TAKING THE PULSE OF THE WATERSHED

A proposal for an Integrative Project, submitted by Rosemary Knight, 25 July 2025 on behalf of:
Greg Beroza, Ettore Biondi, Bill Ellsworth, Scott Fendorf, Zerina Kapetanovic, Ching-Yao Lai, Olav Solgaard, William Tarpeh, Daniel Tartakovsky, Howard Zebker

PART 1. THEORY OF CHANGE

Describe the systems-level sensing approach and how it relates to the watershed management focus.

Many countries around the world face a crisis in terms of the diminishing supply of freshwater available to support the needs of humans and ecosystems. Climate change, population growth, and land-use change are negatively impacting both the quantity and quality of available water. "Sustainable water management" requires the allocation of water to meet the needs of today and in the future, while promoting the continued survival of the social, economic, and ecological systems that rely on the water supply. The transformative contribution that we will make, to support sustainable water management, is the ***development of a sensor-informed analytical framework that will allow us to accurately quantify connected changes in human-ecological-hydrologic systems across scales and varying climatic, topographic, geologic, and landcover settings.*** We will develop a framework at the watershed scale to analyze water availability and use patterns and to inform future management by identifying human and natural drivers of change in water quantity and quality. The framework will be used to take the pulse of the watershed through the analysis and interpretation of data, which can only be successfully implemented if there are adequate observational data. Therefore, the defining component of this project is the integration of data acquired using sensors deployed on satellites, aircraft, drones, and land/water-based platforms and the translation of those data into messages that inform resource management. We will advance the utilization of existing sources of data and develop the capabilities to acquire, process, and interpret new forms of data. The sensor-informed analytical framework will be structured so that it can be adopted, with minor modification, at the local, regional, and global scales.

Describe the long term (i.e. 10-year/decadal) impact envisioned and the near term (5 year) strategy and approach for addressing this systems challenge.

We envision, in 10 years, a global network of sensors, with the data pipelines in place, to map, measure and monitor the key parameters in the human-ecological-hydrologic systems which drive changes in water quantity and water quality. With these sensors in place, the analytical framework that we will develop can be adopted to provide the basis for the ***adaptive management***, with monitoring capabilities, of hydrologic systems while ensuring human prosperity and ecosystem health; the time scale needed for assessing/adapting management practices will determine the temporal and spatial sampling required for monitoring. Over the next five years, we will develop a sensor-informed analytical framework for the San Joaquin Valley Watershed. We will use a modular approach that allows us to identify and focus effort on the “weak links” where Stanford faculty are poised to make rapid advancements in a data-driven system for freshwater management, focusing on both water quantity and water quality. The successful completion of this project will lead to the next stage - the development of a water budget dashboard that can serve as a decision-support tool for water allocation, balancing the needs of people and nature.

Share how insights and results could inform similar challenges in other regions and communities, and describe efforts to build pathways for insights to be applied to other regions and watersheds.

We emphasize that, from the start, the sensor-informed analytical framework will be structured so that it can be adopted, with minor modification, at the local, regional, and global scales. There are

common challenges faced by many regions, communities, watersheds, etc. in terms of data availability to capture key components of the human-ecological-hydrologic systems. Through our project we will improve the capacity to utilize existing data, for example by developing robust methods that directly utilize well-based measurements that are common to many areas, and also leverage them to downscale satellite data and other regional-scale measurements to useful management scales. We will develop new data pipelines to move publicly available data acquired with satellites or aircraft or land/water-based sensing to actionable data, with models/products that support the improved integration of these data into decision-support tools for freshwater management. We will also develop new sensors where needed due to either a complete lack of sensors to meet a specific need or the high costs of deployment and/or maintenance. For all forms of sensor data, a high priority is developing computationally efficient methods for data interpretation and integration across a wide range of spatial and temporal scales so as to make the enormous volumes of data and derived products accessible and useful for the research community and for end-users involved with the development and implementation of policy to achieve sustainable freshwater management. These results will be immediately transferrable throughout the western U.S. through our partnerships and connections with local and state water agencies. The results will also be of great value to locations around the world which have a sparsity of well data, so are highly dependent on satellite data. Transfer to these locations will require leveraging the activities of others at Stanford, for example, through the international work being conducted under NatCap and through centers such as the new Center for Southeast Asia.

PART 2. PROPOSED WORK AND MILESTONES

Describe the proposed work, including a clear outline of the project plan, the new sensing or data processing approach, the link to solutions/management, external partner engagement, intended milestones and deliverables for each year, and the responsible co-PIs.

Based on discussions at past meetings with faculty and external partners, we have selected the San Joaquin Valley Watershed as the starting location for conducting and exemplifying the field- and sensor-based research, extending to other regions as appropriate to explore issues related to transferability and scaling. We have, as the policy framework for our work, the Sustainable Groundwater Management Act, passed by the California Legislature in 2014, requiring that local water agencies manage all groundwater to avoid six undesirable effects related to the quantity and quality of groundwater and surface water. What is required to support sustainable management is an analysis of past, and monitoring of future, variables that provide information about the human-ecological-hydrologic system. Given the time and funding constraints of this project, we will rely on current practices for characterizing the human and ecological systems. **The innovation is in the new approaches we will develop for characterizing the hydrologic system, and for the integration of data across the human-ecological-hydrologic system to inform sustainable management.** In these research areas we draw on the unique strengths of Stanford faculty and heavily leverage recent and ongoing research.

