversion factor (from EC in micromhos per centimeter to TDS in milligrams per liter) depends on the specific constituents within the sample and can range from 0.5 to 0.75 (Rusydi 2018). For plotting purposes, an average conversion factor of 0.625 was used. The most recent measurement from each well was used, but only for measurements after 2005. TDS values within the Salinas Valley Groundwater Basin range from 125 milligrams per Liter (mg/L) to greater than 3,500 mg/L.

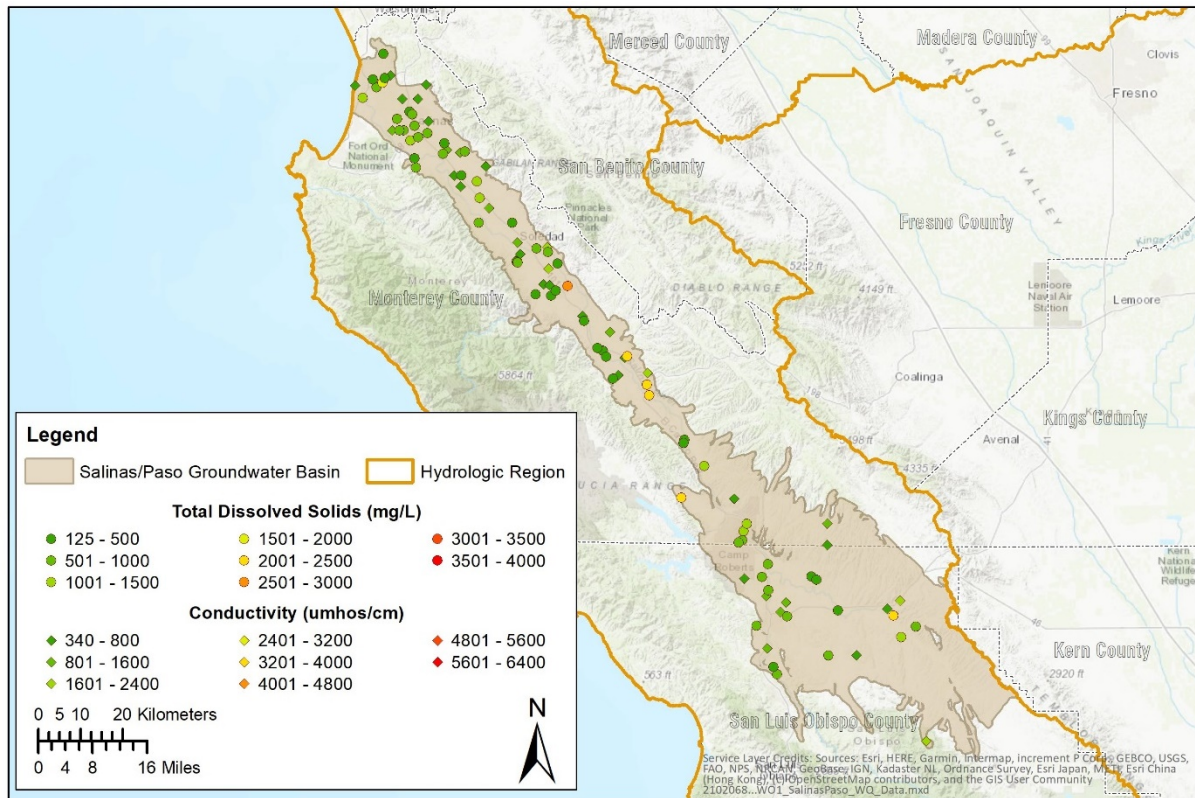


Figure 2-3 Map showing the groundwater quality, TDS and Conductivity, in the Salinas basin between 2005 and 2018. Lower levels of TDS and conductivity (125-1500 mg/L or 340-2400 umhos/cm) are shown in green, moderate levels (1501-2000 mg/L or 2401-4800 umhos/cm) are in yellow/orange, and higher levels (3001-4000 mg/L or 4801-6400 umhos/cm) are in red.

3. AIRBORNE ELECTROMAGNETICS SURVEY

3.1 Basin AEM Survey Methodology, Objectives and Flight Line Planning

This section introduces the methodology used for the AEM data acquisition, describes survey objectives, and discusses procedures taken for flight planning.

3.1.1 AEM Survey Methodology

The AEM survey method being used is a time-domain or transient electromagnetic method, known as TEM. The TEM methods are based on the principle of inducing electrical currents into the subsurface and receiving Earth's response over a short period of time. The TEM-instrumentation consists of a transmitter loop, a receiver coil, electronic instrumentations, and several auxiliary devices.

During each transient measurement, direct current is initiated through the transmitter loop. After a short time, the current is abruptly turned off. This abrupt turn-off induces electrical currents (called eddy currents) in the subsurface, which in return, generates secondary magnetic fields that decay with time. The decaying magnetic fields are measured using the receiver coil as a voltage timeseries, also referred to as a sounding. An optimization algorithm, called inversion, is then applied to the processed data to yield estimates of the subsurface resistivity structure, called resistivity models.

The TEM system can be deployed on the ground surface for stationary measurements or carried on moving platforms such as sleds, boats or, in the case of AEM, carried by a helicopter or airplane. Figure 3-1 provides an image of the actual AEM system, operated by SkyTEM Surveys, and helicopter, owned by Sinton Helicopters, being used in the DWR AEM statewide surveys.

An example of a single sounding of AEM data in the study area and corresponding resistivity model of the subsurface is shown in Figure 3-2. During the inversion, the entire AEM dataset is inverted together and the resistivity model for each sounding is constrained. This is done by introducing a dependency in between models for neighboring soundings, as discussed in Section 4.2 and Appendix 3.

More information on the physical principles of the TEM method can be found in Ward and Hohmann (1988) and Schamper et al. (2013) and in Appendix 2. A detailed description of the SkyTEM/AEM system used in this survey can be found in Section 3.2.1 and Appendix 2.

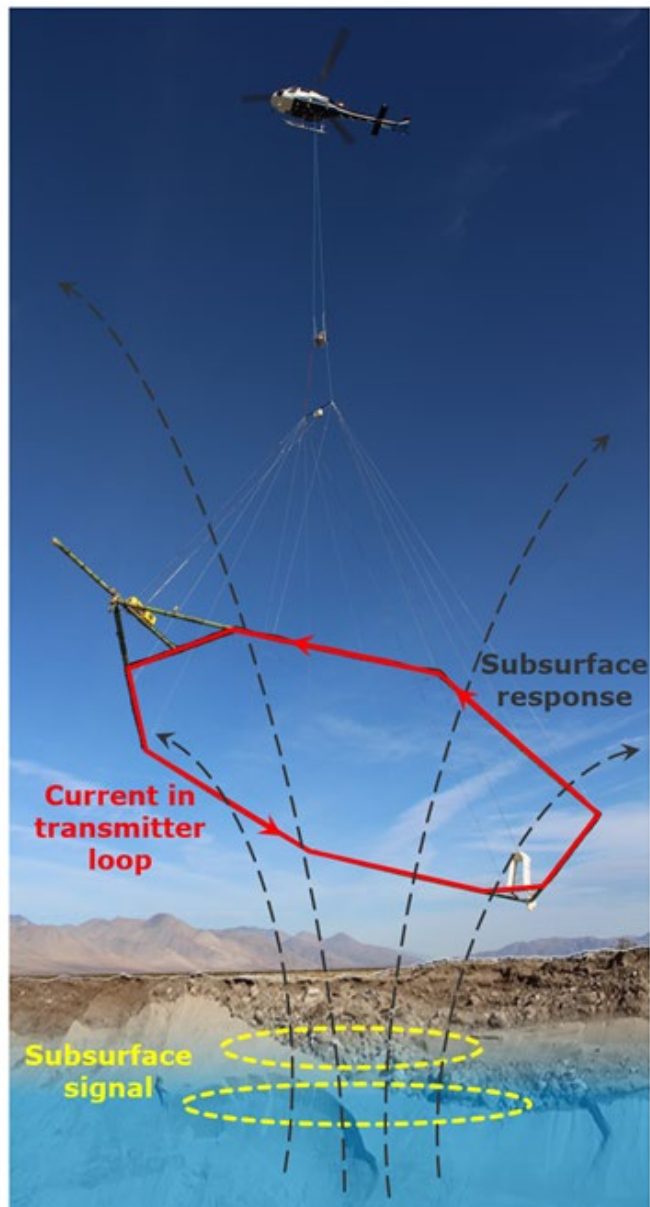


Figure 3-1 Figure showing the Airborne Electromagnetic Survey Schematic including the transmitter loop (current in red), subsurface signal (in yellow), and subsurface response (in dashed black lines) which is picked up by the system receiver. Note: the illustration does not include primary magnetic fields.

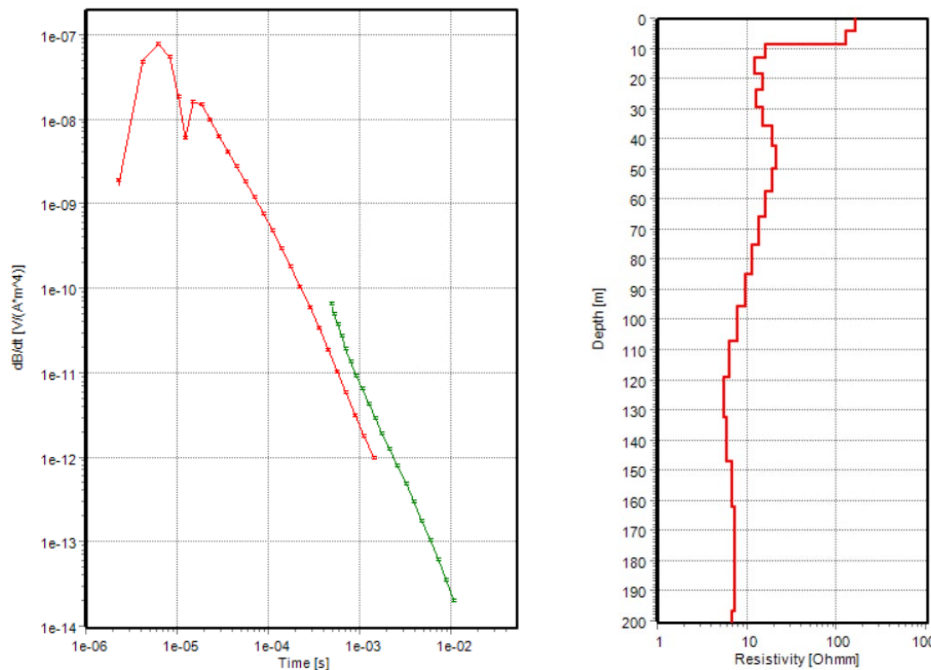


Figure 3-2 An example of a single sounding of acquired AEM data (change in magnetic field as a function of time) shown on the left-hand side, and a corresponding resistivity model showing the modeled resistivity from the ground surface to a depth of 200 meters (650 feet).

3.1.2 Salinas Valley Basin AEM Survey Flight Line Planning

The flight lines for the AEM survey were prepared by DWR as discussed in Section 1.1.2, and provided to Ramboll for execution. Ramboll, SkyTEM and Sinton Helicopters conducted a review of the planned flight lines on aerial photos from Google Earth and aeronautical charts to identify possible safety considerations in relation to:

- Built up areas which will need to be diverted around
- Trees and forested areas which the pilot will need to climb in elevation or divert around
- Towers, power lines, and other infrastructure that the pilot will need to climb in elevation or divert around
- Major roads which the pilot will need to navigate around
- Restricted air space
- Restricted areas due to endangered species

A proposed flight line plan was then prepared incorporating the safety review of the DWR flight lines and landing zone bases (small airports) that were identified for survey logistics, equipment checks and data downloads, and fueling. The safety considerations and proposed flight line plan were presented to DWR for final review, and subsequently approved for execution.

Figure 3-3 shows a map of the planned flight lines along with the land use within the Salinas Valley Groundwater Basin. During flight line execution, Sinton Helicopters sometimes had to diverge slightly from the planned flight while flying based on visual observation of potential safety issues such as the presence of people, livestock or other safety hazards (shown in Figure 3-5).

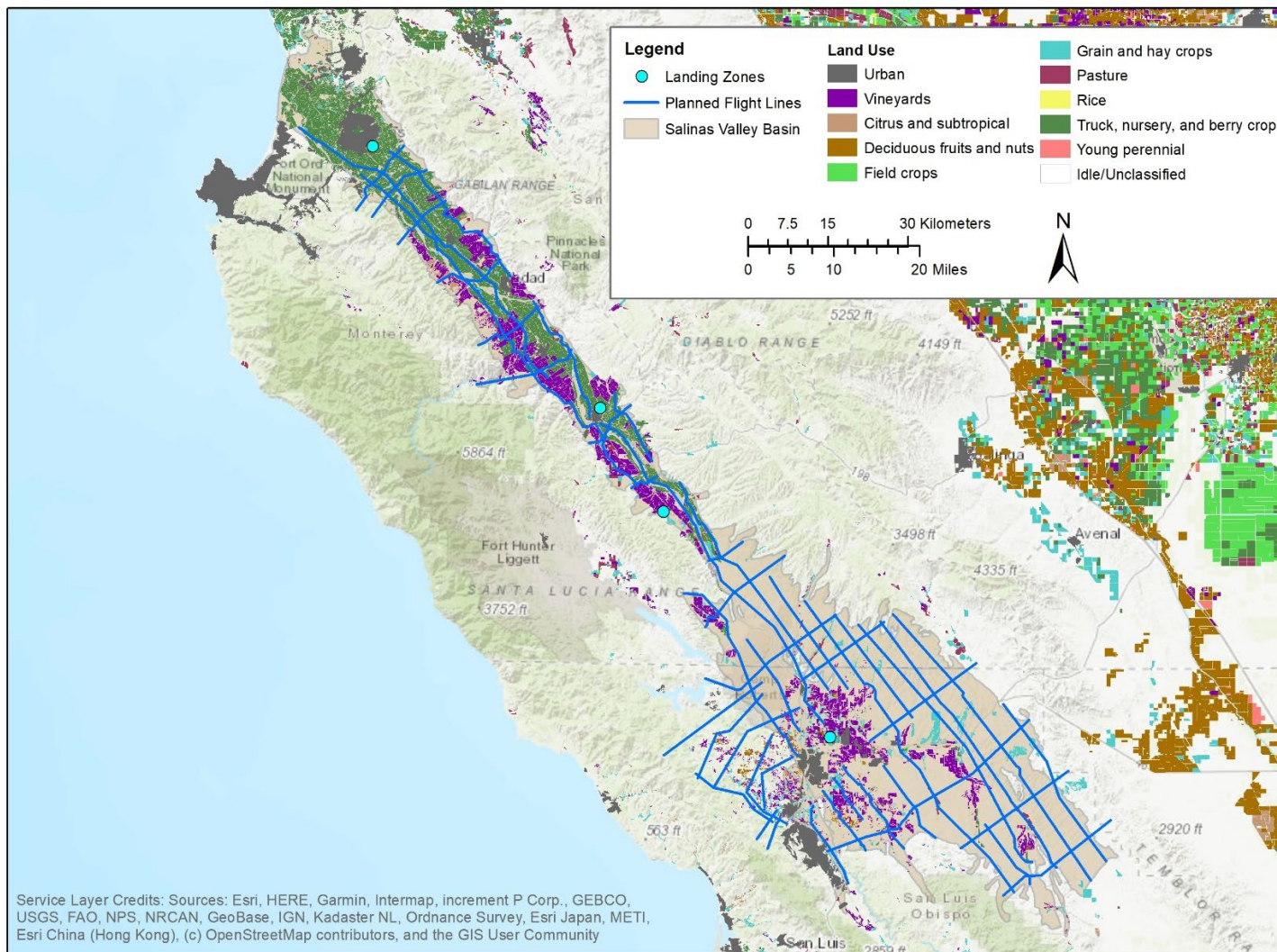


Figure 3-3 A map showing the planned flight lines (dark blue), the landing zones (light blue circle) and the surrounding land use types. Urban areas are shown in grey, vineyards are in purple, and the remaining areas are various types of agriculture.

