

From knowledge into action: The launching of the state-wide airborne electromagnetic project in California

Rosemary Knight¹

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Abstract

In 2014, legislation was passed in California requiring the sustainable management of groundwater. This presented an opportunity to advance the adoption of the airborne electromagnetic (AEM) method for the acquisition of needed subsurface data. The process of moving “knowledge into action” began in 2016 with a university-funded demonstration project showing the capability of the SkyTEM system to image the sediments of the groundwater system in the Tulare Irrigation District in California’s Central Valley. This was followed by a white paper to the Governor’s Office proposing a state-wide project, voter-approved funding, and the three-year Groundwater Architecture Project (GAP). The GAP brought together more than 30 participants from academia, consulting, and local and state water agencies to conduct the focused research needed to define the optimal workflow for using the AEM method to image groundwater basins in the state. The successful move from knowledge into action concluded with a state-wide AEM project led by the Department of Water Resources between 2021 and 2023. This journey from knowledge into action can be an example to use for other applications and in other locations where the state of the practice could be/should be raised to the state of the science through the adoption of advanced technologies.

Introduction

For decades, groundwater was treated as our freshwater savings account — a supply of water that would be available when needed. But now, throughout the world, there is growing awareness of the dramatic depletion of this source of freshwater that has occurred and a growing commitment to sustainably manage the resource. The challenge we face is acquiring the data needed to map, monitor, and manage our groundwater supplies. The traditional approach, using data acquired by borehole drilling, provides limited spatial coverage and is slow and expensive when data are required over a large region.

Over the past 8 years in California, the state has moved from a dependence on wells for characterizing groundwater systems to the adoption of the airborne electromagnetic (AEM) method for the acquisition of data required to support sustainable groundwater management. With the need in many other states, and in many other countries, for improved methods of subsurface characterization, I have often been asked to describe the process, starting in 2014, that led from a

university-funded demonstration project in 2016 to the 25,000 line-km of AEM data now publicly available covering 95 of the 515 groundwater basins of California (California Department of Water Resources, DWR airborne electromagnetic (AEM) surveys data, 2025). There are six components that I believe were critical to the successful transition from university research to the launching of the state-wide project: a regulatory framework that made clear the need; access to the right technology; a successful demonstration of value added; the focused research, demonstration, and testing to develop the optimal workflow for conducting a state-wide project; the needed funding at critical steps along the path from knowledge into action; and, throughout it all, the people — the research team, the practitioners, and the partners in the water agencies. Although all these components were essential, it was the people (named below) who made this taking of “*knowledge into action*” the best experience of my academic career. I am keen to share this story, as I believe it can serve as a template for use in other places to address other needs where there is an opportunity to raise the state of the practice to the state of the science through the adoption of advanced technologies.

The regulatory framework

By 2014, California had experienced approximately 30 years with periods of drought. This, combined with an increased demand for water, led to the extensive pumping of groundwater to compensate for the loss of a supply of surface water. This resulted in declining groundwater levels and many related adverse effects. With climate change predictions of increasing frequency and severity of droughts, the political will was in place (under Governor Jerry Brown) to pass the Sustainable Groundwater Management Act (SGMA) in the California Legislature (Sustainable Groundwater Management Act, 2014). This three-bill legislative package defines “undesirable outcomes” related to water quantity and water quality that must be avoided to achieve sustainable groundwater management by 2040. Undesirable outcomes include significant and unreasonable groundwater-level declines, land subsidence, seawater intrusion, groundwater storage reductions, interconnected surface-water depletions, and water quality degradation. For 96% of the groundwater basins in the state, the level of groundwater depletion was such that plans were required to be in place by 2020 or 2022.

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¹Stanford University, Stanford, USA. E-mail: rknight@stanford.edu.

A detailed description of the hydrogeology of California is contained in California Groundwater (Department of Water Resources, Bulletin 118; <https://water.ca.gov/programs/groundwater-management/bulletin-118>). Many of the groundwater aquifers in the state are found in the top few hundred meters and are composed of thick packages of sediments overlying bedrock. The sediments vary in grain size from coarse-grained sand and gravel, with cobbles in regions adjacent to the Sierra Nevada, to fine-grained clay and silt. There are regions where the groundwater is of poor quality, thus limiting its use as a supply of freshwater.

