SEPTEMBER 2015

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

Sponsored by the Delta Science Program and the UC Davis John Muir Institute of the Environment

ESSAY

Moving from Aquifer Stress to Sustainable Management with Remote Sensing and Local Knowledge

Alexandra S. Richey[1]

Volume 13, Issue 3 | Article 3
doi: *http://dx.doi.org/10.15447/sfews.v13iss3art3*

INTRODUCTION

Groundwater is a hidden resource, out of sight and out of mind. We rely on it in our times of need, and assume it will always be available to buffer our surface water supplies. Unlike the iconic rings of a drying reservoir, the increasing pressure on groundwater is subtle and slow moving. The signs of increased stress manifest in millimeters of subsidence or in the increased pumping and well costs farmers must bear. There now exists a clear need to improve how groundwater in California is managed to ensure long-term availability. Management of common pool resources like groundwater is most effective when built on transparent information about stocks and flows in the system (Schlager et al. 1994; Dietz et al. 2003). Such information is lacking on a large scale in California, which, combined with the historical water rights granted to early California settlers, presents a uniquely complex natural system for management.

Groundwater was exempted from California state regulation by the Water Commission Act of 1914, protecting private use of groundwater under historical property rights. A century after it was first exempted, California's current drought has advanced the long-needed conversation regarding management of the state's groundwater, culminating in the Sustainable Groundwater Management Act of 2014. The groundwork for this legislation was initiated in 2009 with the California Statewide Groundwater Elevation Monitoring (CASGEM) Program. This program established guidelines to prioritize California's alluvial groundwater basins and sub-basins, and assist in allocating limited resources for implementation of the CASGEM program. The 2014 Sustainable Groundwater Management Act stated that medium- and high-priority basins identified by CASGEM must establish groundwater plans by 2020, and achieve groundwater sustainability by 2040.

---

1 Department of Civil and
Environmental Engineering,
Washington State University
Pullman, WA 99164 USA
sasha.richey@wsu.edu

Though the Sustainable Groundwater Management Act called for sustainability by 2040, the meaning of sustainability for this application was not quantitatively defined. Identifying the sustainable capacity of an aquifer requires an understanding of the dynamic links between pumping for human consumption and the natural response of a groundwater system. The definition of a sustainable use rate for groundwater, or a "safe yield," is an elusive and oft-debated topic in groundwater hydrology (e.g., Bredehoeft 1997; Sophocleous 1997; Alley et al. 1999), despite being a key component for determining the stress placed upon an aquifer and what "sustainability" means for each system.

The natural response of an aquifer to pumping is the establishment of a new equilibrium. A new balance can be reached with a reduced outflow to streams (baseflow) and a higher rate of replenishment through recharge. The combined response of decreased baseflow and increased recharge is called "capture." If the rate of capture can't balance the effect of pumping then there is a loss of water in storage (Theis 1940). It may take hundreds of years for an aquifer to reach a new equilibrium assuming ideal conditions of constant pumping and steady recharge (Bredehoeft and Young 1970). California's natural groundwater systems alone may not be able to reach a new equilibrium under the combined weight of both increased pumping and reduced recharge brought on by drought in a majority of the state's agricultural region. Only by monitoring withdrawals, capture, and depletion can physically-based sustainability targets be set for an aquifer system.

Traditionally, knowledge of groundwater systems has been thought of as a "bottom up" study. Information from individual well measurements and isolated soil samples are interpolated to form a bigger picture of the surrounding aquifer. Large gaps in measurement locations are filled by assuming aquifer properties are transferable between regions with similar characteristics, such as soil type. Unfortunately, groundwater is heterogeneous, and conditions measured at one point in an aquifer may have little bearing elsewhere in the same system. A large number of reliable observations made throughout the entire aquifer system and over a long period of time are necessary to understand the response of a groundwater system to both natural variations, such as drought, and human use. The CASGEM program provides only the start of what is necessary to characterize groundwater dynamics across California where groundwater data is limited.

REMOTE SENSING FOR GROUNDWATER MONITORING

Observations from the Gravity Recovery and Climate Experiment (GRACE) satellite mission provide a unique perspective to identify broad sustainability goals under the Sustainable Groundwater Management Act. GRACE was launched as a joint endeavor between the National Aeronautics and Space Administration in the United States and the *Deutsche Forschungsanstalt für Luft und Raumfahrt* in Germany. The mission's original purpose was to better map Earth's gravity field but it has since been used to evaluate large regional water budgets. Though not a substitute for a robust network of monitored groundwater wells, the GRACE satellite mission can provide a glimpse of the big-picture state of large aquifers like the Central Valley Aquifer System. The mission's 13-year history of measuring the combination of human- and naturally-induced total terrestrial water storage changes (as the sum of changes in snow, soil moisture, groundwater, and surface water) can begin to quantify integrated human and natural effects on large aquifers.