3.2 Basin AEM Survey

3.2.1 Basin AEM Survey Equipment and Instrumentation

The helicopter-borne SkyTEM312M time-domain electromagnetic system was used during this survey. Throughout this report, the terms SkyTEM, SKyTEM312M, SkyTEM312, and AEM are used synonymously to indicate the geophysical survey equipment.

The AEM system is carried as a sling load, suspended 30 m (98 ft) beneath the helicopter and flown 30-50 m (98-164 ft) above the land surface (Figure 3-4) while flying at a groundspeed of 80-100 kph (50–62 mph). The system is designed for hydrogeological, environmental, and mineral investigations. The SkyTEM312 system has a transmitter loop area of 342 m² (3,681 ft²) contained within a hexagonal frame towed beneath the helicopter.

In addition to acquiring electromagnetic data, which provides information about the resistivity structure of the subsurface, the system also collects magnetic data, which are primarily used for mapping magnetic anomalies, fractures, and faults. Auxiliary data are also recorded and include GPS data for positional accuracy, the pitch and roll of the system, laser altimeter data for elevation, and video for a record of the ground surface along the flight path. A more comprehensive description of the TEM methodology can be found in Appendix 2.

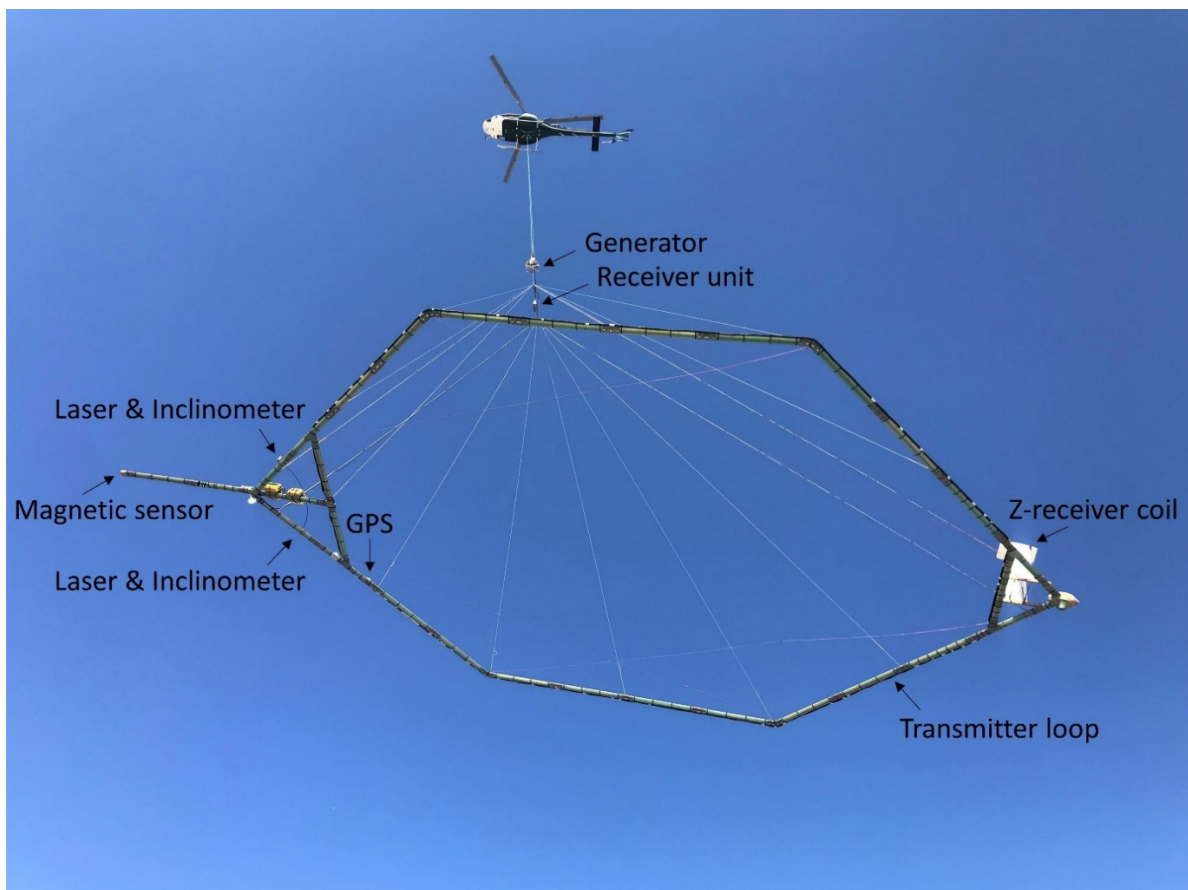


Figure 3-4 AEM Equipment and instrumentation configuration. The picture shows the helicopter towing the hexagonal transmitter loop. The front of the loop contains the GPS, laser, inclinometer and magnetic sensor. At the back of the loop is the Z-receiver coil. Suspended between the transmitter loop and the helicopter are the generator and receiver unit.

3.2.2 Landing Zones

Multiple locations were used as landing zone bases throughout the survey. These included the Paso Robles Municipal Airport (August 2nd, 5th, 6th, 7th, and 8th), Circle Ranch (August 9th), King City Airport (August 10th and 11th) and Salinas Airport (August 11th), see Figure 3-5.

3.2.3 Basin AEM Survey Data Acquisition

The AEM survey was carried out between August 2 and 11, 2021. A total of 1,273.6 line-km (791.4 line-miles) of data were acquired.

Before, during and after the acquisition of the AEM data, several measures were taken to ensure that the AEM system functions properly, and the quality of the acquired data was acceptable. During the initial on-site SkyTEM system set-up phase, very high-altitude tests, waveform, configuration settings and null positions were checked in

collaboration with SkyTEM to ensure that the configuration and specifications were as agreed upon in the contract.

During the survey, SkyTEM provided daily updates, including a map of daily production, high altitude test, raw electromagnetic, magnetic, and reference line data (see Appendix 2), which was quality control checked on a daily basis by Ramboll. The quality of the data evaluated daily during the Salinas Valley Groundwater Basin AEM survey was found to be acceptable.

Figure 3-5 shows the actual flown flight lines compared with the planned flight lines. In general, it was not necessary to deviate significantly from the planned flight lines in the Salinas Valley Groundwater Basin. Figure 3-6 shows three photos of the AEM array during data acquisition in the Salinas Valley.

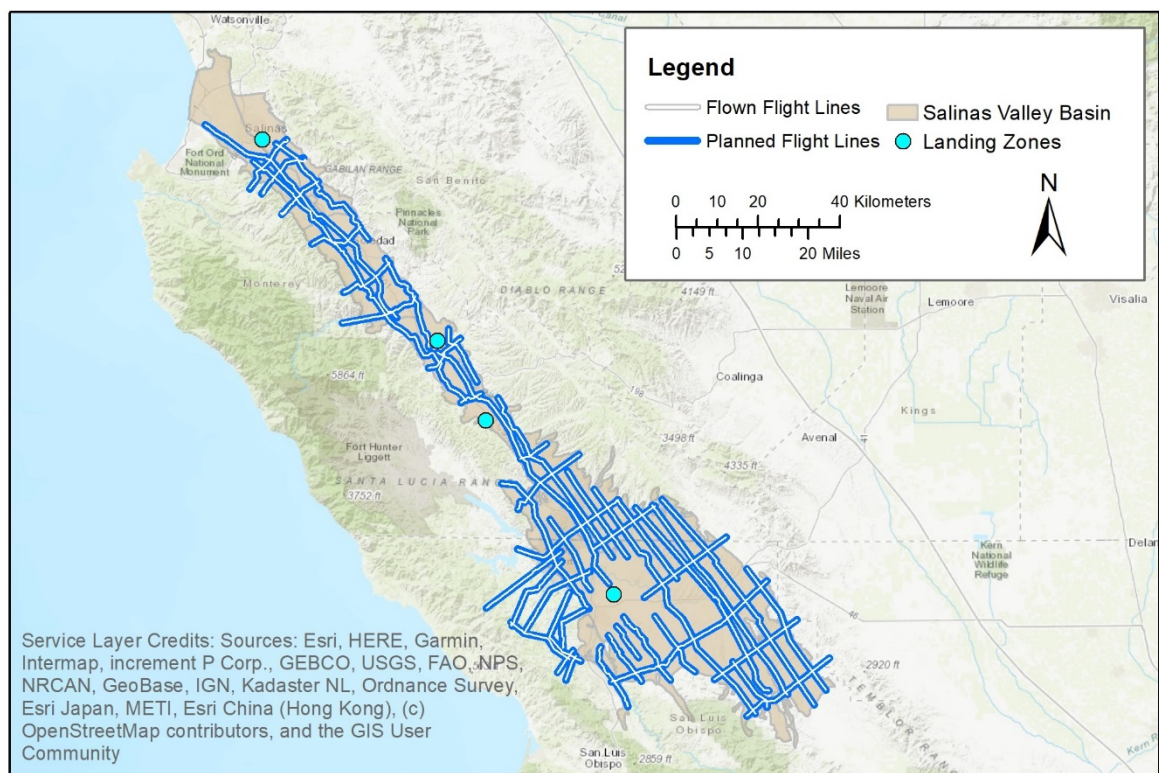


Figure 3-5 Map showing the planned and flown flight lines in the Salinas Valley Area. The planned flight lines are shown as the thicker dark blue lines and the actual flown lines are shown as thin white lines. The light blue dots show the location of the landing zone bases for the flights conducted in the area.



Figure 3-6 Photos of the AEM flights in the Salinas Valley Area. The top photo shows the AEM system resting at Paso Robles airport. The bottom left shows the system during take-off and the bottom right shows the helicopter towing the array during the survey.

3.2.4 Reference Lines

Reference lines are flight lines that are repeated, with the purpose to compare the initial and repeated flight line results to ensure the reproducibility of the AEM system during the survey to validate instrument performance, to identify any potential drift and to document the stability of the data processing and inversion algorithms. One or more reference lines were flown during each production day during the August 2-11, 2021 survey, which resulted in a total of twelve reference lines in 3 locations ranging from ~ 1,400 m to ~ 2,100 m (4,593-6,890 ft) in length.

The results of the reference lines demonstrate that the AEM system was not affected by drift or instrumentation issues. It also showed that the processing and inversion schemes were consistent, and the results demonstrate that the data is highly repeatable. More information and the results of the reference lines can be found in Appendix 2.

4. AEM DATA PROCESSING, INVERSION, AND RESULTS

The AEM dataset acquired during the survey is a set of voltage time series, the measured response resulting from the electromagnetic pulses produced by the AEM transmitter loop. To obtain quantitative information on the subsurface resistivity from the raw AEM data, the data must go through the steps of processing and inversion. Processing refers to actions that prepare the data for inversion, including the removal of noisy or coupled data, and the application of averaging filters to the data. Inversion refers to the numerical optimization algorithm that will find the subsurface resistivity distribution that agrees with the AEM data. Filters are applied to obtain usable, noise-free data and optimize lateral resolution. Here, we present an overview of the processing and inversion, as well as a selection of the resulting resistivity models. A more thorough review of the processing and inversion is presented in Appendix 3, and the full set of resistivity models resulting from the processing and inversion steps are shown in Appendix 6 and Appendix 7.

4.1 AEM Data Processing and Inversion

After the raw (electromagnetic & auxiliary) data were checked for quality, they were imported into the Aarhus Workbench software to be prepared for data processing and inversion, which comprised the following steps:

1. Process auxiliary data (e.g. GPS, height)
2. Process AEM data automatically and manually
3. Run inversion on AEM data
4. Calculate the depth of investigation from AEM data
5. Run uncertainty analysis on AEM data

4.1.1 Data Processing

The first data to be processed are the auxiliary data: these data include pitch and roll (tilt) data, transmitter height data, and GPS data. The tilt and transmitter height data affect the raw AEM measurement and must be accounted for during the inversion, while the GPS data are needed to relate each measurement with its correct geographic position. Each type of auxiliary data was quality control checked before being used in the inversion. To relate the resistivity models to the topography of the landscape, a terrain elevation was assigned to each electromagnetic sounding using a digital elevation model (DEM). For more information about these steps see Appendix 3.

