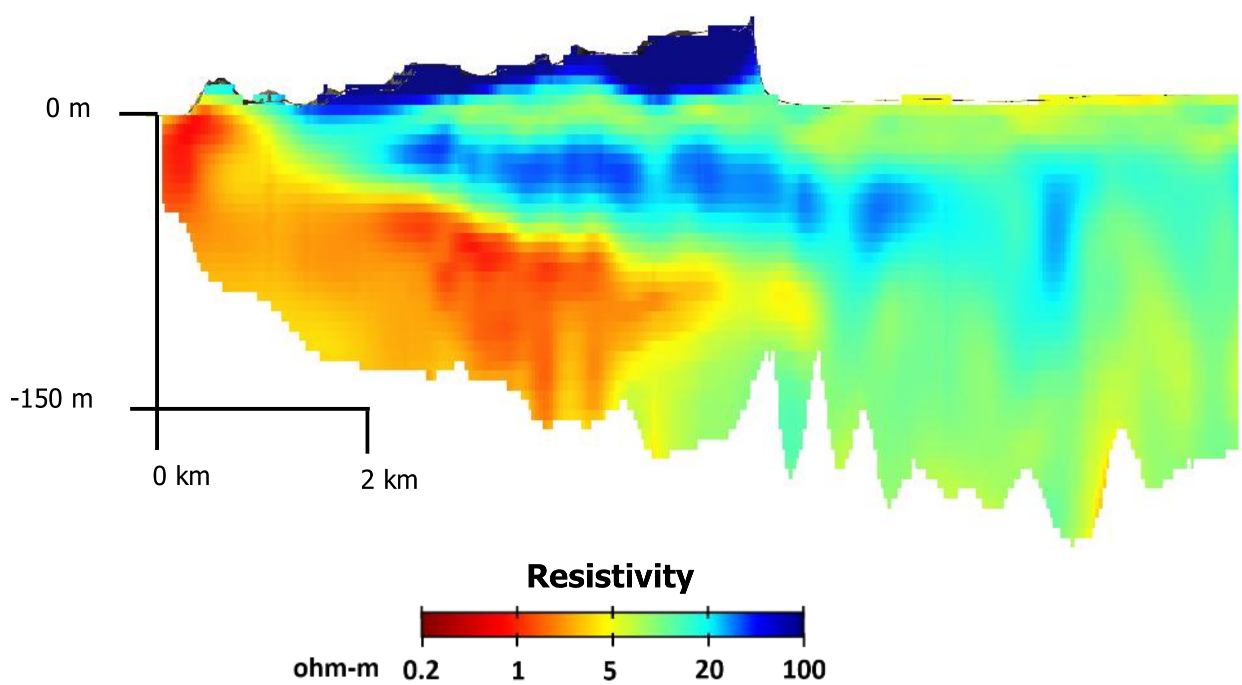
Interpretation of Hydrostratigraphy and Water Quality from AEM Data Collected in the Northern Salinas Valley, CA

Ian Gottschalk, Rosemary Knight, Stanford University, Stanford, CA
Ted Asch, Jared Abraham, Jim Cannia, Aqua Geo Frameworks, Mitchell, NE
15 March 2018



Prepared for

Marina Coast Water District
11 Reservation Road
Marina, CA, 93933

Table of Contents

Cover Figure: Cross-section of resistivity measurements derived from the airborne electromagnetic survey conducted in May 2017 in the Northern Salinas Valley. The cross-section runs roughly perpendicular to the coast in the Marina area, with the coast on the left hand side of the figure. Low resistivity values in red reveal the intrusion of saline ocean water into the coastal aquifers.

Introduction

Groundwater management, in the Monterey area of California, requires an accurate understanding of the hydrostratigraphy of the coastal aquifer system, as well as an understanding of the groundwater quality variability within that system. The hydraulic properties of, and connectivity between, the individual units in the aquifer system determine potential routes for the movement of groundwater within and between aquifers. An understanding of the distribution of water quality within the aquifer system and an understanding of the hydrostratigraphy of the system are needed to evaluate the current state of groundwater resources, and to assess the potential impact of any proposed activity on the groundwater resources in the area.

The focus of this study is the Northern Salinas Valley. Figure 1 shows the specific region of interest outlined in pink. The orange contour shows the extent of saltwater intrusion into the uppermost aquifers in this area, as determined from well data by the Monterey County Water Resources Agency as the regions where groundwater contains concentrations of chloride greater than 500 mg/L. But there is some question as to whether this contour accurately captures the extent of saltwater intrusion into these aquifers. The detection of water with anomalously low concentrations of total dissolved solids in five newly constructed monitoring well clusters suggests the presence of isolated lenses of fresher groundwater in the Dune Sand Aquifer and Perched Dune Sand Aquifer (outlined in light blue) and in the 180-Foot Aquifer (outlined in dark blue) (Hopkins Groundwater Consultants, 2016). The locations of seven wells from the Monterey Peninsula Water Supply Project (MPWSP) are also shown in Figure 1 as red diamonds, and wells owned by the Marina Coast Water District (MCWD) are shown as green circles. The two groundwater subbasins in the region of interest—the Monterey Subbasin and the 180/400 Aquifer Subbasin—are outlined in purple and blue, respectively.

The objective of this study was to use the geophysical method, airborne electromagnetics (AEM), to evaluate the current understanding of the hydrostratigraphy in this area and to interpret the distribution of groundwater quality indicated by available well data. To evaluate the understanding of the hydrostratigraphy, a hydrostratigraphic model of the region of interest was first built using existing data, and was then updated with the information supplied by the AEM data. This approach was followed for two separate initial models. The first initial model was based on the North Marina Groundwater Model (NMGWM), developed by Geoscience Support Services as part of the MPWSP. The second initial model was built in-house using lithology data and hydrostratigraphic interpretations from a variety of previously published reports. Our interpretation of the distribution of groundwater quality in the region is based on statistical relationships built between water quality samples and borehole geophysical data collected in the wells shown in Figure 1.

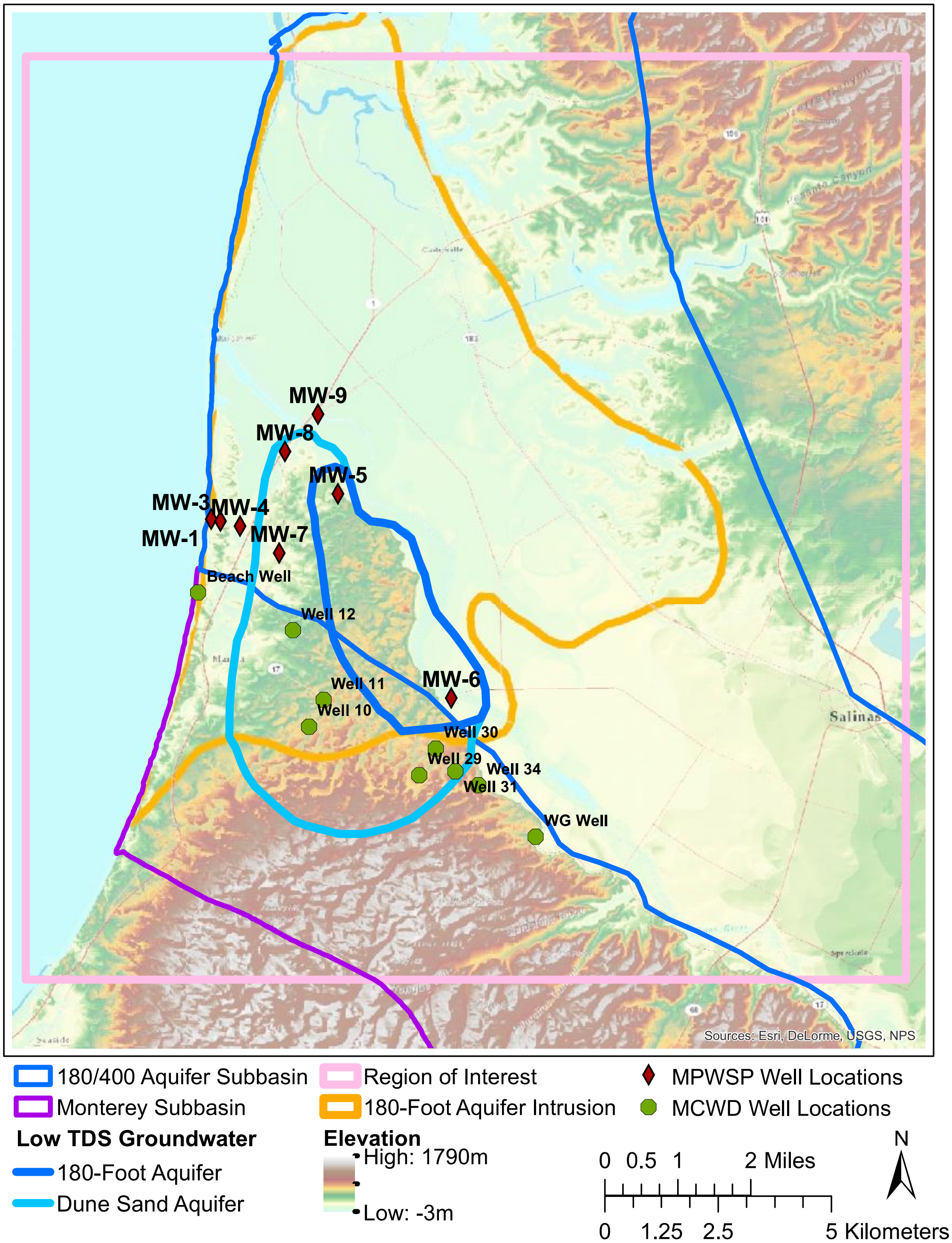


Figure 1: Map of the Northern Salinas Valley with the region of interest outlined in pink. Plotted as red diamonds seven of the eight monitoring wells for the Monterey Peninsula Water Supply Project, which are used in the analysis of this report. The locations of wells owned by Marina Coast Water District (MCWD) are shown as green circles. Outlined in orange is the extent of saltwater intrusion in the uppermost aquifers, as mapped by the Monterey County Water Resources Agency. The light blue and dark blue shapes the center of the figure outline the estimated extent of groundwater with anomalously low TDS concentrations in the Dune Sand Aquifer and the 180-Foot Aquifer, respectively. Outlined in blue and purple are the 180/400 Aquifer Subbasin and the Monterey Subbasin, respectively.

Definitions of Water Quality

Within this report, we have focused on differentiating the quality of groundwater by the concentration of total dissolved solids (TDS). Measurements of TDS are useful for assessing the suitability of groundwater for overlying beneficial land uses including drinking water. The dissolved solids within water are comprised largely of inorganic salts, and, sometimes, minor amounts of organic matter. While the specific salts dissolved in the groundwater may vary between locations, TDS is useful measure to assess the suitability of groundwater for a drinking water source. The cost associated with treating groundwater for municipal or agricultural purposes is also related to the TDS concentration. Finally, TDS concentrations and measurements of electrical conductivity in water are closely related. This relationship exists due to the conduction of electrical current by the dissolved salts within groundwater. For many groundwater sources, a site-specific linear relationship can be constructed between measurements of the electrical conductivity of the water and the TDS concentrations in the water. In this way, electrical measurements of the groundwater can aid interpretation of water quality if site specific data are available. We note that alternative methods exist by which to define groundwater quality. For example, the Monterey County Water Resources Agency uses chloride concentrations to map saltwater intrusion into the Northern Salinas Valley, since high chloride concentrations are indicative of seawater.

In our analysis of the water quality in the region of interest, we have defined four groupings, or ranges, of TDS concentrations: 0-1,000 mg/L, 0-3,000 mg/L, 3,000-10,000 mg/L, and 10,000+ mg/L. These ranges reflect the definitions of groundwater sources created by the State Water Resources Control Board (SWRCB) (2006) and by the United States Environmental Protection Agency (US EPA) (1988). Here, drinking water is considered a subset of a source of drinking water, which is why the TDS ranges defined for drinking water and sources of drinking water overlap. Table 1 shows these TDS ranges and the terms used in this report for water with the corresponding TDS concentration.

TDS range	**Groundwater term in this report**	**Source**
0-1,000 mg/L	Drinking water	Title 22, Article 16, State Water Resources Control Board, 2006
0-3,000 mg/L	Source of drinking water	Title 22, Article 16, State Water Resources Control Board, 2006; SWRCB Resolution 88-63
3,000-10,000 mg/L	Water of potential beneficial use	US EPA, 1988
10,000+ mg/L	Water of limited beneficial use	US EPA, 1988

Table 1: TDS concentration ranges and the term used in this report to refer to water within each TDS concentration range.

Hydrostratigraphy

Previous hydrogeological studies in and around the region of interest provide detailed background information about the regional hydrostratigraphy (Fugro West, Inc., 1995; Harding ESE, 2001; Kennedy/Jenks Consultants, 2004; MACTEC, 2005; Geoscience Support Services, 2014; Hopkins Groundwater Consultants, 2016). Historically, in hydrostratigraphic investigations, the region that lies north of the Salinas River, which comprises most of the Salinas Valley basin, has been treated independently from the region south of the Salinas River, which includes the Marina and Fort Ord areas. While there are geological and geographic differences between the two regions, most of the equivalent aquifers produced for beneficial uses in each region are hydraulically connected. Here, we present a brief review of the hydrostratigrapy in the coastal region of interest, noting major differences between the regions north and south of the Salinas River. The units discussed in this section, are those included in the hydrostratigraphic models developed later in this report. The units are discussed roughly in order of highest to lowest elevation.

Dune Sand Aquifer

The Dune Sand Aquifer is present south of the Salinas River, and is the predominant unconfined aquifer in the Marina and Fort Ord areas. Within much of the Marina and Fort Ord areas, the Dune Sand Aquifer overlies a clay layer known in Fort Ord groundwater investigations as the Fort Ord-Salinas Valley Aquitard (FO-SVA), and known more generally as part of the Salinas Valley Aquitard (SVA). When underlain by the SVA, the Dune Sand Aquifer is also referred to as the Perched Dune Sand Aquifer (Hopkins Groundwater Consultants, 2016), or the A-Aquifer (Ahtna Environmental Inc., 2017). The underlying SVA is considered to create a perched or semi-perched condition for the Dune Sand Aquifer. In June 2017, water table elevations were recorded as high as 28.6 meters above sea level (masl) in the southern Fort Ord area during June, with the groundwater gradient in the aquifer pointing towards the coast.

Near the coast and south of the Salinas River, the SVA thins out, bringing the Dune Sand Aquifer and the underlying Upper 180-Foot Aquifer into hydraulic connection. The thinning of the SVA is coincident with a drop in the hydraulic head in the Dune Sand Aquifer. Here the groundwater enters the underlying Upper 180-Foot Aquifer, and flows southeastward, according to the hydraulic gradient (Ahtna Environmental Inc., 2017). The flow of groundwater from the Dune Sand Aquifer to the Upper 180-Foot Aquifer appears to mound groundwater in the Upper 180-Foot Aquifer near the coast, creating a local groundwater barrier against encroaching saltwater.

Shallow Aquifer (or Perched "A" Aquifer)

The "Shallow Aquifer" (Kennedy/Jenks, 2004) or the Perched "A" Aquifer (Geoscience, 2014) is a shallow surficial aquifer in the Salinas Valley basin north of the Salinas River and overlies the

Salinas Valley Aquitard in some areas (Monterey County Flood Control and Water Conservation District, MCFCWCD, 1960). Typically, low permeability and poor groundwater quality is expected in the aquifer. The aquifer may be salinized due to the buildup of salts from agricultural activities, but is not affected by saltwater intrusion.

Salinas Valley Aquitard (SVA)

The Salinas Valley Aquitard is a laterally extensive clay and sandy clay layer covering much of the Salinas Valley basin, east of Fort Ord, and from the Monterey Bay south past Salinas. It is approximately 30 meters thick west of Salinas (Kennedy/Jenks, 2004). South of the Salinas River, a similar unit of clay is locally called the FO-SVA. Harding, ESE (2001) concluded that the SVA and the FO-SVA are "either the same or at least hydraulically equivalent". Within this report, the two units are referred to collectively as the SVA. In the Salinas Valley basin, the SVA is thicker and relatively flat, while in the Fort Ord area, the SVA is higher in elevation and dips more steeply toward the coast (ibid).

180-Foot Aquifer

The 180-Foot Aquifer underlies the SVA, and is the uppermost aquifer that has historically been used for its groundwater resources. The aquifer ranges from 15 to 45 meters in thickness, and within the Salinas Valley basin, the top is often encountered 30 to 45 meters below ground surface (mbgs) (Kennedy/Jenks 2004). South of the Salinas River, the 180-Foot Aquifer is separated into three units: the Upper 180-Foot Aquifer, the Intermediate 180-Foot Aquitard, and the Lower 180-Foot Aquifer (MACTEC, 2005). The Upper 180-Foot Aquifer, believed to be 6 to 18 m thick (Harding ESE, 2001), is considered to be in hydraulic connection with the Dune Sand Aquifer near the coast, as the SVA thins out. The Intermediate 180-Foot Aquitard, a sequence of silty and clayey beds, hydraulically separates the sandy Upper 180-Foot Aquifer from the gravelly Lower 180-Foot Aquifer throughout most of the Marina and Fort Ord area.

180/400-Foot Aquitard

This aquitard separates the 180-Foot Aquifer from the underlying 400-Foot Aquifer. It is a zone of "discontinuous aquifers and aquitards", of which the aquitards comprise the 180/400-Foot Aquitard (Geoscience, 2014). The discontinuity of the 180/400-Foot Aquitard was documented first by MCFCWCD (1960) and was a subject of focus for Kennedy/Jenks (2004) north of the Salinas River. South of the Salinas River, the 180/400-Foot Aquitard is relatively thin, and has been recorded to pinch out at least within the Main Garrison area of the former Fort Ord (Harding ESE, 2001).

400-Foot Aquifer

This aquifer is areally extensive and is composed of sand and gravel packages, typically encountered between 83 and 143 mbgs (Kennedy/Jenks, 2004). The thickness and depth of encounter are variable. Near Salinas, the aquifer is largely continuous, while near Castroville, it is comprised of multiple sandy packages, separated by thin clay layers. South of the Salinas River, the 400-Foot Aquifer consists of mostly sand.

In regions where the 180/400-Foot Aquitard thins out, the 180-Foot Aquifer and the 400-Foot Aquifer are hydraulically connected. Hydraulic connection will allow groundwater to flow unhindered from the aquifer with higher hydraulic head to the aquifer with lower hydraulic head. Generally speaking, the 400-Foot Aquifer has a lower hydraulic head than the 180-Foot Aquifer. In areas of hydraulic connection between these two aquifers, saline water in the 180-Foot Aquifer, which has been recorded farther inland than in the 400-Foot Aquifer, can migrate vertically into the 400-Foot Aquifer, deteriorating water quality in the aquifer.

400-Foot/Deep Aquitard

Beneath the 400-Foot Aquifer is an aquitard which can be "several hundred feet thick" (Kennedy/Jenks, 2004).

Deep Aquifer

The Deep Aquifer has received different definitions from various reports. Kennedy/Jenks (2004) define the Deep Aquifer as the group of deep aquifers located between the depths of approximately 240 and 460 mbgs.

Ancillary Data

We have assembled from the region of interest a database that includes 318 well locations and corresponding lithology information, borehole geophysical measurements, water quality measurements, and water level measurements. Much of the analysis in this report relies specifically on data collected between 2014 and 2015 as part of the assessment phase of the Monterey Peninsula Water Supply Project (MPSWSP). The locations of the MPWSP wells are shown in Figure 1. We used this information due to the high quality lithology, geophysical, water quality, and water level data collected in the wells.

Lithology

Many of the well locations and the corresponding lithology information came from well completion reports cataloged by the Monterey County Water Resources Agency, who shared the cataloged data with us. Further lithology information was obtained from a study prepared for the Monterey Regional Waste Management District (EMCON Associates, 1991), as part of an ongoing monitoring project in the former Fort Ord (Harding ESE, 2001), and a study prepared for California American Water, as part of the MPWSP (The Hydrogeologic Working Group of the Monterey Peninsula Water Supply Project, 2017). In each of these studies/projects, procedures were in place to ensure the quality of the lithology information collected. It is likely that, in many cases, core samples were used to assist with developing the description of lithology.

During lithology logging in most wells, the driller may note grain size, color, and texture of the material encountered during drilling, but these descriptions do not generally correlate to a standard, such as the Unified Soil Classification System (USCS). As a result, after all lithology data were gathered in a central lithology database, there were a total of 288 unique lithology descriptors. These unique values were grouped into a much smaller set of 25 descriptors to aid with the interpretation of the hydrostratigraphy of the region of interest. The translation table between the descriptors used in this report and those from the USCS, which was used in describing the lithology in the MPWSP monitoring wells, is shown in Table 2. The USCS is a division of the International Union of Soil Scientists (http://www.iuss.org/).

USCS descriptor	Descriptor in this report
CH	Clay
CH-CL	Clay
CL	Silty Clay
CL-CH	Clay
GC	Clayey Gravel
GP	Gravel/Boulders
GP-GC	Clayey Gravel
GP-SP	Sand and Gravel
GW	Gravel/Boulders
MH	Silt/Loess
ML	Silt/Loess
ML-MH	Silt/Loess
SC	Clayey Sand
SC-SM	Clayey Sand
SM	Silty Sand
SM-SC	Silty Sand
SP	Sand
SP-GC	Sand and Gravel
SP-GP	Sand and Gravel
SP-SC	Clayey Sand
SP-SM	Sand
SW	Sand
SW-GP	Sand and Gravel
SW-GW	Sand and Gravel
SW-SC	Clayey Sand

Table 2: Translation table between lithology descriptors in the Unified Soil Classification System and the lithology descriptors used in this report.

Geophysical Data

Geophysical logging data were collected in the boreholes of seven of the eight MPWSP monitoring well clusters; only MW-3 lacks a geophysical log. The logs include induction-based resistivity (deep and medium length), spontaneous potential, and gamma radiation. Geophysical logging measurements were collected on average 11 days after wells were drilled in 2014/15. Before working with the borehole resistivity logs, we removed the topmost and bottommost measurements in the wells as they had been affected by the start and end of the logging process.

Water Quality and Water Level

Each of the eight MPWSP well clusters is comprised of three wells, each screened at a different interval, corresponding roughly to the three aquifers nearest the ground surface in the region of the wells (the Dune Sand, 180-Foot, and 400-Foot Aquifers). A baseline water quality analysis of water from each screened interval was collected approximately 1 to 2 months after drilling; wells were bailed before taking a water quality lab sample. On average about 2 months after drilling, a continuously logging pressure transducer and electrical conductivity meter were installed in each well of every cluster, and have reported submerged pressure, water density, and electrical conductivity (or its inverse, electrical resistivity) of the water in the well every 5 to 15 minutes since the installation in early 2015. Electrical conductivity of the well water can be used to estimate the total dissolved solids in the water, while the pressure reported by the transducer is used to estimate the water level in the well.

