

Groundwater and geophysics in California — A Bay Area Geophysical Society panel discussion

On 21 November 2025, Bay Area Geophysical Society (BAGS) Vice President Michael Wilt convened an online panel on the application of geophysical technology to groundwater management. The panel was presented to a live audience. Wilt, an assistant editor for *The Leading Edge*, also served as the coordinator for this issue's special section on the same topic. Wilt was joined by panel co-convenor Kris MacLennan, a former BAGS president.

The panel brought together four experts:

- Rosemary Knight, a Stanford University professor and the lead of that university's program on the application of geophysical technology for groundwater management in California.
- Katherine Dlubac, a senior engineering geologist and project manager for the Department of Water Resources (DWR) Statewide Airborne Electromagnetic Surveys and Basin Characterization Program, who also aids in implementing the Sustainable Groundwater Management Act (SGMA).
- Seogi Kang, an assistant professor at the University of Manitoba whose specialty is data analysis and inversion, and who has considerable experience in interpretation of airborne electromagnetic data.
- Craig Ulrich, a research geophysicist at Lawrence Berkeley National Laboratory who most recently worked on applying geophysical technology to groundwater recharge.

A transcript of the panel session, edited for length and readability, is presented over the following pages. A recording of the online forum is currently available at the following location: <https://bayareageophysicalsociety.org/videos>.

Michael Wilt: As a preamble to this discussion, the Sustainable Groundwater Management Act (SGMA) of 2014 has fundamentally altered California's approach to groundwater. It mandated the creation of local groundwater sustainability agencies, with the intention to achieve sustainability within each agency by 2040 (for critically overdrafted basins).

Kris MacLennan: Rosemary, the first question we have is for you. What technology, geophysical or otherwise, is being applied right now to map and manage groundwater resources? What is it being used for?

Rosemary Knight: I will be talking about technologies that image parts of the subsurface using sensors deployed on satellites, aircraft, or through ground-based systems, and now on drones. These technologies deliver images of the subsurface that we interpret to recover the information that we want about the groundwater systems.

In the past, geophysical methods applied for groundwater resources were primarily used for exploration. The interpretation

was qualitative, looking for packages of sand and gravel or for the weathered zone above the bedrock. Now it's increasingly being used to inform groundwater management. This change from exploration has been driven by an improvement in the technology and by increased partnerships. There's now a close back and forth between the geophysicists and the partners — the groundwater managers.

One of the most useful earth imaging technologies is a satellite-based method — InSAR, or interferometric synthetic aperture radar. This is a way of processing SAR data that reveals deformation of the ground surface. Millimeter-scale deformation can be picked up, and after processing you can be mapping deformation with a spatial resolution less than a few hundreds of meters. And the satellite now available will revisit points on the ground surface every six to 10 days.

Figure 1 shows an InSAR image over the San Joaquin Valley (California) from 2015 to 2022. The deformation on the surface is telling us what's happening in the groundwater system. Extracting a large amount of water from the subsurface is causing the ground to sink.

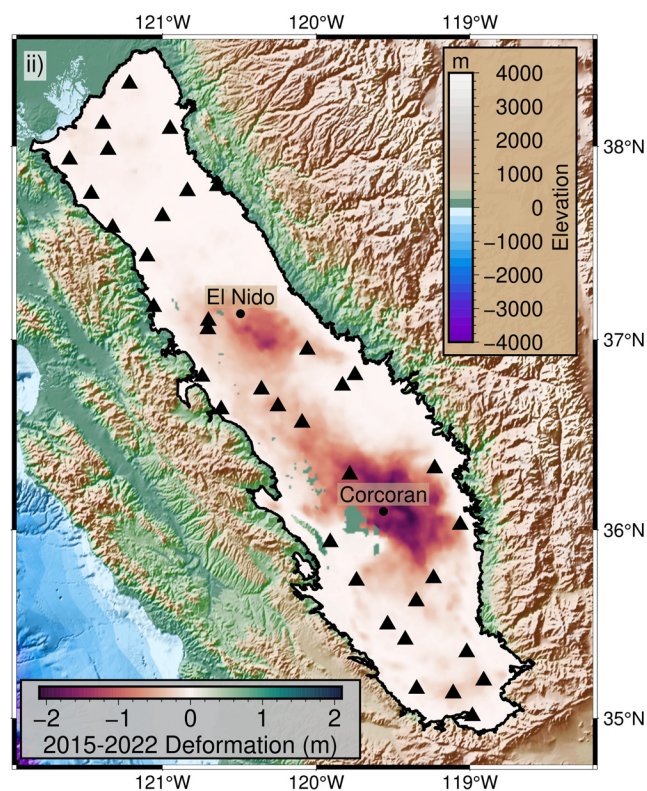


Figure 1. The subsidence revealed in InSAR data in the San Joaquin Valley in the time period 2015–2022. The black outline is the boundary of the San Joaquin Valley, and shading within that boundary represents deformation. (Note that a negative deformation corresponds to subsidence and positive deformation to uplift.) Shading elsewhere corresponds to the topographic elevation. Black triangles represent the locations of GNSS stations. Modified from Figure 1 in Lees and Knight (2024).