Developing plans for sustainable groundwater management requires subsurface data to model and predict outcomes of various management actions, given changing climatic and land use conditions. To implement SGMA, there was a need to map the large-scale structure of the groundwater systems — What are the dominant sediment types and their spatial distribution? Where are there continuous confining units? Where is there connectivity between aquifers? Where is there connectivity between aquifers and the rivers, streams, floodplains, and wetlands, essential for supporting the biodiversity of the state? Where is there seawater intrusion along the coast? With the regulatory framework in place, answering such questions was no longer optional, but required for robust planning. There was an opportunity to move forward, advocating for the adoption of geophysical imaging with the AEM method as the only viable solution to acquiring the data that were required, in the time frame that was required, about the groundwater systems of the state.

Access to the right technology

By 2014, the optimal technology for imaging the groundwater systems in California (and in other parts of the world) was in place. Although the AEM method was originally developed for mineral exploration, the use of the AEM method for groundwater applications began in the 1960s, with significant improvements made in hardware and software since that time. The system best suited for use in California was the helicopter-deployed, time-domain system SkyTEM (Sorensen and Auken, 2004). This system was designed specifically for groundwater applications; its dual-moment transmitter makes it possible to acquire high-quality data in the top few tens of meters as well as at greater depths, up to hundreds of meters. The AEM data are inverted to obtain models of the electrical resistivity of the subsurface. Commonly used inversion techniques are those that have been developed to impose the expected spatial continuity in resistivity through a spatially constrained inversion (Viezzoli et al., 2009; Auken et al., 2015). As reviewed in Knight and Endres (2005), the electrical resistivity of geologic materials depends on a set of material properties: the sediment or rock type, the water content, and the salinity of the water. By defining the rock physics relationship linking electrical resistivity to material properties, the resistivity models can be transformed to models displaying the material property of interest.

It is interesting to note that the development of the SkyTEM system was largely driven by regulations put in place in Denmark in the 1990s, requiring the mapping of the groundwater systems of the country. By 2015, there was SkyTEM coverage of Denmark totaling approximately 60,000 line-km, acquired as part of the national groundwater mapping program. The real start for me of my *knowledge-into-action* journey was when Esben Auken (one of the developers of SkyTEM) spent time at Stanford in 2008. Esben was one of the leaders in the SkyTEM mapping of Denmark, and it was his slides that I began using in 2008 to advocate that the same be done in California. Met with limited enthusiasm, I began commenting that no one would take the use of geophysical methods for imaging groundwater systems seriously until we had, as in Denmark, the regulatory framework in place; I was right.

The start of the “into action” in California — a successful demonstration of value added

Despite the successful use of SkyTEM in Denmark, and in many other locations around the world and in the United States, it seemed that what was needed was to demonstrate that this could be a game-changer in supporting groundwater management in California. I will argue that it was the stunning image of the data acquired with the SkyTEM system in October 2016 near Tulare in California's Central Valley (Knight et al., 2018) that triggered the groundswell of support for AEM in California. Here, the critical combination of the people and the funding came together.

Having heard me talk about the need for AEM data in California for about 10 years, colleagues at Aqua Geo Frameworks (Jim Cannia, Ted Asch, and Jared Abraham) offered to conduct a SkyTEM survey for me, at low cost (approximately \$30 k) by combining with a private contract, but with only 2 weeks' notice. Pam Matson, the Dean at the time of my school at Stanford, had been very supportive of my commitment to scaling the use of geophysical imaging methods for groundwater applications in California. Given the lack of funding I had been able to secure from external sources, she had provided discretionary funding. I drained the remaining funds, recruited my Ph.D. student Ryan Smith to drop everything else, and we began the search for local partners to identify the survey area. A cold call to the Tulare Irrigation District was the start of a long-term partnership with the water managers there who at the time were Paul Hendrix (now retired) and Aaron Fukuda (now the General Manager). They agreed to take on the public notification required, helped us define an interesting location for the subsurface imaging, and met us at the Tulare Airfield on the morning of 17 October 2015 (Figure 1).