Airborne Electromagnetic Data
A total of 635 line-km (395 line-miles) of AEM data were acquired in the Northern Salinas Valley May 16-18, 2017, using a SkyTEM 304M system. The data were processed and inverted by Aqua Geo Frameworks (AGF), and the resulting resistivity models provided to Stanford. The flight lines corresponding to the data retained for processing and inversion are shown in Figure 2, along with the outline of 180/400 Aquifer groundwater sub-basin in blue, and the outline of the Monterey sub-basin in purple, for reference. The inversion of the AEM data by AGF provided 2-D sections along the AEM flight lines that display the variation in electrical resistivity of the subsurface.

Resistivity values obtained from the AEM data span a wide range, exceeding 500 ohm-m in regions above the water table in the Fort Ord area, and falling below 1 ohm-m in zones near the coast. In every display of the data, we show resistivity values above the depth of investigation (DOI). Below the DOI, the resistivity values are poorly resolved. The DOI depends on the resistivity structure of the subsurface. If the resistivity of the subsurface is, on average, low, the DOI occurs at a shallower depth than if the resistivity is high. While the DOI varies significantly across the region of interest, it is approximately 50 mbgs in saline, less resistive regions along the coast, and between 150 and 200 mbgs in more resistive inland regions.

In Figure 3 we show the map from Figure 1 along with three cross-sections displaying the variation in electrical resistivity derived from the AEM data. The red bars in the map indicate the locations of the cross-sections. Plotted with the AEM data are borehole resistivity measurements for comparison. The number above each borehole represents the distance of that borehole from the cross-section. The region shaded in gray signifies the region below the DOI. Gaps appear in the AEM cross-sections due to the spacing of the flight lines, and data removal due to noise. The primary source of noise in this study was due to powerlines. In most locations, borehole resistivity measurements agree very well with the resistivity values in the nearest AEM cross-section, providing confidence in the AEM data.

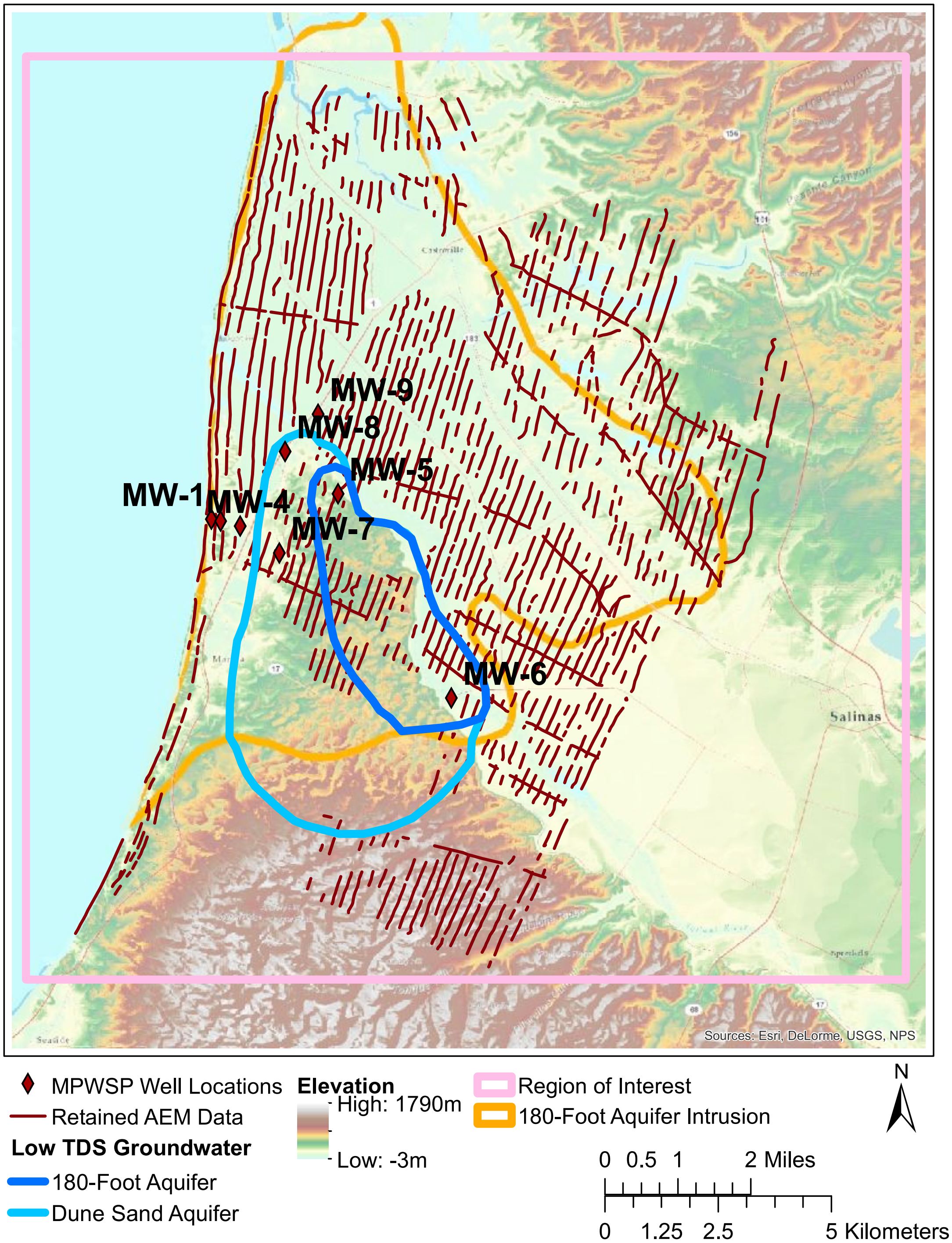


Figure 2: Flight lines where data were retained for processing and inversion from the AEM data acquisition. As in Figure 1 are shown the extent of saltwater intrusion in the 180-Foot Aquifer in orange and the extent of groundwater with anomalously low TDS in the Dune Sand Aquifer and the 180-Foot Aquifer, in light blue and dark blue, respectively. Plotted as red diamonds are the locations of the MPWSP monitoring wells used in the analysis of this report.

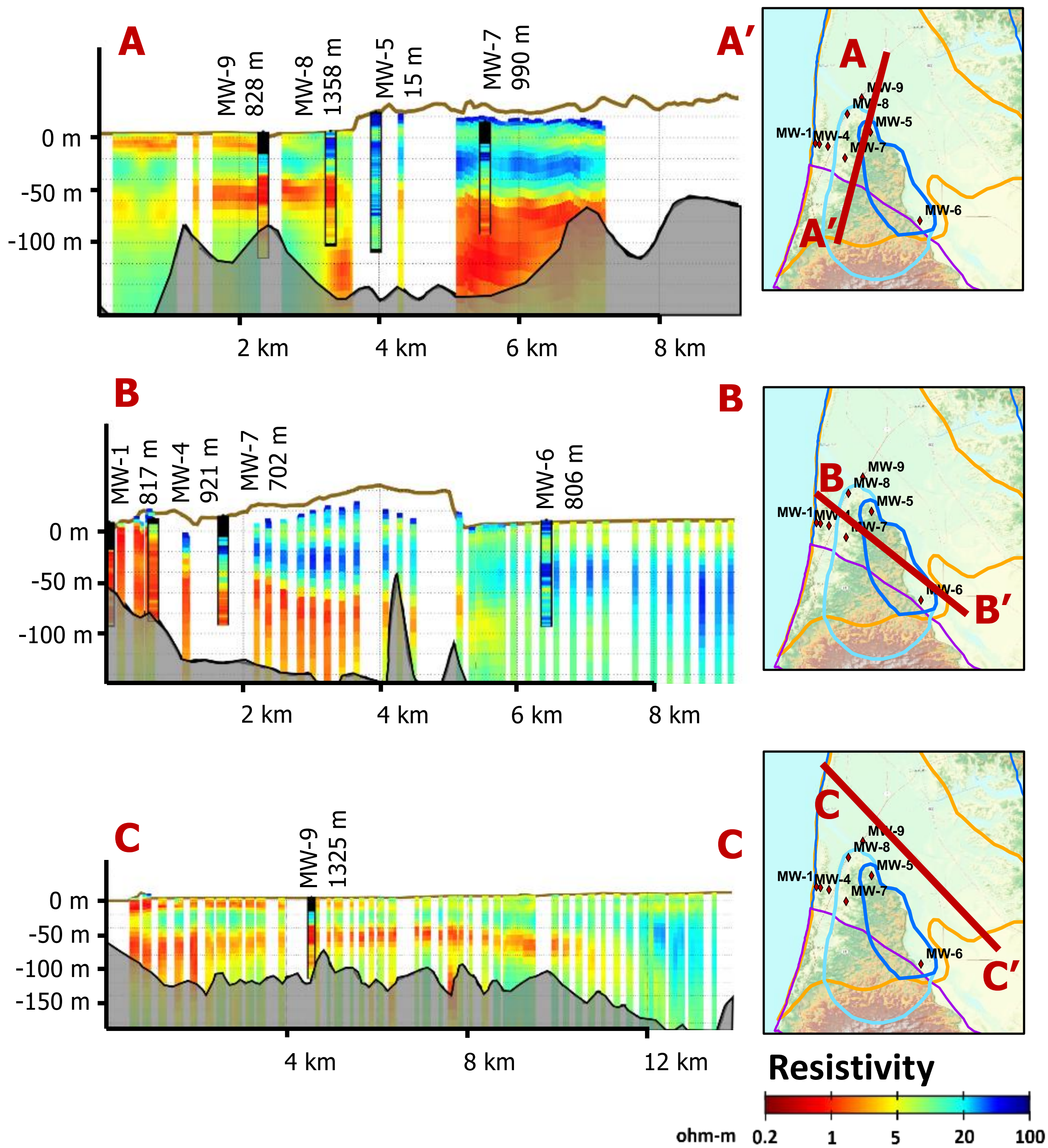


Figure 3: Cross-sections of AEM data, along with nearby geophysical logging data (long induction resistivity), and a map showing the location of the cross-section in red. Topography in each cross-section is shown as a brown line. Sections of geophysical logs where data were affected by the start and end of the logging process are shown in black, and regions below the depth of investigation are shaded in grey.

Interpretation of the Airborne Electromagnetic Data

Our objective was to use the AEM data to evaluate the current understanding of the hydrostratigraphy and to determine the variation in water quality in the region of interest. To successfully interpret AEM data for these purposes, the AEM data and their relationship to lithology, water quality, and water saturation must first be understood.

The resistivity measured by the AEM system is the resistivity of a volume of subsurface material composed of sediments containing air and/or water. While measurement of the electrical resistivity of the water alone (typically reported as the inverse parameter, electrical conductivity) can be a direct indicator of the salinity of the water (the more salts in the water, the lower the electrical resistivity), the electrical resistivity of a volume of subsurface material is determined not just by the salinity of the water, but is also affected by the texture and mineralogy of the sediments and the volume of water present. Very simply, increasing the amount of clay, the amount of water, and/or the salinity of the water all decrease the electrical resistivity.

Within the saturated zone, resistivity values can vary significantly. If the subsurface were lithologically homogenous, and sediment texture/mineralogy and porosity (the volume of water) did not change, changes in resistivity could be attributed simply to changes in the pore water resistivity, and therefore to changes in TDS. In the region of interest in this study, the lithology of the subsurface is documented as being very heterogeneous, where aquifer units contain numerous silt and clay lenses from fluvial and alluvial deposits. The presence of finer-grained—especially clay-bearing—sediment will impact the measured resistivity of the bulk material in the same way that pore water of high salinity does. An additional complicating factor is the presence of unsaturated materials as the top layer at the ground surface. Moving from the saturated to unsaturated zone, resistivity values typically increase significantly and abruptly due to the lack of water for electrical conduction.

To gain confidence in the AEM data collected, we first compared AEM resistivity measurements to nearby resistivity measurements in the boreholes of the seven MPWSP monitoring wells. Next, in order to use the AEM data to extract water quality information in the region of interest, we needed to first map the water table in order to separate the unsaturated zone from the saturated zone, and then define the relationship between AEM resistivity and water quality in the saturated aquifer zones.

<u>Comparison with Lithology and Borehole Geophysical Data</u>

We compared the resistivity measurements of the AEM sounding closest to each MPWSP monitoring well with the geophysical logging data and lithology data within that nearby MPWSP well. The induction conductivity logs in the MPWSP monitoring wells can be used to evaluate the quality of the AEM data. Because of the much larger measurement area in the AEM data, the AEM data can provide insight into the area surrounding each MPWSP well. The distance between the MPWSP wells and the nearest AEM sounding ranged from 88 m to 349 m. The elevation of the ground surface in each AEM sounding was estimated from a 5-meter digital elevation model, while the elevation of each MPWSP monitoring well was surveyed.

Despite the two-year time gap between the geophysical logging measurements and the AEM measurements, differences between the two datasets are small, and only in select locations. Differences between the datasets are found in regions where the salinity has changed significantly in the past two years. This change is supported by the trends in electrical conductivity of water recorded by the continuous data loggers in the MPWSP wells. Differences between the AEM and borehole geophysical data also exist at depth, where the borehole resistivity measurements have better resolution than the AEM measurements.

Figures 4 though 10 show the resistivity measured in the MPWSP monitoring well boreholes in red, along with the resistivity measured at the nearest AEM sounding in dark blue. Shown in light blue is the resistivity interpolated from nearby AEM resistivity measurements and plotted at the location of the MPWSP borehole. A radial basis function was used to interpolate the AEM measurements, where the highest weight was given to the closest lateral measurements. Any values beyond 450 m away were not used in the interpolation. On the right hand side of each figure in teal boxes are shown the screened intervals of the MPWSP well cluster. Finally, on the far right hand side the lithology descriptions are shown that correspond to the well. The lithology in each MPWSP borehole was logged using USCS descriptors. The lithology key includes the descriptors in our lithology database, translated from their original USCS descriptors (shown in Table 2). The lithology descriptors are translated so as to standardize the descriptors used throughout the region of interest. The depth interval in each of these figures is shown as depth from the ground surface at the location of the MPWSP monitoring well plotted. To roughly accommodate for differences in ground surface elevation between the MPWSP monitoring well and the nearest AEM sounding, the dark blue line was shifted according to the difference in elevation between the two points.

MW-1

Figure 4 shows the comparison between lithologic and geophysical data in MW-1. The high TDS concentrations in baseline water quality, all well above the 10,000 mg/L threshold defining water of limited beneficial use, are considered to be water of limited beneficial use. The high TDS concentrations are a result of saltwater intrusion in the region. In their seawater intrusion monitoring program, the Monterey County Water Resources Agency has determined this area to have been impacted by saltwater since at least 1975.

Water levels in the screened intervals of MW-1 indicate that water in the shallow and medium screened intervals are not hydraulically separated, but that water in the upper two screened intervals is hydraulically separated from the deep screened interval.

The resistivity values from the nearest AEM sounding are 88 m away from MW-1. While the borehole resistivity in MW-1 measures some sudden jumps in resistivity, (e.g. at 40 mbgs), the resistivity measurements from the nearest AEM sounding trace out an average resistivity. The interpolated AEM values closely follow the values from the nearest AEM sounding.

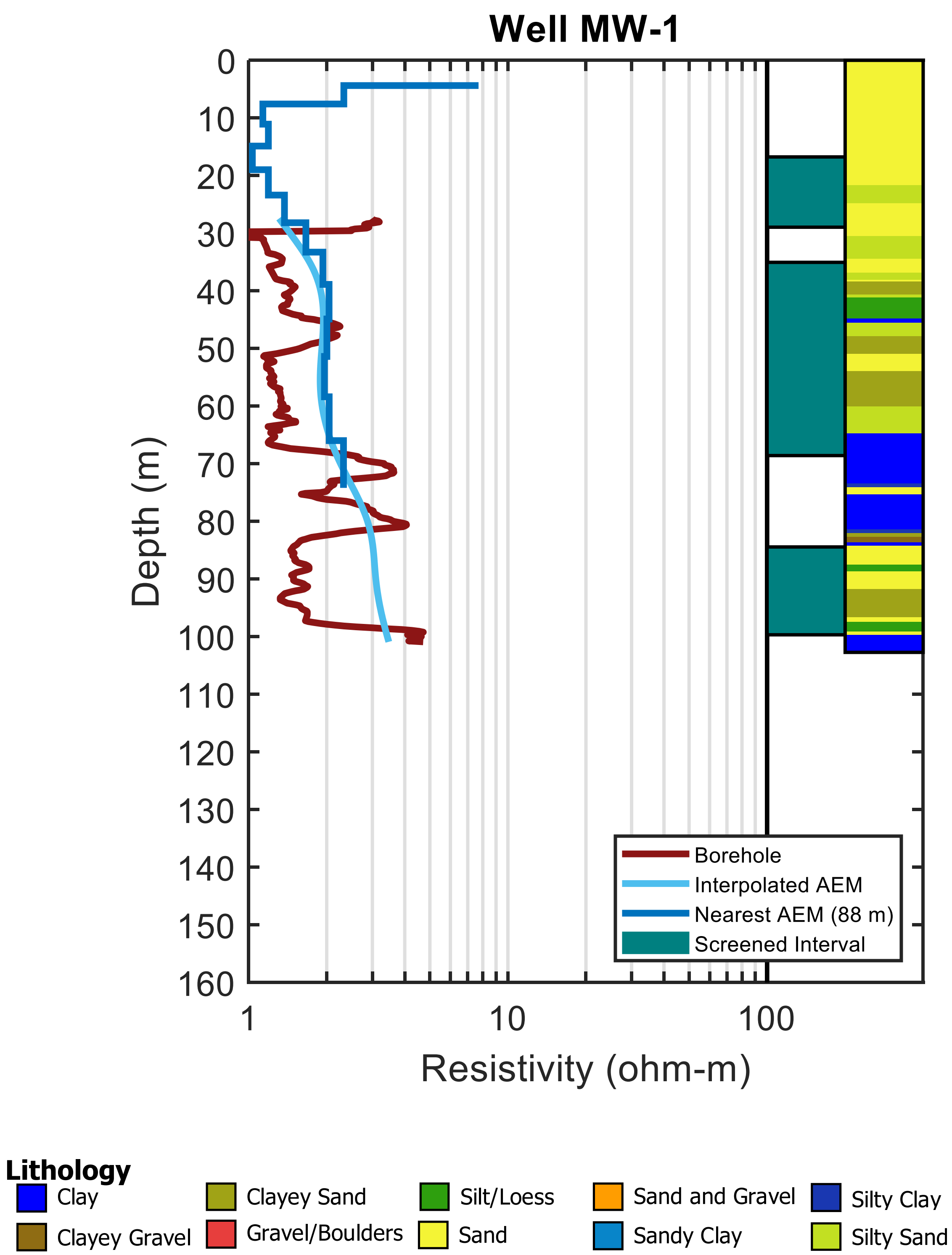


Figure 4: Comparison between lithologic and geophysical resistivity data in and near MW-1.

MW-4

Figure 5 shows the comparison between lithologic and geophysical data in MW-4. In MW-4, baseline TDS measurements were taken in March 2015. TDS concentrations in the screened intervals were measured at 11,900 mg/L, 17,900 mg/L, and 27,500 mg/L, from shallow to deep. The water conductivity in MW-4, as measured by an instrument attached to the transducer in each screened interval, has remained stable in the deep screened interval and has increased in the middle screened interval. In the shallow screened interval, which corresponds to the Dune Sand Aquifer, the electrical conductivity has decreased This trend is interpreted as a result of fresher water in the Dune Sand Aquifer flowing toward the coast, according to the groundwater gradient pointing seaward, inferred from water levels in the shallow screened intervals of MW-1, MW-3, MW-4, and MW-7 during test slant well operation. This groundwater gradient may be due in part to pumping from the coastal Test Slant Well of the MPWSP. During pumping, the Test Slant Well creates a depression in the groundwater potential, drawing groundwater in its direction. Based on numerical groundwater modeling of the site done as part of the MPWSP, the water levels in the Dune Sand Aquifer should decrease over time in the vicinity of MW-1, MW-4, and MW-7, with the hydraulic gradient pointing toward the Test Slant Well. The especially wet winter of 2016/2017 supplied more recharge to the Dune Sand Aquifer than normal winters, which may also increase some of the outflow of fresh water to the coast during the time of the AEM survey in May 2017. However, it should be noted that the decline in water conductivity in the shallow screen of MW-4 did not cease after the winter of 2016/2017, but has continued its trend of decrease into 2018; in this case, the wet winter of 2016/2017 does not appear to be the dominant cause of changing groundwater conductivity. In early February 2018, the water conductivity at the depth of the probe was measured below 3,200 µs/cm, a 70% decrease from its initial readings near 11,000 µs/cm. Since TDS concentrations in water generally follow a linear relationship with the electric conductivity of water, the 70% decrease in water conductivity should correspond to a similar decrease in TDS concentrations in the shallow screen of MW-4.

Water levels in the screened intervals of MW-4 indicate that water in the shallow and medium screened intervals are at least partially hydraulically separated. Water level measurements in the Fort Ord area by Ahtna Environmental (2017) show that Salinas Valley Aquitard thins out toward the coast at a distance in the vicinity of MW-4. This is reflected by the very thin clay layer found in MW-4 at a depth of approximately 38 mbgs. Water within the medium and deep screened intervals also appear to be hydraulically distinct.

The resistivity values from the nearest AEM sounding, 156 m away from MW-4, are very similar to those logged within MW-4. Differences between the resistivity values in the two models largely depend on the difference in resolution between the two measurements, where the thickness of the AEM resistivity model is 3 m at the surface, and increases linearly to over 20 m by 300 mbgs. The interpolated AEM values match the values from the nearest AEM sounding very closely, indicating that that the resistivity profile from the nearest AEM sounding are similar to resistivity profiles from other nearby soundings.