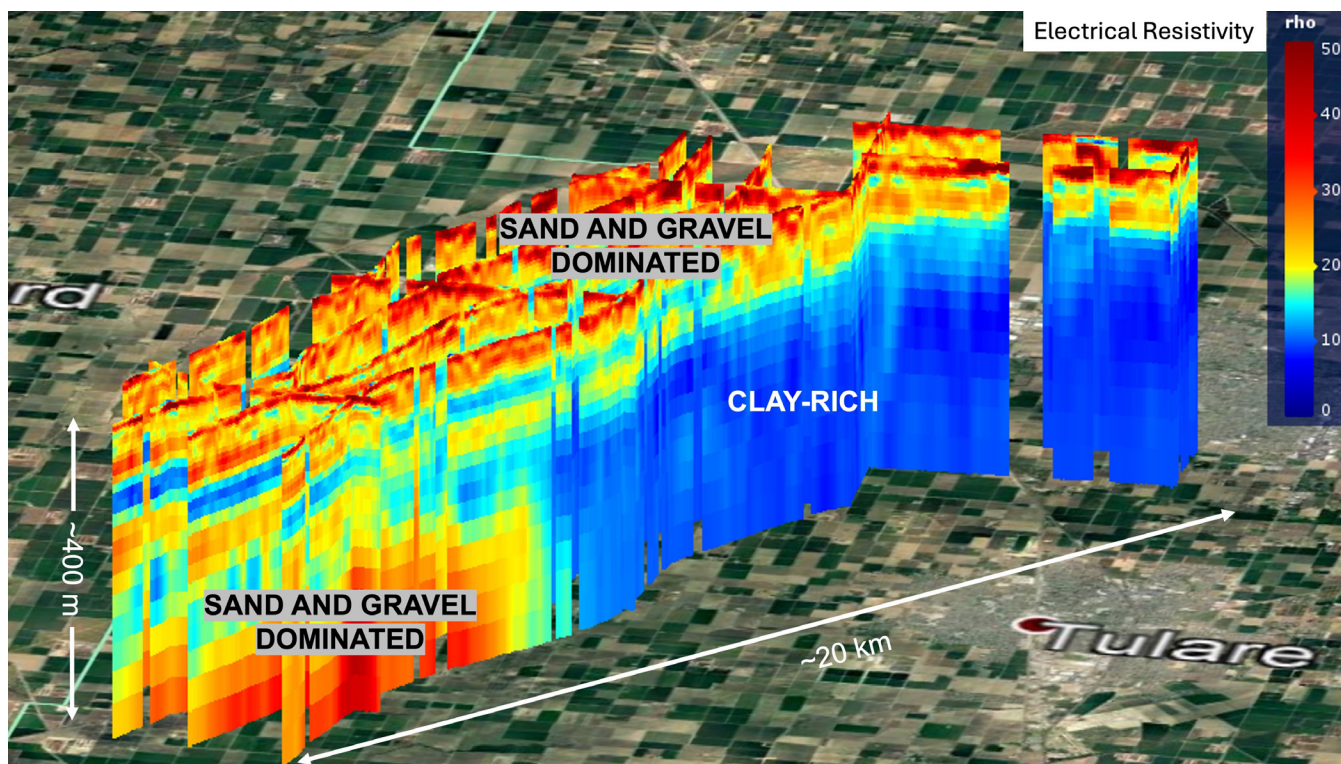


Figure 2. The resistivity profiles recovered from AEM data acquired in the Tulare Irrigation District, 17 October 2016, overlaid on a Google Earth image showing the town of Tulare. Displayed are resistivity values (ohm-m) with warm colors corresponding to high resistivity and cool colors corresponding to low resistivity. The AEM data are from the study described in Knight et al. (2018).

In ground-based geophysics, measuring electrical resistivity, which contains information about the rock or sediment type, has been found to be useful — the most resistive rocks being the bedrock and then the weathered bedrock. Less resistive are sands and gravels, with the least resistive being clay. This makes electrical resistivity tomography (ERT) a great way to map out sediments and rock types. It is important to note that resistivity is also sensitive to salinity: as the salinity of the contained water goes up, the resistivity goes down. If you can assume that one is constant, you can map out sediment/rock type or salinity.

We can also obtain estimates of resistivity with electromagnetic (EM) methods. The EM methods don't need ground contact and hence can be deployed with airborne systems, methods which are commonly referred to as airborne EM or AEM. Figure 2 is an example of a subsurface resistivity image obtained from AEM data acquired in the Central Valley in October 2016. We see imaging at this location to a depth of 400 meters. In the red (resistive) regions, we're imaging sands and gravels. The blue is the clay-rich material.

When the legislature passed SGMA, everyone had to manage their groundwater. Addressing the question of "What can geophysics do?" we wrote a white paper. This was sent to the governor's office saying, "You are not going to get to sustainable groundwater in this state without acquiring data with this airborne EM system. You need to acquire 20,000 line-kilometers and spend \$10 million, and it's going to take two years." I was the lead of the two-year Groundwater Architecture Project that we ran out of Stanford.