In terms of variables characterizing the human system, for the purposes of freshwater management in the San Joaquin Valley, these are primarily related to the use of water for agriculture so they will include land cover with crop type determined, water usage and irrigation types for different crop types and geographic areas, surface water deliveries for irrigation, and estimates of groundwater pumpage; the last will be obtained in most place from estimates of evapotranspiration due to the lack of metering on wells. We will integrate ongoing work to improve consumptive use estimates in agriculture via OpenET (Melton et al., 2022), overlaid with new knowledge of irrigation water supply sources to better map seasonal changes in groundwater and surface water use requirements in agriculture. We note that we are not attempting to consider other elements of the human dimension, related to socio-economic considerations or governance frameworks; we include only the listed variables, quantifying them with existing forms of measurement. In terms of characterizing ecosystems, the variables to be included are the type and extent of the major ecosystems present in the valley and the source water supporting ecosystems.

Our research in these two areas (human systems and ecosystems) will be limited to employing existing data sources and methods of analysis. The innovation will be in how the data are integrated with hydrologic variables.

We show in Figure 1 the hydrologic variables typically included in constructing a water balance of a watershed that focuses on water quantity. One primary research focus, required to address a critical need in current water management, is the development of new approaches to monitoring changes - at the scale relevant for management - in the volume of water stored as groundwater (referred to as groundwater storage); this shown in larger bold and red font, with a "?", in Figure 1. The groundwater component of the hydrologic cycle is hidden from view, difficult to access, and poorly sampled through the drilling of wells. Given the focus of SGMA - groundwater - quantifying changes in groundwater storage is a significant and challenging need, in terms of SGMA implementation and compliance. This involves research that builds on recently completed Stanford research, as detailed below, putting us in the position of a high probability of success in achieving a breakthrough in the near term in this area.

Many of the other variables shown in Figure 1 are currently estimated using data acquired with satellite or land/water-based sensors; our research will focus on the development of new data pipelines to improve the accuracy of the estimates and to expedite the integration of these sources of data. As an example: we will apply algorithms recently developed at Stanford to estimate soil moisture (SM) (Wig et al., 2024) so as to improve both the accuracy and spatial resolution. While not attempted in the typical water balance approach, we also plan to develop ways to map and monitor the exchange of water between surface water and groundwater, some of which occurs as the river-sourced recharge of the groundwater which is one component of the total recharge (R). Determining the ways in which pumping to meet human demand may impact streamflow, and thus ecological health, is needed in order to set sustainable management criteria. In our study of surface water-groundwater connections we will address the need for inexpensive sensors to provide the spatial density of measurements required for accurate estimates of streamflow (Q).

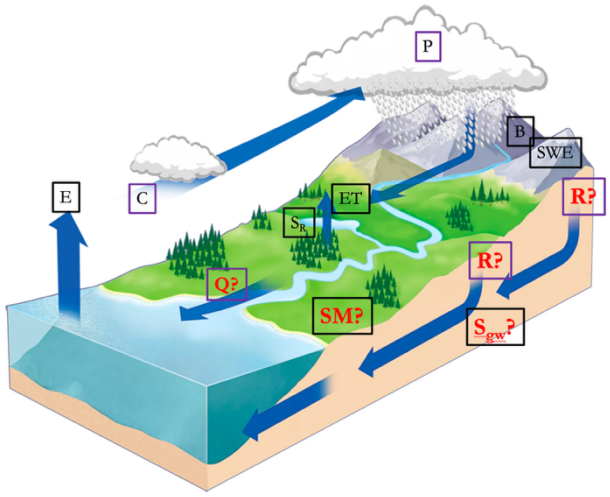

Figure 1: A schematic showing the hydrologic variables typically included in quantifying a water balance of a watershed. In our research we will focus on those in larger, bold, red font which include the volume of water stored in groundwater, referred to as groundwater storage (Sgw) and as soil moisture (SM); and the flux term recharge (R). The other variables include the volume of water stored in snow, quantified as the snow-water-equivalent (SWE) and in surface water, referred to as surface water storage (Ss); and the fluxes which include precipitation (P), evaporation (E), evapotranspiration (ET), streamflow or discharge (Q), and two variables that we will neglect given our purpose: condensation (C) and sublimation (B).

The hydrologic variables referred to above are essential for monitoring water quantity. But a large volume of water, with low water quality, cannot meet the needs of humans or ecosystems. Groundwater quality combines with quantity to dictate the usability and availability of water resources. In the San Joaquin Valley, water quality (or chemistry) is threatened by a host of naturally occurring contaminants, with arsenic and uranium being the principal risks. Additionally, anthropogenic activity can introduce

contaminants such as nitrate into groundwater. In this project we focus on changes in water quality related to the recent adoption of managed aquifer recharge practices that involve the flooding of agricultural land to move more excess surface water down into the groundwater systems. While the benefits in terms of water quantity are clear, there are growing concerns about the impact on water quality and, under SGMA, management practices cannot cause degradation in terms of water quality. The key to limiting the impacts of contaminants on groundwater quality during managed aquifer recharge is two-fold: (1) Utilize recharge systems that minimize the release or introduction of contaminants and (2) have early detection that allows changes in infiltration chemistry to avoid groundwater degradation. What is needed is the ability to sense the chemistry of recharging waters at high temporal and depth resolution in order to modify recharge management quickly, avoiding costly groundwater contamination. In short, we need a sentry system that alerts us to impending problems. Our vision, shown in Figure 2, is to have sensors throughout a watershed monitoring changes in water quality to support adaptive management of recharge operations.

