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California Water Institute

Monitoring Groundwater Recharge Using Gravimetric Survey Technology

A Project White Paper

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Research Team

Mike Berber

Dr. Mike Berber is a faculty member in the Department of Civil and Geomatics Engineering at California State University, Fresno. His expertise is in Geodesy, Global Navigation and Satellite System, Geodetic Measurement Techniques and Hydrographic Surveying.

Currently, Dr. Berber has published three books/monographs, around fifty journal papers and many conference proceedings. He has worked as a referee for several journals and serves on the Editorial Board of Survey Review academic journal. In terms of research, Dr. Berber has worked on a range of projects from “Greenhouse Gas Emissions from Peat Soils” to “Monitoring the Impacts of Climate Change on Coral Reefs” to “Determining Absolute Sea Level Change for Florida.” He has also delivered several bathymetric projects.

Cordie Qualle

Cordie Qualle began his professional engineering career in 1974 at the Fresno Metropolitan Flood Control District. In 1978, he entered private consulting engineering with Lars Andersen & Associates and later with Blair, Church & Flynn Consulting Engineers beginning in 1981 and retiring from there in 2017. Mr. Qualle provided engineering management for many projects that directly affected the Fresno/Clovis metropolitan area in flood control, drainage, and wastewater management.

Following his almost 40 years of experience as an engineering consultant, Mr. Qualle became a lecturer at California State University, Fresno in the Civil and Geomatics Engineering Department of the Lyles College of Engineering.

Mr. Qualle obtained a Bachelor of Science in Engineering degree from California State University, Fresno, and a Masters in Cilil Engineering from Norwich University. He obtained his Professional Engineering license in Civil Engineering in 1977.

Problem Statement

It has become prevalent knowledge that water sustainability is a major conservation problem that needs a solution for future generations. The necessity to develop sustainable groundwater supplies was brought into sharp focus during the 2012 through 2016 drought that occurred in the state of California. The loss of surface water supplies during this drought forced farmers and urban systems to compensate for that loss with an increased use of groundwater. The prolonged use of groundwater led to dramatic decreases in groundwater quantity, as evidenced by significant drops in the water table, and in water quality. California and the Central Valley's groundwater basins have never recovered from that drought. Bringing California's groundwater table back to a level and quality that is accessible to all who rely on groundwater as their water supply is a goal of California's landmark legislation, the Sustainable Groundwater Management Act (SGMA). A common solution the decrease in groundwater storage proposed by the Groundwater Management Plans required by SGMA is to develop and implement groundwater recharge programs and monitor their ability to effect positive change in the groundwater storage as evidenced by first stabilizing the groundwater table and second by causing it to rise.

Monitoring the elevation of the groundwater table is the primary standard for determining the success of the Groundwater Sustainability Plan developed by the GSAs to stabilize groundwater conditions within their boundaries. Typically, this is accomplished by measuring the depth to groundwater from the well casing at discreet well sites within the GSA. While this provides a picture of the groundwater's status, it may not be complete or in locations that provide a comprehensive picture of the groundwater within the GSA.

This project proposes to address the problem of monitoring groundwater elevations within the GSAs with a newer technology, gravimetric surveys, which uses a portable gravimeter and Global Positioning System (GPS) survey technology to determine the elevation of the groundwater table within groundwater subbasins.

Technical Background

Drought has reduced the availability of surface water to meet the irrigation demands of the San Joaquin Valley, which has caused farmers in the Valley to rely on pumping from groundwater wells to meet their irrigation needs. Overdraft of the groundwater table resulting from the pumping has caused undesirable effects such as lowered groundwater tables, subsidence, and, in coastal areas, seawater intrusion. The majority of the San Joaquin Valley lies in critically over-drafted groundwater basins as defined by the California Department of Water Resources. The state of California responded in 2014 to the overdraft condition by passing the Sustainable Groundwater Management Act (SGMA). SGMA requires that critically overdrafted groundwater basins create Groundwater Sustainability Agencies (GSAs) to manage groundwater on a local basis by following the requirements of the law and the State Water

Resources Control Board regulations. The act requires that each GSA prepare and adopt a Groundwater Sustainability Plan (GSP). The GSP must be approved by the California Department of Water Resources. Its primary goal is to reduce the overdraft and balance the use of groundwater with recharge such that a sustainable groundwater elevation is achieved with the groundwater basin (2014).