Katherine worked on it as well. What came out of it was approximately 25,000 kilometers of raw and interpreted AEM data.

We used a helicopter-deployed system from Denmark, originally developed at Aarhus University and called SkyTEM. Another Aarhus technology that's seeing a lot of use in California to look for recharge locations is towed-TEM, or t-TEM. With it, you can see details down to about 50 meters. So, to go back to your question, what technology? I would say my favorites in California are satellite remote sensing, InSAR, ERT, airborne EM, and t-TEM.

MacLennan: This is an excellent segue since you've talked about how geophysics is being used in California. Katherine, how is the state of California using geophysics to support groundwater evaluation and sustainable management?

Katherine Dlubac: DWR has a long history of characterizing groundwater basins in California. We've been publishing California's Groundwater: Bulletin 118 since the 1960s. After the passing of SGMA, people were motivated to characterize their groundwater basins. At DWR, we serve two roles under SGMA. As a regulatory agency, we review the groundwater basin's progress toward sustainability, and we also provide technical support.

Pilot studies in 2018 to 2020 helped us understand how AEM surveys could help us map our groundwater basins, and a white paper outlining the benefits of AEM in California was submitted to our governor. The state then received \$12 million to conduct

AEM surveys across California, and in 2023, we completed 26,000 line-kilometers of AEM data at a coarse grid spacing. We worked with a consulting firm who did the geophysical data processing, inversion, and interpretation.

We interpreted the AEM data for texture, the percent coarseness to the percent fine within the aquifer. We also digitized 16,000 well completion reports and thousands of geophysical logs. We made it all publicly available within a six-month turnaround from data collection to data publication.

We published everything on the California Natural Resource Agency Open Data Portal (<https://data.cnra.ca.gov/dataset/aem>), including the raw data sets. But unless you have geophysical software, it can be difficult to view the data. So, to ensure public access to the data, we developed data visualization platforms, including California's Groundwater Subsurface Viewer (<https://subsurfaceviewer.water.ca.gov>) that shows the data in 3D and profile forms. Figure 3 is a sample AEM resistivity profile. Both the electrical resistivity and the coarse fraction data can be displayed.

We then launched our Basin Characterization Program to develop tools to utilize the AEM data, to continue to collect and interpret data, and develop maps and models that serve as decision support tools for groundwater managers. For example, maps showing where to conduct groundwater recharge.

To create maps showing where to conduct recharge, our team developed tools to integrate the AEM data with lithology logs and geophysical logs to create texture models that describe, in a voxelized space, the percent fine-grained and percent coarse-grained materials in the aquifer. These texture models can help us better understand where there are groundwater flow pathways. We use these pathways together with soil information and groundwater levels to develop aquifer recharge potential maps that help groundwater managers understand the best locations to put water into the ground.

Next, we're working with local groundwater managers and interested landowners at sites that have higher recharge potential to collect t-TEM data. These higher resolution data help us see small-scale features that may inhibit groundwater recharge.

Wilt: How well is this output absorbed? How well do the growers and agencies understand this? Is there a big education process?

Dlubac: There are a few levels there. One is connecting with groundwater consultants, which has not been easy because not many consultants have experience working with AEM data. It takes quite a few conversations, webinars, and presentations to show how to use the tools we've developed to use the AEM data. It's also important to make data products as simple as possible, and data visualization platforms also help, like the SGMA Data Viewer and the California Groundwater Subsurface Viewer. Because of SGMA, folks are becoming more aware that groundwater exists under their feet and that geophysics is a thing.

Lastly, we mailed over 100,000 letters to parcel owners within a buffer of the flight lines. The letters told them about the AEM surveys, showed them a picture of the system, and explained that we were going to collect data in their area. This was successful at spreading the word that geophysics can be useful in understanding groundwater resources.

MacLennan: Thank you, Katherine. You talked about creating aquifer recharge potential maps, so this is a great pivot to Craig. What technologies do you see are being used to understand and control the man-made recharge in these areas, and can we use these to estimate natural recharge?

Craig Ulrich: What I'm going to talk about is how to better understand the subsurface heterogeneity and quantifying recharge. I really like what Katherine was saying about reaching out to farmers and letting them know that this technology is available. A lot of folks, even in the geotechnical side, that are building best management practices (BMPs) don't know about geophysical methods.

A quick note: BMPs are a description for infrastructure like bioswales, dry wells, infiltration galleries, etc., that are used to convey water into the subsurface for doing managed aquifer recharge in small-scale areas like urban settings. The technologies include arrays of geophysical sensors and pressure transducers and monitoring wells to get groundwater levels and see how they rebound. We also use distributed temperature sensors on fiber-optic cables. We deploy these vertically in a well to monitor the temperature flux into the ground. We can use that to convert to infiltration rates. But now we're also integrating geophysics into