Next, the raw AEM data (voltage timeseries) were processed to prepare for inversion. The AEM system continuously makes electromagnetic measurements, which results in approximately 25-35 measurements per kilometer along each flight line. The AEM data processing involves both automatic and manual processing of the data. The automatic processing requires selection of appropriate filters and other parameters. After automatic processing, the data are manually reviewed for noise, as well as interference from infrastructure, such as powerlines or pipes. The distance of AEM data locations to human-made structures was considered, and portions of the dataset were selectively

removed. The AEM data processing is an iterative process, which requires revisiting the data after each step, and again after provisional inversion results are visualized. Detailed information about the voltage timeseries data processing steps and settings are provided in Appendix 3.

4.1.2 Inversion

Once the auxiliary and AEM data were processed, the AEM data were used to produce resistivity models through inversion. The inversion is an iterative optimization, where the resistivity model at each location where AEM data were acquired (i.e., each sounding) along each flight line, is used to calculate synthetic AEM data. These synthetic AEM data are compared to the processed AEM data acquired during the survey. The misfit between the observed and synthetic data is used as a criterion to update the resistivity model, and the process is repeated. While minimizing the data misfit, the employed inversion scheme enables applying vertical constraints (i.e., between the resistivity values of adjacent layers) and spatial constraints (i.e., along and between flight lines), to allow the migration of information between nearby AEM data. Once the synthetic AEM data match the acquired AEM data within a specified tolerance, the resistivity model is considered final.

All AEM data were inverted simultaneously using the spatially constrained inversion (SCI) approach (Viezzoli et al., 2008), which accounts for all model parameters, AEM data and spatial constraints. The inversion algorithm requires user input on specific values, including the depth discretization of the resistivity model (i.e., the estimate of the subsurface resistivity structure), the initial estimate of resistivity values, and horizontal and vertical constraints. Each value is selected based on the AEM system setup, depth interval of interest, and background geologic information of the study area; multiple inversions may be run on the same dataset to find the optimal values for these input values. Typically, two to three inversions are run for each dataset to 1) finalize the processing of the data and 2) obtain final input values for the inversion. The system setup information (AEM equipment metrics) is used during the inversion when calculating the synthetic AEM data. Detailed information of the inversion approach can be found in Auken et al. (2015) and Appendix 3.

4.1.2.1 Inversion Schemes

Using the SCI approach with a different setup, the AEM data can be inverted to result in different types of resistivity-depth models. The following inversion schemes were used in this study:

- Smooth inversion: in this scheme, a large number of layers (20-30) are used in the model, where each layer thickness is larger than that of the layer above it. Each layer thickness remains fixed during iterations of the inversion, but the resistivity value of each layer is allowed to vary. Using spatial constraints, resistivity values are restricted to stay within a factor of neighboring resistivity values, resulting in smoothly varying resistivity-depth models.

- Few-layer inversion: in this scheme, a small number of layers (typically 3-6) are used in the model; both the resistivity and thickness of each layer are allowed to vary during the inversion. The few-layer inversion can represent sharp boundaries in the subsurface, unlike the smooth inversion. The few-layer inversion is used in this project for the uncertainty analysis since the uncertainty in the thickness and depth of each layer can be analyzed (unlike in the smooth and sharp inversions).
- Sharp inversion: Like the smooth inversion, the sharp inversion uses a large number of layers. Like the few-layer inversion, the sharp inversion is favorable when expecting sharp layer boundaries. However, unlike the smooth inversion, the sharp inversion is designed to support both gradual and abrupt changes in resistivity values (Vignoli et al., 2015). Furthermore, the sharp inversion overcomes the limitation in the few-layer inversion of setting a small, constant number of layers in the inversion over a large survey area, where conditions are likely to change spatially. Because of these advantages, the sharp inversion is used as input to the resistivity-to-lithology analysis.

For detailed description of the three inversion schemes, see Appendix 3.

4.1.2.2 Depth of Investigation

The resistivity models resulting from each inversion were used to calculate the depth of investigation (DOI). The DOI is dependent upon the geology, water quality and data quality: areas with thick conductive clays and saline water will typically have a shallower DOI than sands and fresh water. The DOI gives an indication of the depth to which a resistivity-depth model can be considered reliable, and below which there is an elevated uncertainty. Since the AEM method is a diffusive method, it is not possible to define an exact DOI, below which there is no information on the resistivity structure. Thus, resistivity information below the DOI still may be useful, but interpretation of resistivity values below the DOI is cautioned. In this study, the DOI was calculated using sensitivity information output from the inversion, following the approach presented by Christiansen et al. (2012). More information about the DOI can be found in Appendix 3. The resulting DOI varies spatially throughout the survey area but is typically 200 – 300 m (650 – 1,000 ft).

4.1.2.3 Inversion Uncertainty Analysis

The acquired AEM data are affected by environmental noise, both natural and anthropogenic, which is presented as the standard deviation or error bars on the data. This uncertainty in the raw AEM data will propagate during the inversion to the estimated resistivity values, and in the case of the few-layer inversion, to the layer thickness; each of these values will also have an associated standard deviation.

For the employed inversion approaches, the model parameter uncertainties are estimated based on the *a posteriori* model covariance matrix and presented as normalized standard deviation factors (STDFs). The STDFs are classified in different intervals, ranging from very well determined parameters (low STDFs) to undetermined

parameters (high STDFs). For details about the calculation of the model parameter uncertainties and how to read the uncertainty sections, see Appendix 3.

4.2 Selected Results

The modelled AEM data represent resistivities along the flown flight lines that can be presented as vertical sections or as plan-view maps. In this section, selected representative results of each are illustrated. The entire set of vertical sections of resistivity models are presented in Appendix 6 and Appendix 7, where Appendix 6 shows the smooth inversion results, while Appendix 7 displays the sharp inversion results and the few-layer inversion results with associated uncertainty analysis. The vertical sections are placed along all the flown lines as sheets with a section length of up to 17 km, where a 1 km overlap is included when a flight line is longer than 17 km.

The entire set of plan-view resistivity maps are shown in Appendix 10, where the resistivity values are depth-averaged and presented as horizontal slices in either elevation intervals or depth intervals of 20 m (66 ft).

A color scale was developed to illustrate the resistivity models as vertical sections and plan-view maps. On each resistivity color scale, cool colors (blues, greens) represent lower resistivity values, while warm colors (reds, purples) represent higher resistivity values. For the resistivity models in this survey, an interval of 3-300 ohm-m was used to illustrate structural variations across the study area. The color scale is shown on Figure 4-1.

4.2.1 Vertical Resistivity Sections

In this section, four vertical model-sections (Figure 4-1 to Figure 4-4) across the surveyed area are provided to illustrate the geographical variations with a focus on how the generated resistivity models compare to well lithology logs, geophysical logs (e-logs), and water levels. Detailed geologic structures (folding and possible faulting) are evident along the sections. In addition, an example of model uncertainties calculated for a specific flight section is illustrated in Figure 4-5.

4.2.1.1 Section 103500, Distance Interval 47-57 km

Figure 4-1 shows a 10-km long section, located in the central part of the basin south of the city of Salinas, with several layers as indicated by the significantly different resistivities, including a relatively homogenous low resistivity layer in the elevation interval from -50 m to -100 m (-164 ft to -328 ft) above mean sea level (amsl). The low resistivity layer correlates well with the interval of finer material observed in the two deep boreholes projected on the section.

4.2.1.2 Section 103600, Distance Interval 40-57 km

Figure 4-2 shows a 17-km long section that is located in the area between King City and Paso Robles and shows a relatively thick conductive layer with overlying coarse

materials forming highlands. It is an area with only one borehole within the search radius of 800 m (2,625 ft).

4.2.1.3 Section 100400, Distance Interval 0-7 km

Figure 4-3 was selected to illustrate an area where the flight line crosses three deep boreholes with geophysical logs (e-logs) and two deep wells. Several layers are evident across the section based on the resistivity distribution. The geophysical logs as well as the lithology from the boreholes are in good agreement with the resistivity models.

4.2.1.4 Section 101800, distance Interval 31-48 km

Figure 4-4 shows a 17-km long section, located southeast of Paso Robles, which was flown over a topographic high that shows less stratification and more geologic complexity. Three lithologic logs are projected on the section.

4.2.1.5 Section 103600, Distance Interval 15-25 km

Figure 4-5 shows model uncertainties along a 10-km long section, located southeast of Kings City. The 4-layer model used to describe the uncertainties (panel 1) as well as resistivity (panel 2), layer thickness (panel 3) and layer depth (panel 4) uncertainties are presented. The residual is presented in the lower part of the resistivity section and can be used to determine if intervals with high uncertainties are caused by a poor data fit. Above the sections the flight height is shown with a thin line as instrument height can cause a poor data signal/noise ratio and hence more uncertain model parameters.

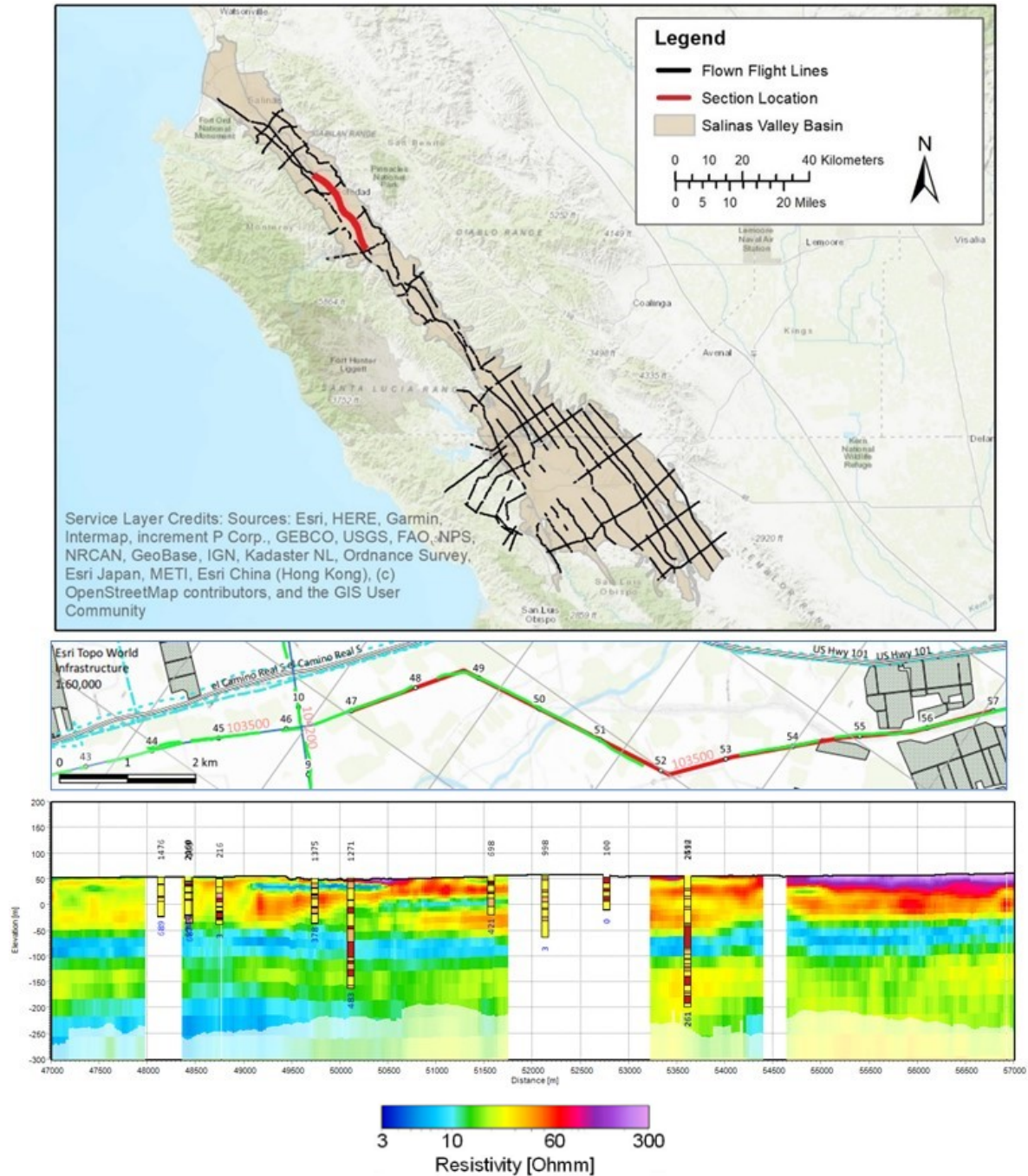


Figure 4-1 Resistivity along Section 103500. The location of the section within the study area is provided on a terrain map (top panel), with the full extent of the flight line shown on a topographic base map (middle panel). Green lines show parts of the data used for inversion (middle panel), with the vertical resistivity displayed from 47 to 57 km (bottom panel). Well lithologic logs near the section are projected onto the section, with well IDs above and numbers below the log indicating distance in meters from the well to the section.