It is estimated that about 750,000 acres of farmland will become fallow land as a solution to decrease the amount of groundwater needed to achieve sustainable groundwater levels (Ellen Hanak 2019). One technology that groundwater management plans are considering, along with land fallowing, is the implementation of groundwater recharge systems at the farm level. The optimization of agricultural land for the use of recharging groundwater aquifers has been researched as FloodMAR, the flooding of farmland with excess floodwater, and has been shown to be a viable recharge technology. Two drawbacks to FloodMAR are the potential damage to permanent crops from standing water, and the potential to leach legacy nutrients and chemicals from the root zone into the groundwater. Another recharge technology that utilizes primarily farmland but can be used in large open areas such as parks, is Subsurface Artificial Groundwater Recharge (SAGR). This approach to groundwater recharge is a series of underground perforated pipes placed below the root zone that allow recharge water to percolate into the groundwater table. The technology can use both relatively clean canal water, when it is available, and excess floodwater. This technology can have many benefits. Among them are the ability to continue to farm the land while recharging, damage to permanent crops from standing water is eliminated as the system is located below the root zone, and the possibility of leaching legacy contaminants is eliminated.

The ability to accurately measure the positive effects of groundwater recharge, e.g., the rise in the groundwater table is a vital component of any recharge program. Groundwater levels can be measured in several ways. The primary method is to measure the groundwater level in existing monitoring wells, which are in discreet locations, expensive to construct, maintain, and measure on an individual basis, and are not always located in the best locations to effectively illustrate the groundwater table within a GSA. Gravimetric surveys can measure groundwater levels quickly without the need to construct and maintain wells. Gravimetric surveys use a gravity meter that can be easily moved from location to location to measure the earth’s gravitational field at specific locations. Gravimetric surveys have been used for numerous applications in engineering and environmental studies, including locating subsurface voids, karst features, underground stream valleys, and mapping water table levels and volume (Heiskanen and Vening Meinesz, 1958; Torge, 1989; Telford et al., 1995; Hofmann-Wellenhof and Moritz, 2006). The technology utilizes the differences in the acceleration of gravity caused by different mass densities within the soil matrix, which produce measurable variations in the gravitational field. These variations can then be interpreted by a variety of analytical and computer software methods to determine the depth, geometry, and density that causes the gravity field variations (Mickus, 2004). The change in the density of soils above and below the water table provides the information needed by the gravimetric survey to determine the groundwater table within 500 mm (approximately 20 inches).

Technical Challenges

There are two technical challenges facing the implementation of gravimetric surveys. Both challenges involve the accurate interpretation of the data gathered by the gravimetric survey. The technology utilizes the differences in the acceleration of gravity caused by different mass densities within the soil matrix, which produce measurable variations in the gravitational field. These variations can then be interpreted by a variety of analytical and computer software methods to determine the depth, geometry, and density that cause the gravity acceleration variations (Mickus, 2004). For instance, the change in the density of soils above and below the water table provides the information needed by the gravimetric survey to accurately determine the groundwater table. The accurate interpretation of the differences in the acceleration of gravity caused by the different soils and the presence of groundwater is critical to the success of the use of this technology. The technical challenge is to calibrate the gravimetric information utilizing control situations to interpret the changes in acceleration and reference that information in the analytical software to produce useable mapping of the groundwater levels within the GSA. A typical control situation is to measure the gravimetric accelerations at monitoring wells where the stratigraphy and depth to groundwater is known. The correlation of the gravimetric survey output with the known stratigraphy and groundwater elevation allows the calibration of the output which can then be used at other locations with confidence. The correlation process will involve multiple observations at multiple existing groundwater monitoring well sites and the interpretation of the resulting data using GeoSoft software to develop the correlation constants which will allow for the correct interpretation of the gravimetric survey output data in a field application.

The second challenge follows once the calibration process is completed, which is the specific process of performing the first gravimetric survey of a groundwater subbasin, interpreting the data output from the survey, and mapping the groundwater elevations within the subbasin. This process will involve the selection of a groundwater subbasin, the mapping out of the proposed gravimetric survey locations within the subbasin and conducting the survey. Conducting the gravimetric survey will include GPS at each location to provide precise vertical and horizontal positioning information for it. Horizontal positioning will be provided in latitude and longitude, or state plane coordinates in NAD83(2011) Epoch2010. Vertical positioning will be provided in NAVD88 datum.