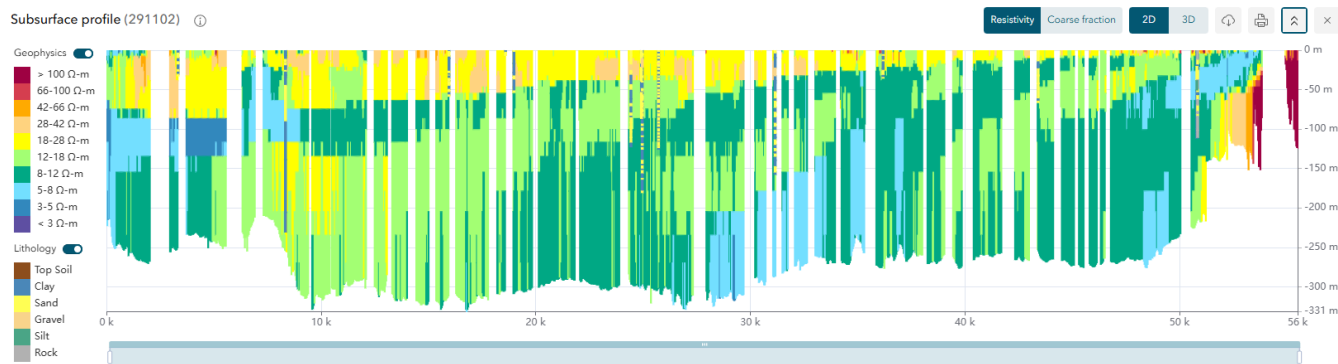


Figure 3. AEM profile on the California Groundwater Subsurface Viewer.

a multiple-method approach to understanding and quantifying recharge.

We've been working with the Metropolitan Water District (in Los Angeles) and Los Angeles County Department of Public Works to understand infiltration patterns and rates in their basins. Previously they may have had a single infiltration rate for a basin, and that might be all. The opportunity is to use high-resolution geophysical methods to better understand and quantify spatial infiltration rates. In Figure 4, we see the background resistivity distributions for Pond 10 in the top left. The water flows through sands via small, quick infiltration paths and then the rest of that pond catches up, with most of the flow down through one side of the basin. Overall, this pond drains about 1.5 acre-feet per day, with 2 to 3 feet of standing water. Contrast to the adjacent pond — and keep in mind there are 30 ponds at this facility — where we have just under 0.5 acre-feet of recharge per day due to low permeability silty clay covering half of the ponds surficial soils.

It looks like it's all the same type of soil, but it's not, and we can demonstrate it. We can use the geophysics to provide information about how these basins are likely to perform. We can do pilot experiments and quantify how much water is going into the subsurface and how deep. The water agencies want to know this because it determines what credit they get from DWR to meet SGMA requirements. At an almond orchard, the soils were designated with a moderately poor potential, but we found sand lenses that come up near the surface and conveyed almost all the water into the subsurface. This is useful for a farmer because if they're worried about not wanting to inundate the full field, they could reroute their berms to focus at locations of high infiltration soils.

While we use all sorts of technology, we prefer electrical resistivity because it's one of the best performing systems for monitoring changes in water content when everything else is held constant. We know the conductivity of the input water and we know (that of) the soils, so the changes in our data are due to soil moisture and infiltration.

To quantify recharge, we use thermal sensing to estimate recharge rate. We can also estimate recharge rates by transforming EM data through a fit with hydraulic conductivity for each pond. Then we use a 3D hydrogeologic model and estimate recharge rates per pond or per basin. We can also modify these potential basins to increase their recharge and improve our water recharge capacity.

We are finding the most useful technologies for capturing recharge in urban settings, then using that data to scale into larger areas. For the basin scale, satellite monitoring can be used. We now have these geophysical tools that characterize the subsurface, from site scales all the way up to basin scale, and I think that's really exciting.

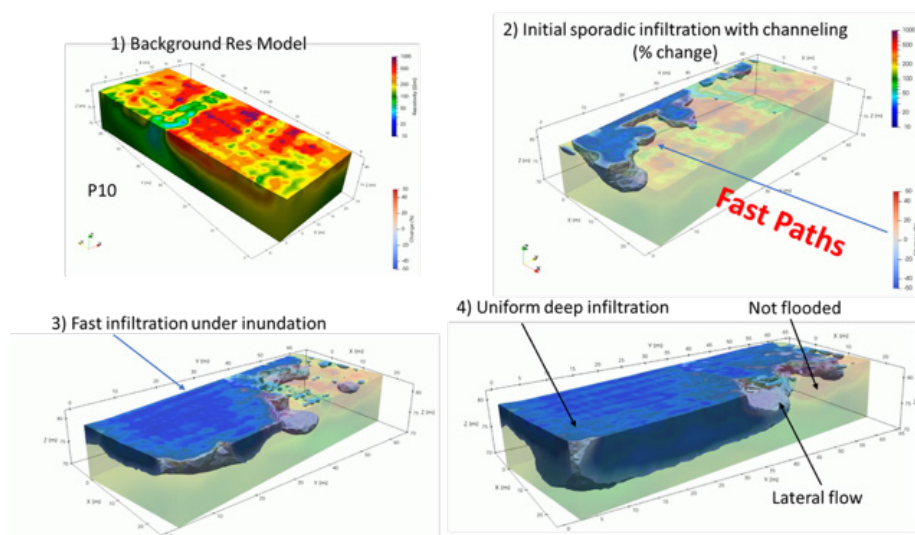


Figure 4. Time-lapse imaging of groundwater recharge into different ponds.