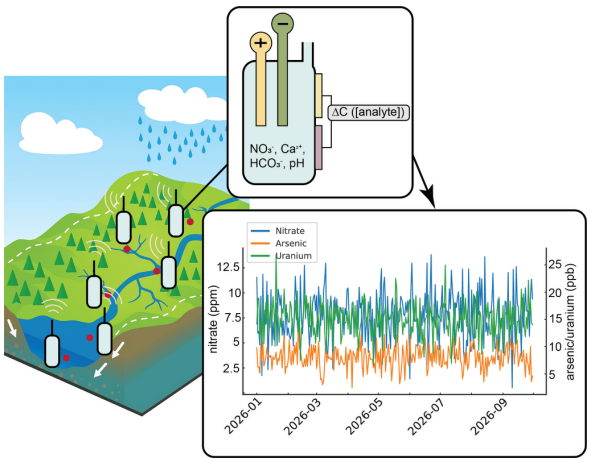

Figure 2: An illustration showing a network of low-cost and low-maintenance sensors deployed in a watershed. The top right inset shows the concept of our detection mechanism based on electrochemical sensing and capacitive readout. The sensors will generate datasets with unprecedented high spatiotemporal resolution to reveal the dynamics of the water quality

As detailed below, central to our project is advancing the ways in which we map, measure, and monitor all variables in the human-ecological-hydrologic system and integrate the many diverse forms of data across spatial and temporal scales. This integrative project is ambitious in terms of the scope of the proposed research with the proposed work described under the following four Objectives and Tasks. Within each we will describe the planned research and other activities, in the context of solutions, summarize partner engagement (covered in more detail in Part 3), and list intended milestones and deliverables.

Objective 1. Development of the "digital twin" of the watershed.

We do not need to develop a detailed numerical model of the human body to manage human health; we can use various forms of sensors to "take the pulse", making measurements at selected times and locations to support adaptive management. We take the same data-driven approach with the San Joaquin Valley Watershed (SJVW), developing a data-driven representation of the human-ecologic-hydrologic system of the SJVW. We will develop a digital twin that will be used to understand connections within the human-ecologic-hydrologic system so as to obtain the predictive capacity required to support sustainable freshwater management. It will also form the basis for the development of a decision-support dashboard that we anticipate will be adopted at the scale of subbasins, for local groundwater management, and at the scale of the state, to support the larger scale perspective required to inform policy. Throughout the project, we will continually update all Tasks to incorporate new sources of data resulting from the research being conducted under the other three Objectives.

Our external partners: For this component of our work we will work closely with partners at both the state level and the local, subbasin level; these partnerships are described in more detail in Part 3. At the state level, we have a formal commitment from The Office of Data and Innovation which serves to enable and champion innovative methods. This group advances the way in which large and complex data drive decision-making. We have also initiated engagement with the Department of Water Resources, the state department responsible for regulatory oversight of, and ongoing assistance, with SGMA. At the local level, we are partnering with three Groundwater Sustainability Agencies in the Kaweah subbasin. We will also be communicating our plans for this project through various state-wide newsletters and direct outreach to local water agencies and consultants, inviting others to join us as partners.

Obj. 1 Task 1 (Tartakovsky, Knight): Fusion of all available data relevant for the human-ecologic-hydrologic system using the platform Redevis. Year 1-3 Milestone: Completed design of a data pipeline to efficiently ingest large-scale satellite data/imagery. Year 1 Milestone and deliverable: All data available through state and federal agencies publicly available. Year 2 Milestone and deliverable: All data available through local agencies publicly available, masking metadata as needed for confidentiality.

Obj. 1 Task 2 (Lai, Tartakovsky, Knight): Development of physics-informed machine learning methods to explore decades of data to assess links between variables in the human-ecologic-hydrologic system of the SJVW. For example, does a change in crop-type trigger changes in the ecologic and/or hydrologic variables? Year 2 Milestone: Completed development of ML algorithms given variables of interests. Year 3 Deliverable: Results of analysis of all variables showing spatial and temporal connections between all variables in the system. Open-source software, shared through github, and data shared through Redevis.

Obj. 1 Task 3 (Tartakovsky, Lai): Development of the "digital twin" of the watershed, that will allow us to explore the connections within a platform/framework for data fusion. We will work closely with external partners to ensure the digital twin maps to management needs. Year 1: Meetings with external partners to identify what the management needs are, what is currently available to address those needs, and what form of data/information should be delivered for the needs to actually be met. Year 2: Design and implementation of information-theoretic methods for bidirectional scaling and correlation of various sensor data to hydrologic data needed to parameterize groundwater models and their computationally efficient surrogates used in decision-support systems. Year 3: Development and deployment of reduced-order models (based, e.g., on dynamic mode decomposition) and deep neural networks (e.g., graph neural networks trained on multifidelity data) of the SJVW. Year 4: Incorporate the data-informed models into an environmental decision support system consisting of an ensemble of these predictive tools evolving through data acquisition, aquifer/watershed monitoring and control, and self-learning AI modules. The resulting digital twin of the SJVW would amount to a scalable multi-fidelity framework, which enables quantitative forecasting at various scales and levels of complexity. Given the limited computational resources and only partially informative measurements, we will incorporate uncertainty and resource-aware particle filter and model selection approaches. Deliverable start of Year 5: Shared link to decision support system available for external partners. Further development, requiring the hiring of software engineers, would be needed to make this open to all interested parties.

Objective 2. Monitoring changes in groundwater storage (through various sensor types).

The current state-of-the practice for monitoring groundwater is to rely on measurements made of water levels in wells. High quality water level measurements can only be made in dedicated monitoring wells, each of which cost ~$120,000. Well observations can provide high-fidelity hourly measurements, but are only representative of conditions within a few tens of feet around the well, are too few to meet the monitoring needs in the SJVW, and are often nonexistent in many parts of the world. The more typical form of measurement in the SJVW uses instruments in pumping wells (commonly corrupted due to the pumping) and reports only two measurements a year, typically before and after the irrigation/growing season.

Over the past few years, there have been significant advancements in the use of satellite data and seismic data to obtain estimates of the change in stored groundwater, referred to as groundwater storage.