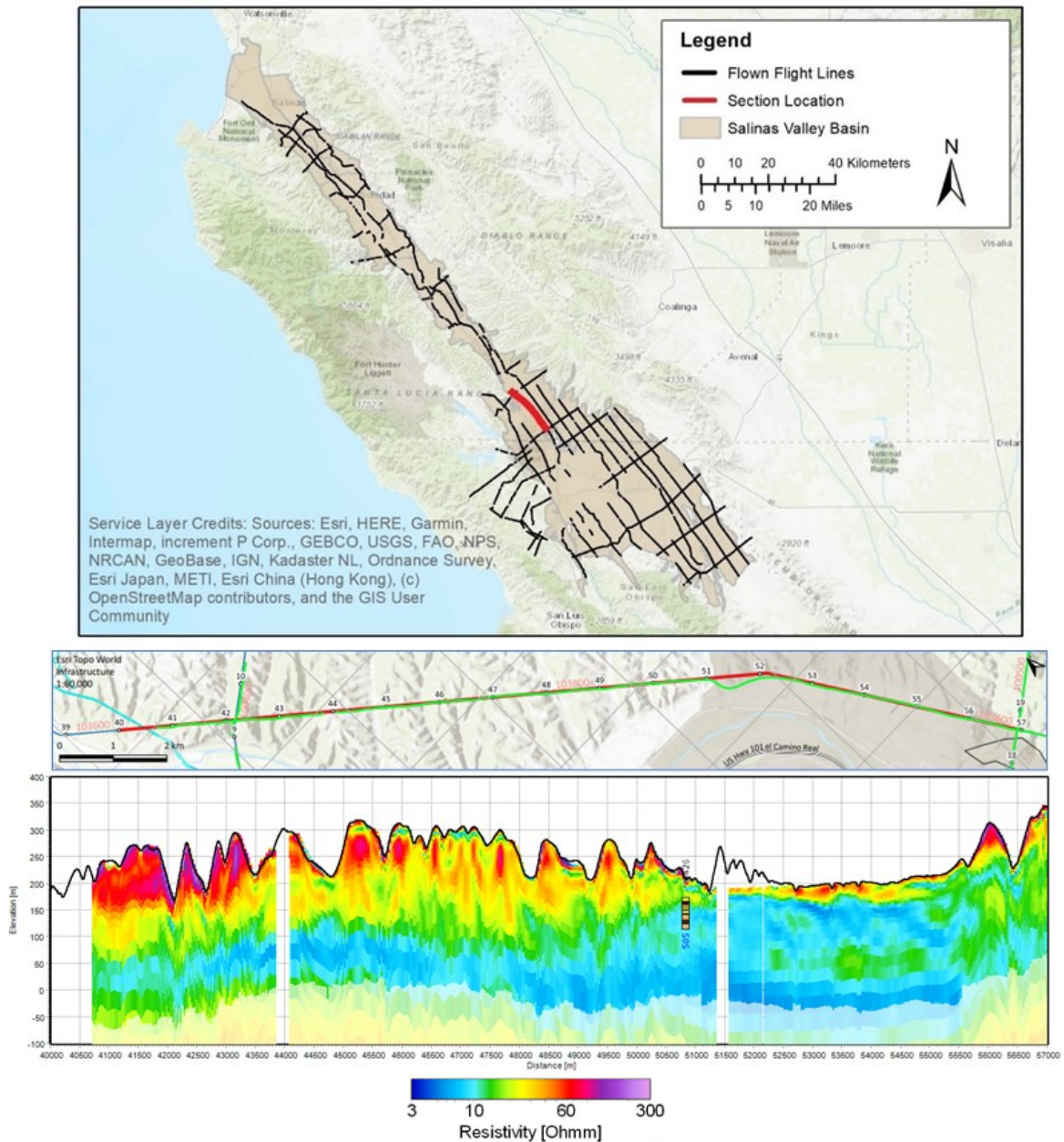


Figure 4-2 Resistivity along Section 103600, distance interval 40-57 km. The location map of the section within the study area (top panel), with the extent of the flight line shown on a topographic base map (middle panel). Green lines show parts of the data used for inversion (middle panel), with the vertical resistivity section shown in the bottom panel. Well lithologic logs near the section are projected onto the section, with well IDs above and numbers below indicating the distance in meters from the well to the section.

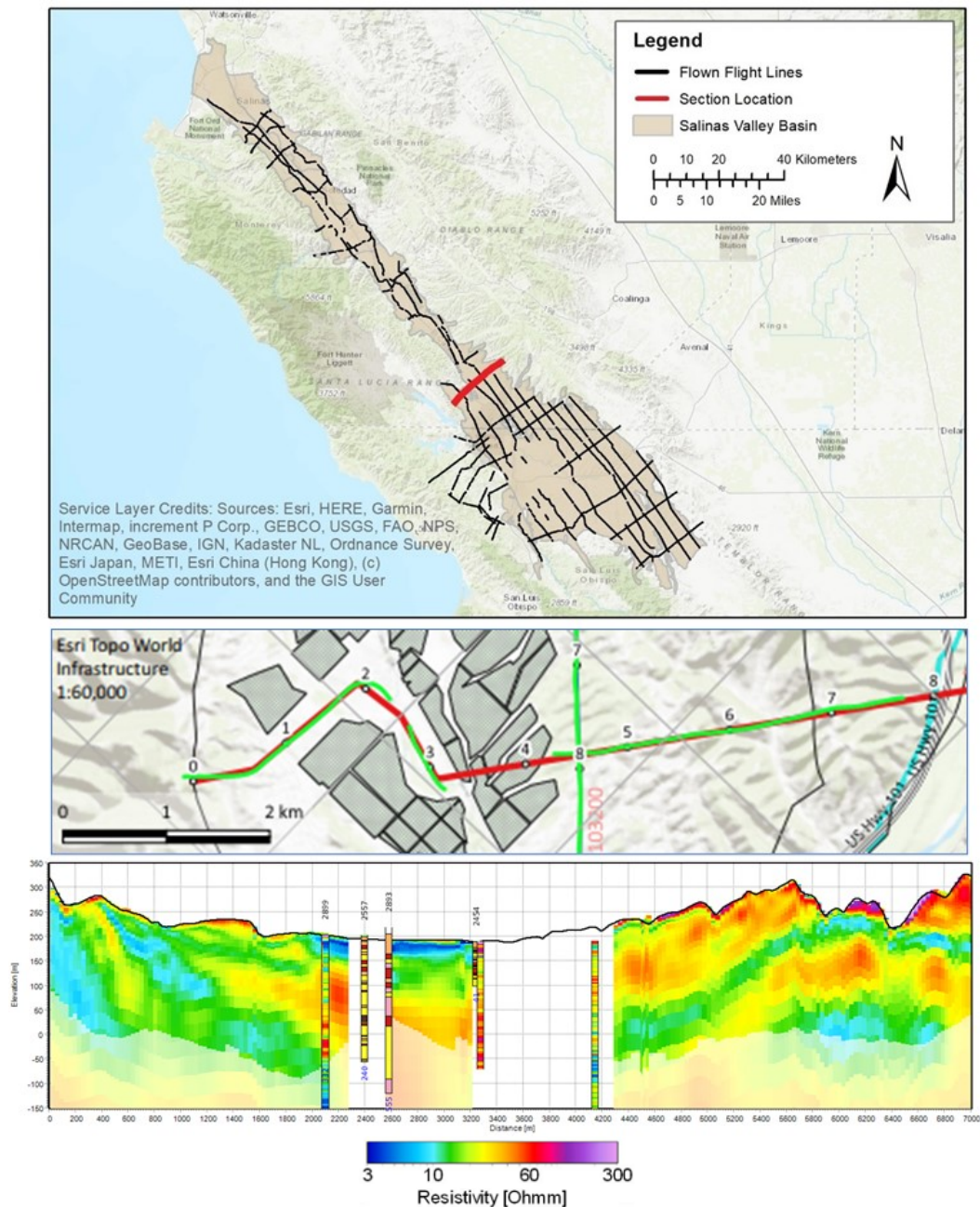


Figure 4-3 Resistivity along Section 100400, distance interval 0-7 km. The location map of the section within the study area (top panel), with the extent of the flight line shown on a topographic base map (middle panel). Green lines show parts of the data used for inversion (middle panel), with the vertical resistivity section provided in the bottom panel. Well lithologic logs near the section are projected on the section, with well IDs show above and numbers below indicating the distance in meters from the well to the section.

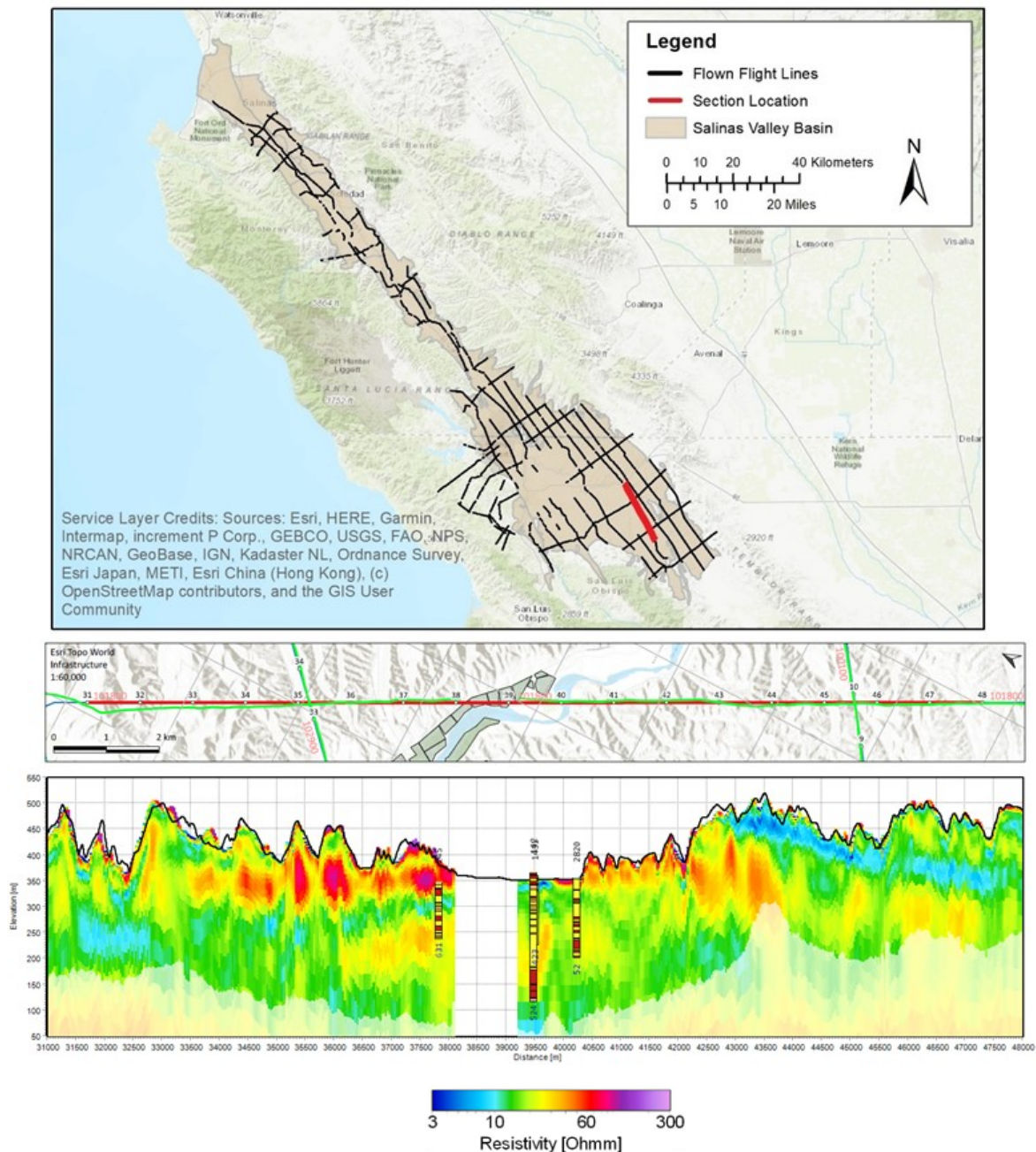


Figure 4-4 Resistivity along Section 101800, distance interval 31-48 km. The location map of the section within the study area (top panel), with the extent of the flight line shown on a topographic base map (middle panel). Green lines show parts of the data used for inversion (middle panel), the vertical resistivity section provided as the bottom panel. Well lithologic logs near the section are projected on the section, with well IDs shown above and numbers below indicating the distance in meters from the well to the section.

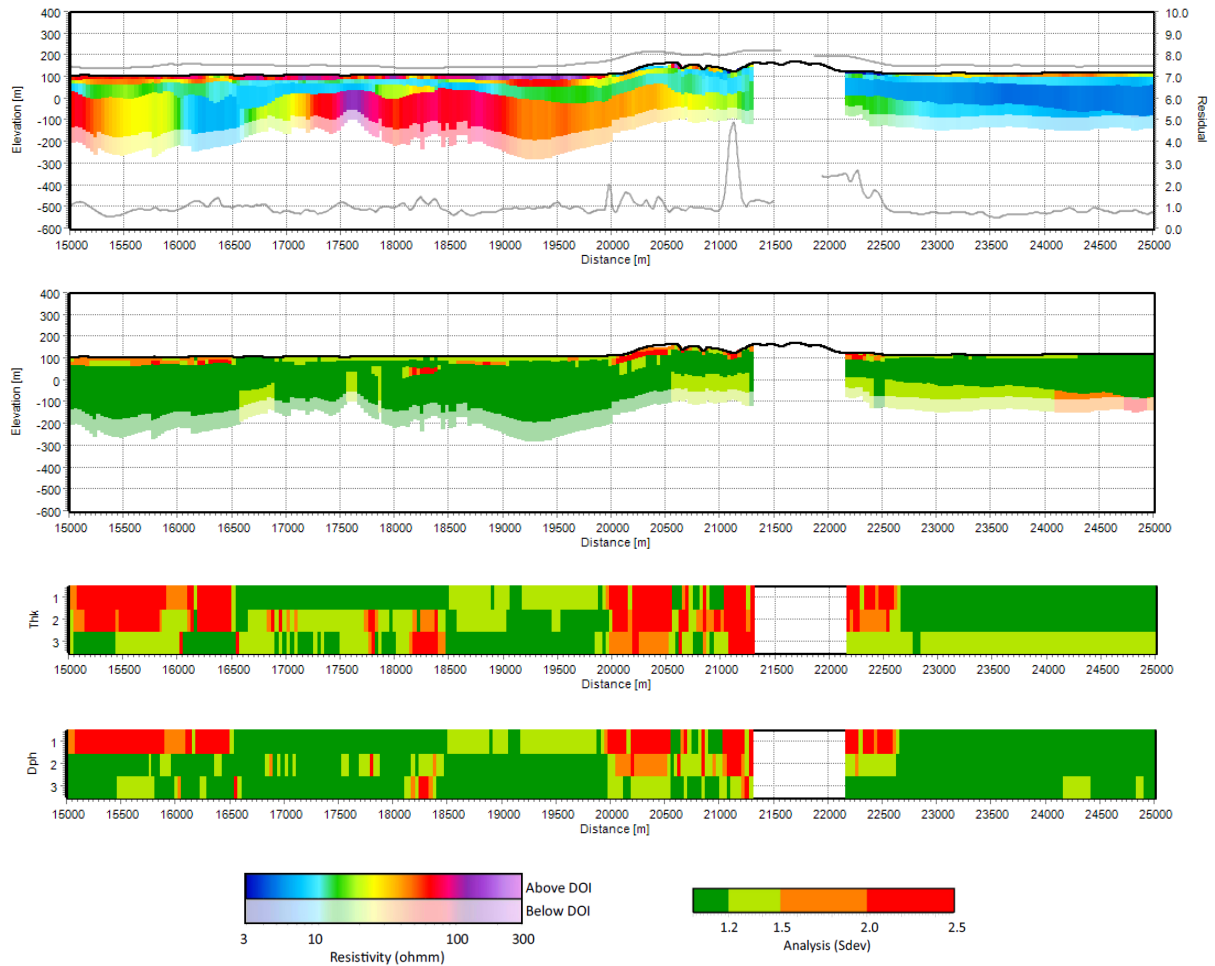


Figure 4-5 Example of illustration of the model uncertainties along a representative 10-km-long vertical section of flight line 103600. The top panel shows the vertical 4-layer resistivity model section used for sensitivity analysis of the model parameters. Uncertainty analysis of the resistivities is shown on panel 2. Uncertainty analysis of layer thicknesses 1, 2 and 3 is shown on panel 3 and the uncertainty analysis of depths 1, 2 and 3 is shown on panel 4.