Wilt: Are they using these now? For example, if you have a wet year, do they find out how much natural recharge has been going into the ground versus flowing out to the sea?

Ulrich: California typically uses 60% surface water and 40% for subsurface water in any given year. But with changing snow-pack distribution, surface water storage is diminishing and the models we use for prediction of recharge are breaking down. We have groundwater drought issues almost everywhere across the U.S., so it's not unique to California. California and other states are still over-extracting aquifers annually, and we need to build more optimized recharge sites using large-scale geophysics like airborne EM to site-scale geophysics to ensure we are optimizing existing and new recharge sites.

One of the shining examples is Santa Monica: they expect to be 85% off of imported water by 2030. They've been doing the types of things we're discussing here, using geophysics to characterize the subsurface, estimating where is going to be the best place to put water in the ground, and then building the infrastructure to do it.

MacLennan: So last, we come to Seogi. The first three speakers relate the data with the physical characteristics of the earth. What methods or combination of methods do you find available to define this aquifer environment? And do you see a role for AI or machine learning in the data processing and inversion steps?

Seogi Kang: First, thanks for this amazing event. For defining aquifer environment, we need to bring in other data sets like driller's logs, head level data, satellite data, and multiple types of geophysical data with different scales. We really need to have all the information integrated in a way that can answer questions about stratigraphy, water storage, and quality.

I'm an electromagnetic geophysicist. To me, at a high level we are injecting some sort of EM energy and then getting its interaction from the subsurface that's a function of the electrical

resistivity. We're not directly sensing the hydrogeology. Once you collect the data, we use an inversion to find a resistivity model that can fit the data. The data have indirect information about resistivity, so it's critical to use additional data to relate the resistivity with hydrogeology.

Speaking of scale, Figure 5 shows the airborne EM at a regional scale, a Central Valley 700 kilometers length scale. We can also use the same data at a subbasin scale, like 60 by 60 kilometers, and if we're going into a local recharge site, say, 800 meters by 800 meters, then we need to use a different data set. Rather than airborne EM, we may use t-TEM or an ERT method for higher resolution. It's important that we have multiple methodologies that can give us multiple scales of resolution of resistivity images.

In Figure 6 we show the same AEM data set, where the red coloring is an indication of coarse-grained materials. If I pick a location between the airborne EM lines, then we have to interpolate. Based on the interpolation, that area is likely to have a large amount of coarse-grained materials. Surveying in the area with a higher resolution method, the distribution of the coarse-grained material changes a lot.

That was sort of about the first question. And the second question: do you see a role for AI? Yes, and obviously I'm seeing a trend. There's an increasing amount of geophysical data collected throughout the world. The Central Valley study is one example, but in Australia, they're collecting continent-wide data sets, and basin-scale data are being collected in Kansas and New Mexico. There's a need to rapidly process and invert the data to a three-dimensional resistivity model that people can interpret.

The first place is using an automated processing scheme on collected data. If I want to invert the data, it needs to be of high quality, so we need to filter out the noise and obtain an error estimate. That part of inversion preparation takes time, so automating that process can save cost and time.

The second use for AI is more challenging. At the end of the day, we want to integrate all this information for a user. And one

potential way to use AI is to bring in all this geophysical data, and in-situ data, into groundwater modeling for an aquifer environment. We are working on this, but it's challenging.

MacLennan: Thank you, Seogi. Can I ask for a bit more detail on that? "AI" is a very broad and kind of buzzwordy thing. Is there a specific kind of AI process or machine learning process that you would see being useful?

Kang: I think that for processing you can use very traditional neural nets, which work well and are straightforward. But for the modeling, where a lot of research is focusing, there is big potential but a lot of unknowns.

Wilt: Could you walk us through the workflow? They collect the data with airborne EM, and now you get a whole bunch of transients. How do you go from there to your 3D resistivity model?

Kang: An acquisition company collects and gives you the raw data with many sampling points. Then you do simple stacking along a flight line over a 30 to 40 meter interval. This also gives you a standard deviation of the data. Then you can address specific noise. For instance, if you're flying over power lines, there's specific shape in the data. You can find those shapes, overlay a power line map, and manually remove data in the affected area. This leaves high-quality data with some estimate of acquisition error. This all could definitely be done with machine learning.

Wilt: Do you start with a 1D distribution or is it always 3D?

Kang: I think for most hydrogeology cases, the typical tool is a 1D inversion. I haven't seen many 3D inversions. Typically, you invert everything in 1D together with some constraint, such as smoothness of resistivity values in the vertical and lateral dimension.