NASA's GRACE satellite mission – the Gravity Recovery And Climate Experiment – uses a pair of satellites to detect changes in the mass of water stored in the land surface, including groundwater, with the data analyzed to isolate information about changes in groundwater storage (Rodell et al., 2009, Richey et al., 2015, Rodell et al. 2018). Research at present is focused on reducing the current footprint of the measurement from ~500 km, or approximately the size of the combined Sacramento and San Joaquin River Basins, to ~100 km or smaller to support the scale of management needs (e.g. groundwater subbasins for SGMA). A second approach, also using satellite data – InSAR (interferometric synthetic aperture radar) data, uses the subsidence of the ground surface associated with the pumping/withdrawal of groundwater to determine the change in storage at a horizontal resolution of ~100 m where high-quality InSAR data are available (Lees and Knight, 2023); these data are available worldwide from the ESA Sentinel-1 satellites and from the upcoming NASA NISAR mission. This approach can provide estimates of change in storage when the withdrawal of the water triggers a change in the water pressure, as will occur in semi-confined or confined aquifers; it is the corresponding increase in effective stress and compaction of the aquifer materials that causes subsidence. Another novel approach involves the use of ground-based sensors to measure change in seismic velocity. Most recently it has been shown that subtle changes in the seismic velocity of the subsurface, monitored using seismometers (Mao et al., 2025) and Distributed Acoustic Sensing (DAS) (Tribaldos and Ajo-Franklin, 2021), can provide estimates of change in groundwater storage.

In this project we will build on these recent developments to advance all methods towards providing a solution to the challenge of obtaining reliable estimates of change in groundwater storage at scales relevant for groundwater management. The time window for our estimates will be from time of sensor installation to present for the seismic monitoring; for the other approaches the time window will be 2015 to present.

Study area and our external partners: We have selected as our study area for testing the new measurement methods the Kaweah subbasin in the southern part of the San Joaquin Valley. Knight has been working for over 10 years with the Groundwater Sustainability Agencies (GSAs) in this subbasin in testing and advancing the adoption of new technologies for groundwater management. Our partners, listed in Part 3, are working with us in identifying field sites for deployment of sensors, planning for the 5-year installation of equipment, and providing data from their agencies relevant for the proposed work. We will work closely with them on the interpretation of the results and the integration of the results into their groundwater management plans.

Obj. 2 Task 1 (Knight): We will build on the recent work of Lees and Knight (2023) to combine estimates of change in storage from InSAR data with estimates from water level measurements (from Obj. 1, Tasks 1 and 2) to determine change in storage over the two depth levels corresponding to an upper aquifer and a lower, confined aquifer, at a horizontal resolution of ~ 500 m. InSAR data are publicly available, but a more robust data pipeline to provide change in storage in the lower aquifer needs to be developed. Year 2 Milestones and deliverables: Storage estimates from the combination of InSAR and well data for upper and lower aquifers, publicly available. All developed code available through GitHub. Year 3, 4, 5 Milestone and deliverable: Annual storage estimates from InSAR and well data for upper and lower aquifers, publicly available. Deliverable Year 5: Results integrated with all other estimates from Obj. 1 with recommendations for how best to adopt new data sources to inform groundwater management; Open Source publication.

Obj. 2 Task 2 (Beroza, Ellsworth): We will follow the approach described in (Mao et al., 2025) to map changes in storage with seismic interferometry measurements**.** We will deploy 12 broadband seismic instruments from the National Science Foundation EarthScope for this purpose. (Approval of the equipment request has been received with delivery of instruments in September 2025). We will collect and process the continuous waveform data that they record and infer changes in groundwater from the processed seismic signals. Year 1 Milestones: Installation of seismometers; six months of data acquisition. Year 2 Milestone: Continuing data gathering, Interferometric seismic processing to provide estimates of change in velocity, and analysis of frequency and lapse time dependence to localize observed changes to upper and lower aquifers. Years 3, 4, 5 Milestones and deliverables: Integration of velocity

measurements, spatial and temporal mapping of inferred groundwater changes for each water year, thus hoping to test the method for variation in annual precipitation, to validate the method and to provide estimates of change in storage for partners; publication of results. Year 5 Deliverable: Results integrated with all other estimates from Obj. 1 with recommendations for how best to adopt new data sources to inform groundwater management; Open Source publication.

Obj. 2 Task 3 (Biondi): We will deploy a Distributed Acoustic Sensing (DAS) unit along a 100-km telecommunication fiber-optic cable and implement the soil moisture monitoring methodology established by Shen et al. (2024). In parallel, we will evaluate the feasibility of integrating DAS data with seismic network observations to expand the monitoring footprint from the linear cable path to a broader two-dimensional extent. Additionally, we will assess the potential of DAS for groundwater monitoring using high-quality, low-frequency strain data, following the approach outlined in Mao et al. (2025) for seismic station data. Year 1 Milestone: Completion of the DAS deployment and preliminary evaluation of data quality and its capability for hydrological monitoring. Year 2 Milestone: Development of algorithms to integrate DAS with seismic station data for improved groundwater monitoring. Year 3-5 Milestones and Deliverables: Integration of DAS-based hydrological data products with complementary datasets (e.g., precipitation records, soil moisture sensors, and well measurements) to assess spatiotemporal variations in groundwater storage and long-term trends. Year 5 Deliverable: Results integrated with all other estimates from Obj. 1 with recommendations for how best to adopt new data sources to inform groundwater management; Open Source publication.