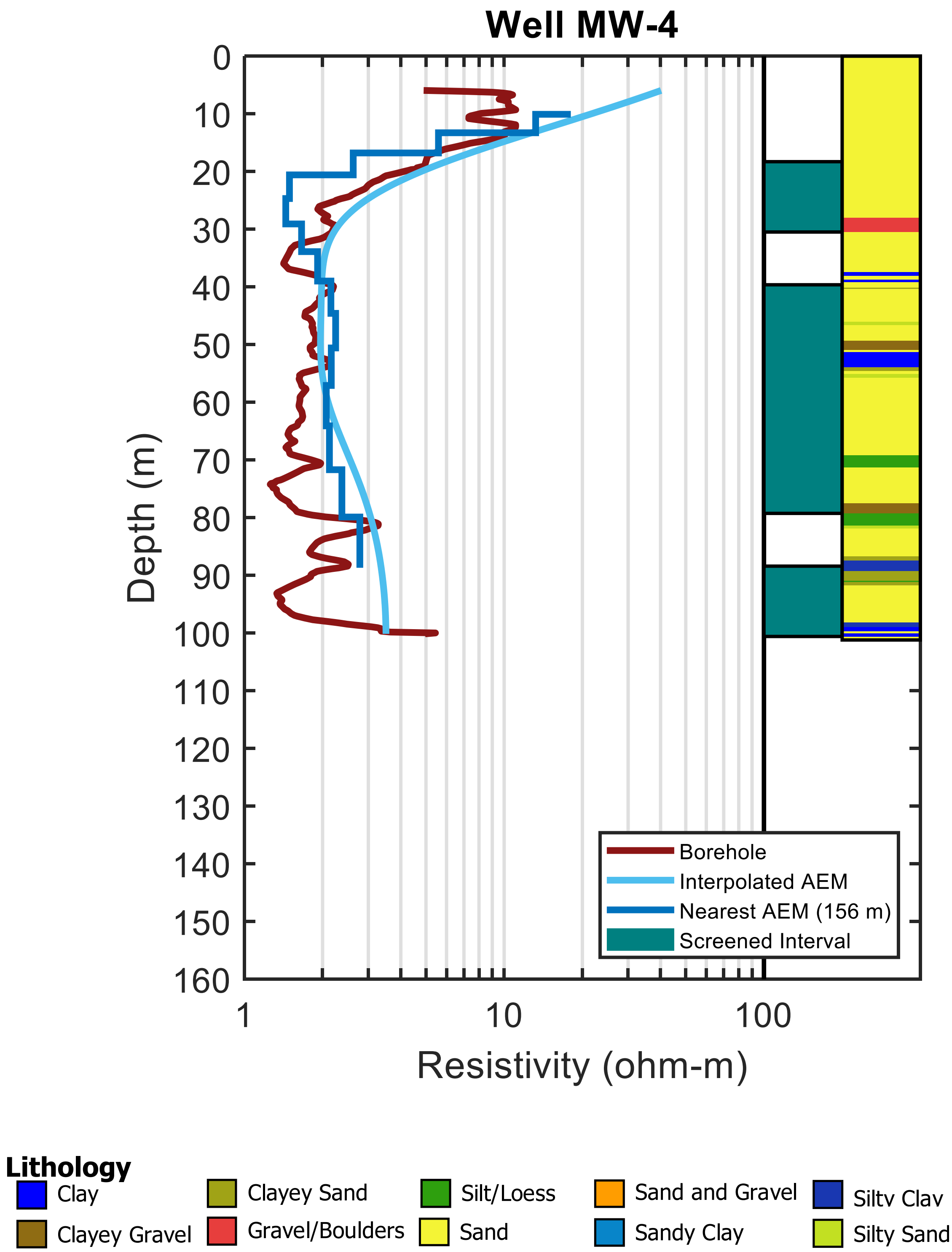


Figure 5: Comparison between lithologic and geophysical resistivity data in and near MW-4.

MW-5

Figure 6 shows the comparison between lithologic and geophysical data in MW-5. The baseline TDS values in MW-5 were measured in February and March 2015. From the shallowest to deepest screened interval, baseline TDS concentrations were measured at 1,166 mg/L, 663 mg/L, and 2,616 mg/L, respectively. The targeted aquifers for these screened intervals are the Dune Sand Aquifer, the 180-Foot Aquifer, and the 400-Foot Aquifer, respectively. Here, the SVA elevates water levels in the Dune Sand Aquifer (encountered in MW-5 around 18-25 mbgs) to approximately 10 meters above sea level (masl). According to the hydrostratigraphy in other hydrogeologic investigations of the area (e.g. MACTEC, 2005; Harding ESE, 2001), the middle screen of MW-5 should span both the Upper 180-Foot Aquifer and the Lower 180-Foot Aquifer, separated at this location by a very thin clay layer (encountered at approximately 67 mbgs).

Based on the borehole resistivity measurements, the average resistivity does not change appreciably between the Upper 180-Foot Aquifer and the Lower 180-Foot Aquifer. However, the AEM measurements at the nearest AEM sounding, collected 198 m away two years later, show that the resistivity monotonically decreases from approximately 20 ohm-m to 9 ohm-m between 30 mbgs and 90 mbgs, which are near the top and the bottom of the middle screened interval, respectively. This may suggest a slight degradation of the water quality within the 180-Foot Aquifer between the time of the MPWSP well installment and the AEM survey. Unfortunately, because the transducer and attached electrical conductivity meter in the middle screened interval of MW-5 lies near 57 mbgs—within the Upper 180-Foot Aquifer—it would not record such changes.

In the interval between 70 and 130 mbgs, the interpolated AEM resistivity values are consistently lower than the resistivity measurements in the closest AEM sounding. This reflects the fact that other nearby AEM soundings have resistivity profiles different from the closest AEM sounding indicating that there is variability around MW-5 in either the geology and/or the water conductivity, suggesting greater salinity in the waters of the adjacent materials.

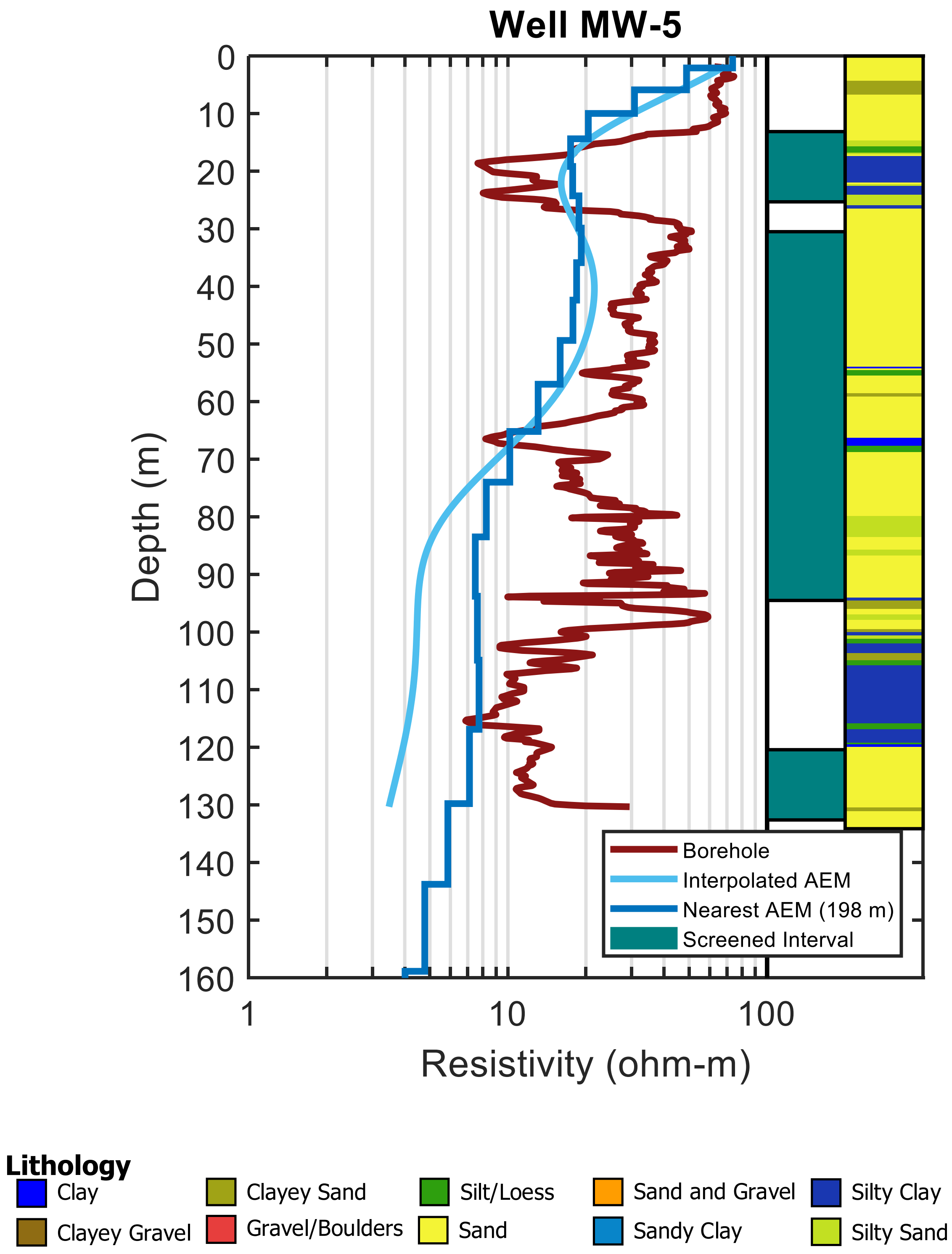


Figure 6: Comparison between lithologic and geophysical resistivity data in and near MW-5.

MW-6

Figure 7 shows the comparison between lithologic and geophysical data in MW-6. The baseline TDS values in MW-6 were measured in April 2015. In the shallow screened interval, a concentration of 608 mg/L was measured, in the middle screened interval, 966 mg/L was measured, and 1840 mg/L was measured in the deepest screened interval. Each of these qualifies as beneficial use water, and the water sampled from two upper screened intervals is fresh enough to be considered drinking water. Electrical conductivity measurements have been taken in the screened intervals of MW-6 either by hand measurements or by the electrical conductivity meter attached to each transducer. Between the installment of the well cluster and the AEM survey, the electrical conductivity had risen in both the shallowest screened interval and the deepest screened interval, with the conductivity in the mid-depth screened interval remaining relatively stable. The water level is calculated each 15 minutes from measurements made by the transducer in each screened interval. These calculated water level measurements suggest that, while the water from the shallowest screened interval is hydraulically separated by the thick clay unit (approximately 20 to 40 mbgs) from the screened intervals below, the water in the two lower screened intervals closely hydraulically connected. The target aquifers for the screened intervals were the Shallow Aquifer/Perched "A" Aquifer, the 180-Foot Aquifer, the 400-Foot Aquifer, from shallowest to deepest screened interval. Subsequent water level and water quality data resulted in the reevaluation and designation of the lower monitoring wells screened intervals being located in the Upper 180-Foot Aquifer and the Lower 180-Foot Aquifer.

The nearest AEM sounding to MW-6 is 118 m away. The resistivity measurements in MW-6 and the measurements from the nearest AEM sounding follow the same trend in depth, moving generally from higher resistivity to lower resistivity with depth. However, the nearby AEM measurements are generally less resistive, in both shallow and deeper zones, than those in MW-6, which reflect the increase in water conductivity found in the shallow and deep screened intervals of MW-6.

The deviations of the resistivity measurements in MW-6 from the nearest AEM measurements may also reflect the fact that this location is near a hydrogeological boundary. Not only is MW-6 on the boundary between the Salinas Valley basin to the north and the dune sands of Fort Ord to the south, but the well is also within the vicinity of the Reliz Fault Zone. The resistivity measured in MW-6 represents the resistivity in the area immediately surrounding the borehole, which in this area may change very quickly over a short lateral extent. The AEM measurements, on the other hand, represent the average resistivity over a larger lateral extent.

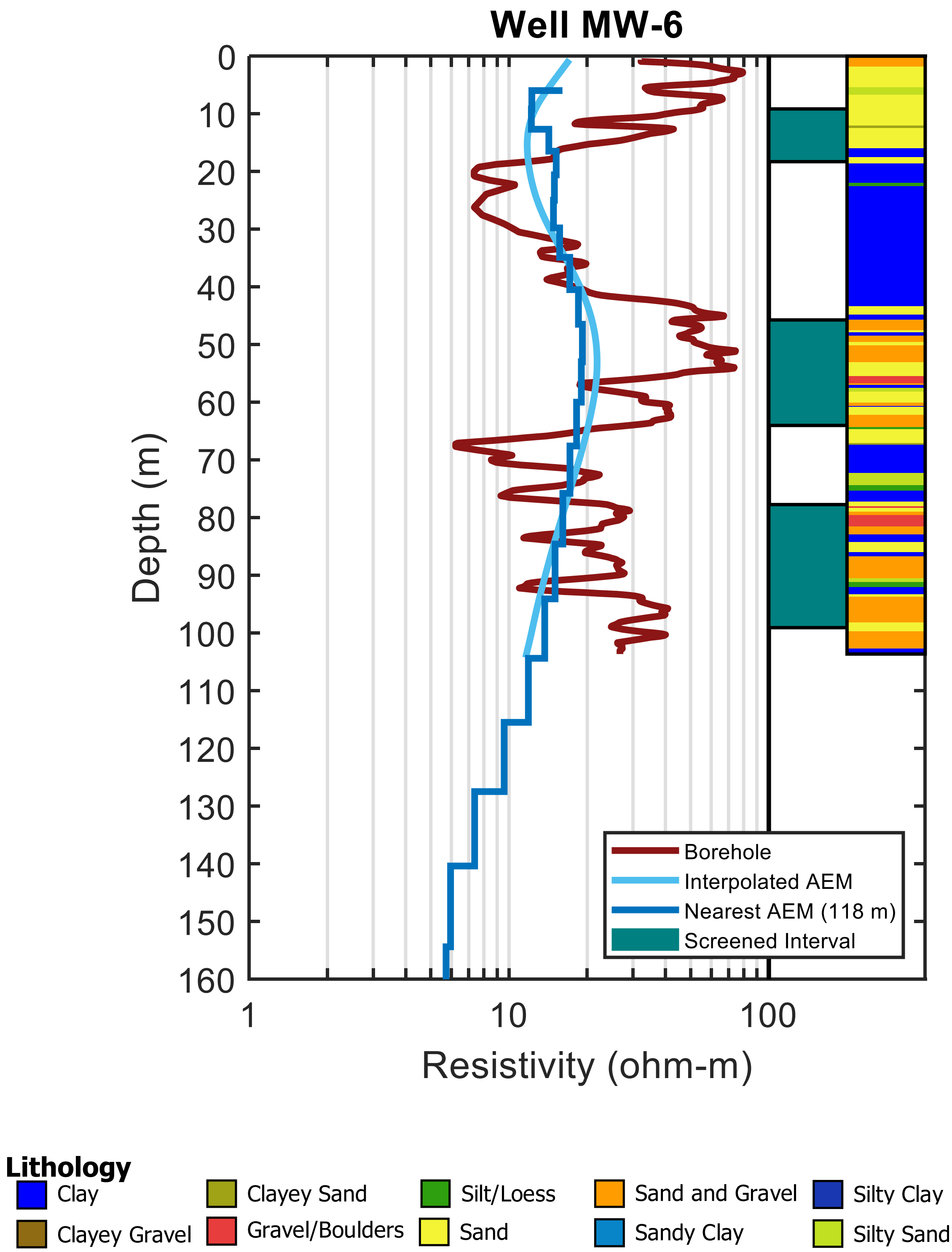


Figure 7: Comparison between lithologic and geophysical resistivity data in and near MW-6.

MW-7

Figure 8 shows the comparison between lithologic and geophysical data in MW-7. The baseline TDS values in MW-7 were measured in August 2015. From the shallow to deep screen, baseline TDS concentrations were measured at 1,200 mg/L, 3,832 mg/L, and 26,700 mg/L, respectively. The targeted aquifers for these screened intervals are the Dune Sand Aquifer, the 180-Foot Aquifer, and the 400-Foot Aquifer, respectively. The jump between the TDS concentrations in the upper two screened intervals and the deepest screened interval suggest a major change in regime between the middle screened interval and the lower screened interval. The 400-Foot Aquifer in the vicinity of MW-7, approximately 1.6 km from the coast, is considered to be saltwater intruded by the Monterey County Water Resources Agency. The electrical conductivity readings in the screened intervals of MW-7, have remained relatively constant in the period between the installment of the monitoring well and the AEM survey, suggesting that the TDS concentrations have also remained relatively constant throughout this timespan. The low resistivity values at the base of the middle screened interval suggest that this zone may also be intruded with saltwater.

The nearest AEM sounding to MW-7 is 99 m away. The resistivity measurements in MW-7 and the measurements from the nearest AEM show very good agreement. The borehole resistivity measurements do not show the presence of the SVA indicating the aquitard effectively pinches out between MW-5 and MW-7. The only aquitard layer indicated is at a depth of 30 m where a 15 ohm-m signature is present.

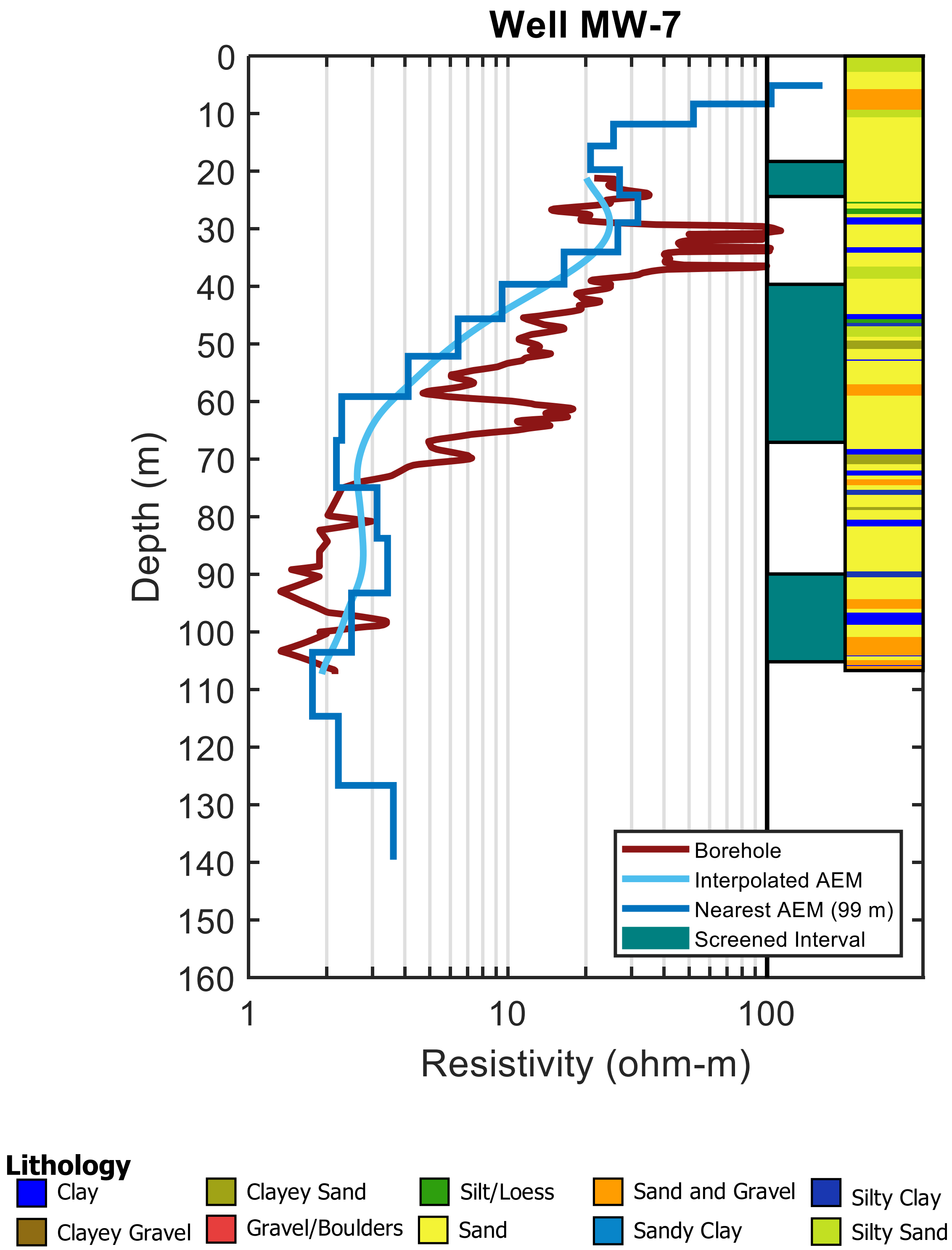


Figure 8: Comparison between lithologic and geophysical resistivity data in and near MW-7.

MW-8

Figure 9 shows the comparison between lithologic and geophysical data in MW-8. The baseline TDS values in MW-8 were measured in August 2015. From the shallow to deep screen, baseline TDS concentrations were measured at 1,260 mg/L, 24,000 mg/L, and 583 mg/L, respectively. The targeted aquifers for these screened intervals were reported as being the Dune Sand Aquifer, the 180-Foot Aquifer, and the 400-Foot Aquifer, respectively. The baseline TDS concentration measured in the shallow screened interval is quite low, while the baseline TDS measurement in the deep screened interval is low enough to be considered drinking water. Meanwhile, the baseline TDS measurements in the middle screened interval are extremely high, suggesting that the screened interval is affected by saltwater intrusion. While the three targeted aquifers are the same for both MW-7 and MW-8, the TDS concentrations found in those screens vary significantly, suggesting a possible change in the lithology and/or water quality somewhere between the two wells. Such a change is also suggested by the AEM measurements, which have mapped out the resistivity between MW-7 and MW-8, as can be seen in Figure 3a. The location of change may coincide with the Reliz Fault Zone.

The nearest AEM sounding to MW-8 is 349 m away. Despite this distance, the resistivity measurements in MW-8 and the measurements from the nearest AEM match each other very well. As suggested by the changing lithology and/or water quality nearby, the interpolated AEM resistivity values, which rely on many of the surrounding AEM soundings, deviate from the closest AEM sounding near the surface.

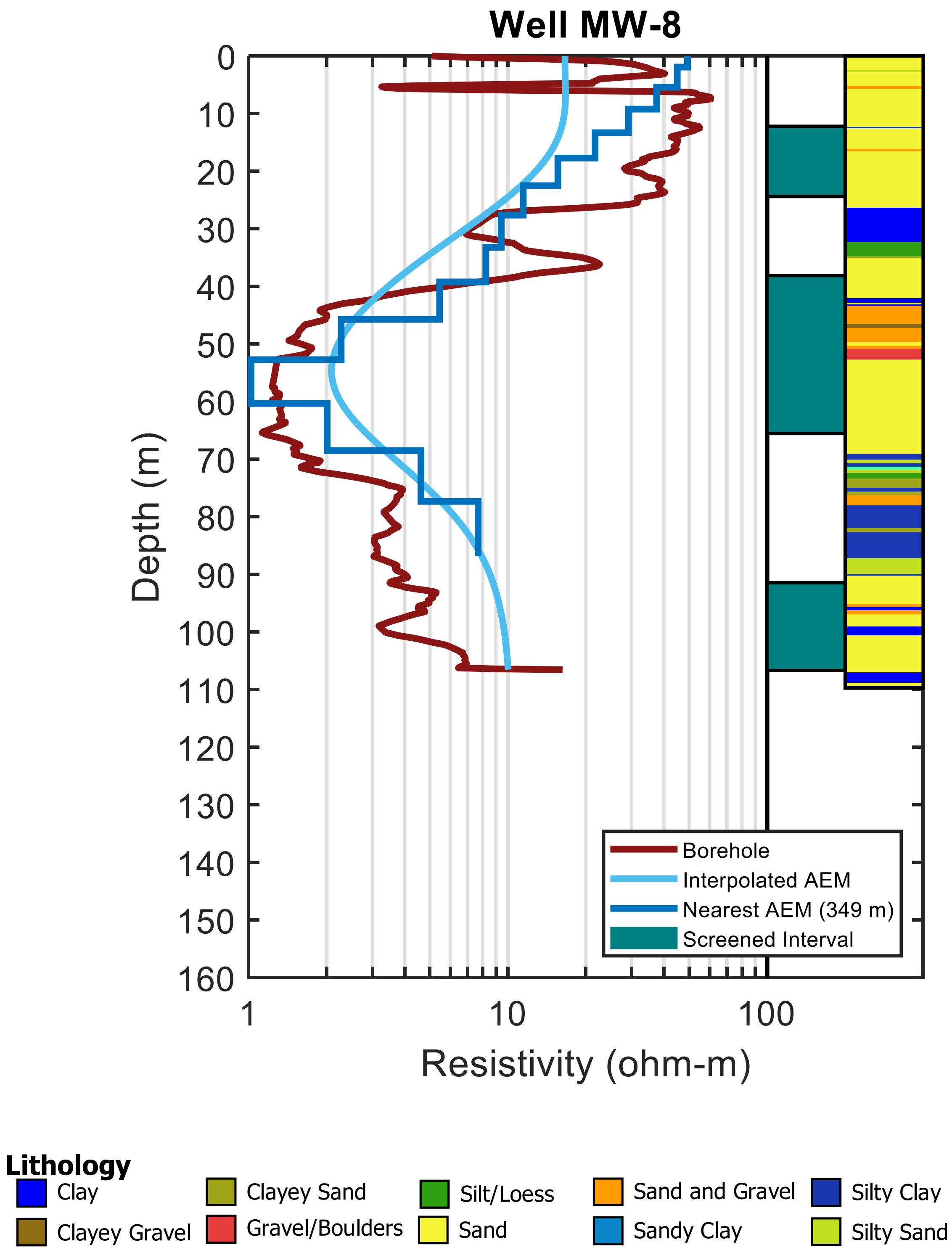


Figure 9: Comparison between lithologic and geophysical resistivity data in and near MW-8.