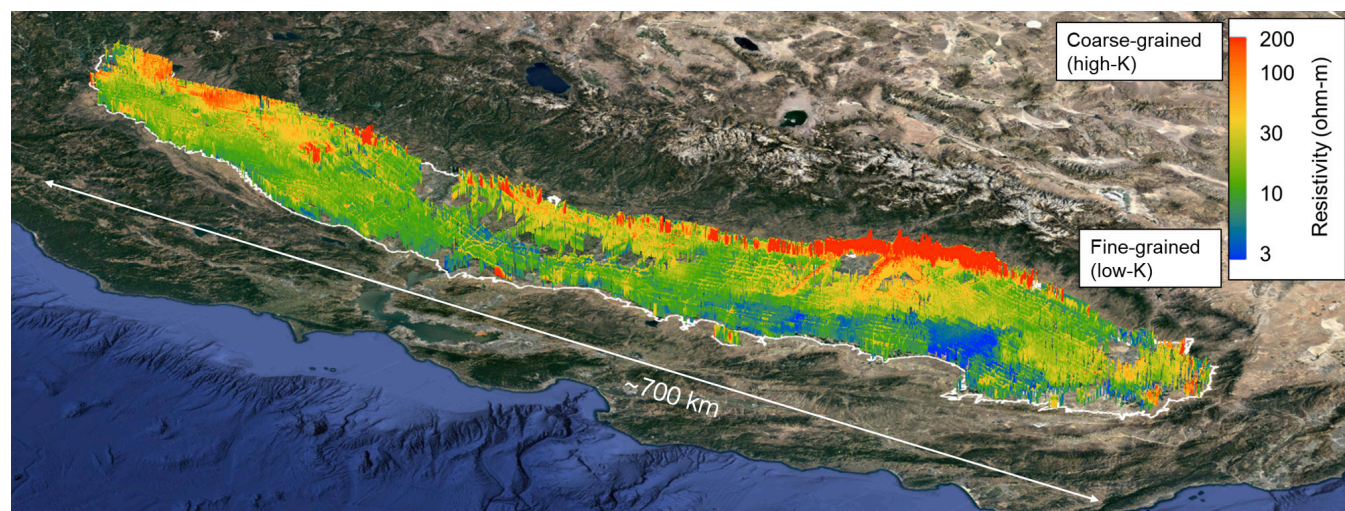


Figure 5. 3D view of resistivity model from AEM data throughout California's Central Valley..

Wilt: Thank you. We've had some very nice foundational discussion. I'd like to open this up to the floor — anyone who's online here that has a question for any of these panelists or any further discussion.

Dave Alumbaugh: Because of the 1D nature of these inversions, it worries me that we are misinterpreting resistivity changes along the line, even if you put the constraints in. In the past, because of data storage limitations, we'd store only an averaged decay curve. But modern systems sample at a high rate and have large storage; they can store the whole waveform. That opens up the possibility of time transforming and doing the 3D inversions in the frequency domain, which are much more tractable than in time domain.

Another thing that's being researched, is using a grounded source. This provides a different sensitivity to the subsurface because you get vertical currents, which are more sensitive to resistive layers at depth. One of the problems with the inductive methods is that you can't really find a sharp boundary at the base of the conductor unless you have good constraints. It always just smears through it. But with a grounded source you get vertical currents going into the subsurface, which are more sensitive to boundaries.

Wilt: Great comments. What about the inversion residuals, the parts of the 1D inversion model that don't fit the data perfectly? Are you looking at the misfit function either for each sounding or for a series of soundings?

Kang: Yes, I usually do. But that doesn't tell me much because even if there is a strong 3D effect, we can still fit the data with the 1D model. Instead, we usually fit the data, and when you see a weird structure that might be due to a three-dimensional effect, then you usually remove those portions of the image. If you have a 3D simulation code, you can test that out, but I find that rarely happens in practice.

Knight: I have a question for my fellow panelists, and I want to tap into the collective wisdom in this room. As I was saying, electrical resistivity can map out sediment type or we could map out salinity, but there's always ambiguity. There are parts of the valley with very low resistivity due to high salinity pore water. You need to measure at a finer scale, or measure something different, to figure out whether you're looking at clay or salt water. I was enthusiastic when Seogi was looking at the IP effect in the airborne EM, but the signal wasn't strong enough. Seismic could tell us if there was clay. Any ideas of how to deal with this saltwater versus clay ambiguity?

Need for local-scale towed EM

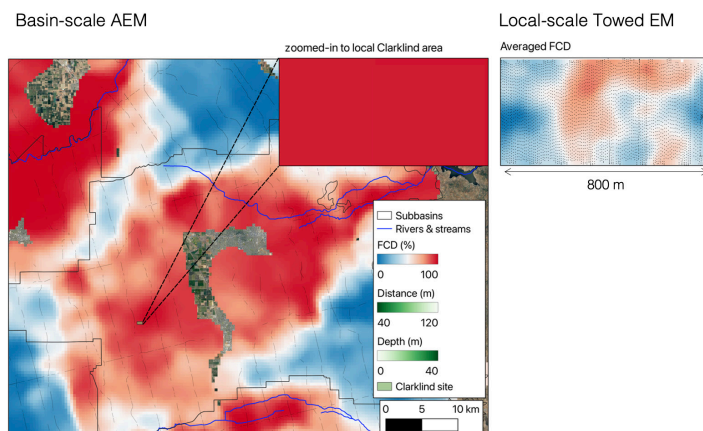


Figure 6. Interpolated (AEM) versus collected data (t-TEM) between flight lines.