Obj. 2 Task 4 (McLarty, external member of the Science Team): Current dynamical and statistical approaches to downscale GRACE data lose reliability when transferred to regions other than where they were trained (machine learning approaches), are limited by the underlying model architecture and assumptions in dynamical approaches that use higher resolution models, and produce results that are more dependent on available input data than on a representation of robust physical processes. Additionally, the use of GRACE to study groundwater is dependent on the quality of the data used to isolate changes in soil moisture, surface water, and snow water equivalent from the GRACE-observations of total water storage change. We will first improve the isolation of groundwater from GRACE by leveraging the high-resolution, high-quality observations collected herein for the remaining water budget components. We will then utilize the higher resolution InSAR and DAS data to establish physically-based scaling relationships of groundwater changes over varying temporal scales to downscale GRACE observations by identifying underlying physical mechanisms instead of relying on existing models and statistical techniques. Year 1 Milestone: Implement current GRACE analysis methods with existing data. Year 2-3 Milestone: Integrate newly-available data, of higher quality and improved spatial resolution, to downscale GRACE observations. Deliverable Year 4: Estimates of change in storage from GRACE for Kaweah subbasin. Year 5 Deliverable: Results integrated with all other estimates from Obj. 1 with recommendations for how best to adopt new data sources to inform groundwater management; Open Source publication.

Obj. 2 Task 5 (Zebker): Closely related to mapping groundwater storage is the question of soil and canopy moisture. While these two terms are not very significant compared to the total stored water, they are the key variables for the critical fluxes between soil and atmosphere. Moreover, these two quantities are precisely the needed variables for many, if not most, of the many applications dependent on freshwater distribution. The focus in this project will be on soil moisture which represents the water available to plants, and hence to agricultural and ecological health. Furthermore, soil moisture is the greatest source of uncertainty in obtaining estimates of groundwater storage changes from both GRACE and radar satellite observations. Here we will leverage recently completed research to utilize satellite data to obtain accurate estimates of soil moisture (Michaelides et al., 2019; Wig et al., 2024). We will deploy soil moisture probes in order to validate the satellite retrievals in the Central Valley study area, and once this is refined it opens the door to worldwide observations. Year 1 Milestone: Develop and refine InSAR phase closure codes to recover soil moisture. Deliverable: algorithms and working codes. Year 2-3 Milestone: Integrate NISAR data into the data flow developed in Year 1 using Sentinel data so that we see

deeper into the soils. Deliverable: comparison of estimates with field soil moisture sensors in study area; Open Source publication.

Objective 3: Advancing the mapping and monitoring of connections between surface water and groundwater.

The fluxes governing the exchange of water between surface water and groundwater vary significantly in time and space. Along one stretch of river, there can be significant seasonal variation in the direction and magnitude of the net flux - groundwater to surface water or surface water to groundwater.

Of critical importance to the groundwater systems of the SJVW is river-sourced recharge, which has been increasing as more rivers experience prolonged losing conditions due to the lowering of the water table. Even though river-sourced recharge makes up 47% of modern (post 1950) groundwater, it remains poorly understood (Jasechko et al., 2021; Visser et al., 2018). Recent research has introduced the ability to use the water-pressure-sensitive satellite InSAR measurement to map and monitor, at a spatial resolution of 10s of meters at the surface, the movement of river/stream water downwards into the deeper confined sections of the groundwater systems of the Central Valley (Neely et al., 2021). By combining the satellite InSAR data with a detailed image of the large-scale structure of the hydrogeology obtained from the analysis of airborne electromagnetic (AEM) data, it was possible to identify a specific pathway for recharge in the San Joaquin Valley (Neely et al. 2024).

Of critical importance to rivers and streams is the contribution of groundwater to baseflow conditions, allowing streamflow to be maintained during the summer months of low precipitation; this is essential for providing water for dependent ecosystems. SGMA explicitly states that groundwater pumping cannot cause the depletion of connected surface water to a degree such that ecosystems and downstream users are adversely affected, thus triggering a need to understand the link between groundwater pumping and streamflow. The impact of groundwater pumping on streamflow can be directly measured by installing steam gauges along a stretch of river. What is needed is sufficiently close spacing between stream gauges in order to isolate the impact of pumping in one location on stream flow. While conceptually this is a very simple approach, the challenge is the cost of a stream gauge: typically ~$15,000 to purchase, with ongoing maintenance costs.

We focus again in this Objective (as in the others above) on the specific areas where 1) there is a compelling need and 2) Stanford expertise and recent/current research sets us up for success.

Study area and our external partners: We have selected two study areas - the Kaweah subbasin and the region where the Tuolumne River enters the San Joaquin River. Work in the Kaweah subbasin will be a continued partnership with the GSAs in that area. Of great interest to the GSAs is understanding where groundwater pumping is having an impact on streamflow given their need to define sustainable management criteria. The second study area is where Knight has been working for the past two years with the NGO River Partners, developing the use of geophysical measurement systems to study groundwater recharge at restored floodplains. River Partners will work with us in the selection of field sites and will make available data acquired through their studies of the two rivers. The interests of River Partners include the way in which surface water-groundwater connectivity impacts both the groundwater recharge and ecosystem health. As such, the research we are conducting is seen as developing new data sources they can use in their field studies.

Obj. 3 Task 1 (Knight): The need we address in this task is to advance the ability to represent river-sourced recharge in a water budget and in groundwater management plans. We will build on recently completed research to develop a robust methodology that would allow end-users to combine an analysis of satellite InSAR data and AEM data to map out locations in the SJVW where river-sourced recharge of the lower aquifers is taking place. We presume that once we identify recharge pathways, the occurrence of recharge along these pathways will depend on available river/stream water in any given year. Year 1 Milestone: Develop robust workflow for the combined analysis of InSAR and AEM data to identify locations in the SJVW where river-sourced recharge is occurring. Year 2 Milestone: Apply methodology to identify locations in SJVW where river-sourced recharge occurred in the wet years of

2017 and 2023. Year 3 Deliverable: Public release of maps showing results from Year 2; presented in publication. All code for methodology available on GitHub.