MW-9

Figure 10 shows the comparison between lithologic and geophysical data in MW-9. MW-9 is the only well of the MPWSP monitoring wells north of the Salinas River. The baseline TDS values in MW-9 were measured in June 2015. From the shallow to deep screen, baseline TDS concentrations were measured at 3,204 mg/L, 29,000 mg/L, and 366 mg/L, respectively. The targeted aquifers for these screened intervals were reported as being the Shallow Aquifer/Perched "A" Aquifer, the 180-Foot Aquifer, and the 400-Foot Aquifer, respectively. This profile of TDS concentrations—moving from relatively low concentrations to extremely high, and then to extremely low—mirrors the trend seen in MW-8.

The nearest AEM sounding to MW-9 is 272 m away. The resistivity measurements in MW-9 and the measurements from the nearest AEM match each other well below 40 mbgs. Above 40 mgbs, the resistivity measurements from the nearest AEM sounding, as well as from the interpolated AEM values, are consistently lower than those recorded in MW-9. The electrical conductivity meter in MW-9 has not measured much change since it started logging, but is above the level of the sand-rich interval in which the water quality may be changing, between 20 and 35 mbgs.

Comparing the AEM resistivity values in the shallow screened areas in MW-9 and MW-8, it can be observed that the AEM resistivity values near MW-9 are much lower than those measured in the borehole (5 ohm-m vs 30 ohm-m), whereas for MW-8 the borehole and nearby AEM resistivity measurements are similar.

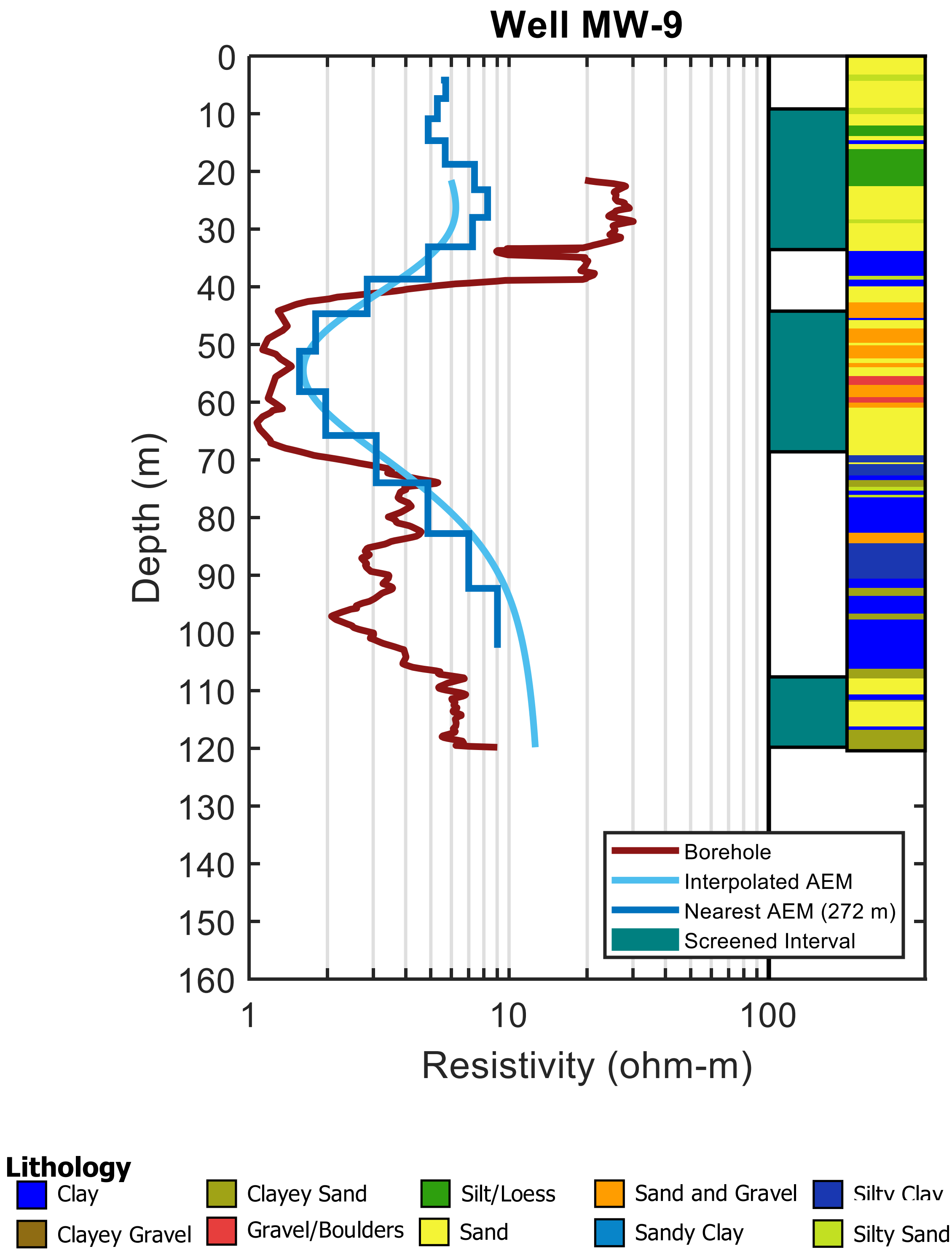


Figure 10: Comparison between lithologic and geophysical resistivity data in and near MW-9.

Mapping the Water Table

It is generally understood that water table elevation tends to be a muted expression of the surface topography. To estimate the water table elevation, an adequate number of measurements are needed, especially in hilly regions where the topography changes over short distances. In this study, few measurements exist in the central and northeastern sections of Marina, where dune deposits have created hilly topography; most wells in the region are not screened in the unconfined Dune Sand Aquifer. However, water table measurements, recorded by the pressure transducers, were available contemporaneous with the collection of AEM data (May 16-18, 2017) in the eight MPWSP wells.

Because we had only the water table measurements from the eight MPWSP wells, the AEM data were used to assist in defining the water table elevation. In much of the unsaturated zone at the eight MPWSP wells, the AEM resistivity values range from 100 to 1000 ohm-m. Below the water table at the eight MPWSP wells, 98% of the resistivity values are below 50 ohm-m. This is an example of the stark contrast commonly found across the interface between the unsaturated and saturated zones. To estimate the elevation of the water table, we defined a resistivity cutoff to be used to separate the unsaturated zone from the saturated zone in the AEM resistivity models. All resistivity values above the cut-off corresponded to the unsaturated zone; all resistivity values below corresponded to the saturated zone, with the interface between the two regions corresponding to the water table. We optimized, through trial and error, the choice of the cut-off, finding that a resistivity cutoff of 75 ohm-m resulted in good agreement between the elevation of the AEM-determined water table and the elevation of the water table based on the measurements in the eight MPWSP wells.

Figure 11 illustrates the use of the 75 ohm-m cutoff. An AEM resistivity cross-section is shown, along with information from two MPWSP wells: the location of the ground surface is shown as a brown line and the water table coincides with the base of the gray rectangle in the boreholes, which displays the extent of the unsaturated zone. Figure 11a (top section) displays all the AEM resistivity values while Figure 11b (bottom section) displays only the AEM resistivity values less than 75 ohm-m. Our assumption is that the upper surface of AEM data in Figure 11b corresponds to the water table; this agrees well with the water table elevations in the MPWSP wells. We found the same to be true when we compared the AEM-determined water table with the water table measurements in the other MPWSP wells. We therefore concluded that it was reasonable to interpret any region with a resistivity greater than 75 ohm-m as unsaturated, and that all other regions were saturated.

Because of the dramatic resistivity contrast between the saturated and unsaturated zones in this area, using a resistivity cutoff allowed us to map the water table where data were not available. Having mapped the water table, we then proceeded with our analysis of the data, interpreting (as described in the next section) regions where the resistivity values were the highest as being freshwater-saturated sediments, and regions with the lowest resistivity values as being saltwater-saturated sediments.

Note that the use of the AEM data to locate the water table is a source of uncertainty in our interpretation. It is possible that there are freshwater-saturated regions, with a resistivity greater than 75 ohm-m, which we have interpreted as unsaturated. Alternatively, there could be regions with resistivity values lower than 75 ohm-m which we have interpreted as freshwater and are, in fact, unsaturated. In the first case we would underestimate, and in the second case we would overestimate, the amount of freshwater. For studies such as this, where the objective is to map freshwater that occurs at the top of the saturated zone, it is desirable to have good control on the elevation of the water table.

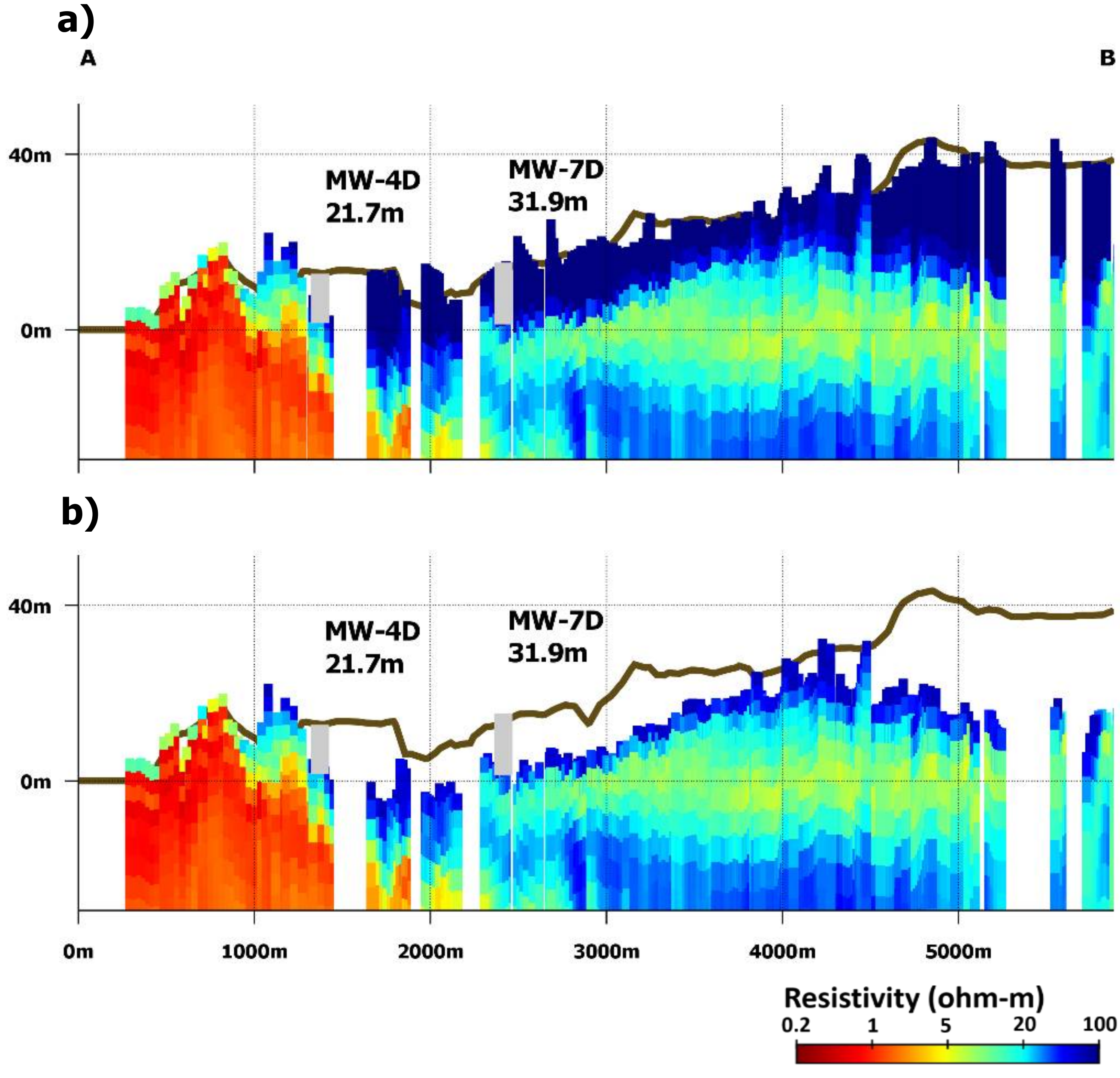


Figure 11: Mapping the water table. A cross-section running roughly perpendicular to the coast is shown, along with AEM resistivity measurements, as well as the unsaturated zone, measured in two MPWSP wells and shown as grey rectangles. The distance of the MPWSP wells from the cross-section is shown in meters underneath the well name. In the top figure a) all AEM data is shown, whereas in the bottom figure b) only AEM data < 75 ohm-m are shown.

From Resistivity to Water Quality in the Saturated Zone

In relating the AEM resistivity values to water quality, we had for reference information about the resistivity of freshwater and saltwater saturated sediments in the coastal Seaside area (Goebel et al., 2017); this is summarized in Table 3. Note that here, freshwater and saltwater are not defined in terms of TDS concentrations. This table was developed using 10 measurements from borehole resistivity logs from the Seaside Basin Water Master Sentinel wells where, along with the resistivity measurements, the salinity and lithology were described and corroborated with gamma log measurements. While resistivity values vary with both lithology and salinity, we can conclude that the lowest resistivity values will always correspond to saltwater-saturated sediments and the highest resistivity values (in the saturated zone) will always correspond to freshwater-saturated sediments. It is interesting to note that the maximum resistivity observed in freshwater-saturated sediments is 70 ohm-m, very close to the value of 75 ohm-m, which we defined as being the maximum resistivity in saturated sediments.

Resistivity (ohm-m)	Sand and Gravel	Silt	Clay
Freshwater Saturated	30–70	N/A	7–12
Saltwater Saturated	0.7–3	1.2–3	1.5–5

Table 3: Expected resistivity values of sediments in coastal Seaside area, CA (adapted from Goebel et al., 2017).

We also used measurements, made in seven MPWSP wells, of the resistivity of saturated sediments and the salinity of the well water (assumed to be the salinity of the contained pore water in the sediments) to determine the relationship between a resistivity measurement and water quality. The water quality measurements were made within two months of the resistivity measurements.

Within each screened interval, in each well, ranging between approximately 9 and 64 m in length, one TDS value was measured. But within that screened interval, there were approximately 60 to 425 resistivity measurements made with a vertical sampling interval of 15 cm, as the geophysical log was moved through the borehole. In Figure 12 we show the histogram of all the borehole resistivity measurements from the seven MPWSP wells, color coded to correspond to four TDS ranges of concentration, defined as in Table 1 (0-1,000 mg/L corresponds to drinking water; 0-3,000 mg/L corresponds to a source of drinking water; 3,000-10,000 corresponds to water of potential beneficial use; and >=10,000 mg/L corresponds to water of limited beneficial use).

As expected, the highest TDS range of concentrations corresponds to the lowest resistivity values. The range with lowest TDS values corresponds to the highest resistivity values. The two middle TDS ranges overlap the resistivity values in both the lower TDS range and the higher TDS range. This overlap is expected, since resistivity measurements are sensitive to water quality, the volume of water and the sediment type.

For our purposes, we would like to obtain, from the AEM data, a conservative estimate of the volume of water with TDS <= 3,000 mg/L, and >= 10,000 mg/L. We therefore define resistivity ranges where only those TDS values are observed: TDS <= 3,000 mg/L corresponds to resistivity values greater than 20 ohm-m and TDS >= 10,000 mg/L corresponds to resistivity values less than 3 ohm-m. Because of our conservative cutoff, we expect to under-estimate the amount of water corresponding to the lowest and highest TDS ranges. This is especially true for the lowest TDS range, where Figure 12 shows 64% of the resistivity values in the low TDS range overlap resistivity measurements from the middle two TDS ranges. We note that the results in Figure 12 affirm our choice of a 75 ohm-m cutoff to define the water table, since only 4 values (0.14%) of saturated resistivity values exist above 75-ohm in the MPWSP geophysical borehole measurements. There are very few resistivity values in Figure 12 where the resistivity measurements correspond to TDS concentrations <= 1,000 mg/L, without overlap from another TDS range. The range of resistivity values is approximately between 55 and 75 ohm-m. Because of the low percentage of AEM

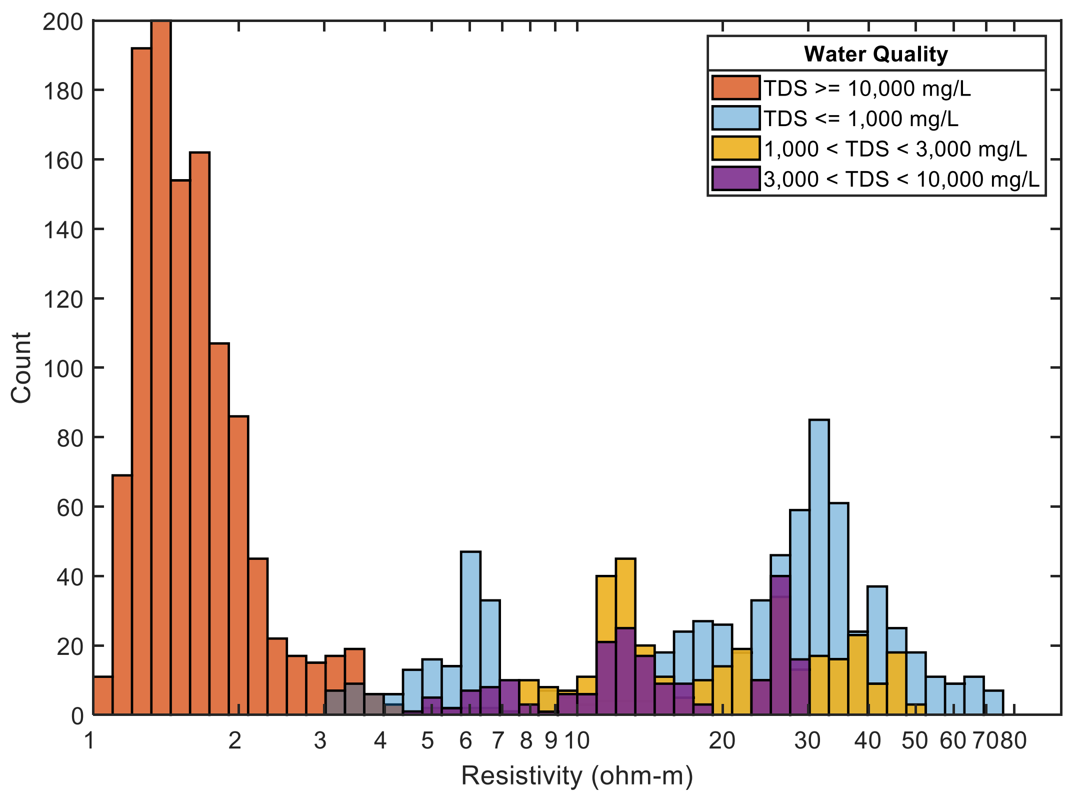


Figure 12: Resistivity values from geophysical measurements in MPWSP monitoring wells, colored according to the defined TDS ranges.

resistivity measurements corresponding to this range, we focus primarily on sources of drinking water in this report, rather than on drinking water.

We consider our choice of a 20 ohm-m cutoff to be a conservative estimate of water with TDS <= 3,000 mg/L, despite a group of resistivity measurements between 20 and 30 ohm-m in the TDS range between 3,000-10,000 mg/L. These measurements are considered to be outliers, and are not considered representative. Each of these resistivity measurements comes from the geophysical borehole measurements from MW-9 (Figure 10), within the shallow screened interval. Within this interval was measured a baseline TDS concentration of 3,204 mg/L, which places the measurement narrowly into the middle TDS range. The borehole resistivity was measured between 20 and 30 ohm-m within the sandy unit at the bottom of the screened interval (between 23 and 35 mbgs). Above this sandy interval, from approximately 20-23 mbgs, the borehole resistivity measurements begin to drop, indicating that the water quality may be have changed along with the recorded lithologic change to a more silt rich sediment. The resistivity measurements from the nearest AEM sounding, 272 m away, reflect this drop in resistivity as well. Since the shallow screen of MW-9 spans intervals that may have very different TDS concentrations, it is expected that the baseline measurement of 3,204 mg/L represents a mixture of water with those different TDS concentrations. For this reason, the TDS measurement is not considered representative of the screened interval, and the resistivity measurements corresponding to this screened interval were not considered when the resistivity cutoffs were chosen.

There are some underlying assumptions in this approach that need discussion. The borehole geophysical measurements have a vertical sampling interval of 15 cm, so they can be assumed to sample discrete lithologic units. We are assuming that the water quality measurements are a measure of the TDS of the pore water that corresponds to each resistivity measurement. But each water quality measurement corresponds to the entire screened interval from which it was taken, a cumulative sample of water, with the sampled water most likely to come preferentially from the more permeable sediments such as sands and gravels, as opposed to silts and clays. Ideally we would have a measure of water quality over every interval where we have a measure of resistivity.

As noted earlier, the borehole geophysical data collection and the water quality measurements were separated by two months on average. While the water quality could change within this one or two-month time span, the trend in electrical conductivity measurements of the well water shows that, on a monthly time scale, changes are negligible; therefore, we consider the water quality measurements to approximate the water quality in the wells at the time when borehole resistivity was measured.