Changes to groundwater storage can be isolated from the total water storage changes from GRACE by subtracting out changes in surface water, snow, and soil moisture using observations or model estimates of changes in these variables. These estimates of groundwater storage change provide the first-ever look at large regional aquifer system dynamics. Their accuracy relies on the strength of the independent measures of snow, soil moisture, and surface water, which highlights the importance of maintaining and advancing monitoring systems for all components of the water cycle. In California, for example, Famiglietti et al. (2011]) used observation-driven records of snow water equivalent from the National Operational Hydrologic Remote Sensing Center, public records of changes in surface water from the state's 20 largest reservoirs from the California Department of Water Resources, and modeled estimates of soil moisture changes, since soil moisture is rarely measured on the ground. In recent stress studies described below, such observation-based data was not available in all of the study aquifers and therefore only model output was used to isolate groundwater. Despite incurring additional errors, the studies provided the first globally consistent estimates of sub-surface storage change in these large aquifers.

GRACE AND GROUNDWATER STRESS

The persistent drought and lack of groundwater governance has pushed the Central Valley Aquifer System into a highly stressed state (Richey et al. 2015a). Water stress has historically been defined in a variety of ways that attempt to quantify human effects on natural supplies. Originally applied in Africa, levels of stress were determined based on the amount of renewable water available per capita (Falkenmark 1989) and evolved to be a ratio of water use to availability (Döll 2009; Wada et al. 2010). In these studies, "renewable" supplies refer to fluxes of water that are considered to be replenished annually through the water cycle, typically river runoff. The theory is that the amount of water that can be used sustainably is equivalent to the amount that can be naturally replenished. For groundwater studies, the renewable supply is debated to be between the rate of capture and the rate of recharge.

Determining the actual groundwater used, particularly in agricultural regions, is complicated and often compromised by the limited availability of data. In

California, for example, groundwater use is not monitored, and Well Completion Reports from newly drilled wells are confidential, despite containing valuable information on the state of the local aquifer. Where information on groundwater use exists globally, it is often tightly held by governments, even those with a critical reliance on trans-boundary aquifer systems. Available groundwater-use statistics are typically compiled as a single per-capita use number for an entire country, and that number is often severely outdated. For example, the most recent per capita groundwater use estimates from the United Nations for both the United States and India are from 1990.

In two recent companion studies, colleagues and I suggested that satellite remote sensing could be used as a novel tool to quantify groundwater stress (Richey et al. 2015a, 2015b). Instead of relying on outdated statistics to quantify human effect on large aquifers, these studies used estimates of sub-surface storage change from GRACE observations in a stress ratio. Stress was defined based on the rate of depletion in an aquifer, thus incorporating into aquifer stress the combined influence of drought, withdrawals, and capture. The rate of depletion was compared to the natural rate of recharge to quantify change in the aquifers from a natural state as a stress ratio. Being able to quantify stress with consistent data that did not rely on local reporting methods or data limitations has allowed for the identification of the world's most stressed aquifers. The Central Valley Aquifer System was in the top third of the most stressed systems in the world, with the fifth-highest depletion rate of the 37 study aquifers, at 8.9 ± 1.9 millimeters per year (Richey et al. 2015a). This depletion rate is more than one-third the rate of its natural replenishment; therefore, the Central Valley Aquifer System is characterized as "highly stressed." The Arabian Aquifer System was identified as the most overstressed, with a depletion rate of 9.1 ± 0.9 millimeters per year, comparable to the Central Valley, but with negligible natural replenishment.

CAN GRACE INFORM GROUNDWATER MANAGEMENT?

The CASGEM basin prioritization was conducted on 515 basins across 170,000 square kilometers of groundwater-dominated area; GRACE observations are limited to estimating changes across a single region of that same size. The disparity in scale between each of the 515 basins and the entire Central Valley Aquifer System may seem prohibitively large to inform groundwater management plans with GRACE. However, GRACE data provides a unique, consistent, and publicly available perspective to assess the sustainability of a whole system and to quantify the net volume of water conservation that must be applied across the entire Central Valley. By setting the goalposts of conservation for the whole aquifer based on GRACE-derived depletion estimates, individual basin objectives can be set using CASGEM data to distribute the conservation efforts locally. Such an approach can follow Southern California's Orange County Water District (OCWD). The OCWD closely monitors water storage changes to identify conservation and additional water supply needs to keep water table fluctuations within a range it determines to be sustainable. They use active recharge from a variety of sources, including treated stormwater and wastewater, to maintain adequate supplies in the local aquifer (Woodside and Westropp 2015).