The compelling image, shown to groups throughout the state, is in Figure 2. In addition to having the needed AEM technology, Adam Pidlisecky (then Chief Research Officer for Seequent), and Thomas Krom (Seequent Environmental Segment Director) had arranged a licensing and partnership agreement with Seequent that gave us access to the Seequent

software suite, in particular, Leapfrog. This allowed us to produce 3D models displayed in slides and videos that were shown to many groups throughout the state. The quality of the data presentation, using Leapfrog visualization, left little doubt as to the value of SkyTEM data.

Shown in Figure 2 are the electrical resistivity profiles along the flight lines, capturing the large-scale structure of the subsurface — the low-resistivity thick package of clay at depth to the east and the upper and lower aquifers to the west, with higher levels of resistivity, separated by the low-resistivity continuous confining clay unit, the Corcoran Clay. There were very few wells at that time that were deeper than approximately 100 m, so these results revealed regions of the groundwater system that were unsampled, providing an understanding of the subsurface, due to the continuity seen in the imaging, that had not been achieved working with well data alone. At the first showing of this image to water managers, drillers, and growers in the Tulare Irrigation District, there was animated discussion at the back of the room by drillers who had just found the deeper packages of sand and gravel.

In 2016, my persistent promotion of AEM for groundwater applications in California had caught the attention of Keith Van Der Maaten, then general manager of the Marina Coast Water District (MCWD). His interest was in the use of SkyTEM to image the extent of seawater intrusion along an approximately 25 km stretch of the coast, just north of Monterey. Ph.D. student Ian Gottschalk became the Stanford lead, assisted by Jesse Crews (at that time a staff scientist with my research group). Ted Asch and Jared Abraham at AGF managed the data acquisition by SkyTEM and conducted the processing and inversion of the data. The costs for this were covered by MCWD. This was the first time that I had found an agency willing to completely cover the project costs. I took this as evidence of the growing enthusiasm for, and acceptance of, the value of the AEM method for groundwater management. The SkyTEM data, 635 line-km, were acquired in May 2017, and the results (Gottschalk et al., 2020) were fantastic. Again, with Leapfrog for model-building and visualization, we had a spectacular image to share — a textbook example of the saltwater wedge, as shown in Figure 3. We were on a roll!

The results obtained with SkyTEM in the Central Valley and along the Monterey coast demonstrated the tremendous potential of the derived images to support groundwater management in California. Invited by Debbie Francos, then the Senior Adviser for Water and Rural Affairs, I made a presentation to the Governor's Office of Planning and Development in which I strongly advocated for the adoption of the AEM method to map the groundwater basins of California. This was followed by a requested white paper (Knight et al., 2016), coauthored with Paul Gosselin (at that time the Director of Butte County Department of Water Resource Conservation), and Graham Fogg (Professor of Hydrology at UC Davis). Assistance from Jim Cannia, Ted Asch, and Jared Abraham from AGF was extremely helpful in writing the white paper. They were involved with a large-scale SkyTEM mapping project in Nebraska, so could advise on what should be included in any

proposal for state-wide mapping in California. The white paper begins as follows:

"California has embarked on a historic journey to achieve groundwater sustainability through the Sustainable Groundwater Management Act (SGMA). Local agencies are vested with the responsibility for achieving sustainability. For most of the state,



Figure 1. Rosemary Knight gives a thumbs up at the Tulare Airfield in 2015 at the start of the helicopter-deployed AEM survey using the SkyTEM system.

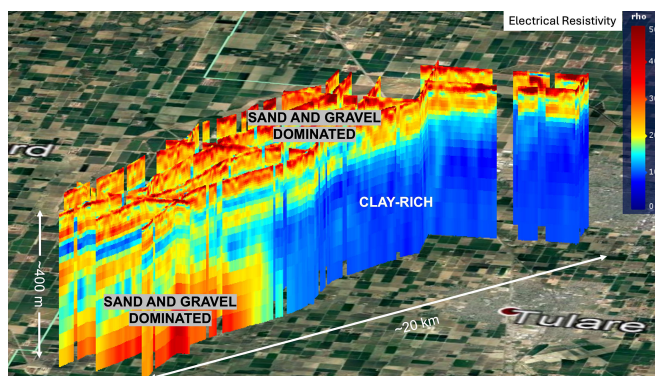


Figure 2. The resistivity profiles along the flight lines from the demonstration project in the Tulare Irrigation District, 17 October 2015 (Knight et al., 2018); overlaid on the Google Earth image showing the town of Tulare. Displayed are resistivity values (ohm-m) with warm colors corresponding to high resistivity and cool colors corresponding to low resistivity.