The relationship between resistivity and water quality generally follows the pattern that higher TDS concentrations relate to lower resistivity values. Such a monotonic relationship does not exist for the relationship between resistivity and lithology in this study area, due to the complicating factor of changing water quality. As a result, the relationship between resistivity and lithology tends to be much more site-specific. Figure 13 shows histograms with the same borehole resistivity measurements in the MPWSP monitoring wells as in Figure 12. Figure 13a, color-coded according to a binary lithology classification, has blue bars showing all resistivity measurements that correspond to lithology descriptors containing the word "clay". This includes "Clay" as well as "Gravelly Clay", but not "Clayey Gravel". In yellow are the resistivity values corresponding to all other lithology descriptors, named "Sand" in the legend for convenience, since they are assumed to be, on average, coarser grained. Regions where blue and yellow bars overlap appear as blue-green. In Figure 13b, the resistivity measurements color coded with blue correspond to lithology descriptors with containing either the word "clay" or "clayey". This would include descriptors "Clay", as well as "Gravelly Clay", and "Clayey Gravel". In yellow are the resistivity values corresponding to the remaining lithology descriptors.

In an area where groundwater TDS concentrations are low and can be considered constant, we would expect clay-related lithology descriptors to be related to low resistivity values. However, we find in the case of both Figure 13a and 13b that the clay-related lithologies in this region have a wide span of resistivity values, the majority of which are between 1 and 20 ohm-m. The remaining lithologies, assumed to be coarser grained, span an even wider range of resistivity values, with a distinctly bimodal distribution. The two resistivity modes, with peaks near 1.5 and 30 ohm-m, represent sediment saturated with water of high TDS concentration, and water of low TDS concentration, respectively. The bimodal nature of these resistivity values demonstrates the site-specific nature of relating resistivity measurements to lithology; in this case due to the complicating factor of the change in the salinity of the pore water.

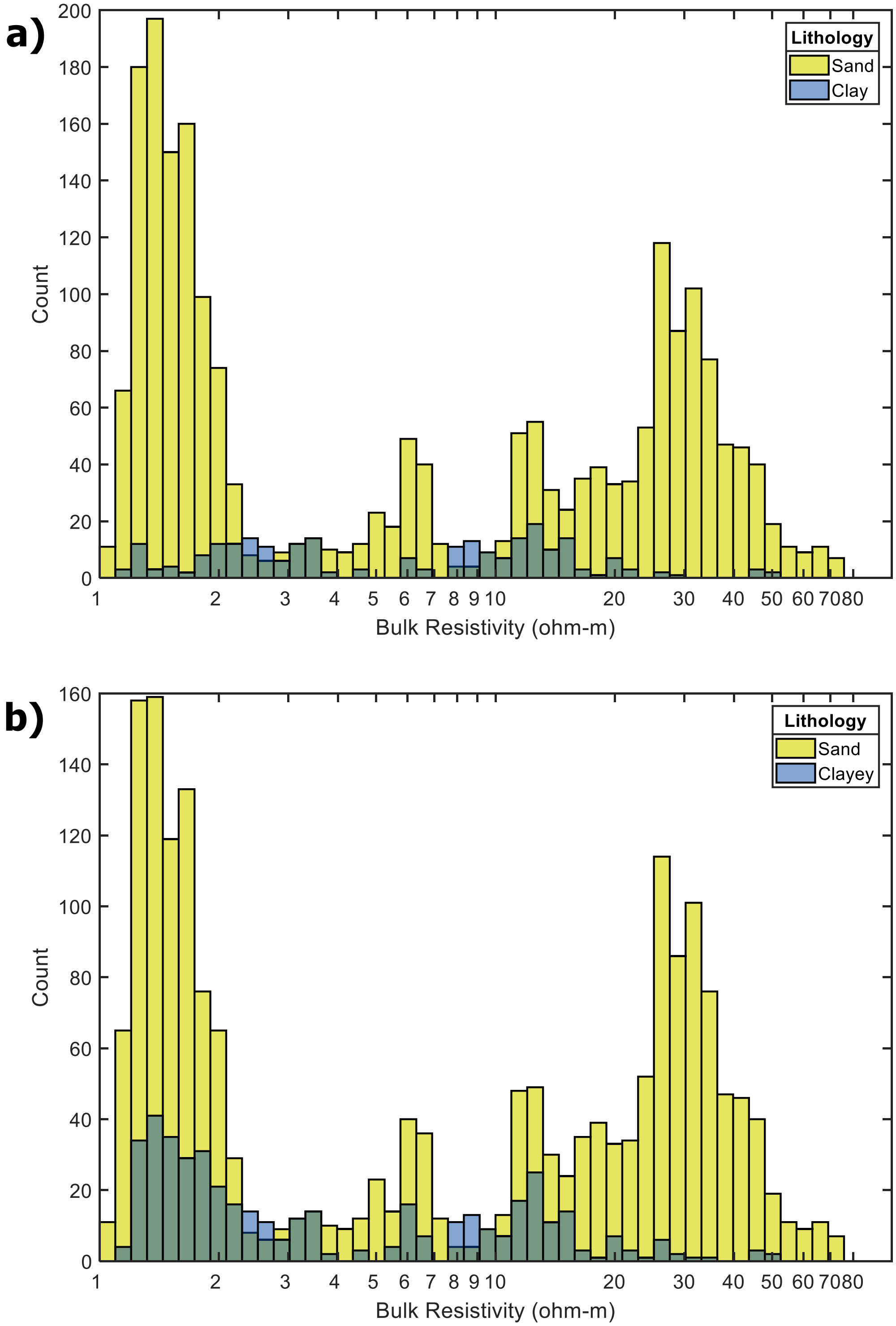


Figure 13: Resistivity values from geophysical measurements in MPWSP monitoring wells, colored according to a binary lithology classification. In a) all values are colored yellow, aside from any lithology descriptor containing the word "clay", which are colored blue. In b) the values colored blue are expanded to include any lithology descriptor including the word "clay" or "clayey". Regions where blue bars overlap yellow bars appear blue-green.

Hydrostratigraphic Modeling

The approach taken here to modeling hydrostratigraphy is comprised of three phases. The first phase involved building a hydrostratigraphic model from existing data, excluding AEM data, referred to as the "pre-AEM" model. The second phase involved updating the model built in the first phase using the acquired AEM data. A final phase involved comparing the resulting hydrostratigraphic models with lithology, water quality, and water level data, and occasionally updating the layer boundaries according to these data. The updated model is referred to as a “post-AEM” model. This approach was followed for two separate pre-AEM models. One pre-AEM model was constructed using hydrostratigraphic interpretations from previously published reports, along with lithology data from our database. The second pre-AEM model was based on the North Marina Groundwater Model (NMGWM), developed by Geoscience Support Services as part of the Monterey Peninsula Water Supply Project (MPWSP) (Geoscience, 2014). Each of the 3-dimensional hydrostratigraphic models was built in the program Leapfrog Geo, a 3D visualization and modeling software (http://www.leapfrog3d.com). The hydrostratigraphic models are defined inland throughout the entire region of interest, extending vertically from the ground surface to 210 mbsl. The hydrostratigraphy beneath the ocean was not considered.

Given the variability in previous interpretations of the hydrostratigaphy in the region of interest, we chose to develop two sets of models. This was an attempt to capture and communicate the level of uncertainty in developing such models. Specifically, the hydrostratigraphic interpretations of Kennedy/Jenks (2004) and those in Geoscience (2014), used to build the NMGWM, differ notably. These differences exist despite that the lithologic logs and cross-sections from Kennedy/Jenks (2004), among data from other reports, were used to define the model boundaries of the NMGWM. Multiple cross-sections from the two reports either intersect or are located near each other, making comparison of the interpretations straightforward. Generally speaking, the 180-Foot Aquifer and the 400-Foot Aquifer were interpreted in Kennedy/Jenks (2004) to be channeled, sinuous, and variable in thickness over short lateral distances. Furthermore, the 180/400-Foot Aquitard was interpreted by Kennedy/Jenks (2004) to be discontinuous in some regions of the Salinas Valley basin. In contrast, the cross-sections from Geoscience (2014) contain smooth, laterally continuous aquifers and aquitards. Furthermore, the hydrostratigraphy interpreted in Geoscience (2014) tends not to coincide as closely with borehole lithology data as does the hydrostratigraphy interpreted in Kennedy/Jenks (2004). The reason for the differences between these interpretations may reflect their different purposes. The NMGWM was constructed by Geoscience Support Services for use as a groundwater flow model. For the sake of computational efficiency, many groundwater flow models usually adopt a simpler interpretation of hydrostratigraphy.

<u>Pre-AEM Model Based on Cross-Sections from Previously Published Reports</u>

The boundaries between units for the pre-AEM model were delineated by using the boundaries interpreted from cross-sections in previously published reports, and by using lithology data assembled in our lithology database. The cross-sections used to map out boundaries between hydrostratigraphic units came from the following reports:

- "Hydrostratigraphic Analysis of the Northern Salinas Valley" (Kennedy/Jenks, 2004)
- "Operable Unit Carbon Tetrachloride Plume Groundwater Remedial Investigation/Feasibility Study" (MACTEC, 2005)
- "Hydrogeologic Investigation of the Salinas Valley Basin in the Vicinity of Fort Ord and Marina; Salinas Valley, California" (Harding ESE, 2001)
- "Seismic Shear Wave Reflection Imaging at the Former Fort Ord, Monterey California" (USGS, 2007)

The cross-sections from the Geoscience (2014) report were not used when building this model, since they mirror the hydrostratigraphy in the NMGWM, and the cross-sections differ notably from cross-sections in Kennedy/Jenks (2004), as discussed above.

From each cross-section, the boundaries between units were marked with control points in locations where the cross-section used nearby borehole information to interpret the boundary. Far from borehole information, or where the interpretation was marked as uncertain, no control points were added. Lithologic heterogeneity exists within each mapped unit, owing to the complex nature of the hydrostratigraphy of the region of interest. Instead of mapping all lithologic heterogeneity, our objective was to map the outer boundaries of each hydrostratigraphic unit. After the boundaries in each cross-section had been marked with control points, preliminary bounding surfaces were interpolated between the control points. Afterwards, borehole lithology descriptions were used to add new control points where no cross-sections were available. After all control points had been added, the final bounding surfaces were interpolated between the points.

Post-AEM Model Based on Cross-Sections from Previously Published Reports

The largest changes to the pre-AEM model were made in the Salinas Valley Aquitard, the 180-Foot Aquifer, and the 180/400-Foot Aquitard. Due to the depth of investigation of the AEM data, the lower boundary for the 400-Foot Aquifer was not always imaged with detail; therefore, the 400-Foot Aquifer, the 400-Foot/Deep Aquitard, and the Deep Aquifer in the pre-AEM model were only occasionally updated. The most significant updates made to the pre-AEM model are as follows:

- The SVA south of the Salinas River was extended westward toward the coast. The SVA in the post-AEM model pinches out near MW-4, which is also supported by nearby lithology and water quality data.
- The boundaries between the Upper 180-Foot Aquifer, the Intermediate 180-Foot Aquitard, and the Lower 180-Foot Aquifer were updated to reflect the boundaries identified in the AEM resistivity model. Generally, the thickness of the Intermediate 180-Foot Aquitard was reduced, and in some locations, gaps were made in the aquitard.
- Gaps were also made in the 180/400-Foot Aquitard, as indicated by the AEM resistivity model. Gaps in the 180/400-Foot Aquitard have been suspected since the Kennedy/Jenks (2004)

report, and some have been substantiated by the 2015 saltwater intrusion map produced by the Monterey County Water Resources Agency, who found isolated regions of saline groundwater in the 400-Foot Aquifer, laterally disconnected from the saltwater intrusion wedge within the aquifer. Some gaps in the aquitard had already been included according to the interpretations in Kennedy/Jenks (2004); however, additional gaps in the aquitard both north and south of the Salinas River were suggested by the AEM resistivity model. There is some question as to whether some of the communication we see between the 180-Foot Aquifer and the 400-Foot Aquifer could be caused by conduit wells. Figure 14 shows a cross-section of the Salinas Valley basin that demonstrates the identification of gaps in the 180/400-Foot Aquitard using AEM data. In Figure 14a (top section), the post-AEM model is shown, along with lithology information. In Figure 14b (bottom section), the AEM resistivity model is superimposed on the same cross-section. Based on the vertical continuity of the low resistivity values across the 180-Foot Aquifer and the 400-Foot Aquifer in the center of Figure 14b, a gap was added to the 180/400-Foot Aquitard.

Note that in some cases, such as on the left hand side of Figure 14b, the vertically continuous low resistivity feature is understood to indicate a gap in the aquitard, despite clay being described in a nearby lithology log at the elevation of the aquitard. While borehole lithology information is very useful for building models of hydrostratigraphy, Figure 14 demonstrates that lithologic units captured in 1-dimensional borehole lithology data might not be laterally continuous.

<u>Pre-AEM Model Based on the North Marina Groundwater Model</u>

The NMGWM is a numerical groundwater flow model, compatible with the program MODFLOW. The model is divided into a 3-dimensional rectangular grid. At each cell within the grid are defined the necessary hydraulic properties and boundary conditions to simulate groundwater flow by solving the groundwater flow equation, as well as the transport equation, should transport of dissolved solids be simulated. The NMGWM is defined in terms of hydraulic properties (e.g. hydraulic conductivity), although the units in the NMGWM are designed to match an interpretation of the hydrostratigraphy of the region.

The layers in the NMGWM, and the hydrostratigraphic units they correspond to, are listed in Table 4 (adapted from Hydrogeologic Working Group, 2017). The NMGWM does not include any distinction between the Upper 180-Foot Aquifer, the Intermediate 180-Foot Aquitard, and the Lower 180-Foot Aquifer. Furthermore, the NMGWM does not include the SVA south of the Salinas River, except for in a small area near the coast, where it extends approximately 1 km from the Salinas River.

Within Leapfrog Geo, the boundary between each layer the NMGWM was marked and named. The resulting pre-AEM model looks very similar to the original MODFLOW model, but is described by hydrostratigraphic units, and not by hydraulic properties.

The NMGWM is publicly available at the California Public Utilities Commission website:

http://www.cpuc.ca.gov/environment/info/esa/mpwsp/comms_n_docs.html .

Post-AEM model based on the North Marina Groundwater Model

As was the case with the pre-AEM model based on previously published cross-sections, the largest changes to the pre-AEM model based on the NMGWM were made in the Salinas Valley Aquitard, the 180-Foot Aquifer, and the 180/400-Foot Aquitard. The most significant updates made to the pre-AEM model are as follows:

- North of the Salinas River, the SVA was extended to the north. In the pre-AEM model, the Salinas Valley Aquitard extends through the majority of the region of interest north of the Salinas River, dipping and thickening toward the center of the Salinas Valley basin, and thinning toward the edges. The aquitard does not extend beyond the basin. The post-AEM model maps the Salinas Valley Aquitard beyond the edge of the Salinas Valley basin, and also maps the Salinas Valley Aquitard as an undulating, but generally continuous, aquitard with a nearly flat dip.
- The SVA was extended south of the Salinas River, below the Dune Sand Aquifer. The SVA thins out to the west near MW-4, which is also supported by nearby lithology and water quality data.
- Gaps were added to the 180/400-Foot Aquitard, as indicated by the AEM data. No gaps in the 180/400-Foot Aquitard existed in the pre-AEM model based on the NMGWM. Figure 15 shows a map of the region of interest, which coincides with the model domain, overlain by the model of the 180/400-Foot Aquitard in the post-AEM model based on the NMGWM. Gaps in the aquitard are seen where the map is visible within the extent of the model. Above the 180/400-Foot Aquitard are shown where AEM data were collected and retained for processing. In regions where no AEM data were collected, such as within the Marina and Fort Ord areas, the thickness of the 180/400-Foot Aquitard was not updated from the thickness in the pre-AEM model.
- The 180-Foot Aquifer was subdivided into three units south of the Salinas River: the Upper 180-Foot Aquifer, the Intermediate 180-Foot Aquitard, and the Lower 180-Foot Aquifer, in accordance with the naming scheme from the MACTEC (2005) report. The decision to subdivide the 180-Foot Aquifer was based largely on the AEM resistivity model, which showed significant changes in resistivity between these three units. Lithology descriptions and water level measurements in this region support this subdivision as well. Figure 16a presents the post-AEM model in the Marina area based on the NMGWM, along with lithology information from the well logs. The left-hand side of Figure 16b displays these pathways. From highest to lowest elevation in the AEM data, the dark blue region represents the unsaturated zone, followed by a thin light green zone, which represents a thin perched aquifer on top of the Salinas Valley Aquitard. Beneath this zone is a deeper blue, which represents the Upper 180-Foot Aquifer, followed by another thin green zone, representing the Intermediate 180-Foot Aquitard, and then a region of red, which is the Lower 180-Foot Aquifer and 400-Foot Aquifer, both intruded by saltwater.

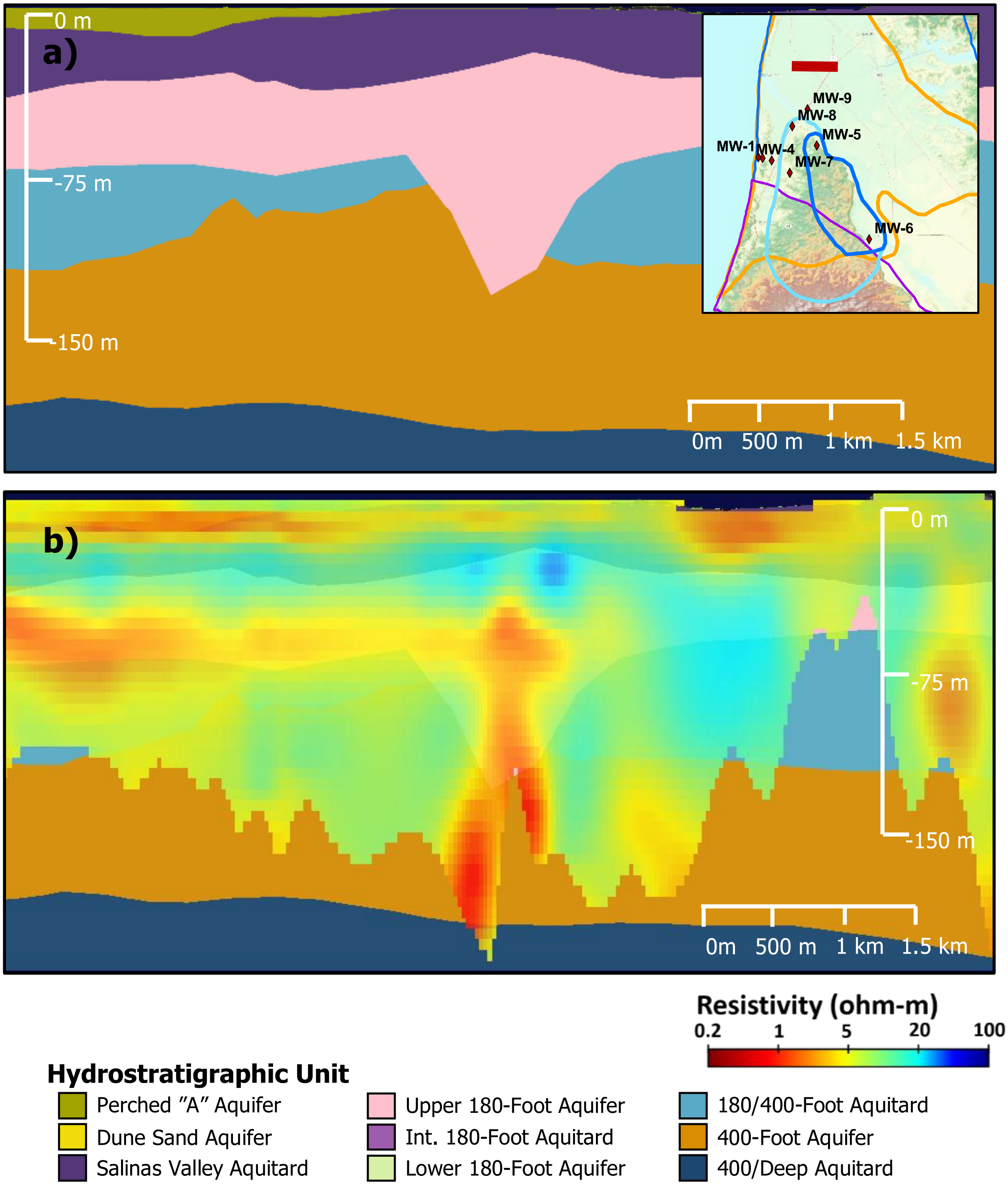


Figure 14: Determining gaps in the 180/400-Foot Aquitard from AEM data. Above, a) shows a cross-section of the post-AEM model based on cross-sections from previously published reports, with an inset map showing the approximate cross-section location as a red bar. Below, b) shows the same post-AEM model with the AEM resistivity model superimposed. Opacity of the AEM resistivity model is set to approximately 80%.

NMGWM Layer	Units Corresponding to NMGWM Layer
1	Ocean
2	Dune Sand Aquifer Perched "A" Aquifer
3	Salinas Valley Aquitard (SVA)
4	Upper 180-Foot Aquifer Lower 180-Foot Aquifer
5	180/400-Foot Aquitard
6	400-Foot Aquifer
7	400/Deep Aquitard
8	Deep Aquifer

Table 4: Layers in the NMGWM and the aquifers in the region of interest they were constructed to correspond to (adapted from Hydrogeologic Working Group, 2017).