Obj 3 Task 2 (Solgaard): Our goal is to develop low-cost (~$500) stream gauges that can be deployed as needed along rivers/streams to provide the accurate measurements needed to determine - and then address - the impact of groundwater pumping on streamflow. The stream gauge we are developing is based on laser doppler velocimetry. Using this technique, we have demonstrated velocity resolution better than 0.001 m/s in the laboratory. During the first two years of the program, with funding from other sources, we will develop and refine this stream gauge to enable measurements of the full profile of water velocities in laboratory settings. In Years 3 through 5 of the project we will develop a fully functional, field-deployable instrument. Year 3 Milestone: Design, fabricate and test first field-deployable stream gauge. Year 4 Milestone: Calibrate stream gauge by comparison to well-established (and expensive) stream gauges. Use lessons learned from calibration to refine the field deployable stream gauge. Year 5 Milestone: Design and fabricate stream gauge that is inexpensive, robust and simple to deploy and operate.

Objective 4. Avoiding groundwater quality degradation using automated sensor networks.

Current practices to measure/monitor water quality involve the manual sampling of monitoring wells and water analyses conducted separately at commercial labs. The cost and sampling frequency are such that it is close to impossible to detect early changes in water quality, thus limiting the ability to track changes in water quality early in the recharge process. Further, existing commercial sensor technologies are poorly suited for monitoring changes in water quality due to, and during, recharge. Their high cost, intensive maintenance requirements, and requirement for continuous power supply limit scalability. Moreover, the low concentrations of contaminants—particularly nitrate at tens of ppm, arsenic and uranium in the ppb range, demand highly selective and sensitive detection methods, further driving up the cost of current solutions. In this objective, we will develop a low-cost, autonomous water quality sensing network tailored for high-resolution, distributed monitoring of infiltrating water chemistry that can be deployed across the San Joaquin watershed.

This effort draws on the combined expertise of the Fendorf lab (geogenic soil contaminants and aqueous chemistry), the Tarpeh lab (advanced electrochemical separation of nitrogen compounds), and the Kapetanovic lab (novel strategies for low-power, autonomous sensor systems). Together, we will enable continuous, low-maintenance detection of chemical conditions that may jeopardize groundwater quality. The resulting data will provide unprecedented spatiotemporal resolution of infiltrating water chemistry, allowing recharge management to avoid groundwater quality issues.

Study area and our external partners: We will deploy our sensing system within newly constructed groundwater recharge basins of the Madera Irrigation District (MID). Multi-level monitoring wells are being installed by existing MID partners, providing an ideal deployment opportunity. To support project-level integration, we will also be deploying the sensing system in the Kaweah subbasin, partnering with the three Groundwater Sustainability Agencies in the subbasin.

Obj. 4 Task 1 (Tarpeh, Fendorf): Develop sensing mechanisms for simultaneous detection of nitrate, arsenic, and uranium. We will develop a first-of-its-kind, multiplexed sensor capable of simultaneously detecting nitrate and key proxy analytes—pH, calcium, and bicarbonate ions—that induce arsenic and uranium release into groundwater. Nitrate detection is relatively mature; efforts here will focus on device optimization and testing. In contrast, proxy-based detection of arsenic and uranium is less developed. Work in this area will prioritize scoping viable detection mechanisms and establishing their analytical performance.

Task 1a (Tarpeh)**:** Develop a low-cost, continuous, and low-maintenance nitrate sensor. We leverage Tarpeh lab's electrochemical innovations for separation and concentration of dilute nitrate in environmental samples to develop the nitrate sensor. Specifically, we first electrochemically reduce nitrate to ammonium, and then perform electrodialysis to selectively concentrate the converted ammonium for measurement. This allows us to use a cost-effective and energy-efficient capacitive sensor to measure the amount of ammonium. We will develop models to quantitatively relate

ammonium concentrations to original nitrate levels, incorporating environmental variables such as temperature, pH, and salinity to ensure robust performance across diverse groundwater conditions. **Task 1b** (Tarpeh, Fendorf): Scope detection mechanism for reliable measurement of factors that trigger arsenic and (pH & DO) uranium (pH, Ca2+, bicarbonate) release to groundwater. We will scope electrochemical and chemical detection mechanisms and reaction designs for multiplexed, continuous measurement of the proxy variables that reveal whether arsenic and uranium concentrations will become problematic. This allows us to reveal conditions that will result in increased arsenic and uranium concentrations and to circumvent both the difficulty of directly detecting dilute arsenic and uranium compounds; rather, we leverage the more abundant environmental markers (such as calcium and bicarbonate ions) to measure the target compounds. We will use common electrochemical reactions (such as oxygen reduction reaction) that are affected by the concentration of the proxy variables, and build models to correlate the characteristics of the reactions (such as onset potential and reaction kinetics) with the concentrations of the proxy variables.

Obj. 4 Task 2 (Kapetanovic): Develop power and data management strategies**.** We will integrate low-power readout circuitry and connectivity solutions to support the sensing mechanisms described in Task 1. The electrochemical sensors require a capacitive readout, which we will implement using the TI FDC2212 and an STM32 microcontroller. To wirelessly transmit data, we will incorporate both IoT satellite and LoRa connectivity solutions to support a diverse set of deployment scenarios. Long-term operation will be enabled by developing techniques to support energy-aware sensing and data transmission. For example, aggregating data to minimize the number of data transmissions over time and incorporating energy-harvesting techniques (e.g., solar). We will develop a custom printed circuit board to support the aforementioned hardware features. It is estimated that the overall power consumption of the readout circuitry (including data transmission) will be less than 150 mA during active mode. We propose having a single readout board supporting several sensors placed at depths ranging from 10-100ft.