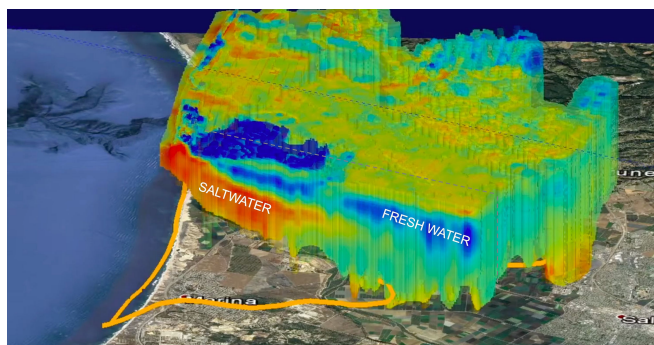


Figure 3. A section of the resistivity profiles from the SkyTEM survey along the Monterey coast in 2017; overlaid on the Google Earth image. The resistivity model extends to a maximum depth of approximately 200 m and approximately 8 km inland. Displayed are resistivity values with warm colors corresponding to the low resistivity regions where sediments contained saltwater and cool colors corresponding to the high resistivity regions where sediments contained freshwater. The orange line is the contour showing the landward extent of seawater intrusion, based on salinity measurements in wells.

the basis for making decisions lacks sufficient understanding of the structure of groundwater basins. Traditional methods of characterizing aquifers are slow, expensive, and insufficient. There is a well-established geophysical method, the airborne electromagnetic (AEM) method, which has the potential to make a significant contribution to the way we map and manage groundwater systems in California. The following describes how a statewide reconnaissance program using AEM could advance the goals of groundwater sustainability and increase the likelihood of successful SGMA implementation.”

Figure 4 was included in the white paper to display the proposed plan. To summarize: We proposed a reconnaissance-scale survey involving the acquisition of 20,000 line-km, an upper-bound cost estimate of \$10 million, and an estimated time of completion of 16 months, once a pilot project had been completed. What followed were presentations I made to audiences including representatives from the Department of Water Resources, the State Water Resources Control Board, and numerous local agencies. Then came the critical leap forward that brought together the right people and the needed funding: the Stanford Groundwater Architecture Project (GAP).

The Stanford Groundwater Architecture Project: The people, the funding

At the same time as the implementation of SGMA, with all the related data needs, was starting up in California, the

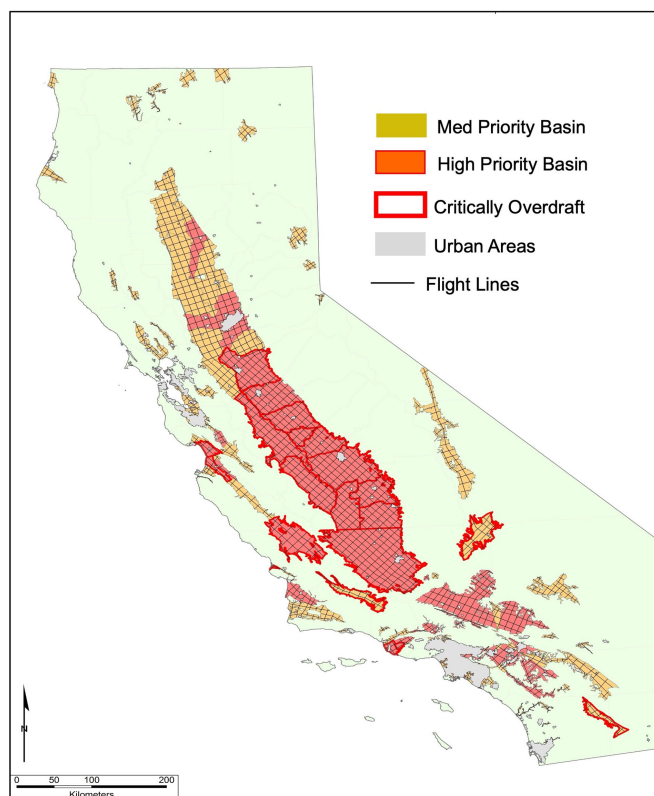


Figure 4. Suggested flight lines for the acquisition of AEM data at the reconnaissance scale in the high and medium priority groundwater basins in California. Produced by Jessie Crewes. From Knight et al. (2016).