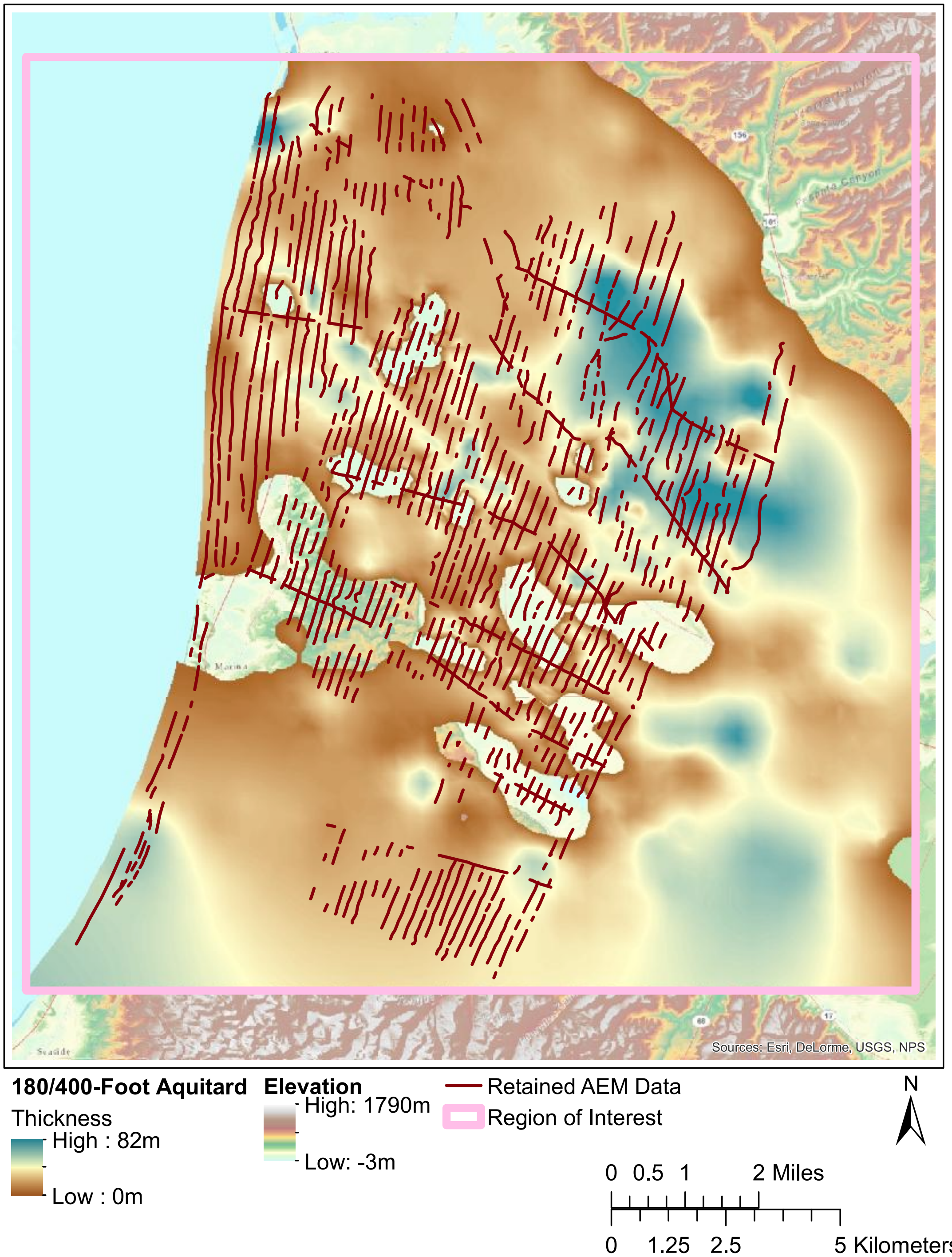


Figure 15: Map view of the 180/400-Foot Aquitard in the post AEM model based on the NMGWM, shown in a color scale ranging from brown to blue, representing a thickness of near 0 m to 82 m, respectively. Underlying the 180/400-Foot Aquitard is a map of the region of interest. Above the 180/400-Foot Aquitard is a display of the flight lines retained for data processing, represented as red lines, as shown also in Figure 2. Gaps in the aquitard can be seen where the map is visible underneath the aquitard. According to the NMGWM, the 180/400-Foot Aquitard intersects the ground surface near Prunedale, in the northeast section of the region of interest. In regions where without AEM measurements, the thickness of the 180/400-Foot Aquitard was not updated.

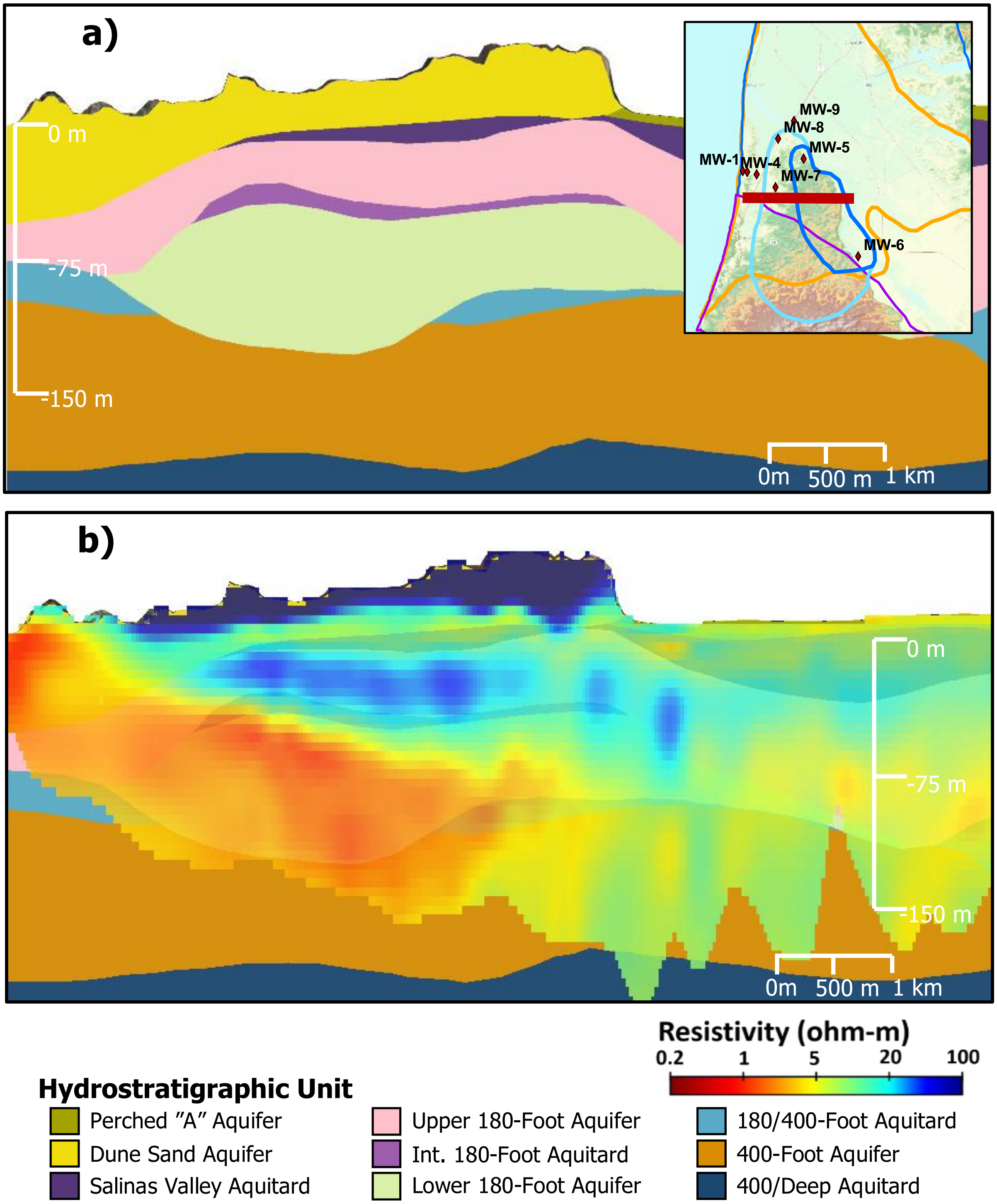


Figure 16: Cross-section of a) the post-AEM model in the Marina area based on the NMGWM, along with lithology information from well logs. The 180-Foot Aquifer is subdivided here into the Upper 180-Foot Aquifer, the Intermediate 180-Foot Aquitard, and the Lower 180-Foot Aquifer, in accordance with the naming scheme from the MACTEC (2005) report. An inset map shows the approximate location of the cross-section as a red bar. Beneath, b) shows the same post-AEM model with the AEM resistivity model superimposed. Opacity of the AEM resistivity model is set to approximately 80%.

Interpretation of Water Quality

The final stage of our analysis was to interpret the distribution of drinking water (0-1,000 mg/L), sources of drinking water (1,000-3,000 mg/L), and water of limited beneficial use (greater than 10,000 mg/L). We worked with both post-AEM hydrostratigraphic models, with the unsaturated zone removed. While the relationship between resistivity and TDS and lithology is complex, as discussed earlier, we are confident that resistivity values greater than 20 ohm-m indicate the presence of sediments saturated with a source of drinking water, and resistivity values less than 3 ohm-m indicate the presence of water of limited beneficial use. Water of potential beneficial use (TDS concentrations of 3,000 to 10,000 mg/L) does not enter into this interpretation of water quality, because the range of resistivity values associated with water of potential beneficial use is completely overlapped by the ranges of resistivity values associated with drinking water and with sources of drinking water, as shown in Figure 12.

Each of the two post-AEM models presents an interpretation of the hydrostratigraphy within the region of interest. The variability between the two post-AEM models represents the uncertainty in the interpretation of the hydrostratigraphy. In regions where AEM data are informative for delineating hydrostratigraphic units, few differences appear between the two post-AEM models. In regions where boundaries could not be reliably identified by AEM data, the models differ more, since in those regions the post-AEM models reflect their respective pre-AEM models more closely. Although there are differences in the hydrostratigraphy between the two post-AEM models, there are no differences in the maps we obtain of the distribution and volume of drinking water sources and of water of limited beneficial use.

Figure 17 is a map of the region of interest. Plotted on the map are four white horizontal stripes, each of which marks the location of a cross-section where the post-AEM models are compared in Figures 18 through 21. In each of these figures, on the left hand side is shown the post-AEM model built using cross-sections from previously published reports, referred to as Model A. On the right hand side is the equivalent section from the post-AEM model built from the NMGWM, referred to as Model B.

Cross-section 1

In Figure 18, we show the two post-AEM models at Cross-section 1. The western half of Cross-section 1 lies south of the Salinas River, while the eastern half lies in the Salinas Valley basin, north of the Salinas River. At this location, major differences exist between the two models in the units that comprise the 180-Foot Aquifer, and in the thickness of the 400-Foot Aquifer. In Model A cross-section, the units that comprise the 180-Foot Aquifer (the Upper 180-Foot Aquifer, the Intermediate 180-Foot Aquitard, and the Lower 180-Foot Aquifer) dip toward the coast, while the same layers in Model B do not dip notably in any direction. In the eastern half of Cross-section 1, the AEM resistivity model does not show a clear delineation between the 400-Foot Aquifer and the underlying 400/Deep Aquitard. Therefore, each post-AEM model in this region reflects the pre-AEM model it was created from. In the case of Model B, the 400-Foot Aquifer was interpreted to be 50-60 m thick throughout much of the region of interest.

At the eastern edge of the Dune Sand Aquifer, shown in Cross-section 1, a source drinking water has been identified, as well as within the Upper 180-Foot Aquifer, extending partially into the Lower 180-Foot Aquifer, which, north of the Salinas River, is not generally hydraulically separated from the Upper 180-Foot Aquifer. Water of limited beneficial use is found adjacent to the coast, as a result of saltwater intrusion.

Cross-section 2

In Figure 19, presenting Cross-section 2, the differences between the post-AEM models are compared. A thick region of water of limited beneficial use, which is a result of saltwater intrusion, extends inland and descends vertically. In both post-AEM models, the 180/400-Foot Aquitard and the Intermediate 180-Foot Aquitard thin out in a section near the coast, interpreted by the apparent migration of the water of limited beneficial use from the Dune Sand Aquifer all the way into the 400-Foot Aquifer.

Major differences in the post-AEM models are found in the SVA and the units that comprise the 180-Foot Aquifer. In Model A, the SVA and the units comprising the 180-Foot Aquifer dip toward the ocean. Furthermore, the Lower 180-Foot Aquifer thickens, while the 400-Foot Aquifer thins. In Model B, the SVA and the 180-Foot Aquifer are flat, and the Lower 180-Foot Aquifer thins while the 400-Foot Aquifer thickens. Near the coast in the region of Cross-section 2, the depth of investigation of the AEM data is at its shallowest, near 50 mbgs, due to the salinity of the pore water. Below this depth, the AEM data offer no guidance for updating the model boundaries.

In Cross-section 2, sources of drinking water are encountered throughout the Dune Sand Aquifer and throughout the Upper 180-Foot Aquifer south of the Salinas River. North of the Salinas River, sources of drinking water are certainly encountered within regions of the 180-Foot Aquifer.

Cross-section 3

In Figure 20, the differences between post-AEM models are compared along Cross-section 3. Almost all of Cross-section 3 is north of the Salinas River. Within the 180-Foot Aquifer, saltwater intrusion has produced volumes of water of limited beneficial use that extend between 7 and 8 km inland. While the bodies delimiting the water of limited beneficial use appear in Figure 20 as isolated patches, the resistivity measurements show that this low-resistivity feature is laterally continuous. Gaps are encountered in the 180/400-Foot Aquitard where resistivity measurements suggested vertical migration of low-resistivity water.

Near the eastern edge of Model B, all units from the 180-Foot Aquifer to the Deep Aquifer begin to dip southwest, toward the center of the Salinas Valley basin. This differs from Model A, which shows the 180/400-Foot Aquitard thickening, with only minor dipping from the other units.

Cross-section 4

In Figure 21, the differences between post-AEM models are compared along Cross-section 4. This section runs into the northern edge of the Salinas Valley basin. The hydrostratigraphy in the western half of Cross-section 4 resembles that of Cross-section 3. Gaps are encountered within the 180/400-Foot Aquitard. In Figure 21, the vertical migration of water of limited beneficial use is apparent. Small, isolated sources of drinking water exist within the 180-Foot Aquifer as well.

The eastern half of Cross-section 4 is outside the region where AEM data were collected. The lithology descriptions in Cross-section 4 suggest that clay-rich units dominate the hydrostratigraphy in this area. This is reflected in Model A, in which the 400-Foot Aquifer thins out, and the 180/400-Foot Aquitard, and the 400/Deep Aquitard thicken significantly. The NMGWM does not account for this large increase in clay content near the northern edge of the Salinas Valley basin. Without AEM data nearby to update Model B, the post-AEM model reflects the hydrostratigraphy in the pre-AEM model at this location, where the 400-Foot Aquifer and the 180-Foot Aquifer dip southeast, and eventually intersect the ground surface.

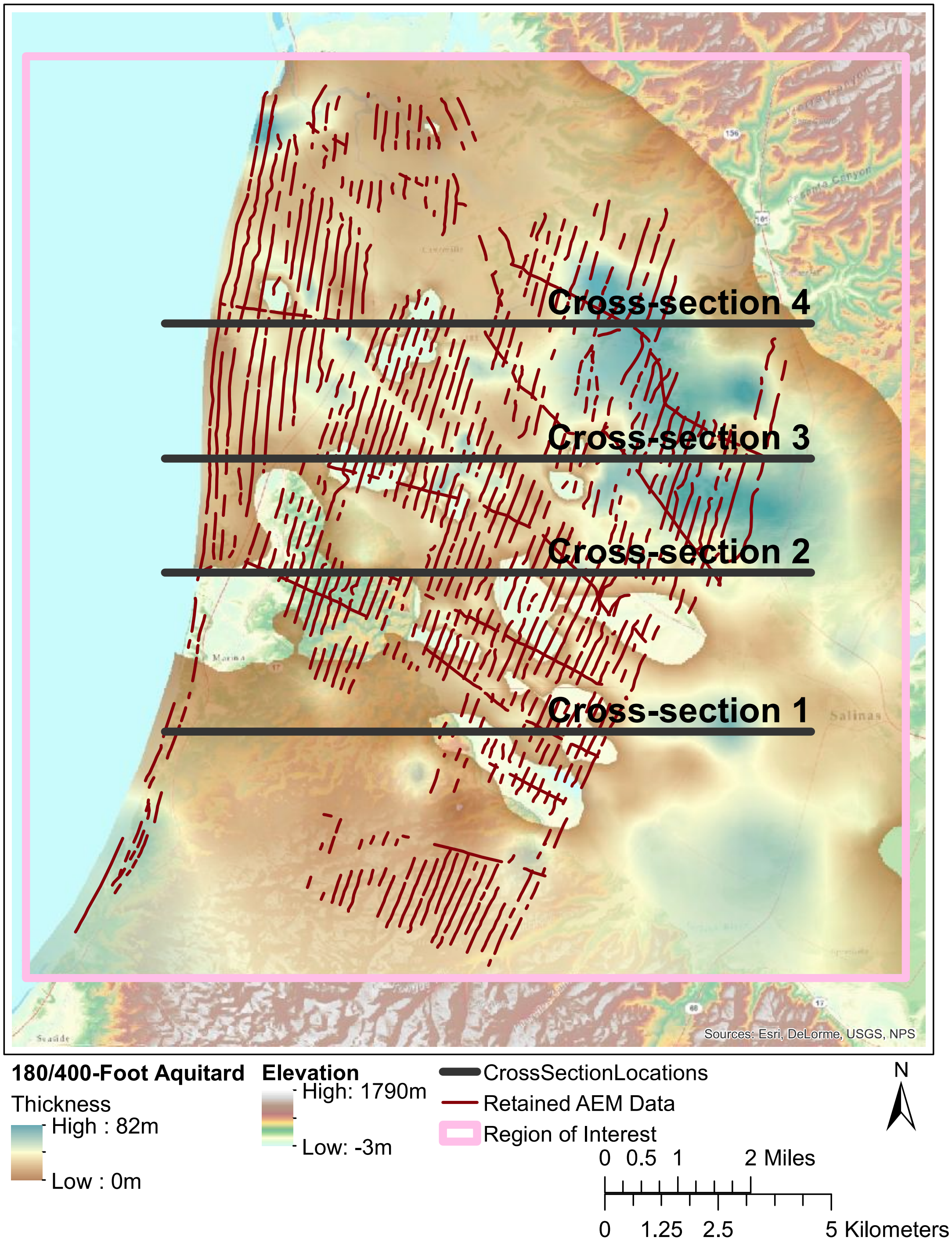


Figure 17: Map view showing the location and extent of the cross-sections shown in Figures 18 through 21. Each cross-section is approximately 14.23 km long, extending west to east. The northings of the sections, in order from lowest to highest, are: 4,059,000 m; 4,062,500 m; 4,065,000 m; and 4,068,000 m (NAD 1983 UTM Zone 10N). Shown also on the map are the locations where AEM data were retained for processing, in red. The thickness of the 180/400-Foot Aquitard in the post-AEM model based on the NMGWM, as seen in Figure 15, is shown here with 30% transparency.

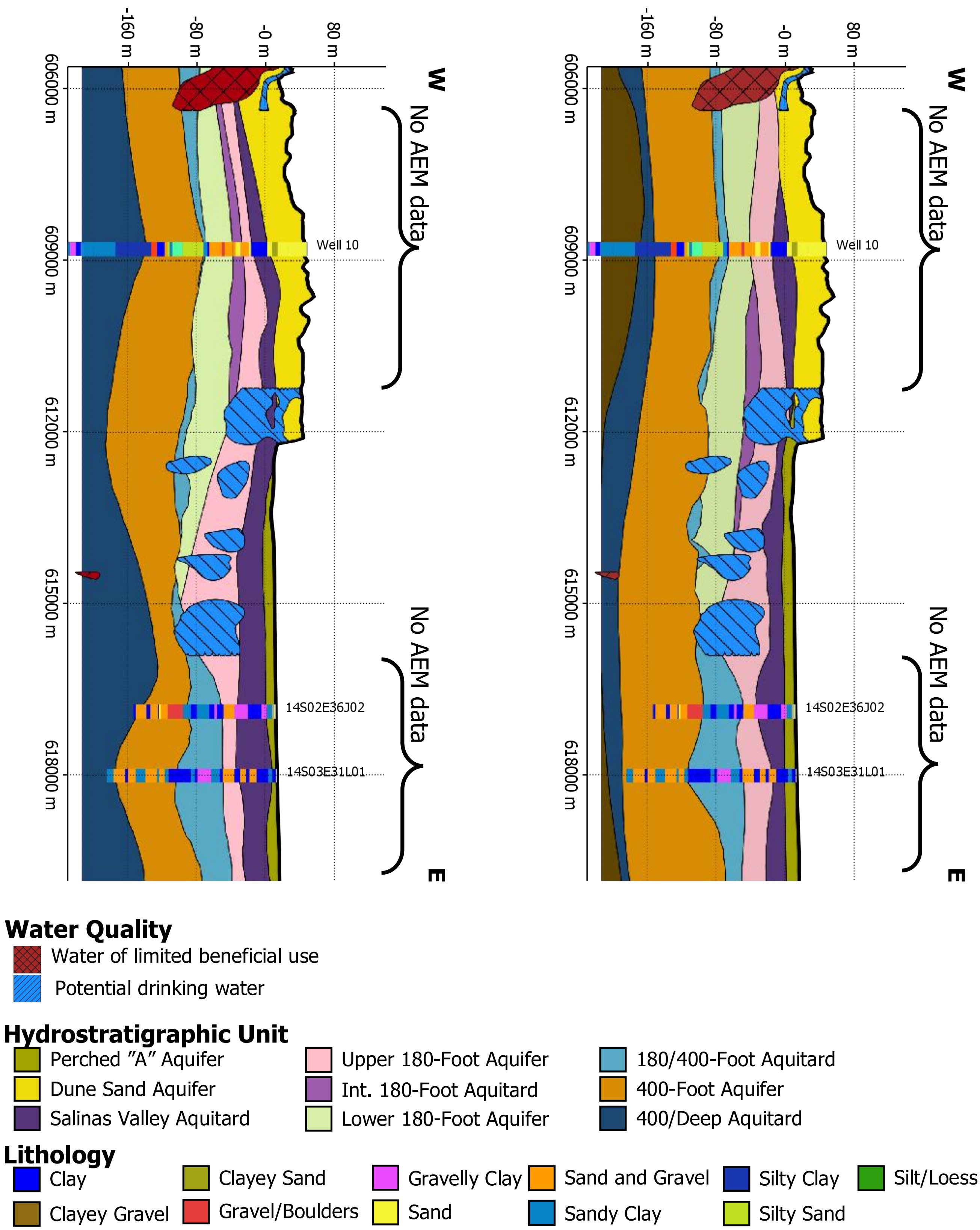


Figure 18: Cross-section 1: cross-sectional comparison of post-AEM models. On the left is Model A, based on cross-sections from previously published reports. On the right is Model B, based on the NMGWM. The brackets to the right of each cross-section indicate regions without processed AEM data. Cross-section location: 4,059,000 m north (NAD 1983 UTM Zone 10N).