Alumbaugh: Typically, these systems measure vertical components only. Horizontal components might be more sensitive to the IP effect, and you should be able to rig up something with the towed TEM, or using a grounded source with the drone (for a receiver).

Knight: Well, we did that in the Tulare Irrigation District where we had the source loop wound completely around the almond grove and the drone carrying the receiver flew up and down between the trees.

Alumbaugh: Whereas if you just put out a couple grounded sources that are in different polarizations and then do that same survey instead of with a large loop, that's where you might be able to get the IP information from the measurements.

Kevin Mendoza: If you could put a few seismometers out, you could probably back out whether an anomaly is due to some sort of fluid infiltration rather than just very salty or clay. The problem with using ambient noise tomography is that you need your sensors deployed out for at least a few days to get enough correlation stacks to make a good demographic model.

Knight: You're right. You need to leave the seismometers out for a long time. We have just deployed 12 three-component seismometers in the Kaweah subbasin, and we're leaving them out for three years. A faculty colleague is also leasing a stretch of telecommunication fiber-optical cable and will be doing continuous monitoring for three years. I am excited to see what we can do with ambient noise imaging at this scale.

Mendoza: I had a question about making these inverse models. What is the proportion of these inverse methods that are a Monte Carlo kind of forward model evaluation versus traditional inversion? And is there a preference across different methods?

Kang: DWR provided only gradient-based inversion. Stochastic types of inversion are useful for high data density, which we have, but they are challenging with the existing computing capabilities. So, if you're going in that route, you need to really define a specific kind of question in the context that you're trying to measure.

Alumbaugh: CSIRO in Australia, has come up with a 1D Bayesian constrained inversion, and it's quick enough that it has been used to invert all of the publicly available airborne EM groundwater characterization data across the continent of Australia.

Dave Nichols: My question is, what is the outcome you want from publishing this discussion in *The Leading Edge*? Is it to get more funding for EM for groundwater research? To recruit students? Is there something you want readers to do with the information and data presented here?

Knight: I want readers to understand what we, as geophysicists, need to do to have geophysical methods more widely adopted. As geoscientists, we love our research and we can spend all day doing it, but we need to think about who needs to know what we are doing and how it can be used. Using slides from Esben, I started talking about AEM in California in 2008. When someone said, "Oh, you need to go to the top," I did, with a whitepaper to the governor's office. Then they said, "Oh, you need to talk to the locals," so I went to meet with the local groundwater agencies. The message I want to get out there: if we want geophysics to be adopted, we have to go to the people who can use it.

I was just talking to someone from Los Angeles last week who had been out with his engineering team putting in water pipes. They were working on a road where there were about 30 different utilities. They had an old PDF showing the layout, they had their spray paint markings, and his thought at the time — "There must be a better way to do this." Sure enough, they brought in GPR and, as described to me, the field engineers were crying tears of delight with the time savings and accuracy. We just need to be changing who we're talking to, or we need to be walking into someone's office and not leaving until they'll listen.

MacLennan: What would it take to implement geophysics for groundwater management outside of California? What is the best way to copy yours and California's success? What kind of regulations do we have in place now that you see other states could take California's lead on?

Dlubac: I'd say passing state legislation that requires sustainable groundwater management. In California, we were experiencing such exceptional drought that there was a need to push for sustainable groundwater management and to change the regulations, and it takes an extreme event like that. But the pushing comes from the people. As for other places, we are certainly having conversations with other states and sharing with them our work and what we see in our geophysical data. Our data viewers make it easy for other non-expert users to access and see the benefits.

In California, this statewide approach has gotten traction, and so we have high-level cheerleaders for geophysics. I'll hear

the director of the DWR talk about the statewide AEM surveys, or the secretary for the California Natural Resource Agency talking about the data. The word is getting out there, and they're sharing this information with other states and showing that the data is valuable. This can help what's now becoming a groundwater management problem across the state and many places in the country because a lot of states in the West are having drought issues.

Mendoza: One question that comes to mind is, if you're a student or a geophysicist who wants to get more involved in this kind of work, or maybe pivot their career this way, do any of the panelists have thoughts on what the career market and the opportunities might look like in the near future?

Knight: I have consulting firms approaching me that can't hire enough geophysicists. In California right now there are many people recognizing the value of geophysics, and there soon will be in other states. So, I encourage students to consider geophysics.

One comment I want to make, related to the idea that the work we did here in California is transferable elsewhere. I've had people say to me, "Can you bring what you did to my area?" We used the SkyTEM technology that is being flown around the world, but before using it state-wide in California it took two years of pilot studies, thinking through the optimal workflow. I tell people, for a large-scale project, there should be at least a year of pilot studies and thinking about how best to use the AEM technology. What's the optimal way to acquire data? Do you really want to use SkyTEM or another AEM system? At a high level, the method and technology are completely transferable, and that's a great message, but don't just take what we did here and apply it elsewhere.

Ulrich: In different meetings across the (U.S.) Southwest, assembly members have asked what they can do to move the needle toward water supply sustainability, and I said that they should be advocating for large-scale surveys like California has done to better characterize their water basins and focus on making regulations that allow a fast response to water diversions for recharge instead of permitting that takes years.