Scientific Approach - *Gravimentric Survey of Groundwater*

In this study, gravity meter surveys will measure the change in gravity resulting from the change in total water stored in an aquifer. Pool (2008) stated that gravity-change data are useful for estimating aquifer-storage change, for estimating recharge in groundwater systems, and for estimating the aquifer storage coefficient. Prior to gravity surveys, groundwater monitoring wells were drilled to monitor the water-table level. Monitoring wells are expensive to drill, require permitting, permission or easements to construct and access, and maintenance to ensure they are safe. A well's water level does not translate exactly to groundwater storage because the properties of the soil subsurface and the aquifer composition must be known using pumping tests. Gravimetric surveys are completely noninvasive and have none of the permitting requirements or potential for contamination that exist when drilling groundwater monitoring wells.

In this project a relative gravimeter (for example, a CG–6 AutoGrav gravity meter manufactured by Scintrex) (Scintrex Corporation 2018) will be used to measure the distance from the ground surface to the groundwater table. To do so, a grid system will be established at the project site and will be surveyed regularly with the CG6 relative gravity instrument. Using the GeoSoft software, collected data will be analyzed and water table changes will be determined; for example, every month, every season, etc. The survey points (stations) in the grid system will be connected to a base station (the base station may be a relative or absolute-gravity station) and will be measured to create a closed loop. This loop will start with the base station and will be repeated in the same order multiple times during a field survey to ensure measurement repeatability. Each grid point will be occupied for 10 minutes to ensure consistency, five minutes to stabilize the gravity meter and five more minutes to take the measurement. These occupation times will ensure consistency of gravity measurements and minimize measurement errors. Then these measurements will be averaged to obtain the tide-corrected gravity value for a given grid point, which will be later processed to remove instrument drift. Care will be taken while moving the gravity meter from station to station. Using this approach, we expect to determine groundwater-storage volume with high accuracy. Gehman et al. (2009) stated that water level changes predicted from the gravity data agree on average to within ±0.45 m. As such, we expect to determine water level changes in our project site with approximately 0.5 m precision.

Deliverables

The purpose of this project is to use gravimetric surveys to collect data on the changes in the groundwater table within a groundwater subbasin. The deliverables for this project will include:

- Correlation Report
  - Will include an Abstract, Introduction, a Literature Review, a Description of the Procedure, a Review and Analysis of the Gravimetric Survey Results, a Discussion of the Results, and the Conclusions and Recommendations resulting from the correlation.

- Year Two Report
  - Will include an Executive Summary, an Introduction, a Description of the Gravimetric Survey, a Description of the Subbasin, a Description of the Survey Process, a Review and Analysis of the Gravimetric Survey Results, a Discussion of the Results, a Discussion of the Refinement of the Survey and Analysis, and the Conclusions and Recommendation resulting from the survey.

- Year Three Report
  - Will include an Executive Summary, an Introduction, a Description of the Gravimetric Survey, a Description of the Subbasin, a Description of the Survey Process, a Review and Analysis of the Gravimetric Survey Results, a Discussion of the Results, a Discussion of the Refinement of the Survey and Analysis, and the Conclusions and Recommendation resulting from the survey.

Schedule

This is a three-year project to correlate gravimetric survey data, conduct a first gravimetric survey and analyze the data, and conduct a second gravimetric survey to confirm the analysis of the first survey. The proposed three-year schedule is displayed in the following table.

Year 1, Year 2, Year 3			
Year	**Process**	**Gravimetric Survey**	**Analysis**
1 Approximately 6 months of working time	Correlation Process	Select monitoring wells. Obtain monitoring well groundwater table elevation and stratigraphy. Conduct gravimetric surveys.	Analyze gravimetric survey output to correlate gravimetric survey groundwater table elevation with actual measured elevation.
2 Approximately 6 months of working time	First Gravimetric Survey	Select groundwater subbasin. Determine gravimetric survey locations, including blind test locations at monitoring wells. Obtain blind test location monitoring well groundwater table elevations and stratigraphy. Conduct gravimetric survey.	Analyze gravimetric and GPS survey information. Utilize correlation analysis to determine groundwater table elevations. Map groundwater table elevations. Compare mapped groundwater table elevations at blind test monitoring wells and refine analysis if necessary.

Year 1, Year 2, Year 3			
3 Approximately 6 months of working time	Second Gravimetric Survey	Select groundwater subbasin Determine gravimetric survey locations, including blind test locations at monitoring wells Obtain blind test location monitoring well groundwater table elevations and stratigraphy. Conduct gravimetric survey.	Analyze gravimetric and GPS survey information. Utilize correlation analysis to determine groundwater table elevations. Map groundwater table elevations Compare mapped groundwater table elevations at blind test monitoring wells and refine analysis if necessary.

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