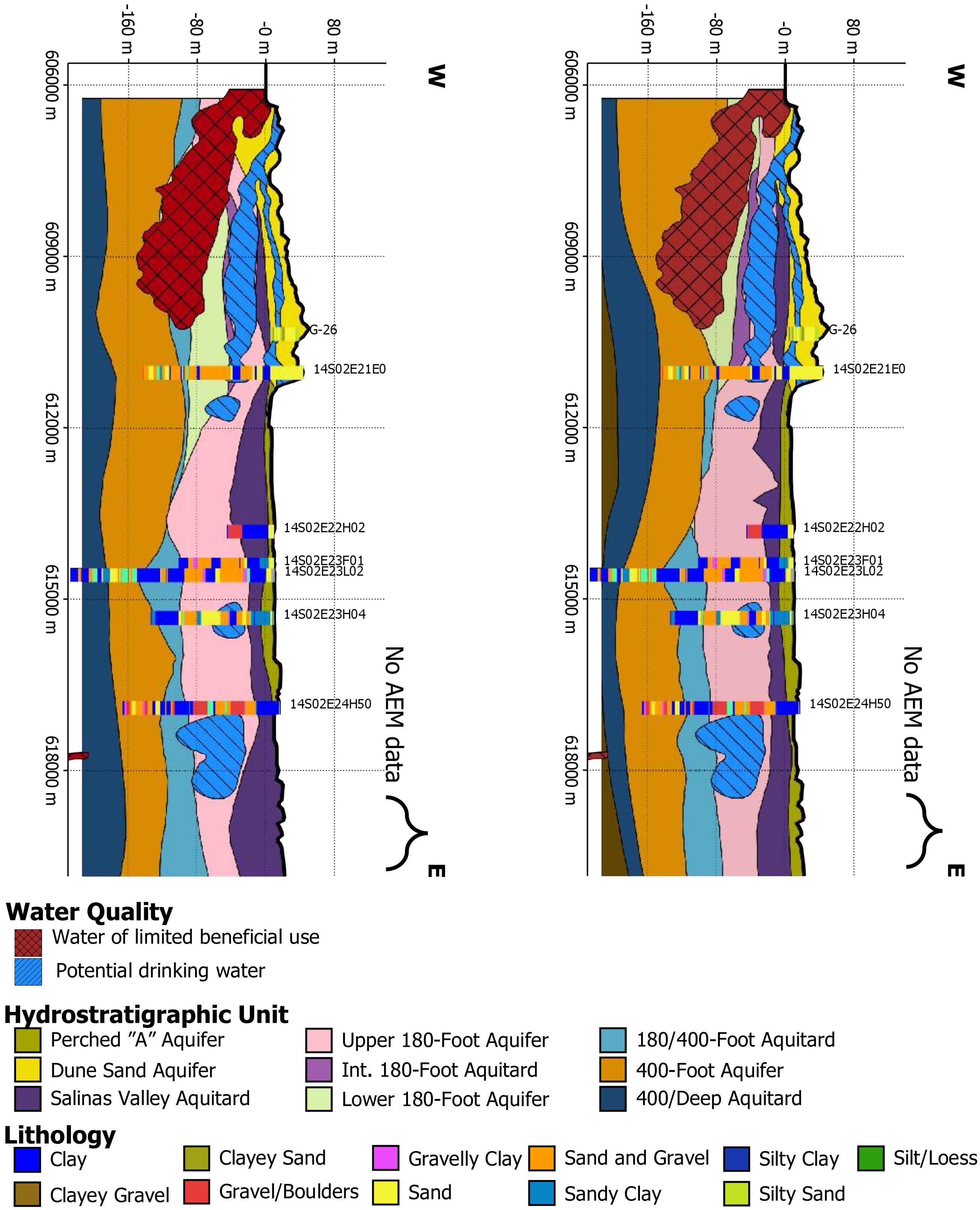


Figure 19: Cross-section 2: cross-sectional comparison of post-AEM models. On the left is Model A, based on cross-sections from previously published reports. On the right is Model B, based on the NMGWM. The brackets to the right of each cross-section indicate regions without processed AEM data. Cross-section location: 4,062,500 m north (NAD 1983 UTM Zone 10N).

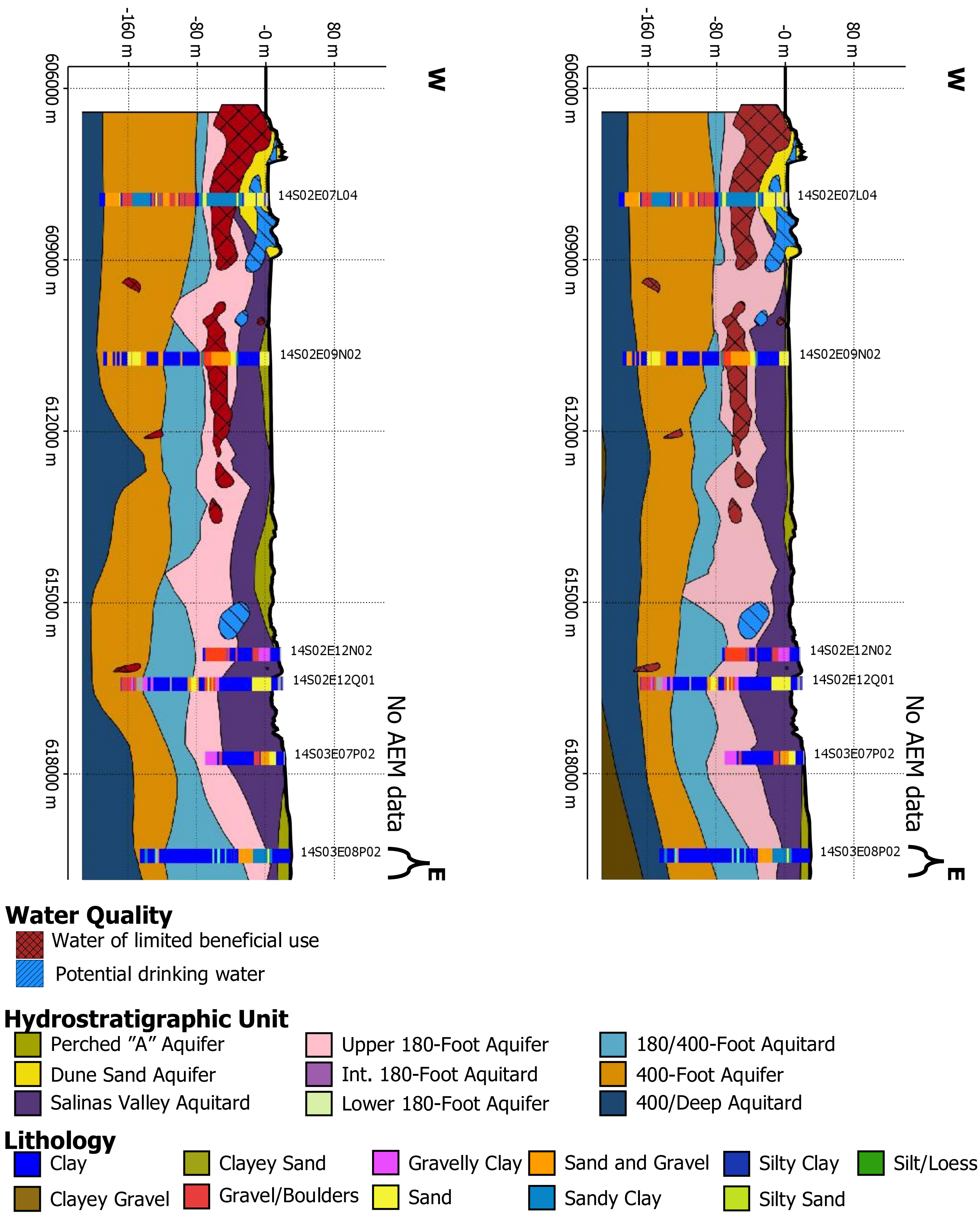


Figure 20: Cross-section 3: cross-sectional comparison of post-AEM models. On the left is Model A, based on cross-sections from previously published reports. On the right is Model B, based on the NMGWM. The brackets to the right of each cross-section indicate regions without processed AEM data. Cross-section location: 4,065,000 m north (NAD 1983 UTM Zone 10N).

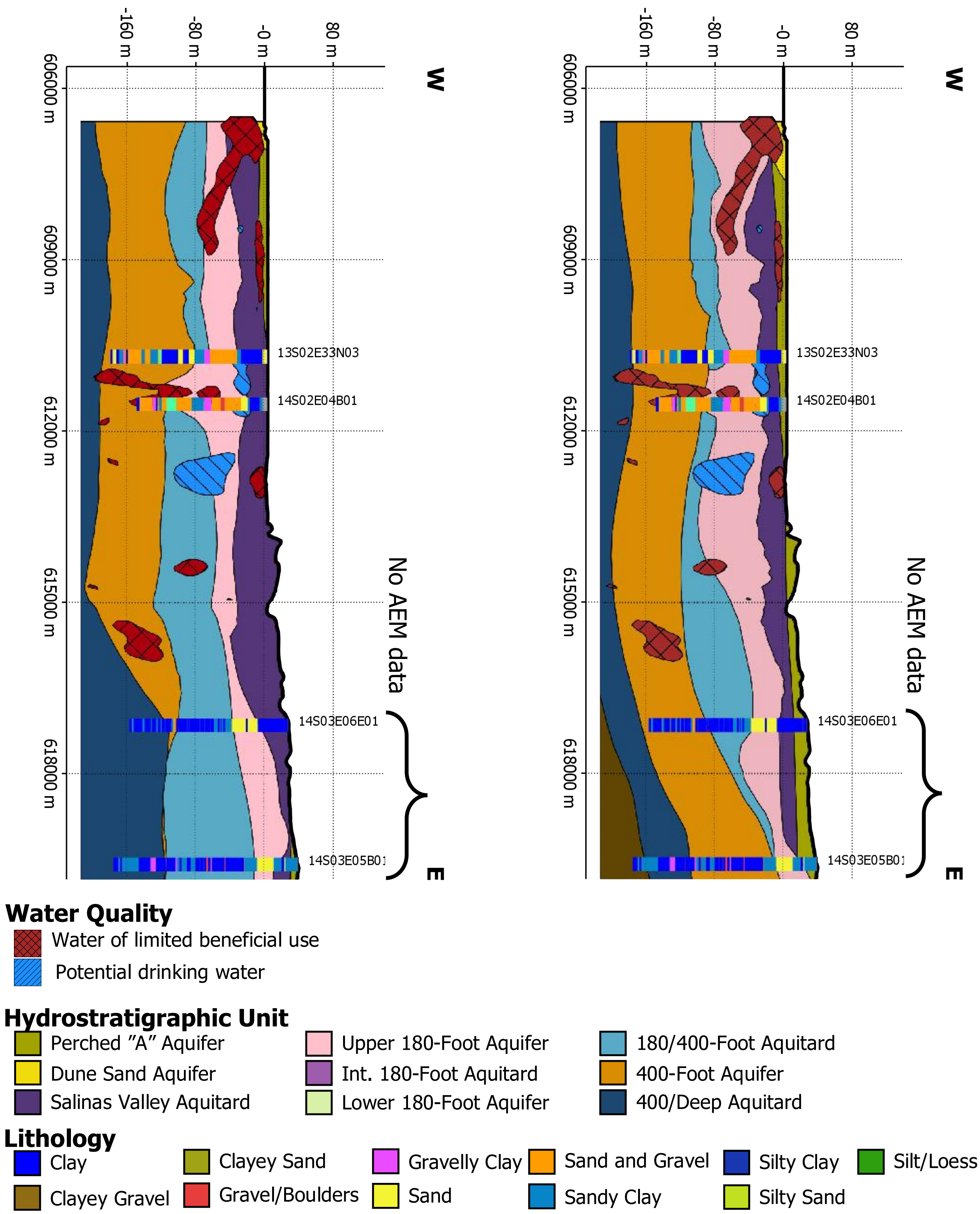


Figure 21: Cross-section 4: cross-sectional comparison of post-AEM models. On the left is Model A, based on cross-sections from previously published reports. On the right is Model B, based on the NMGWM. The brackets to the right of each cross-section indicate regions without processed AEM data. Cross-section location: 4,068,000 m north (NAD 1983 UTM Zone 10N).

Volume Estimates of Regions Containing Potential Drinking Water and Water of Limited Beneficial Use

We have evaluated the distribution of sources of drinking water, as well as the distribution of water of limited beneficial use, within the region of interest. We have achieved this by applying to the AEM data cutoff ranges of resistivity values derived from the borehole resistivity measurements and TDS measurements in Figure 12. The range of resistivity values we defined for water of limited beneficial use (TDS >= 10,000 mg/L) was <= 3 ohm-m. The range of resistivity values we defined for sources of drinking water (TDS <= 3,000 mg/L) was 20-75 ohm-m (above 75 ohm-m was defined as the unsaturated zone and was removed from our analysis).

The defined ranges of resistivity values were designed as conservative estimates for the distribution of water of limited beneficial use and of sources of drinking water. In the case of sources of drinking water, applying the defined range of resistivity values is expected to underestimate the true volume of sources drinking water. In Figure 12, approximately 41% of the measurements measured with a TDS <= 3,000 mg/L had a resistivity below 20 ohm-m. Many of the low resistivity measurements of sources of drinking water are expected to come from finer grained material, whereas low resistivity measurements in coarse grained material are likely be related with water of higher TDS. Identifying sources of drinking water from resistivity measurements below 20 ohm-m requires supporting data and should be evaluated on a case-by-case basis. Final volume estimates will be given for the conservatively defined ranges of resistivity, with the understanding that these will underestimate the true amount of sources of drinking water in the region of interest. The estimated volume of water of limited beneficial use should be closer to the true value, according to the limited overlap in Figure 12 between the high and middle ranges of TDS concentrations.

In each of Figures 22 through 25, a map of the region of interest is shown, along with the interpreted thickness of the subsurface containing sources of drinking water, shown in a color scale ranging from purple to light blue, representing 0 to 150 meters, respectively. The thickness of the subsurface containing sources of drinking water is shown within the Dune Sand Aquifer in Figure 22, within the Upper 180-Foot Aquifer in Figure 23, within the Lower 180-Foot Aquifer in Figure 24, and within the 400-Foot Aquifer in Figure 25. The aquifers defined in the post-AEM hydrostratigraphic model based on cross-sections from previously published reports (Model A) were used in Figures 22 through 25. The areas interpreted to contain sources of drinking water were calculated using the AEM resistivity measurements between 20 and 75 ohm-m. Therefore, the areas interpreted to contain sources of drinking water regions were only calculated where AEM data were collected and processed. Locations where AEM data were retained for processing are shown in Figures 22 through 24 as black lines. Areas interpreted as containing sources of drinking water within the Perched “A” Aquifer are not show due to their small volume in comparison to the volume of sources of drinking water in the other aquifers within the region of interest.

The interpreted thickness of the subsurface containing sources of drinking water in the Dune Sand Aquifer, shown in Figure 22, covers nearly the entire area where AEM data were collected and processed within the Dune Sand Aquifer. The Dune Sand Aquifer lies south of the

Salinas River, aside from the dune sand deposits along the coast within the Salinas Valley basin, which are also treated as part of the Dune Sand Aquifer here. In the Upper 180-Foot Aquifer, the interpreted thickness of the subsurface containing sources of drinking water, shown in Figure 23, covers most of the area where AEM data were collected south of the Salinas River. Figure 24 displays the thickness of sources of drinking water in the lower 180-Foot Aquifer. Most of the sources of drinking water within the 180-Foot Aquifer is contained within the Upper 180-Foot Aquifer. North of the Salinas River and within the Salinas Valley basin, sources of drinking water were interpreted to be in the east, near Salinas. This area containing sources of drinking water generally coincides with the eastern extent of saltwater intrusion in the 180-Foot Aquifer, as interpreted by the Monterey County Water Resources Agency. Near the northern extent of the Salinas Valley basin, the area containing sources of drinking water extends further west than it does within the Salinas Valley basin. Within the 400-Foot Aquifer, the areas containing sources of drinking water, shown in Figure 25, are limited a region approximately halfway between Marina and Salinas, spanning both south and north of the Salinas River.

In Table 5 we show volume estimates of regions of the subsurface containing water of limited beneficial use, as well as of the sources of drinking water in the region of interest. The volume estimates are separated into regional categories as well as aquifer categories. The regional categories include the Monterey groundwater Subbasin and the 180/400 Aquifer Subbasin. Separated out from these two regions is the area west of Highway 1, which represents the region most severely impacted by saltwater intrusion. The aquifer categories include the Dune Sand Aquifer, the Upper 180-Foot Aquifer, the Lower 180-Foot Aquifer, and the 400-Foot Aquifer, which are evaluated from the post-AEM model based on cross-sections from previously published reports. The final column shows the volume of sources of drinking water within each region or aquifer, assuming 20% porosity throughout the entire region of interest. The value of 20% was chosen as a reference, and is considered a lower bound estimate for mixed sands and gravels (Fetter, 2000), although it should be emphasized that porosity is expected to vary throughout the region of interest. The total volume surveyed was 227.1×10^8 m^3.

Volume estimates are reported as cubic meters of subsurface. To calculate the volume of water in any water-saturated sediment requires knowledge of the porosity of the sediment. Without knowing at least the average porosity of each aquifer, reliable groundwater volumes are difficult to estimate. Volume estimates are also reported as a percent of the total volume within the AEM surveyed region; note that the AEM measurements did not span the entire region of interest.

In areas where the aquitard separating two aquifers is missing, there is some uncertainty regarding where the upper aquifer ends and where the lower aquifer begins. This uncertainty carries through to the volume estimates, since estimated volumes of groundwater near these boundaries may belong to either aquifer.

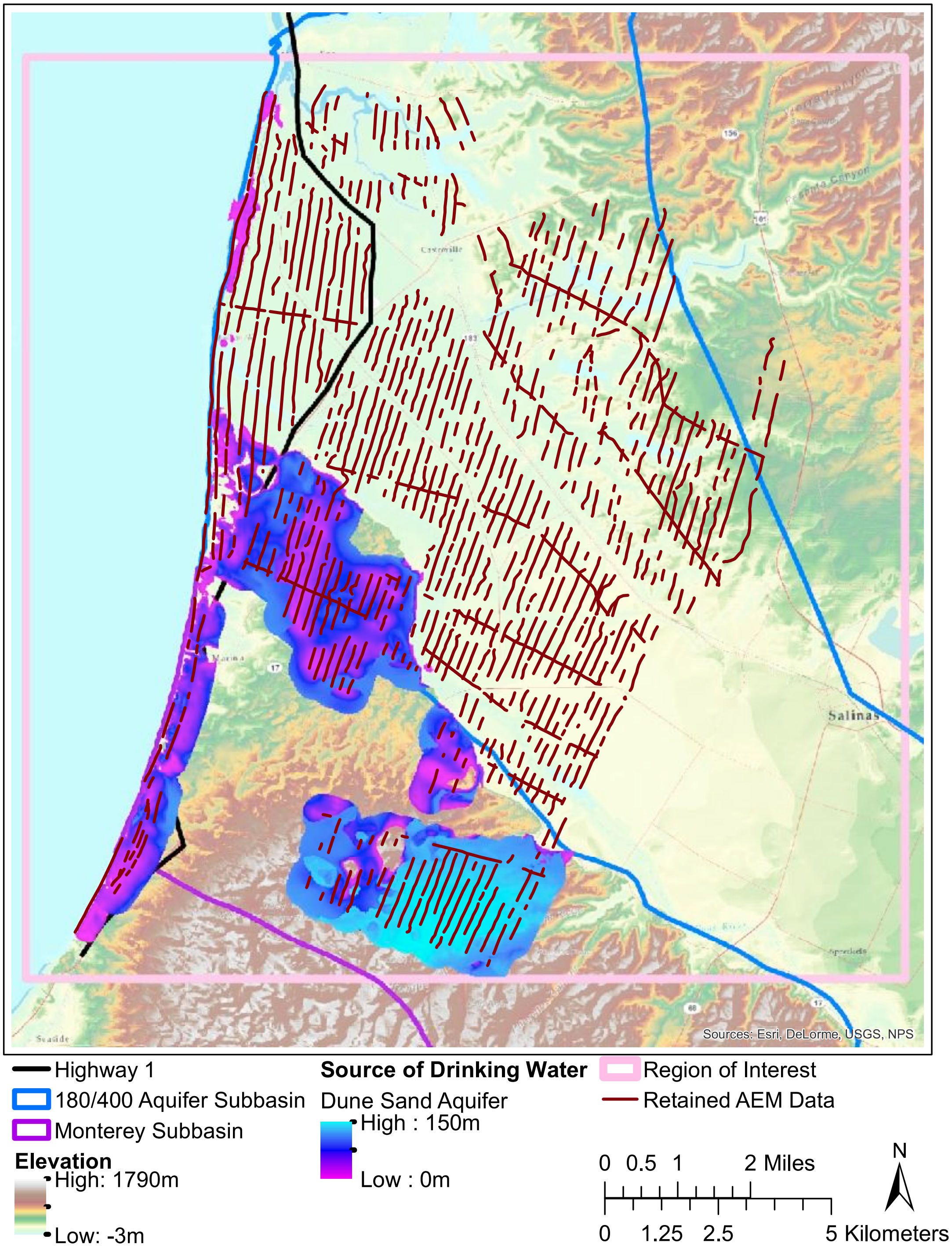


Figure 22: Interpreted thickness of the subsurface containing sources of drinking water within the Dune Sand Aquifer in the region of interest, shown in a color scale ranging from purple to light blue, representing 0 m to 150 integrated meters of the source drinking water, respectively. Overlaying the thickness of sources of drinking water are the locations where AEM data were collected and retained for processing, shown as red lines. The Dune Sand Aquifer lies south of the Salinas River, aside from the dune sand deposits along the coast within the Salinas Valley basin, which are also treated as part of the Dune Sand Aquifer here. The boundaries used in calculating the regions containing sources of drinking water, Highway 1, the 180/400 Aquifer Subbasin, and the Monterey Subbasin, are shown as black, blue, and purple lines, respectively.