4.2.2 Mean Resistivity Plan-View Maps

Mean resistivity plan-view maps of horizontal slices along the flight lines are displayed at different depth and elevation intervals and illustrate detailed structures and provide insight into variations across the surveyed area at each interval. Three representative maps of mean resistivities at different depth and elevation intervals are provide in Figure 4-5 and Figure 4-7. The two elevation intervals present the variations in resistivity in the highest terrain towards south and the lower elevation terrain in the central part of the Salinas valley – especially towards north. More information on how each interval’s mean resistivity is calculated can be found in Appendix 3.

Figure 4-5 illustrates the mean resistivity in the depth interval 15 m to 30 m (49-98 ft) below the land surface. It is evident that trends in the variations in resistivity can be followed from flight line to flight line though there are also areas where the resistivity appear to change rapidly, suggesting a level of geologic heterogeneity in the area surveyed.

Depth slices representing intervals 0-5 m, 5-15 m, 15-30 m, and 30-60 m are provided in Appendix 10.

Figure 4-6 shows the mean resistivity in the elevation interval 360 m to 380 m (1181-1247ft) amsl. A significant portion of the area from the city of Paso Robles all the way to the north end of the basin is not represented on the map. This is due to the fact that the land surface elevation is below the mean resistivity elevation interval.

Figure 4-7 shows the mean resistivity in the elevation interval -20 m to 0 m (-66 ft to 0 ft) amsl. A portion of the area to the south is not represented due to the relatively higher land surface elevation resulting in the DOI elevation exceeding the -20 m to 0 m mean resistivity elevation interval. The entire model is presented in Appendix 10 as horizontal 20-m thick slices starting at the highest elevation in the survey area going down to the lowest elevation within the depth of investigation.

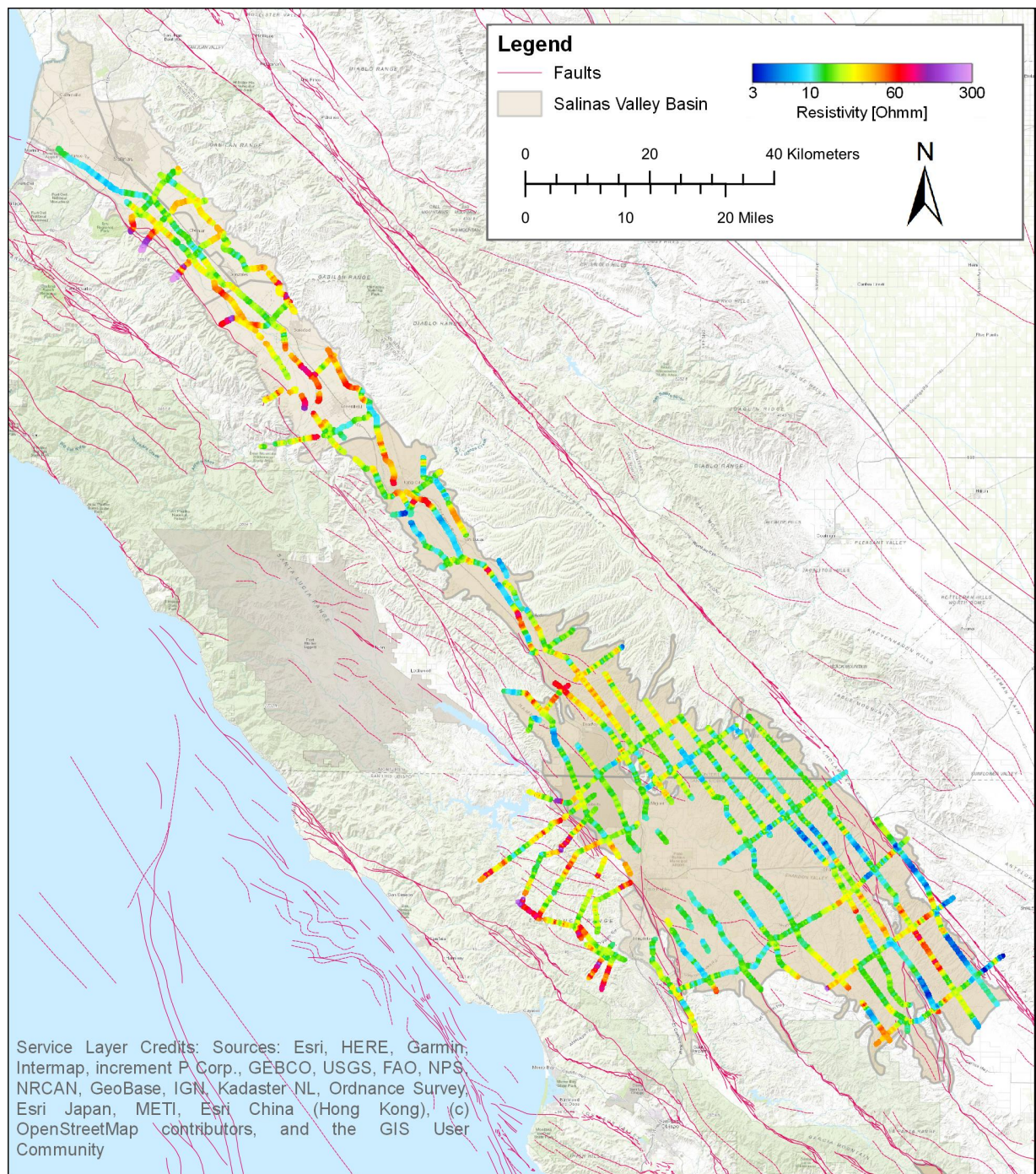


Figure 4-6 Mean resistivity plan-view map in the depth interval 15-30 m (49-98 ft) below land surface. The colors represent the resistivity, with blue colors representing the lower resistivities, below 10 ohm-m, the yellow and green colors representing the moderate resistivities, between 10 and 50 ohm-m, and the orange and red colors representing the higher resistivities, over 50 ohm-m.

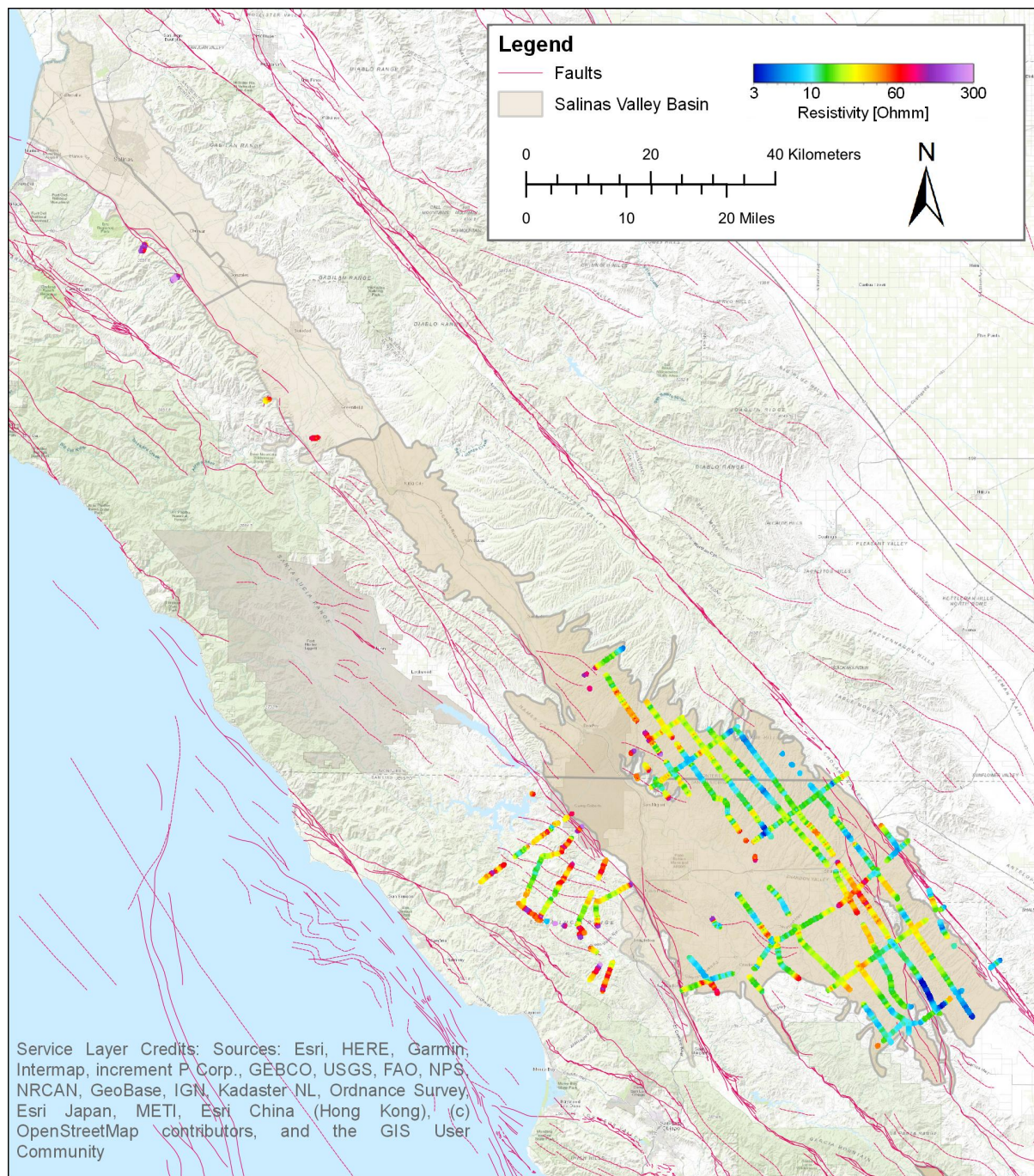


Figure 4-7 Mean resistivity plan-view map in the elevation interval 360-380 m (1,181-1,247ft) amsl. The colors represent the resistivity, with blue colors representing the lower resistivities, below 10 ohm-m, the yellow and green colors representing the moderate resistivities, between 10 and 50 ohm-m, and the orange and red colors representing the higher resistivities, over 50 ohm-m.

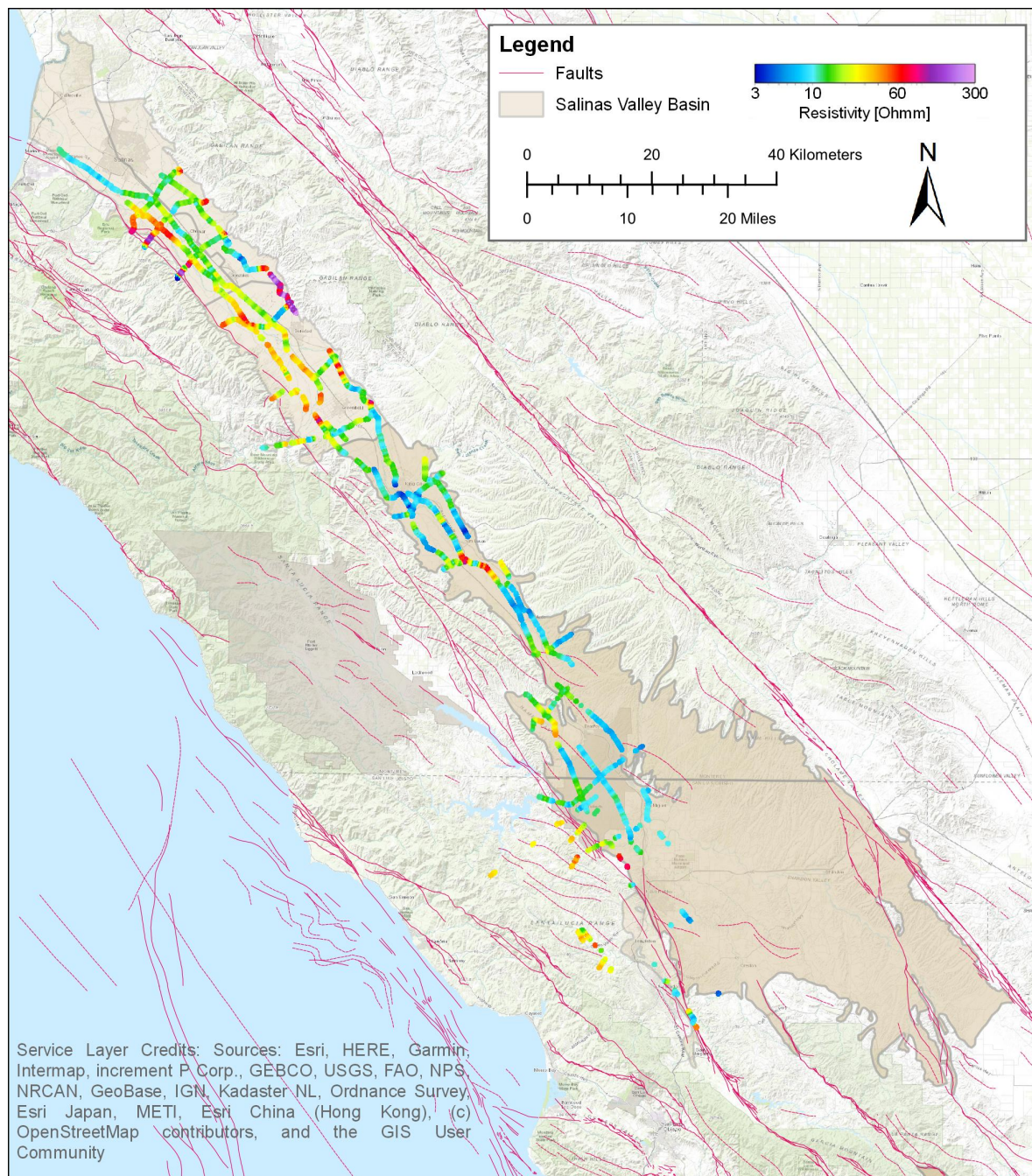


Figure 4-8 Mean resistivity plan-view map in the elevation interval -20 m to 0 m (-66 ft to 0 ft) amsl. The colors represent the resistivity, with blue colors representing the lower resistivities, below 10 ohm-m, the yellow and green colors representing the moderate resistivities, between 10 and 50 ohm-m, and the orange and red colors representing the higher resistivities, over 50 ohm-m.