Wilt: What's next for California for this project? All this airborne data have been collected already, so are there other data sets to be collected or is there other geophysics to do? And what are the goals going forward?

Dlubac: We're really focusing on how to use the AEM and integrating it with other data sets to create 3D maps and models that become decision support tools. The goal is to take the data from that geophysics space to a groundwater manager usable space. We're using the AEM to do optimization for recharge potential mapping and then supporting locals by collecting this higher resolution towed TEM data.

Knight: We've just started a five-year project with 10 Stanford faculty and about 30 others, called "Taking the Pulse of the Watershed." It's about using AEM data to give you the large-scale

structure of your groundwater basin, and then using other forms of satellite data or ground/well-based sensors to monitor and adaptively manage our freshwater systems toward sustainability. We're mapping, measuring, and monitoring everything we can.

I'm very excited about the advancements being made in building low-cost sensors like stream gauges. Trying to understand interconnected surface water and groundwater is much easier to do with more data. At present we have far too few stream gauges in the San Joaquin Valley. A stream gauge currently costs at least \$50,000, and it can be more than \$30,000 a year to maintain. But someone at Stanford is building a lidar-based stream gauge that, once commercialized, would cost \$500. I am most excited now about the new sources of ancillary data we can use to fine-tune the interpretations. How can we build these low-cost sensors? How can we get cheap soil moisture sensors that we can deploy everywhere? What can we get from existing telecommunication cables and the monitoring of ambient noise?

Ulrich: To add to what Rosemary just said, these new devices constitute the "Internet of things." In the stormwater industry, with cheap radar velocity sensors installed inside manholes of recharge infrastructure, we can monitor pipe flow in real time from a distance. Distributed temperature probes can relay back data in real time. You could use the diurnal heat flux to estimate recharge inside the river, and couple that with your stream data to understand the changes. The advancements in sensor technology, cost, and power are just continuing to take off.

Kang: I have a question for Katherine. Are the logistics for a statewide airborne EM survey easier than for a local scale survey? We can't do fine-scale surveying everywhere the airborne survey covers. People might want their land to be surveyed, or maybe not. How are you prioritizing those local scale surveys and how are you communicating with the locals?

Dlubac: Sometimes it's more difficult to help folks for free than you'd expect. We first connect with the groundwater managers who then connect us with locals. In the Fresno area, we're collecting data over detention basins that are already planned and helping them better understand what engineering should be utilized in those basins. If it's slow recharge in an area, maybe some additional infrastructure will be needed to get water down more quickly, because these are basins that are already under development.

In other areas we're working directly with growers. For example, in Madera, the Groundwater Sustainability Agency had a list of landowners interested in recharge. We also had aquifer recharge potential maps that showed which parcels had higher potential. So, given this information, we could target outreach to landowners who are interested in recharge activities and have parcels with higher recharge potential to say, "Are you interested in conducting these towed TEM surveys to better understand what the recharge potential would be beneath your parcel?"

But it can be difficult to do the outreach to find locals that are interested. Even getting boots on the ground to collect data is difficult because there are license agreements and

environmental concerns. This is why it's taken us almost a year to start land-based geophysical surveys and why drone-based methods have become appealing.

MacLennan: Seogi, you mentioned this earlier when you were discussing interpretation of results and crafting models. In your experience, how do you communicate uncertainty to other people? The thing that often sinks geophysics is when we tell them our results say one thing and it turns out to be not exactly what we've told them. And then they say, "Oh, well, this is hogwash." So how do we communicate the fact that what we're giving is our best guess of what's there? And what kind of experiences have you all had with this?

Dlubac: Communicating uncertainty to the public is one of the most difficult things that we do. The best that we can do is to be transparent with everything. We say, "We have provided an interpretation of the AEM data." We have the data available if someone wants to reinterpret it, but this is our best interpretation.

Ulrich: Uncertainty in groundwater was a topic of discussion in a workshop that Seogi and I convened. You have uncertainty going into a model, and it produces more uncertainty. This is a subject that needs some thought on how we convey it, how we deal with it in our models, and how it affects our decision-making process.

Knight: At a meeting, I had been planning to talk about uncertainty because Seogi had been producing sediment type interpretations, shaded to display confidence level. If it's dark, we're very confident that it's sand and gravel, while if it's close to transparent, we are less confident. A fellow geophysicist at a consulting firm said, "If you talk about uncertainty, no one will ever use geophysics again." But I talked about uncertainty and after the meeting, people came up to me and said, to paraphrase, "Thank you. Now we trust geophysics. We never believed, given all the unknowns that you're solving for, that you could possibly be as certain as the produced cross-sections implied." I think we're doing ourselves a disservice by not discussing uncertainty. So, I appreciate the efforts of Katherine and team. My preference is you say, "What are these data being used for?" and then show the resulting uncertainty in whatever it is they're trying to predict.

Dlubac: We're all just trying to produce a useful result. In our program, at least, we try to consider, "Is it necessarily the best result today? Can it be improved? Can we reduce uncertainty?" Usually, yes, but we can't let that desire for perfection stop us from getting something useful today. ■■■

References

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