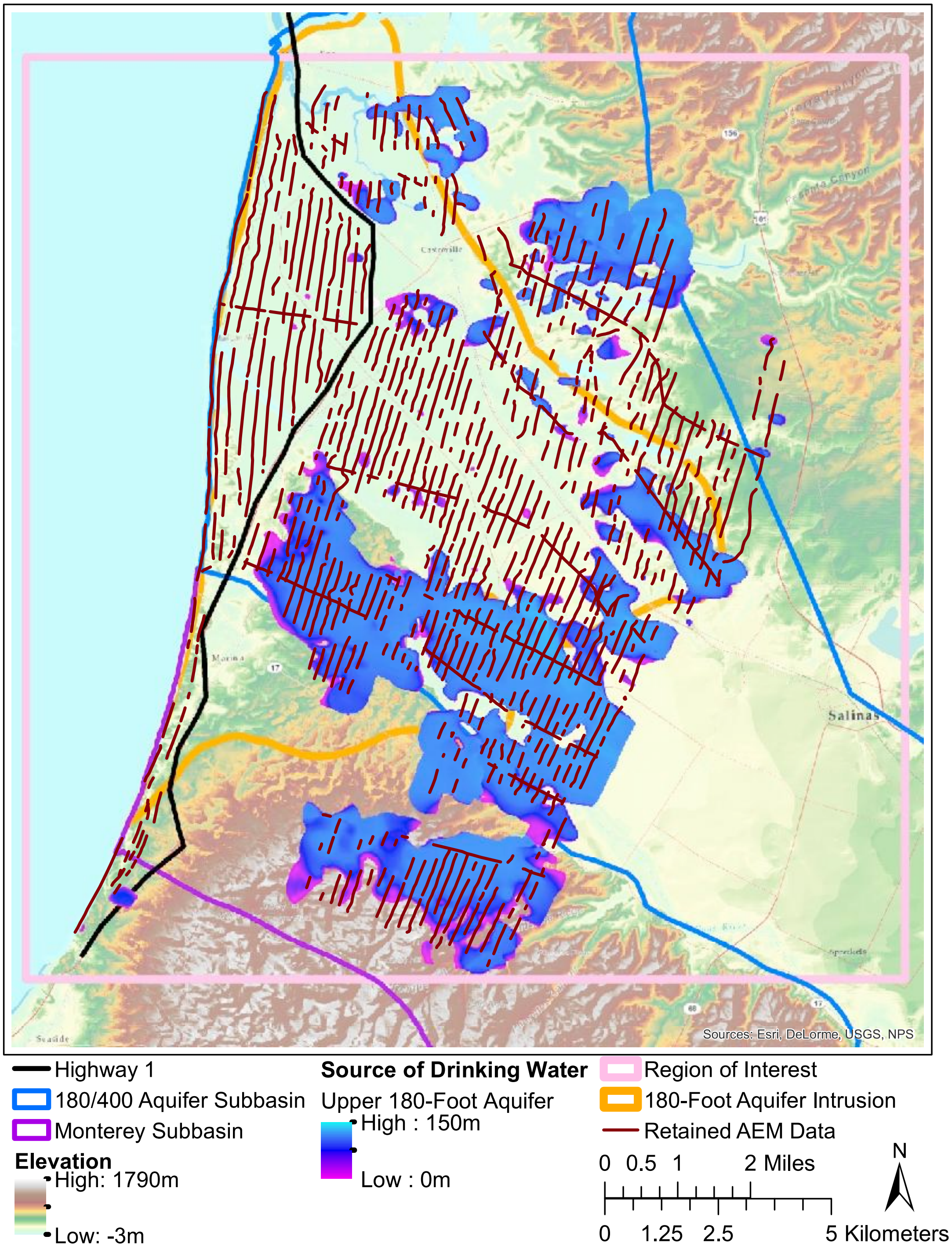


Figure 23: Interpreted thickness of the subsurface containing sources of drinking water within the Upper 180-Foot Aquifer in the region of interest, shown in a color scale ranging from purple to light blue, representing 0 m to 150 integrated meters of the source of drinking water, respectively. Overlaying the thickness of sources of drinking water are the locations where AEM data were collected and retained for processing, shown as red lines. The extent of saltwater intrusion in the 400-Foot Aquifer, as measured by the Monterey County Water Resources Agency, is shown as an orange line. The boundaries used in calculating the regions containing sources of drinking water, Highway 1, the 180/400 Aquifer Subbasin, and the Monterey Subbasin, are shown as black, blue, and purple lines, respectively.

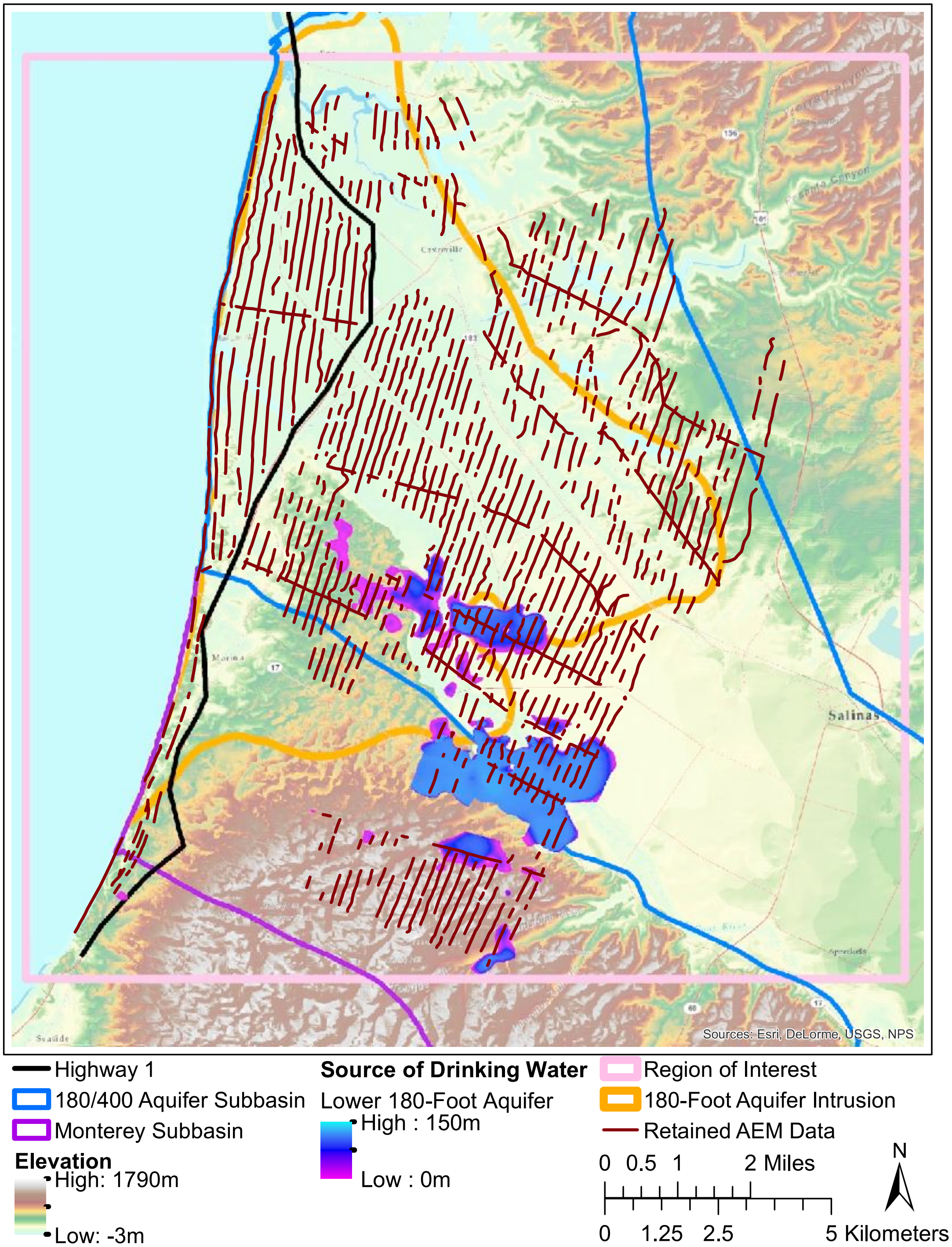


Figure 24: Interpreted thickness of the subsurface containing sources of drinking water within the Lower 180-Foot Aquifer in the region of interest, shown in a color scale ranging from purple to light blue, representing 0 m to 150 integrated meters of the source of drinking water, respectively. Overlaying the thickness of sources of drinking water are the locations where AEM data were collected and retained for processing, shown as red lines. The extent of saltwater intrusion in the 180-Foot Aquifer, as measured by the Monterey County Water Resources Agency, is shown as an orange line. The boundaries used in calculating the regions containing sources of drinking water, Highway 1, the 180/400 Aquifer Subbasin, and the Monterey Subbasin, are shown as black, blue, and purple lines, respectively.

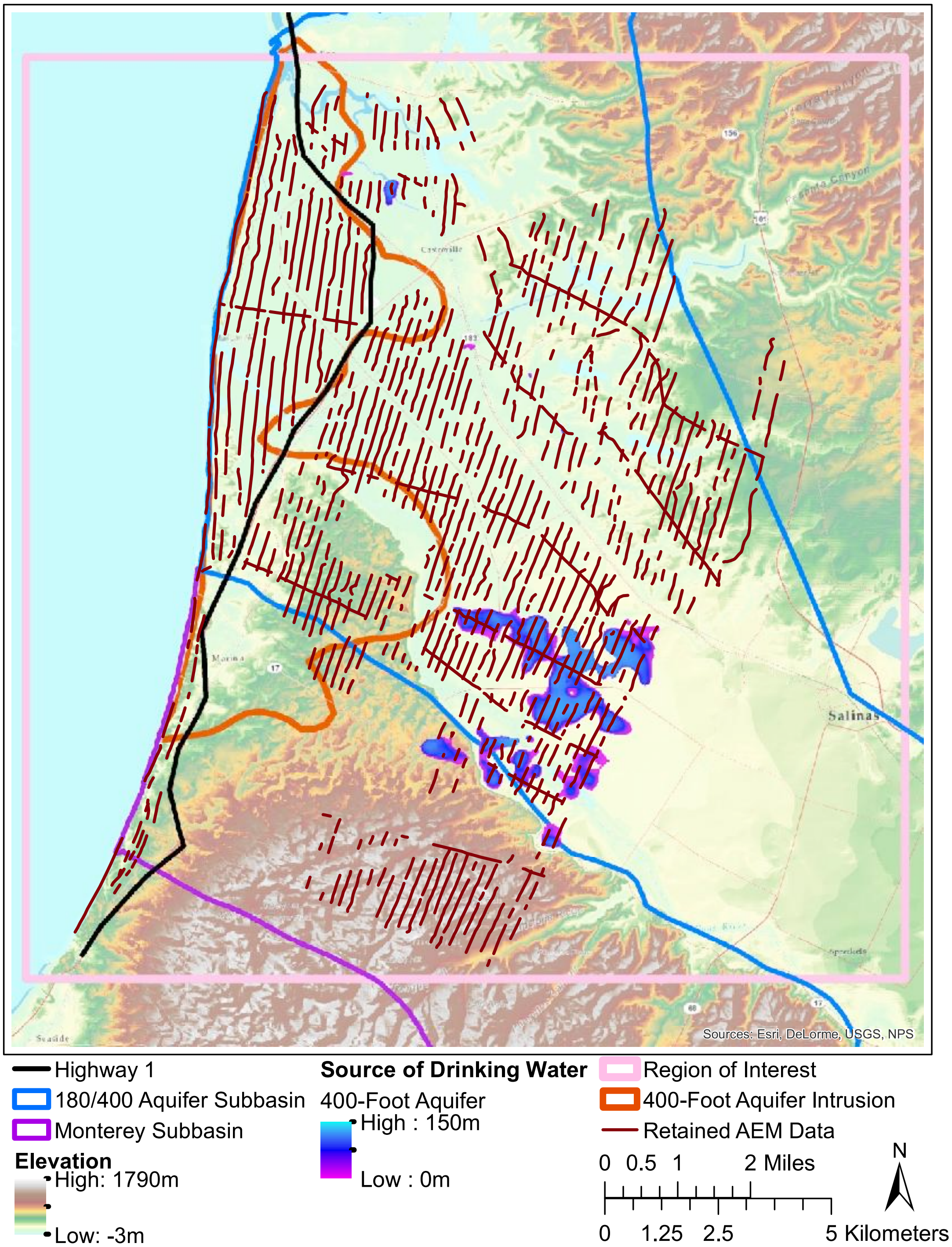


Figure 25: Interpreted thickness of the subsurface containing sources of drinking water within the 400-Foot Aquifer in the region of interest, shown in a color scale ranging from purple to light blue, representing 0 m to 150 integrated meters of the source of drinking water, respectively. Overlaying the thickness of sources of drinking water are the locations where AEM data were collected and retained for processing, shown as red lines. The extent of saltwater intrusion in the 400-Foot Aquifer, as measured by the Monterey County Water Resources Agency, is shown as an orange line. The boundaries used in calculating the regions containing sources of drinking water, Highway 1, the 180/400 Aquifer Subbasin, and the Monterey Subbasin, are shown as black, blue, and purple lines, respectively.

	Units	Total volume, Limited beneficial use	Total volume, Source of drinking water	Water vol., source of drinking water, 20% porosity
Totals	$m^3 x10^8$ (acre-ft $x10^3$)	22.46 (22)	37.43 (37)	7.49 (7)
	Pct of total vol. surveyed	8.1%	13.5%	
By Aquifer				
Perched A/Shallow Aquifer	$m^3 x10^8$ (acre-ft $x10^3$)	0.09 (7)	0.12 (10)	0.02 (2)
	Pct of total vol. surveyed	0.0%	0.0%	
Dune Sand Aquifer	$m^3 x10^8$ (acre-ft $x10^3$)	3.42 (278)	11.60 (940)	2.32 (188)
Figure 22	Pct of total vol. surveyed	1.2%	4.2%	
Upper 180-Foot Aquifer	$m^3 x10^8$ (acre-ft $x10^3$)	6.30 (511)	17.97 (1456)	3.59 (291)
Figure 23	Pct of total vol. surveyed	2.3%	6.5%	
Lower 180-Foot Aquifer	$m^3 x10^8$ (acre-ft $x10^3$)	4.76 (386)	2.92 (237)	0.58 (47)
Figure 24	Pct of total vol. surveyed	1.7%	1.1%	
400-Foot Aquifer	$m^3 x10^8$ (acre-ft $x10^3$)	3.06 (248)	1.30 (105)	0.26 (21)
Figure 25	Pct of total vol. surveyed	1.1%	0.5%	
Total of aquifers	$m^3 x10^8$ (acre-ft $x10^3$)	17.64 (1430)	33.91 (2749)	6.78 (550)

Table 5: Volume estimates of the regions containing sources of drinking water and water of limited beneficial use. Volumes are grouped by aquifer at the top of Table 5, and by region at the bottom of Table 5. Within each group is shown the total volume of the region in cubic meters ($x10^8$) in parentheses as acre-feet ($x10^3$), by percent of the total volume surveyed. The final column shows the volume of sources of drinking water within each region or aquifer, assuming 20% porosity throughout the entire region of interest. The total volume surveyed was $227x10^8 m^3$ (18,400 $x10^3$ acre-feet). Table 5 is continued on the following page.

	Units	Total volume, Limited beneficial use	Total volume, Source of drinking water	Water vol., source of drinking water, 20% porosity
By Region				
Monterey Subbasin	$m^3 x 10^8$ (acre-ft $x 10^3$)	2.37 (192)	16.26 (1319)	3.25 (264)
	Pct of total vol. surveyed	0.9%	5.9%	
180/400 Aquifer Subbasin	$m^3 x 10^8$ (acre-ft $x 10^3$)	0.77 (62)	19.52 (1583)	3.90 (317)
	Pct of total vol. surveyed	0.3%	7.0%	
West of Highway 1	$m^3 x 10^8$ (acre-ft $x 10^3$)	11.47 (930)	0.71 (57)	0.14 (11)
	Pct of total vol. surveyed	4.1%	0.3%	

Table 5 (continued): Volume estimates of the regions containing sources of drinking water and water of limited beneficial use.

Summary

The AEM data collected in the area within the Northern Salinas Valley in May 2017 have been interpreted. Two models of the hydrostratigraphy in the region of interest have been constructed. Beginning with the two separate models built from existing hydrogeologic data, the two final hydrostratigraphic models reflect the information gained by acquiring the AEM data. The distribution of water quality in the region of interest has also been interpreted. Using geophysical logs and water level data, a resistivity cutoff of <75 ohm-m has been defined to distinguish the saturated zone from the unsaturated zone. Based on water quality measurements and borehole geophysical measurements, a resistivity of <3 ohm-m has been defined to correspond to sediment saturated with water of TDS greater than 10,000 mg/L, which is water of limited beneficial use. A resistivity between 20 and 75 ohm-m has been defined to correspond to sediment saturated with water of TDS less than 3,000 mg/L, which is considered to be sources of drinking water.

The AEM dataset processed and inverted by Aqua Geo Frameworks provides valuable information about sources of drinking water and regions saturated by water of limited beneficial use. Further analysis and modeling will continue to enhance the understanding of the hydrostratigraphy and of the distribution of groundwater in the region of interest in the Northern Salinas Valley.

Deliverables

The models built for the preparation of this report, as well as supporting information used to make interpretations in this report are supplied to Marina Coast Water District in the form of a file for use with the program Leapfrog Viewer. Each dataset included in the Leapfrog Viewer file, named "AEM_interpretation.lfview", is listed in Table 6. The datasets included in the Leapfrog Viewer file are: lithology data, borehole resistivity data, interpretations of water quality, the two post-AEM hydrostratigraphic models, and the AEM resistivity model. Leapfrog Viewer allows users to view and interact with the data used in the making of this report, free of cost. Along with the Leapfrog Viewer file is a quick reference guide to using Leapfrog Viewer, with the file name "Leapfrog Viewer Quick Reference.pdf". The Leapfrog Viewer program can be downloaded at: http://www.leapfrog3d.com/products/leapfrog-viewer/downloads. The AEM data processed and inverted by AGF is also included as a CSV file "MCWD3_LCI Inversion_Results_Final.csv". Table 7 displays the name and description of each column within the file, as well as the units corresponding to the values in each column within the file.

Dataset Name in Leapfrog Viewer File	Description
AEM_Resistivity	AEM resistivity model
Topography	Topographic surface with a map of the area within and around the region of interest
Lithology_Interval	Lithology descriptions used in the interpretations for this report
Borehole Resistivity	Borehole geophysical resistivity data collected in the 7 MPWSP monitoring wells (long induction resistivity, log10 scale).
Model A	Post-AEM Hydrostratigraphic model based on cross-section from previously published reports
Model B	Post-AEM Hydrostratigraphic model based on the NMGWM
Source of Drinking Water	Interpolated AEM resistivity values between 20 and 75 ohm-m
Water of Limited Beneficial Use	Interpolated AEM resistivity values lower than 3 ohm-m

Table 6: Name and description of each dataset provided within the Leapfrog Viewer file "AEM_interpretation.lfview".

Column name	Description	Units
LINE	Line Number	--
EASTING_UTM_M	Easting in NAD83, UTM 10 N	Meters (m)
NORTHING_UTM_M	Northing in NAD83, UTM 10 N	Meters (m)
ELEVATION	Elevation according to the Digital Elevation Model used	Meters (m)
TOPO	Topography	Meters (m)
FID	Unique file identifier	--
TIME	Time at which data were acquired during the AEM survey	Seconds (s)
ALT_M	Measured altitude of system above ground	Meters (m)
INVALT	Altitude calculated by inversion procedure	Meters (m)
INVALT _STD	Standard deviation of altitude calculated by inversion	Meters (m)
RESDATA	Residual of individual sounding	--
RESTOTAL	Total residual for all soundings	--
RHO[0] through RHO[28]	Inverted resistivity for each layer	Ohm-m
RHO_STD[0] through RHO_STD[28]	Inverted resistivity error for each layer	Ohm-m
DEP_TOP_[0] through DEP_TOP_[28]	Depth to the top of each layer from the ground surface	Meters (m)
DEP_BOT_[0] through DEP_BOT_[28]	Depth to the bottom of each layer from the ground surface	Meters (m)
THK[0] through THK[28]	Thickness of each layer	Meters (m)
DOI_UPPER	More conservative estimate of the depth of investigation (DOI), below ground surface	Meters (m)
DOI_LOWER	Standard estimate of the depth of investigation (DOI), below ground surface	Meters (m)

Table 7: Name and description of each column within the CSV file "MCWD3_LCI Inversion_Results_Final.csv", as well as the units corresponding to the values in each column within the CSV file

Acknowledgements
The acquisition and processing of the AEM data was funded by the Marina Coast Water District. Additional support to Stanford University was provided by the Zeitgeist Foundation and the S.D. Bechtel, Jr. Foundation. The Leapfrog Geo software used for visualization and hydrostratigraphic modeling was provided by Seequent.

References

- Ahtna Environmental, Inc. Operable Unit Carbon Tetrachloride Plume Second Quarter 2017 Groundwater Monitoring Report, Former Fort Ord, California. Prepared for U.S. Army Corps of Engineers. Report. 2017.
- EMCON Associates. Geologic and Hydrogeologic Study of the Upland Plateau and Proposed Lowland Clay Borrow Source. Prepared for Monterey Regional Waste Management District. Report. 1991.
- Fetter CW. Applied hydrogeology. Prentice hall; 2000.
- Fugro West, Inc. North Monterey County Hydrogeologic Study. Volume 1. Prepared for Monterey County Water Resources Agency. Report. 1995.
- Geoscience Support Services, Inc. Monterey Peninsula Water Supply Project Hydrolgeologic Investigation: Technical Memorandum (TM1): Summary of Results – Exploratory Boreholes. Prepared for California American Water and RBF Consulting. Report. 2014.
- Geoscience Support Services, Inc. Monterey Peninsula Water Supply Project: Test Slant Well Long Term Pumping Monitoring Report No. 107. Prepared for California American Water. Report. 2017.
- Goebel, M., Pidlisecky, A. and Knight, R., 2017. Resistivity imaging reveals complex pattern of saltwater intrusion along Monterey coast. Journal of Hydrology.
- Harding ESE. Final Report: Hydrogeologic Investigation of the Salinas Valley Basin in the Vicinity of Fort Ord and Marina; Salinas Valley, California. Prepared for Monterey County Water Resources Agency. Report. 2001.
- Hopkins Groundwater Consultants, Inc. Technical Memorandum: North Marina Area Groundwater Data and Conditions. Report. 2016.
- Kennedy/Jenks Consultants. Final Report: Hydrostratigraphic Analysis of the Northern Salinas Valley. Prepared for Monterey County Resources Agency. Report. 2004.
- MACTEC Engineering and Consulting, Inc. Operable Unit Carbon Tetrachloride Plume Groundwater Remedial Investigation/Feasibility Study, Former Fort Ord, California. Prepared for U.S. Army Corps of Engineers. Report. 2005.
- Monterey County Flood Control and Water Conservation District (MCFCWCD). Salinas Valley Geologic Investigation. Report. 1960.
- State Water Resources Control Board. Resolution No. 88-63 (as revised by Resolution No. 2006-0008): Adoption of Policy Entitled “Sources of Drinking Water”. Report. February 1, 2006.
- The Hydrogeologic Working Group of the Monterey Peninsula Water Supply Project. HWG Hydrogeologic Investigation Technical Report. Prepared for Monterey Peninsula Water Supply Project. Report. Oct. 2, 2017; revised Nov. 6, 2017.

- United States Environmental Protection Agency. Guidelines for Ground-Water Classification Under the EPA Ground-Water Protection Strategy. Report. 1988.
- United States Geological Survey. Seismic Shear Wave Reflection Imaging at the Former Fort Ord, Monterey, California. Open File Report 2007-1068. Report. 2007.

Reference Tables

Metric to Imperial Conversion Table

Conversion table from metric to imperial		
from	*multiply by*	*to obtain*
meters	0.3048	feet
kilometers	0.6214	miles
square meters	10.76	square feet
cubic meters	0.000811	acre-feet
liters	0.264	gallons
grams	0.0353	ounces

List of Acronyms

Acronyms used in this report	
Acronym	*Meaning*
AEM	Airborne electromagnetics
AGF	Aqua Geo Frameworks
DOI	Depth of investigation
FO-SVA	Fort Ord-Salinas Valley Aquitard
MCWD	Marina Coast Water District
masl	meters above sea level
mbgs	Meters below ground surface
MCFCWCD	Monterey County Flood Control and Water Conservation District
MPWSP	Monterey Peninsula Water Supply Project
NMGWM	North Marina Groundwater Model
SVA	Salinas Valley Aquitard
SWRCB	State Water Resources Control Board
TDS	Total dissolved solids
USCS	Unified Soil Classification System
US EPA	United States Environmental Protection Agency