5. LITHOLOGY MODEL

Lithology Transform and Interpretation Disclaimer

This report provides a resistivity-to-lithology transform and applies it to interpret the AEM resistivity data for lithology. The lithology transform and interpretation are based on available existing supporting data and are designed for informational purposes only. These resources are not intended for regulatory purposes as part of the Sustainable Groundwater Management Act. The Department of Water Resources makes no warranties, representations or guarantees, either expressed or implied, as to the accuracy, completeness, correctness, or timeliness of the information that is presented in the lithology transform and lithology interpretations provided in this report, nor accepts or assumes any liability arising from use of this report or underlying data.

5.1 Introduction

The resistivity values estimated using the AEM method provide value for groundwater management because of the relationship between electrical resistivity and subsurface properties of interest: these include the degree of saturation, groundwater salinity, and lithology. Generally, resistivity will decrease with an increase in fine sediment, salinity, and saturation. The relationship between resistivity values, lithology, and salinity can be seen in Figure 5-1, where the resistivity range corresponding to gravel and sand is higher than that of glacial tills and higher still than that of clays. Similarly, saltwater has a much lower resistivity than does freshwater. Consolidated rocks such as granite will typically have very high resistivities. Shales, on the other hand, can take on a wide range of resistivity values.

The wide range of resistivity values spanned by each bar in Figure 5-1 (most spanning over an order of magnitude) underscores the variable and site-specific nature of the relationship between resistivity and earth materials. Locally variable conditions can cause coarse sediments to have higher resistivity in some areas than in others, and mixtures of sediments (e.g., glacial till) result in resistivity values between those of coarse and fine.

The sharp resistivity model from the data processing and inversion (Section 4.2.1) was used for developing the resistivity-to-lithology transform, since the model prefers to keep resistivity values consistent, but can also accommodate lateral and horizontal variations. The sharp inversion model has 30 layers, with the first layer thickness of 2 m (7 ft), with the layers gradually increasing with depth to 600 meters (1,970 ft); however, the lower boundary in the resistivity-to-lithology transform was set as the DOI which extends to depths of as much as 600 meters (1,970 ft) (Section 4.2.2).

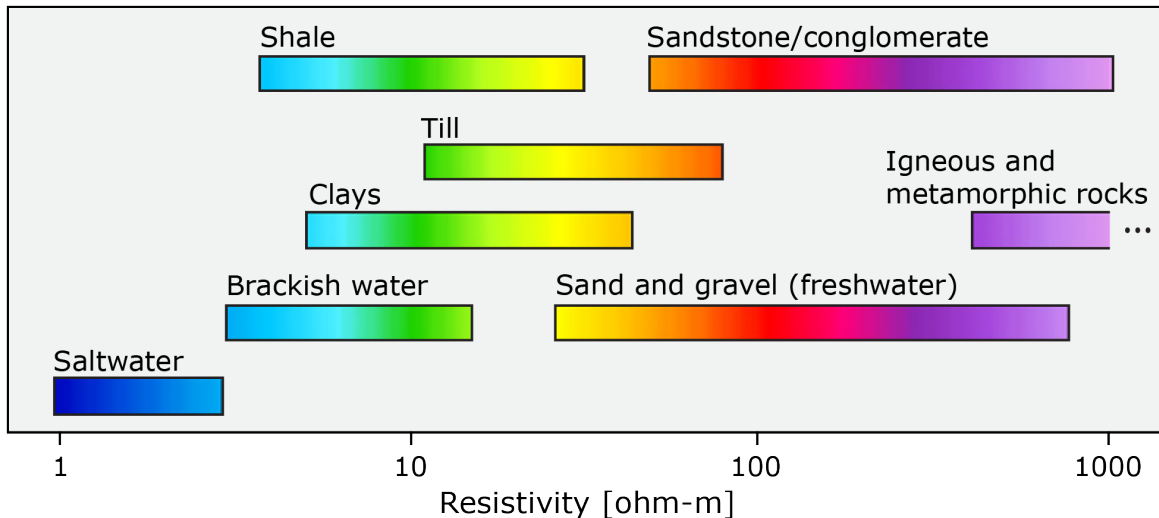


Figure 5-1 Typical relationship between resistivity, lithology, and salinity (after Palacky, 1987).

Establishing a transform to predict lithology from resistivity is a challenging task, because (1) in addition to lithology, the resistivity measurement also depends on other subsurface properties (water saturation and water quality) and (2) the relationship between resistivity and lithology varies spatially. A successful transform should address both of these variables. To predict the lithology using the resistivity models resulting from the AEM surveys in the Salinas Valley Groundwater Basin, a 3D grid of translator functions was applied. The translator functions in the grid were allowed to vary spatially and were calibrated using lithology data from boreholes in the survey area, allowing the resistivity-to-lithology to implicitly account for changes in resistivity due to changes in salinity and saturation, as well as to regional variability in the resistivity-lithology relationship. This section provides a summary of the methods and results of the resistivity-to-lithology transform. A detailed description of the theory, methods and results from the lithology transform are presented in Appendix 4. The lithology transform results and uncertainty for each line is shown on the profiles presented in Appendix 8.

5.2 Resistivity-to-Lithology Transform Methodology

The resistivity-to-lithology transform used in the Salinas Valley Groundwater Basin follows a methodology specifically developed for large AEM datasets (see Foged et al., 2014), using Aarhus Workbench Hydro Structural Modeling module. The resistivity models produced from inversion (Section 4) are used along with well completion report lithology log data (Section 2) to optimize a set of translator functions, each of which can map the resistivity of a depth interval (resistivity model layer) to the amount of coarse material, quantified as the coarse fraction (CF) within the same resistivity model layer. The process is as follows:

1. Simplify lithologic texture descriptions into a binary coarse/fine format
2. Establish a grid of translator functions

3. Best-fit optimization of translator functions using resistivity and simplified lithology to translate the resistivity model to coarse fraction along flight lines
4. Calculate coarse fraction lithology model uncertainty

First, the texture description from each depth interval from each lithology log was aggregated into either “fine” or “coarse”; where fine corresponds to a CF of 0, and coarse corresponds to a CF of 1. Fine materials were considered to include clay and silt sediments (lower permeability), while coarse materials were considered to include sand and gravel (higher permeability). As an intermediary step, the lithology log descriptions were first simplified to four texture categories: fine, fine with coarse, coarse with fine, and coarse. Texture descriptions from lithology logs within 800 m (2,625 ft) of the flown flight lines were used in the analysis. In total, there were 785 lithology logs, resulting in 14,517 separate relationships used for the calculations.

Next, the grid of translator functions was established. The grid was set with a lateral spacing of 900 m (2,953 ft) and a vertical spacing corresponding to the thickness of the resistivity model, i.e., having increased spacing with depth. In this project, the sharp resistivity model was used for the resistivity-to-lithology transform. This model has a first layer thickness of 2 m (7 ft), with layer thickness increasing with depth; however, the lower boundary in the resistivity-to-lithology transform was set as the DOI (Section 4.2.2). Due to the large area covered by the flight lines, the grid of translator functions was divided up into eight sectors, in each of which the transform was optimized separately (see Appendix 4).

Third, each translator function in the grid is optimized to best-fit using nearby resistivity models from the survey area and the simplified texture description from nearby lithology logs. Each translator function has the form as in Figure 5-2. Nearby resistivity values are input into each translator function to predict the CF. Predicted CF values are compared to the simplified texture values from nearby lithology logs, and the translator function is adjusted, through an automated process, to minimize the difference between the CF in the lithology logs and the predicted CF from the translator function. The translator function provides a lower resistivity limit m_{lower} , where all layers with a resistivity lower than this limit will contain only fine sediments, and an upper resistivity limit, m_{upper} , where all layers with a resistivity higher than this limit will contain no fine sediments.

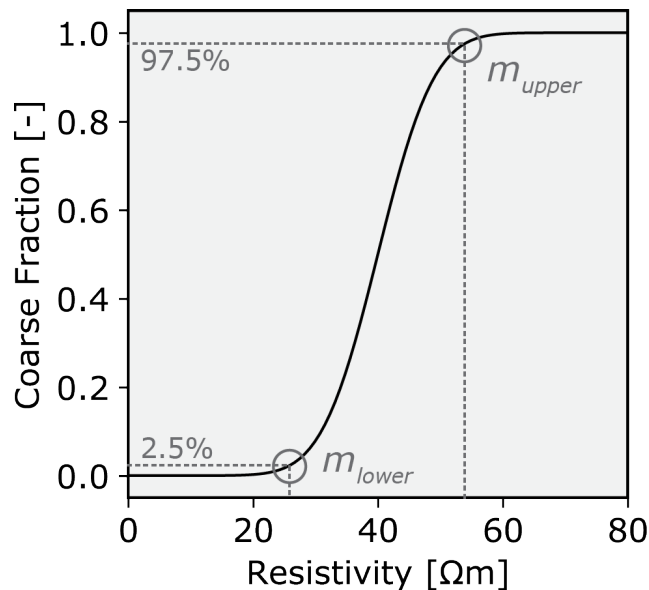


Figure 5-2 An example of a single coarse fraction translator function (after Foged et al., 2014) in the 3D grid. The coarse fraction (CF) ranges from 0 (minimal coarse material) to 1 (coarse dominated). The value m_{lower} represents the lower value where all resistivities below this value represent layers containing only clay, and m_{upper} represents the upper value, where all resistivities higher than this value represents layers containing no clay. In this example, the lower limit is at 25 ohm-m and the upper limit is at 55 ohm-m.

This process is continued until the total residual difference between the predicted and lithology log CF is no longer reduced. The result is that along each of the flight lines a coarse fraction lithology is plotted from the automated iterative process of comparing simplified texture descriptions from nearby lithology logs to the sharp resistivity model.

The final step is to calculate the coarse fraction model uncertainty. The uncertainty is based on the standard deviation from the 30-layer sharp resistivity model. The coarse fraction is calculated for the upper and lower resistivity error limit, providing an upper and lower limit for the coarse fraction. This is converted to a standard deviation factor for the coarse fraction, typically between 1.0 and 1.3, where 1.0 is the most certain with uncertainty increasing as the standard deviation factor increases.

5.3 Transform Results

Figure 5-3 contains a selected profile along a flight line in the Salinas Valley, which shows the lithology model resulting from the resistivity-to-lithology transform. The lithology models for all flown sections are presented in Appendix 8.

The initial results from the lithology model illustrate the viability in utilizing this approach applied to AEM data in the survey area. The model in general had a good correlation between coarse fraction and resistivity values. However, as the survey is reconnaissance level with a wide flight line spacing, the results of the resistivity-to-

lithology transform can only be applied directly along the flight lines; variations away from the flight lines are unknown.

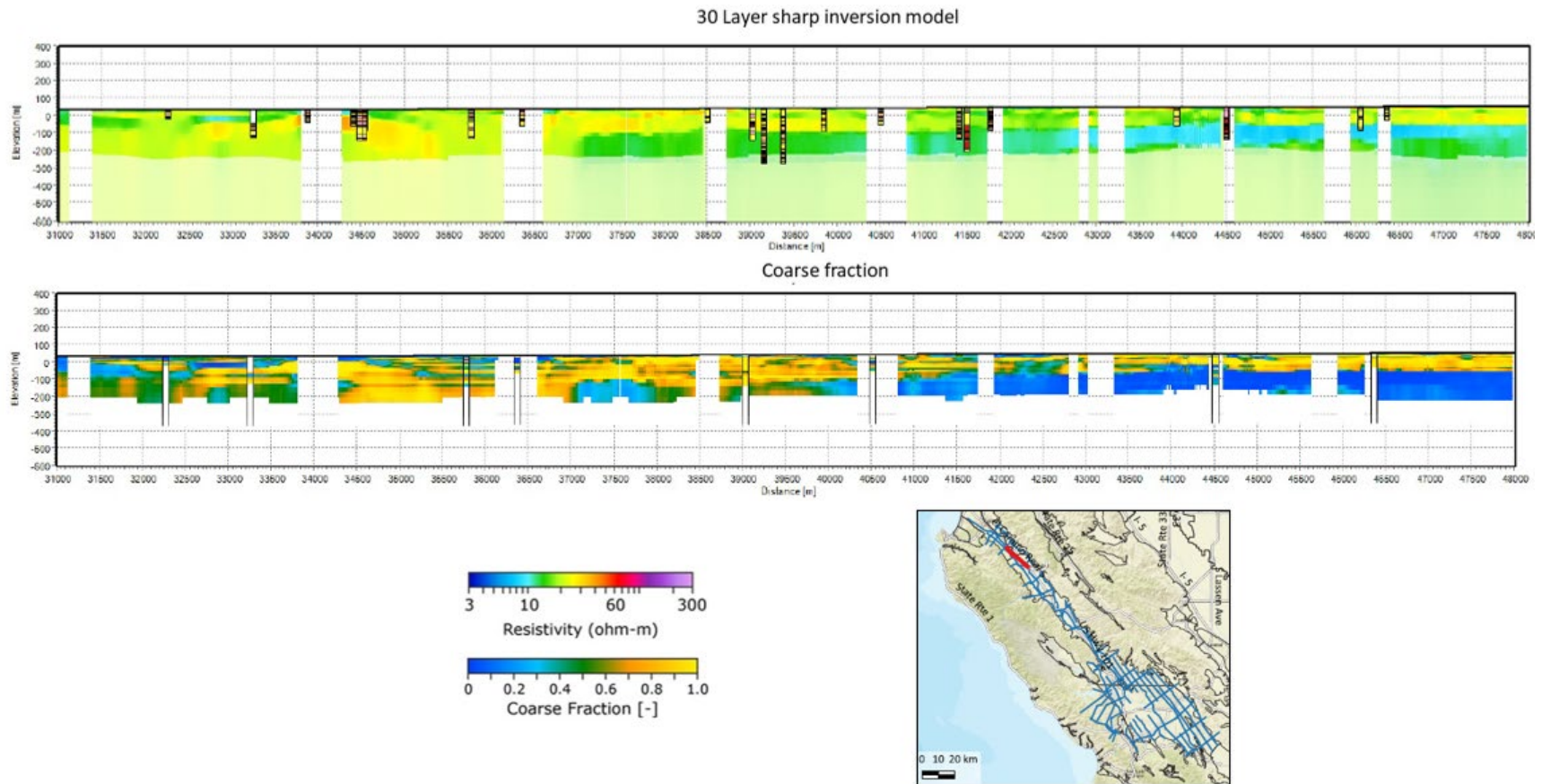


Figure 5-3 Lithology model resulting from the resistivity-to-lithology transform along Profile 103500. The yellow colors show the sediments/materials with high coarse content (CF= 1.0) transitioning to the dark blue colors showing sediments with the highest clay content (CF= 0.0) The vertical columns show the accumulated coarse thickness as calculated in the individual lithology logs.