groundwater mapping program in Denmark was coming to an end. I had long used Denmark as my example of what was needed in California. There were discussions underway in 2016 of a new partnership between Denmark and California, The Water Technology Alliance, taking the technologies developed and adopted in Denmark (including SkyTEM) and applying them in California. This initiative was perfectly aligned with my goal — to have the AEM method adopted for state-wide groundwater applications, so a collaboration began with a group from Denmark led by Max Halkjær (then Senior Geophysicist with the Ramboll Group) and Jacob Vind (then in the Stanford area with the Danish Ministry of Foreign Affairs and The Danish Water Technology Alliance). A project was defined, involving partnerships with local groundwater managers, to show how the AEM method could be used to cover the groundwater basins of the state. This became the Stanford Groundwater Architecture Project (GAP): *Utilizing Advanced Geophysical and Computational Methods for the Development of Hydrogeologic Conceptual Models* (mapwater.stanford.edu). The following, taken from the introduction of the proposal, describes the scope:

“We propose an ambitious two-year project, where we partner with three water agencies in California to develop a template for the optimal workflow that would use AEM data as the foundation for the development of a hydrogeologic conceptual model; a key step in the implementation of SGMA. This includes not only the deployment of the AEM technology to acquire AEM data, but also designing the supporting computational infrastructure for data analysis, interpretation, and archiving.Our approach will focus on lessons learned in Denmark and seek to identify transferable knowledge and technologies. Our project will also involve basic research to discover new methods of data analysis, inversion, and interpretation appropriate for the specific geologic environment and management needs of California.”

We decided early on that the ideal way to determine the optimal workflow was to work in collaboration with local water agencies to design and conduct AEM surveys to address their specific SGMA-related needs for subsurface characterization. Our agency partners: Butte County Department of Water and Resource Conservation in the Sacramento Valley; Indian Wells Valley Water District, located just east of the southern Sierra; and San Luis Obispo County, on the central California Coast. Associated with each water agency was a large group of interested stakeholders, including members of the public and government officials at the local and county level.

There were various sources of funding for the project. Jacob Vind played the lead role in arranging many meetings and working with the various agencies to put together the funding needed for the GAP. We received funding from each of the local agencies (totaling \$700 k), from the Danish MUDP (equivalent to the Environmental Protection Agency) (approximately \$600 k), from the California Department of Water Resources (DWR) (approximately \$350 k) and from the State Water Resources Control Board (approximately \$350 k). The \$2 million GAP project began in November 2017. In addition, I had funding from the Gordon and Betty Moore Foundation

that allowed the Stanford researchers to continue exploring novel ways to interpret the AEM data in parts of the Central Valley. In addition to the GAP partners, this involved a continued collaboration with Aaron Fukuda and other local agencies to acquire and interpret data in the Kaweah subbasin of the Central Valley.

On 15 June 2018, as the GAP was starting up, the voters approved the California Drought, Water, Parks, Climate, Coastal Protection, and Outdoor Access for All Act of 2018 (Proposition 68). This included funding for an AEM survey that was described, using our white paper (Knight et al., 2016) for guidance, as follows (from the AEM Proposition 68 fact sheet <https://water.ca.gov/programs/sgma/aem>): “*The AEM survey will utilize \$12 million on data, tools, and analysis efforts for drought and groundwater investments to achieve regional sustainability in support of the Sustainable Groundwater Management Act (SGMA).*” There was now a green light to move forward with a state-level survey. The funding was in place.

The development of the optimal workflow

With the funding in place through Proposition 68, the California Department of Water Resources became the lead agency responsible for conducting a state-wide AEM survey. There were many questions to be addressed in determining how to take the AEM technology, applied in other locations, and use it to map the groundwater basins of California. This was exactly what the Stanford GAP was established to do. Table 1 lists the people who came together to define, and then conduct, the GAP. Over the 3 years of the project (November 2017 to October 2020), we worked closely as a team of academic researchers, consultants, and water agency end-users, focusing on what was needed to develop a hydrogeologic conceptual model (HCM), with a level of spatial resolution appropriate given the resolution of the AEM method and the groundwater management needs. What resulted was a workflow with recommendations specific to California described in the 174 pages of the final report (Knight et al., 2020) and summarized very briefly below.