To support a large-scale sensor network, we will implement a mesh network topology. All sensor nodes will communicate with one another using LoRa, and designated nodes will act as gateways to transmit data to the cloud using satellite connectivity (e.g., Iridium, Globestar). Year 1 Milestone: Develop prototype of hardware platform (readout circuitry integrated with wireless connectivity solutions and sensors) and evaluate performance in a controlled environment. Year 2 Milestone: Finalize hardware design and develop custom printed circuit board for field testing.

Obj. 4 Task 3 (Fendorf, Tarpeh, Kapetanovic)**:** Develop and deploy field devices for distributed sensing of contaminants. We will integrate the technologies developed in Task 1 and 2 and build low-cost (<$100 per sensor), deployable field prototypes for distributed sensing of water quality. We will first characterize the sensor's field performance including measurement accuracy, power consumption, and range of data transmission. We will deploy the sensors at MID, and we will work with partners to train local personnels and deploy the sensors across groundwater wells. Year 1 Milestone: Develop enclosures for hardware from Task 2 and evaluate durability. Visit deployment sites to inform design decisions. Year 2 Milestone: Deploy for end-to-end system for long-term data collection.

Objective 4 Milestones: Year 1 Milestone: Field-ready prototypes of nitrate sensors. Year 2 Milestone: Field-ready prototypes of sensors for sentries of arsenic and uranium. Year 3 Milestone: Low-power, low-maintenance water quality monitoring network consisting of sensors measuring nitrate and sentries for arsenic and uranium in selected sampling points. Year 4 Milestone: dataset containing one year of water quality data with at least 1 data point per sampling site per day. Deliverable: paper/report detailing dataset and sensor development. Year 5 Milestone: functional model to uncover the water quality dynamics and explore methods to fuse our point data with remote sensing data to enable high-resolution, high-accuracy remote sensing of water quality with applicability beyond the San Joaquin Valley watershed. Year 5 Deliverable: interactive tool for stakeholders to leverage water quality sensing data.

Concluding Comments on Project Integration

The primary platform for project integration is the digital twin, being developed under Objective 1 over the five years of the project. The digital twin will be used to integrate all data sources representing key variables related to water quantity and water quality. Through this integration we will develop an understanding of connections within the human-ecologic-hydrologic system and the predictive capacity required to support sustainable freshwater management. The digital twin will also form the basis for the development of a decision-support dashboard that will be developed with extensive consultation with external partners to ensure that what we develop meets water management needs, at the local and state levels.

Central to this project is the recognized need, and the opportunity at Stanford through this integrative project, to advance the measurements made of the hydrologic system. We will develop new forms of sensors and/or new forms of data interpretation and integration in the Kaweah subbasin. We will continually update the digital twin as new data become available, allowing us to assess the value-added in terms of supporting freshwater management. Our work will provide the research, the development, and the field-testing required to introduce new forms of measurement that could be adopted worldwide for monitoring hydrologic variables. We envision this project as establishing taking the pulse of a watershed, through the deployment and integration of innovative forms of sensing, as the foundation for sustainable, adaptive, freshwater management.

A Note on Project Management

Open Science practices will be adopted throughout the project, working to put practices in place that support collaborative work among researchers at Stanford and with our outside partners. There are many researchers, outside Stanford, who have expressed interest in supporting this effort and contributing, unfunded, to complement the proposed research activities. Initial work, to facilitate collaboration, will involve developing a shared data platform to hold all relevant existing data and all project-generated data. A priority will be the development of outward-facing products to reach end-users at state and local levels. We will be working with Zach Chandler, Director, Open Scholarship Strategy, Center for Open and Reproducible Science, Stanford.

PART 3. TEAM

List of PI-eligible faculty and research staff and postdocs who will contribute to the project.

Rosemary Knight, Lead PI, Stanford Faculty
Greg Beroza, PI, Stanford Faculty
Ettore Biondi, PI, Stanford Faculty
Bill Ellsworth, PI, Stanford Faculty, Emeritus
Scott Fendorf, PI, Stanford Faculty
Zerina Kapetanovic, PI, Stanford Faculty
Ching-Yao Lai, PI, Stanford Faculty
Olav Solgaard, PI, Stanford Faculty
William Tarpeh, PI, Stanford Faculty
Daniel Tartakovsky, PI, Stanford Faculty
Howard Zebker, PI, Stanford Faculty
Meredith Goebel, Research Scientist
Joe Janssen, Postdoctoral Fellow (funded through Thompson Postdoctoral Fellowship, Geophysics Dept.)
Zach Chandler, Director, Open Scholarship Strategy, Center for Open and Reproducible Science, Stanford (funded at ~18% FTE from discretionary funds associated with this project)
Chris Castillo, Director, Shared Field Instrumentation Facility (funded through Geophysics Dept. and SDSS)

In addition to the above Stanford personnel, Sasha McLarty, Associate Professor at Washington State University, will be part of the Research Team, leading Objective 2 Task 4. McLarty will be funded by the Geophysics Department as Visiting Faculty at Stanford in Year 1 of the project, and will continue her collaboration remotely, with occasional visits, in the last four years.

List of external partners.

We list below our external partners. We will hold quarterly zoom meetings with all partners, with additional meetings as needed. Once a year we will host a meeting at Stanford. Once a year Stanford researchers will travel to meet with partners and community members at a location in the Kaweah subbasin. Twice a year Stanford researchers will travel to meet with partners in Sacramento. Funding for all meetings is included in the project budget.