5.4 Specific Cases

Specific cases that can affect resistivity measurements beyond the lithology include, but are not limited to, the degree of sediment saturation, presence of saline water, and the degree of consolidation (bedrock). These specific cases are discussed in the following section.

5.4.1 Saturated and Unsaturated Sediments

Resistivity is not only influenced by the lithology but also by the water quality and degree of saturation in the subsurface. Unsaturated sediments tend to have a higher resistivity than saturated sediment. This difference in the rock physics relationship between saturated and unsaturated zones can be taken into consideration in the translator function, where a separate translator function is produced for the unsaturated and saturated zone. Separating the unsaturated and saturated zones requires information on the elevation of the water table at the location of each well used in the transform; these data are primarily obtained through water level measurements in unconfined aquifers. In the case of the Salinas Valley, it was determined that an insufficient density of water level data was available to reliably estimate the water table elevation across the survey area to separate the saturated from the unsaturated sediments in the resistivity-to-lithology transform. However, even without sufficient information on the water table elevation, through use of the 3D grid of translator functions, the resistivity-to-lithology transform is still able to implicitly account for spatial variation in the depth to saturated sediments.

Figure 5-4 shows a schematic of the grid of translator functions above and below the water table. The colored bars, representing the resistivity models produced from AEM data, have warmer colors (higher resistivity) above the water table, shown as a blue line, than below the water table. The nodes of the grid of translator functions, shown as black dots, are separated laterally by 900 m and vertically by the thickness of each resistivity model cell, which increases with depth. It is noted that, while the translator function nodes are shown on top of the resistivity model cells in this two-dimensional schematic, the nodes of the applied translator grid in 3D did not necessarily intersect a cell in the resistivity model. At each grid node, a translator function (with the shape of the curve in Figure 5-2) is fit to the borehole lithology and resistivity data within the same depth interval. Because each translator function is fit separately, a different transform can result above and below the water table.

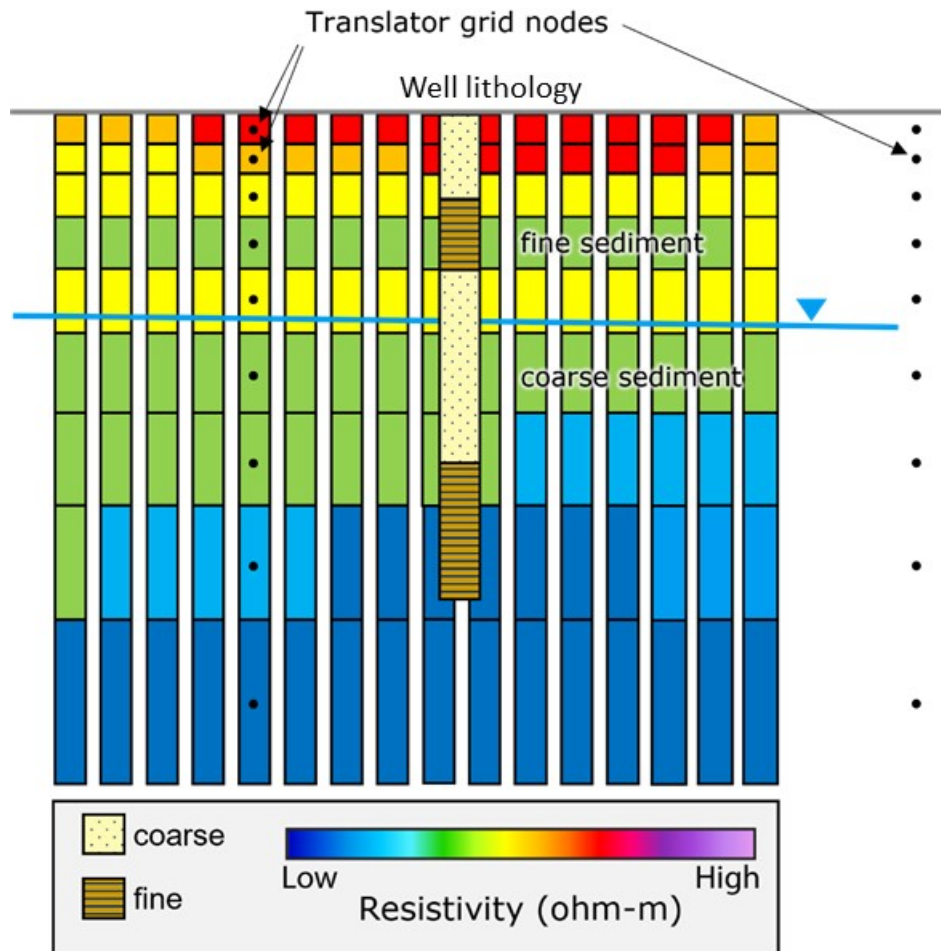


Figure 5-4 Schematic demonstrating the ability of the resistivity-to-lithology transform to implicitly account for the change from unsaturated to saturated sediments. The well shows the simplified lithology from log descriptions.

In the case of Figure 5-4, even if the depth to the water table is unknown, the translator functions above the water table will be fit to the generally higher resistivity values, while those below the water table will be fit to the lower resistivity values there. While the transform can accommodate a small to moderate groundwater gradient in the boundary between unsaturated and saturated sediment, it should be noted that because the grid of translator functions has a lateral spacing of 900 m, a steep gradient is expected to cause some smearing in the lithology model resulting from the resistivity-to-lithology transform.

5.4.2 Saline Water

Groundwater salinity can also influence the observed resistivity in the saturated zone. Groundwater with higher TDS values will have lower resistivity. As with the transition from unsaturated to saturated zones, the resistivity-to-lithology transform can implicitly

account for variations in salinity, assuming (1) the salinity does not change rapidly over a short lateral distance, (2) the salinity is not very high, and (3) the salinity of the coarser sediment is similar or lower than that of the fine sediment. If the salinity varies rapidly over a short distance, smearing will occur in the translator function in a similar way as when the water table gradient is steep. Once the salinity becomes high (about 3,000 mg/L), differences in the resistivity between coarse and fine materials are damped. Finally, if the salinity of the coarse sediment is higher than that of the fine sediment, the translator function will fail, since the function (Figure 5-2) assumes that coarser sediment is more resistive than finer sediment. Coarse sediment may contain more saline water than fine sediment, for example, in areas affected by seawater intrusion, since the water saturating coarse sediments (aquifer) is more readily displaced by intruding seawater than the water saturating fine sediments (aquitard).

To circumvent potential challenges to the resistivity-to-lithology transform in areas of elevated salinity, the resistivity-to-lithology transform can be divided into different zones (e.g., a freshwater zone and a brackish zone), and each zone can be evaluated for whether the resistivity-to-lithology transform should be applied. In the areas of the Salinas Valley near the flight lines, the measured TDS ranged from 300 to 2,800 mg/L (Figure 2-3) and was determined not to have a significant influence on the observed resistivity value.

5.4.3 Consolidated rocks

Consolidated rocks (i.e., bedrock) have different hydraulic properties than unconsolidated sediment, often forming a hydraulic barrier within a groundwater basin. The resistivity-to-lithology transform applied in this project was developed for unconsolidated sediments: the translator function considers a spectrum of fine to coarse sediment.

Since many igneous and metamorphic rocks tend to have a high resistivity (Figure 5-1), the resistivity-to-lithology transform will interpret these rocks as coarse sediment (a high CF value). Given their high resistivity, these rocks can often be distinguished from unconsolidated materials in the resistivity models. On the other hand, consolidated sedimentary rocks, including shales and sandstones, take on a wide range of resistivity values that may be similar to those of unconsolidated sediment; the transform will interpret these rocks as either fine or coarse sediment, depending on their resistivity values in comparison to those of nearby unconsolidated sediment.

When analyzing the lithology model resulting from the resistivity-to-lithology transform, it is important to first remove any areas corresponding to consolidated rocks. Given the variable and region-specific nature of the relationship between resistivity and consolidated rocks, the task of removing consolidated rocks from the resistivity-to-lithology transform was not conducted here; rather, it is left to practitioners with local expertise and understanding of the geologic setting.

6. INITIAL HYDROSTRATIGRAPHIC MODEL

6.1 Introduction

The data acquired during an AEM survey can provide valuable information for developing or refining a hydrostratigraphic model of the surveyed area. However, due to the large amounts of data acquired during a typical AEM survey, including this project, manually interpreting the hydrostratigraphic units corresponding to the resistivity or lithology model can be labor intensive.

Here, an automated approach was applied to produce a model consisting of zones of similar properties from a resistivity model and a lithology model. This model could be used to help develop a better understanding of the regional hydrostratigraphy, or as the basis for a numerical groundwater flow model. The approach uses a clustering algorithm, which classifies a set of data points into a predefined number of groups with similar properties. It is a widely used approach for pattern recognition, image processing and analysis of large datasets where grouping is required. Since resistivity is related to the hydrogeologic properties of interest, the clustering approach relies on the assumption that groups defined from resistivity and borehole lithology data also have similar hydrogeologic properties.

There are other approaches, not pursued here, that can provide an automated conversion of AEM data into an interpreted hydrostratigraphic model. These include, for example, the use of multipoint statistics (Gulbrandsen et al, 2021) or the Octree algorithm for 3D voxel modeling (Jorgensen et al, 2013). It is not within the scope of this project to provide a critical review of the different methodologies that can be applied in the interpretation of AEM data to a hydrostratigraphic model; rather, the clustering approach used here is presented as an example of an approach that could be used, illustrating the value of AEM data as input to a 3D hydrostratigraphic model. The clustering approach used for this project was chosen for the following reasons:

- (1) It provides an automated grouping providing a representation of the hydrostratigraphy
- (2) The grouping is data driven, reproducible, and is geographically and depth independent
- (3) The process requires only the measured resistivity and lithology log data

This section provides a description of the clustering methodology and the resulting hydrostratigraphic model in the Salinas Valley Groundwater Basin.

6.2 Methodology

The clustering modeling methodology, developed by Marker et al. (2015), consists of an algorithm that pairs a lithology model, outlined in Section 5, with a resistivity model to produce a defined number of groups, each of which consists of similar resistivity and lithology values. The resistivity value for each cell in the sharp resistivity model is paired with the corresponding lithology model CF value across the entire basin. The

result is a set of resistivity-CF pairs that can be visualized as a scatter plot. To aggregate the groups of similar resistivity-lithology value pairs, a clustering algorithm is applied to the pairs, with a predetermined user-defined number of groups, or clusters. The resultant groups then represent points with similar resistivity and lithology and are thus presumed to have similar hydrogeological properties.

At first glance, combining the CF values with the resistivity values that produced said CF values may seem circular. However, as described in Section 5, the lithology data used in the resistivity-to-lithology transform is simplified as either coarse or fine. This simplification is necessary for the computation-intensive numerical calculations in the transform; however, details in the lithology information are lost in the process, resulting in some details contained within the resistivity model being muted or lost in the lithology model. By adding the resistivity information back into the clustering process, these details can be captured in the resultant initial hydrostratigraphic model.

The process of developing the initial hydrostratigraphic model begins with determining the number of groups, or clusters, to be identified. Determining the number of groups requires an understanding of the depositional environment(s) of the groundwater basin, including the basin's geological complexity as well as other parameters which could influence resistivity, such as changes in water quality (both horizontal and vertical) and the depth to saturated sediment. If the basin hydrogeology changes significantly across the survey area, the application of the clustering algorithm can be divided into multiple zones.

Once the number of clusters for each cluster model has been determined, each resistivity-CF pair from the resistivity model and corresponding lithology model are entered into the clustering algorithm, which iteratively works to identify the best partitions between groups. The results of the clustering algorithm in the Salinas Valley are shown as a scatterplot in Figure 6-2. The CF value for each resistivity-CF pair is shown along the x-axis, while resistivity value is shown on the y-axis. Each point is colored according to the group it was placed in. Cluster 1, represented by 25% of all the clustered datapoints, contains the lowest resistivities and lowest CF. This cluster represents the units with the highest amount of clay materials in the initial hydrostratigraphic model. Each following group has a sequentially higher CF and resistivity. A more detailed description of the clustering process is presented in Appendix 5.