The GAP workflow for the acquisition of AEM data in the groundwater basins of California:

- 1) *Engagement with local agencies*: The workflow starts with close collaboration with the local agencies to determine what information is needed, and can be obtained, from the AEM data to support their decision-making related to groundwater management. This first step of working with the local agencies is essential for beginning the survey design — selecting the area of interest and the desired spacing of the flight lines. In this step, it is essential to (quoting Jim Cannia) “*manage expectations.*” In the GAP, we had limited our scope to supporting the development of the HCM, required as part of SGMA. We developed simple modeling tools to help explain to agencies the limitations of the AEM method, for example, displaying the thickness of a clay layer that could likely be detected at various depths.

Table 1. Participants in the Groundwater Architecture Project.

Role in project		Affiliation at the time of project
Project leads	Rosemary Knight	Professor of Geophysics, Stanford University
	Esben Auken	Professor of Hydrogeophysics, Aarhus University
	Jim Cannia (deceased August 2020)	Principal and Senior Geologist, Aqua Geo Frameworks
	Ted Asch (replaced J. Cannia 2020)	Research Geophysicist, Aqua Geo Frameworks
	Max Halkjaer	Senior Geophysicist, Ramboll Group
Other key personnel	Niels-Peter Jensen	Chief Executive Officer, I-GIS
	Noah Dewar	Geophysics Ph.D. student, Stanford University
	Seogi Kang	Geophysics postdoctoral research fellow, Stanford University
	Jesper Bjergsted Pedersen	Senior Geophysicist, Aarhus University
	Ahmad Behroozmand	Geophysics postdoctoral research fellow, Stanford University
	Ryan Alward	Ramboll
	Casper Mejer	I-GIS
	Thomas Bager Rasmussen	I-GIS
	Jared Abraham	Principal Geologist/Geophysicist, Aqua Geo Frameworks
	Tim Parker	Parker Groundwater
	Todd Greene	California State University, Chico
	Jef Caers	Stanford University
	Christina Buck	Assistant Director, Butte County Department of Water Resource Conservation
	Paul Gosselin	Director, Butte County Department of Water Resource Conservation
	Catherine Martin	San Luis Obispo County
Water agency partners	Don Zbeda	Indian Wells Valley Water District
	Sam Boland-Brien	California State Water Resources Control Board
	Ben Brezing	California Department of Water Resources
	Katherine Dlubac	California State Water Resources Control Board, then California Department of Water Resources
	Tim Godwin	California Department of Water Resources
State agency representatives	Andrew Renshaw	California State Water Resources Control Board

(Continued)

Table 1. (Continued)

Role in project		Affiliation at the time of project
	Stephen Springhorn	California Department of Water Resources
	Natalie Stork	California State Water Resources Control Board
Other participants and collaborators	Jacob Vind	The Danish Water Technology Alliance (WTA)
	Bill Brown	SkyTEM
	Graham Fogg	University of California, Davis
	Mats Gulbrandsen	I-GIS
	David Shimbukuro	California State University, Sacramento
	Sharla Stockton	Glenn County, Department of Water Resource Conservation
	Le Thanh Vu	I-GIS

Early on, there was a need to clarify that the AEM method could only be used to image features that resulted in a change in electrical resistivity. This meant that it was not possible, in many cases, to differentiate between the hydrostratigraphic units that were commonly used by agencies in building subsurface models.