External Partner: Office of Data and Innovation

With their focus on enabling and championing innovative methods, and the high level of interest in ensuring research efforts translate into operations, this office is the ideal partner as we develop the data-driven analytical framework for freshwater management. Working with us directly will be Monica Bobra, Principal Data Scientist, State of California

External Partner: California Department of Water Resources (DWR)

Discussions are underway with DWR to determine the specific role they will play in the project, and who will be the named contacts for the project.

External Partners: Groundwater Sustainability Agencies (GSAs) in the Kaweah Subbasin.

The following three committed external partners lead the Groundwater Sustainability Agencies (GSAs) in the Kaweah Subbasin.

Aaron Fukuda - General Manager Tulare Irrigation District, Interim General Manager Mid-Kaweah Groundwater Sustainability Agency

Mark Larsen - General Manager, Greater Kaweah Groundwater Sustainability Agency

Michael Hagman – Executive Director, East Kaweah Groundwater Sustainability Agency

External Partners: Consultants to Groundwater Sustainability Agencies (GSAs) in the Kaweah Subbasin.

The following four committed external partners are consultants working with the GSAs in the Kaweah Subbasin:

Ben Lewis, Associate Hydrogeologist, Thomas Harder and Co., Groundwater Consulting

Kaitlin Palys, Water Resources Scientist, INTERA Incorporated

Abhishek Singh, President – Water Resources and Supply, INTERA Incorporated

Matt Klinchuch, Engineer, Provost & Pritchard Consulting Group

Jim Van de Water, Principal Hydrogeologist, Thomas Harder and Co., Groundwater Consulting

External Partner: Madera Irrigation District

Our lead collaborators within MID are:

Thomas Greci, General Manager

Dina Nolan, Assistant General Manager

External Partner: Julie Rentner, President, River Partners

With her depth of knowledge and understanding of the challenges to ecosystem conservation and restoration in the Central Valley, Julie Rentner brings to the project a perspective that will ensure the needs of natural ecosystems will also benefit from advancing our ability to better measure key variables related to water quantity and water quality in the San Joaquin Valley.

REFERENCES

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., and Kirchner, J. W., (2021). Widespread potential loss of streamflow into underlying aquifers across the USA. *Nature*, *591*(7850), 391–395. https://doi.org/10.1038/s41586-021-03311-x

Lees, M. and Knight, R., (2023). Integrating shallow head measurements and InSAR data to quantify groundwater-storage change in San Joaquin Valley, California, *Hydrogeology Journal*, 31:2041-2060.

Mao, S., Ellsworth, W.L., Zheng, Y. and Beroza, G.C., (2025). Depth-dependent seismic sensing of groundwater recovery from the atmospheric-river storms of 2023. *Science*, 387(6735), pp.758-763.

Melton, F.S., J. Huntington, R. Grimm, J. Herring, M. Hall, D. Rollison, T. Erickson et al., (2022). OpenET: Filling a Critical Data Gap in Water Management for the Western United States. *Journal of the American Water Resources Association* 58 (6): 971–994. https://doi.org/10.1111/1752-1688.12956.

Michaelides, R., Zebker, H., and Zheng, Y., (2019). An Algorithm for Estimating and Correcting Decorrelation Phase From InSAR Data Using Closure Phase Triplets. *IEEE Transactions on Geoscience and Remote Sensing*, vol. 57, no. 12, pp. 10390-10397. doi: 10.1109/TGRS.2019.2934362.

Neely, W., Borsa, A., Burney, J., Levy, M., Silverii, F., and Sneed, M. (2021), Characterization of Groundwater Recharge and Flow in California's San Joaquin Valley From InSAR-Observed Surface Deformation. *Water Resources Research*, *57*(4), e2020WR028451. https://doi.org/10.1029/2020WR028451

Neely, W., Knight, R., Kang, S., Goebel, M., (2024), Exploring the InSAR signal associated with river-sourced recharge in California's San Joaquin Valley, *Environmental Research Letters*, 19 074072DOI 10.1088/1748-9326/ad5855

Richey, A., Thomas, B., Lo, M.-H., Reager, J. T., Famiglietti, J., Voss, K., Swenson, S., and Rodell M., (2015), Quantifying renewable groundwater stress with GRACE, *Water Resource Research*, 51, 5217–5238, doi:10.1002/2015WR017349.

Rodell, M., Famiglietti, J.S., Wiese, D.N. et al., (2018). Emerging trends in global freshwater availability. *Nature* 557, 651–659. https://doi.org/10.1038/s41586-018-0123-1

Rodell, M., Velicogna, I. and Famiglietti, J., (2009). Satellite-based estimates of groundwater depletion in India. *Nature* 460, 999–1002. https://doi.org/10.1038/nature08238

Shen, Z., Yang, Y., Fu, X., Adams, K.H., Biondi, E. and Zhan, Z., (2024). Fiber-optic seismic sensing of vadose zone soil moisture dynamics. *Nature Communications*, 15(1), p.6432.

Tribaldos, V. R., and Ajo-Franklin, J. B. (2021). Aquifer monitoring using ambient seismic noise recorded with distributed acoustic sensing (DAS) deployed on dark fiber. *Journal of Geophysical Research: Solid Earth*, 126, e2020JB021004. https://doi.org/10.1029/2020JB021004

Visser, A., Moran, J. E., Singleton, M. J., & Esser, B. K. (2018). Importance of river water recharge to the San Joaquin Valley groundwater system. *Hydrological Processes*, *32*(9), 1202–1213. https://doi.org/10.1002/hyp.11468

Wig, E., Michaelides, R., and Zebker, H., (2024). Fine-Resolution Measurement of Soil Moisture From Cumulative InSAR Closure Phase . *IEEE Transactions on Geoscience and Remote Sensing*, vol. 62, pp. 1-15, 2024, Art no. 5212315, doi: 10.1109/TGRS.2024.3399069.