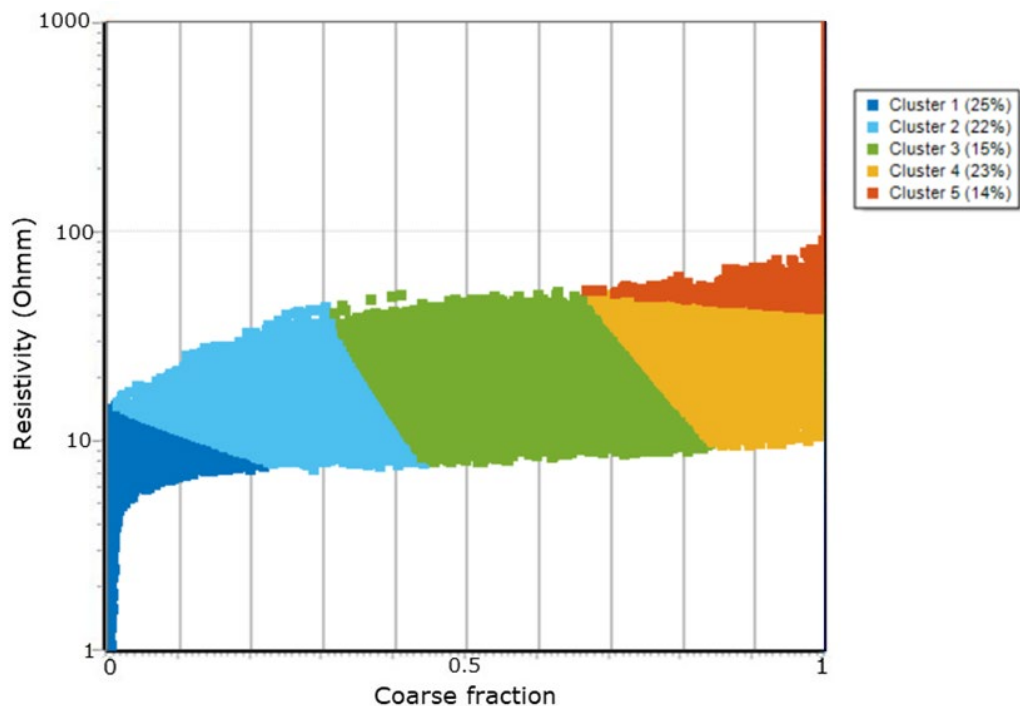


Figure 6-1 The results of the clustering algorithm applied to the data in the Salinas Valley Basin. Percentages in the legend indicate the ratio of resistivity-CF pairs included in the respective group. Note that there is overlap of points within the cluster model.

6.3 Clustering Algorithm Implementation

The first step in the cluster modeling process for the Salinas Valley Groundwater Basin was to determine whether the basin should be divided into separate regions due to changes in the hydrostratigraphy. This included the consideration of whether the unsaturated zone should be clustered separately from the saturated zone. In this case, the depth to the water table ranges from near surface to about 80 meters below ground surface. Generally, the water table is less than 30 meters below ground surface, where only in the northwestern portion of the basin does the depth to the water table exceed 50 meters below ground surface Figure 2-2. Since the depth to the water table was less than 30 meters for the majority of the basin, it was determined that the unsaturated and saturated zone should not be separated for the clustering process.

Groundwater salinity was also evaluated. Available TDS measurements show a relatively small range in salinity around the flight lines in the Salinas Valley, with TDS values between 500 and 3,000 mg/L (Figure 2-3). There is observed very low resistivity, below 5 ohmm, on the westernmost 3 kilometers of Line 103500, which is the line that extends closest to Monterey Bay (see Appendix 6). The low resistivity here could be due to groundwater salinity, however, there were no TDS measurements collected near this part of the flight line, and thus this cannot be confirmed. However,

the rest of the basin where the AEM data was collected was not significantly affected. Therefore, it was determined that salinity did not have a significant influence on resistivity and subsequently did not affect the cluster modeling process.

Five groups were chosen for the clustering algorithm to identify from the resistivity-CF pairs. This decision was based on the observed hydrogeology of the basin, where the different groups could accommodate the different hydrogeology, including coarse layers above and below the aquifer, mixed units, silty fines, clayey fines and the bedrock along the sides of the basin. The choice of five groups was used as a starting point producing an initial hydrostratigraphic model, which was subsequently evaluated as to whether a new iteration with more or less cluster groups was needed.

6.4 Results

The five different cluster groups representing the initial hydrostratigraphic model layers were plotted as profiles along all the flight lines where AEM data were acquired. The initial hydrostratigraphic model was evaluated for how well the chosen five-group model represents the hydrostratigraphy and whether a different number of clusters was needed. A profile showing the resultant initial hydrostratigraphic model is shown on Figure 6-2. Evaluation of the profile lines suggests that the clustering resulted in reasonable, continuous layers and the layering correlated well with the basin's geological features. Thus, it was determined that a second iteration with a different number of clusters was not needed. Profiles of all the initial hydrostratigraphic models are shown on the data sheets in Appendix 9.

The uncertainty for the clustering model is presented as an index showing how close the data point is to an adjoining cluster boundary. The basis of the uncertainty index is that the closer a specific point is to another cluster boundary, the greater the chance is that that specific point may have hydrostratigraphic properties closer to the neighbor cluster, and the lower the numeric value. Thus, points that have an uncertainty index of over 0.5 are closer to the cluster center than the neighboring cluster and have a high certainty of belonging in that cluster. However, points with an uncertainty index of under 0.2 will be near the neighboring cluster and thus have much higher uncertainty whether that specific point belongs in its own cluster or the neighboring cluster. An example of the results showing the uncertainty index is shown on Figure 6-2, and the uncertainty index for all the clustering results are shown on the profiles on the data sheets in Appendix 9.

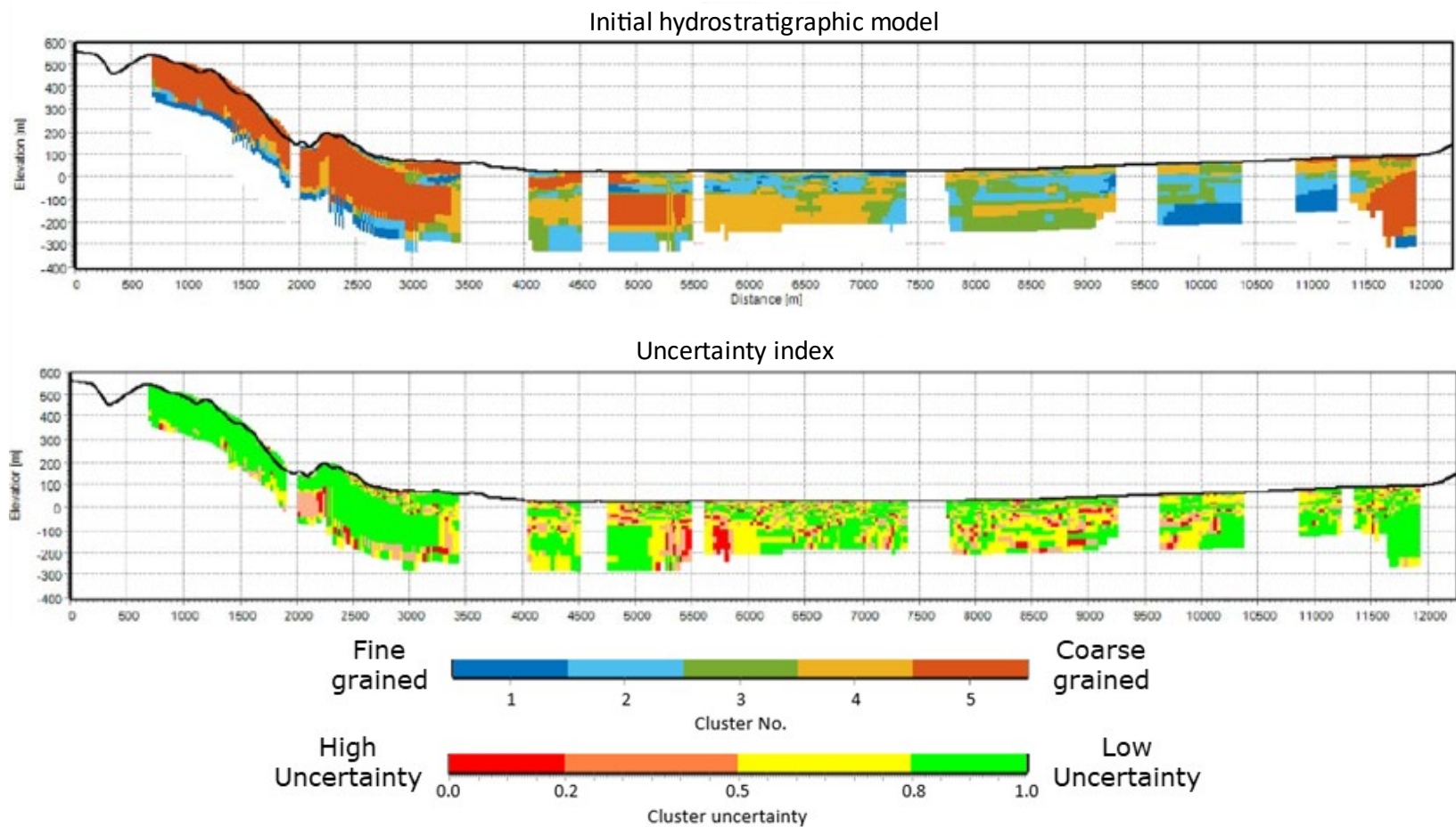


Figure 6-2 Initial hydrostratigraphic model shown along Section 102500. The top bar shows the distribution of the different groups along the section and the bottom bar shows the associated uncertainty, where the red colors represent the areas of the model most uncertain and the green color represents the areas most certain. The location of the section is shown on Figure 4-6.

6.5 Perspectives on the Initial Hydrostratigraphic Model

The cluster modeling process provides the opportunity to handle a large amount of AEM data produced from an AEM survey in order to construct an initial hydrostratigraphic model. The model is generated solely on a statistical analysis of the gathered data and its relationship with observed coarse versus fine materials, and is completely independent from external biases that affect where model boundaries are drawn. As a result, the hydrostratigraphic model resulting from the clustering approach is reproducible.

The main limitation for the use of the clustering model to develop an initial hydrostratigraphic model is the wide spacing of the AEM flight lines. Ideally, the AEM line spacing should be close together, allowing for a 3D AEM model to be developed. With a line spacing in a 2 x 8 mile grid, the spacing is too large to extrapolate the data to the area between the grid lines. Thus, the results of the initial hydrostratigraphic model are only representative along the line where AEM data has been collected. A closer line spacing, on the order of 250 m, will allow for the data to be interpolated between the lines into a 3D model grid, providing the possibility for a direct input into a numerical flow model.

The development of the hydrostratigraphic model is an iterative process. For the purpose of this project, only one iteration was conducted and thus, the result is considered to be an initial hydrostratigraphic model. More iterations could be conducted and compared with the known hydrostratigraphy of the basin to provide more realizations. In addition, in the process outlined by Marker et al. (2015), cluster models with varying number of clusters can be evaluated in the flow model calibration process. In this case, the flow model could be used as input to help define the necessary number of clusters in the hydrostratigraphic model when used as input to a numerical flow model. This is an opportunity that could be realized with further infill along the flight lines where AEM data is interpreted.

7. REFERENCES

Auken, E., A.V. Christiansen, C. Kirkegaard, G. Fiandaca, C. Schamper, A.A. Behroozmand, et al. 2015. An overview of a highly versatile forward and stable inverse algorithm for airborne, ground-based and borehole electromagnetic and electric data. *Explor. Geophys.* 46:223–235. doi: 10.1071/EG13097

California Geological Survey (CGS). 2010. Geologic Map of California. Scale 1:750,000.

DWR. 2020. California's Groundwater – Bulletin 118 – Update 2020.

Foged, N., P. A. Marker, A. V. Christiansen, P. Bauer-Gottwein, F. Jørgensen, A-S. Høyer, and E. Auken, 2014. Large-scale 3-D modeling by integration of resistivity models and borehole data through inversion. *Hydrology and Earth System Sciences* 18, no. 11.

Gulbrandsen, M., Rasmussen, T. and Jensen, N., 2021. Indian Wells Valley – The Multiple Point Statistics Method. The Groundwater Architecture Project (GAP): Utilizing advanced geophysical and computational methods for the development of hydrogeologic conceptual models. <https://mapwater.stanford.edu/>.

Jorgensen, F., Moller, R., Nebel, L, Jensen, N., Christiansen, A. and Sandersen, P. 2013. A method for cognitive 3D geological voxel modelling of AEM data. *Bull. Eng. Geol. Environ.* DOI 10.1007/s10064-013-0487-2.

Marker, P.A., Foged, N., He, X., Christiansen, A.V., Refsgaard, J.C., Auken, E., Bauer-Gottwein, P., 2015. An automated method to build groundwater model hydrostratigraphy from airborne electromagnetic data and lithological borehole logs. 2015. *Hydrological Earth System Science Discussions*, vol. 12, pp. 1555-1598.

Rusydi, A.F., 2018. Correlation between conductivity and total dissolved solids in various type of water: A review. *IOP Conference Series: Earth Environmental Science* 118 012019.

Schamper C., Pedersen, J., Auken, E., Christiansen, A., Vittecoq, B., Deparis, J., Jaouen, T., Lacquement, F., Nehlig, P., Perrin, J. and Reninger, P. (2013). Airborne Transient EM Methods and Their Applications for Coastal Groundwater Investigations. In: Wetzelhuetter C. (eds) *Groundwater in the Coastal Zones of Asia-Pacific*. Coastal Research Library, vol 7. Springer, Dordrecht.

Viezzoli, A., Christiansen, A. V., Auken, E., and Sørensen, K. I., 2008, Quasi-3D modeling of airborne TEM data by spatially constrained inversion: *Geophysics*, 73, F105–F113. doi:10.1190/1.2895521

Vignoli, G., Fiandaca, G., Christiansen, A. V., Kirkegaard, C., and Auken, E., 2015, Sharp Spatially Constrained Inversion with applications to transient electromagnetic data: *Geophysical Prospecting*, 63, pp 243-255. doi: 10.1111/1365-2478.12185

Ward SH, Hohmann GW (1988) Electromagnetic theory for geophysical applications. *Electromagnetic Methods in Applied Geophysics*, vol. 1, (ed MN Nabighian), pp 131–311, SEG publication.