- 2) *Develop the data management system:* This recommendation makes clear that protocols for data format, archiving, and sharing must be carefully considered at the start of the project and the systems/platforms put in place. Throughout the project, one of the systems that had been adopted in Denmark, GeoCloud (<https://i-gis.dk/geocloud/>), was modified for use in California. This facilitated sharing the data and the visualization of results among project participants and with stakeholders.
- 3) *Compile existing data,* including well completion reports and geophysical logs along with geologic cross-sections and subsurface models. One of the most valuable sources of data for interpreting the AEM data and building the HCM is the driller's logs. These are included, in California, as part of the well completion report and describe the sediments and/or rocks encountered over different depth intervals during the drilling of the well. There was a surprise and setback early on in the GAP when we requested "digital driller's logs" and received scanned PDFs, not the machine-readable version that we required. In addition, unlike Denmark, where the country's geologic survey pays great attention to ensuring the quality of the driller's logs, we found that the logs in California could be of very poor quality. We developed recommendations on the number of driller's logs needed, provided guidance on how to define "high quality," and developed procedures for rapid digitizing and categorizing the descriptions in the logs.
- 4) *Design the AEM survey:* Finalizing the design of the AEM survey includes selecting the appropriate AEM system and the data acquisition parameters, and deciding on the locations, orientations, and density of the flight lines. The survey should be designed to best address the needs of the agency. The recommended approach is to use existing driller's logs and geophysical data (and other information as available) to generate a model of the sediment/rock type in the subsurface, with corresponding resistivity values, and then simulate the ability of the various AEM systems under consideration to recover the subsurface model. This process assists in selection of the appropriate AEM system and helps to manage expectations by clarifying what information is likely to be acquired by conducting the AEM survey. At this point, it is important to return to discussions with the agency to confirm that the AEM survey can deliver what they need. Maximizing the accuracy of derived information comes into the survey design. This includes considering the location of high-quality driller's logs and resistivity logs which are used to aid in the interpretation.
- 5) *Acquire the AEM data* using the selected system, with outreach in the local area to explain the objectives and procedures of the survey, and to address any health and safety concerns. Materials were developed for distribution that answered commonly asked questions. Prior to commencing with data acquisition, a signed agreement needs to be in place with the agency. There was no experience in the agencies in California with negotiations related to AEM surveys, so during the project, I worked closely with Bill Brown, the SkyTEM representative responsible for California, who was very receptive to putting in place contractual agreements and a pricing structure for SkyTEM surveys that were compatible with the needs and constraints of the local agencies. In addition to the elements of the survey design discussed above, the final contract needs to include specified limits to flight height, speed, and tilt angles.
- 6) *Analyze the AEM data* to obtain models of electrical resistivity, the geophysical property that is measured. What is recommended is that the steps of processing and inversion of the AEM data be iterative processes with interaction among geophysicists, hydrogeologists, water managers, and local stakeholders. Information is provided in the report about two approaches to conducting the 1D spatially constrained inversion used in the GAP. One was developed by Aarhus University (Viezzoli et al., 2009; Auken et al., 2015) and commercially available through Aarhus

Workbench. The other, *simpegEMID* (Kang et al., 2018, 2021), is available as open-source software through the website <https://www.simpeg.xyz> (Cockett et al., 2015).

- 7) *Interpret the resistivity models:* With the objective of obtaining a HCM, the interpretation of the resistivity models involves transforming resistivity into sediment or rock type. There are two common approaches that can be combined. One that is more qualitative involves viewing all data (the resistivity models, driller's logs, existing cross-sections, and other models) and then identifying zones tens of meters thick that correspond to the large-scale architecture of the subsurface. The other derives a more quantitative relationship, two examples being the development of a relationship between resistivity and clay fraction (Foged et al., 2014) and between resistivity and sediment or rock type (Knight et al., 2018). If there is variation in salinity in an area, it is important to divide the region into areas that can be interpreted independently, taking into account the impact of salinity on resistivity.
- 8) *Integrate all data to generate the HCM* using a computational framework to explore the range of possible models that are compatible with the data. The recommendations specify including existing hydrogeologic interpretations from previous studies; descriptions of the interpreted depositional environment and other geologic events; geologic maps; high-resolution digital elevation models; information from boreholes including sediment/rock type, screened intervals, water levels, water quality, and geophysical logs; geophysical investigations including seismic, gravity, magnetic, electrical, and electromagnetic surveys. The multipoint statistical method is highlighted as a numerical methodology which can be used to generate multiple realizations of the subsurface, all of which are compatible with the data and with the geologic understanding of the depositional environment in the model area. Using the ensemble of equally possible models leads to the ability to calculate statistics and thereby quantify uncertainty of the resulting models.
- 9) *Answer the management questions*, while acknowledging uncertainty, to inform decision-making for sustainable groundwater management. Throughout the workflow, interactions with the water agencies are essential in ensuring that all steps are aligned with the purpose of the AEM survey, as defined at the start in consultation with the agencies. When information is communicated to the end-users, it is recommended that uncertainty is quantified and communicated. In the GAP, we focused on the uncertainty in the HCM derived from AEM data and well data with six major sources of the uncertainty given as: noise in the AEM data (e.g., powerline noise), the AEM inversion, the well data (e.g., location, and driller's logs), the rock physics transform (between resistivity and sediment or rock type), the data density of the AEM and well data, and the geologic and hydrogeologic knowledge (e.g., of the depositional history). Two approaches explored in the GAP were models quantifying/displaying the probability of the

occurrence of specific sediment types (Kang et al., 2021) and the generation of multiple models all compatible with the data, as can be accomplished with the multipoint statistics method.

Into action

In the fall of 2020, with funding in place from Proposition 68, and the GAP in its final stages and providing high-level guidance, the California Department of Water Resources moved “into action” reviewing proposals submitted in response to their Request for Proposals for “Airborne Electromagnetic (AEM) Geophysical Surveys of the Medium and High Priority Basins in California.” Katherine Dlubac was the lead at the Department of Water Resources, with Ramboll and partners selected to execute the state-wide AEM project. The project was launched in 2021 and completed in 2023, after two and a half years. A description of the project and a preliminary interpretation of the AEM data are given in the publication by Dlubac et al. (2024), with all AEM and ancillary data made available (California Department of Water Resources, DWR airborne electromagnetic (AEM) surveys data, 2025). Although some of the individuals involved with the GAP remained involved, many of us did not have a role in the state-wide project. We did, however, all share in the tremendous satisfaction of having played a critical role in launching the first state-wide AEM project in the United States.

Concluding remarks

Six components came together in California to move *knowledge into action*. The regulatory framework under SGMA made it very clear that the AEM method was the only viable way to acquire the subsurface data needed in the time available. The right technology was there in the form of SkyTEM. The funding and people came together, allowing us to conduct the initial demonstration project, with a stunning image that convinced many of the value of AEM data, and then to conduct the three-year pilot study in which we carefully considered every step of the workflow and laid out a plan for a successful state-wide project. Then the funding came together through Proposition 68 to move the generated knowledge into action. At that point, there was a hand-off to the Department of Water Resources who achieved what we had all wanted to see happen — the use of the AEM method to map the groundwater basins of California. Geophysics had been firmly established as foundational for sustainable groundwater management in the state.

The California AEM project has resulted in a remarkable data set of 25,000 line-km of AEM data, along with digitized driller's logs and water level measurements all available through the project website. Although the project is a great example of moving knowledge into action, the next step from this action should be the generation of new knowledge. The available data provide a tremendous opportunity for research — discovering fundamental insights about the AEM measurement and its link to the imaged geologic materials; exploring ways to tap into AI to expedite and improve survey design and data analysis;

grappling with how best to integrate various types of data with large differences in spatial resolution. And can we discover something fundamental about the controls on depositional processes with the view we now have into California's Central Valley? This data set can lead to significant advancements in California — not just for groundwater management but also for groundwater science. **TLE**

Acknowledgments

In the text above, I have included mention of the many people who came together to work on the GAP. There are four of those people whose individual contributions I want to acknowledge. The first two were members of my research group at Stanford during the GAP — Ph.D. student, Noah Dewar, and postdoctoral associate, Seogi Kang. They took time away from their research interests to join me in focusing on the question that needed addressing in the GAP: How to conduct a state-wide AEM project? Their insights, and their rigorous and creative approaches to problem-solving, led to rapid progress in defining the optimal workflow.

The first time I met Tim Godwin, from the Department of Water Resources, was after an early presentation I gave. He came up to me and said, to paraphrase, “This has to happen.” Tim became a champion for the GAP project within the state agencies and was always available to help as needed.

I am not sure that the GAP would have happened without Jacob Vind. Jacob pulled together many of the people and most of the funding. I greatly appreciate his belief from the start in the value of the GAP and his continued celebration of the success of the project.

As I said in the introduction, of the six components needed to move knowledge into action, the most important was the people. This was a team effort with an outcome that I believe could only have been accomplished by this team.

Data and materials availability

The described data sets are all available through the provided references.

Corresponding author: rknight@stanford.edu

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