Another way that GRACE observations can assist in monitoring and managing groundwater is by providing a basin wide constraint for land surface modeling. Historically, the representation of groundwater has been limited in the hydrology portion of land surface models, in part, because of the non-linearity of sub-surface flow and a lack of data to calibrate model parameters. Lo et al. (2010) showed GRACE observations could successfully constrain and improve model simulations of water table depth. This study used just 2 years of GRACE data to calibrate parameters, and then validated the use of these parameters with simulations from 1984 to 1998, before GRACE was launched. By using GRACE to constrain both natural and human dynamics in models, water managers could have a better idea of how policies and future droughts may alter groundwater and surface water availability.

Unfortunately, a key variable that cannot be measured from space is the total amount of water stored in our large aquifers. Although GRACE, and even monitoring wells, can keep track of what the changes are, far more measurements are required to determine the depth of the aquifers, and how much usable fresh water is actually stored in them. In 1975, a California Department of Water Resources report (CDWR 1975) stated the volume of usable fresh water to be just 10% of the total volume in storage in the Central Valley, though great uncertainty in any estimate of storage has been expressed more recently (Faunt 2009; Richey et al. 2015b). Without knowing how much usable water remains, and facing a high current sub-surface depletion rate, the Sustainable Groundwater Management Act's call for sustainability by 2040 may be too late.

CONCLUSION

We have the technological and scientific capacity to offset depletion rates with active management, improve infrastructure to optimize efficiency, and to further explore our aquifers to determine how much groundwater remains. Sustainability goals are within reach but only through a concerted effort to expand the data streams necessary to implement and monitor if plans are working. Remote sensing can assist in this goal and is most effective when combined with local knowledge and measurements.

REFERENCES

Alley WM, Reilly TE, Franke OL. 1999. Sustainability of ground-water resources: U.S. Geological Survey Circular 1186. [cited 2015 Sep 02]. Washington, D.C.: U.S. Government Printing Office. 79 p. Available from: *http://pubs.water.usgs.gov/cir1186*.

Bredehoeft JD, Young RA. 1970. The temporal allocation of ground water: a simulation approach. Water Resour Res 6(1):3-21. doi: *http://dx.doi.org/10.1029/WR006i001p00003*.

Bredehoeft JD. 1997. Safe yield and the water budget myth. Groundwater 35(6):929–929 doi: *http://dx.doi.org/10.1111/j.1745-6584.1997.tb00162.x*.

[CDWR] California Department of Water Resources. 1975. California's Ground Water. Bulletin 118-75. Sacramento (CA): State of California, Resources Agency. [cited 2015 Sep 08]; 135 p. Available from: *http://www.water.ca.gov/pubs/groundwater/bulletin_118/california's_ground_water__bulletin_118-75_/b118-1975.pdf*

Dietz T, Ostrom E, Stern PC. 2003. The struggle to govern the commons. Science 302(5652):1907–1912. doi: *http://dx.doi.org/10.1126/science.1091015*.

Döll P. 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environ Res Lett 4(3): 035006. doi: *http://dx.doi.org/10.1088/1748-9326/4/3/035006*.

Falkenmark M. 1989. The massive water scarcity now threatening Africa: why isn't it being addressed? Ambio J Hum Environ 18(2):112–118. Available from: *http://www.jstor.org/stable/4313541*.

Famiglietti JS, Lo M-H, Ho SL, Bethune J, Anderson KJ, Syed TH, Swenson SC, deLinage CR, Rodell M. 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. Geophys Res Lett 38(3):L03403. doi: *http://dx.doi.org/10.1029/2010GL046442*.

Lo M-H, Famiglietti JS, Yeh PJF, Syed TH. 2010. Improving parameter estimation and water table depth simulation in a land surface model using GRACE water storage and estimated base flow data. Water Resour Res 46(5):W05517. doi: *http://dx.doi.org/10.1029/2009WR007855*.

Richey AS, Thomas BF, Lo M-H, Reager JT, Famiglietti JS, Voss K, Swenson S, Rodell M. 2015a. Quantifying renewable groundwater stress with GRACE. Water Resour Res 51(7):5217–5238. doi: *http://dx.doi.org/10.1002/2015WR017349*.

Richey AS, Thomas BF, Lo M-H, Famiglietti JS, S. Swenson S, Rodell M. 2015b. Uncertainty in global groundwater storage estimates in a total groundwater stress framework. Water Resour Res 51(7):5198–5216. doi: *http://dx.doi.org/10.1002/2015WR017351*.

Schlager E, Blomquist W, Tang SY. 1994. Mobile flows, storage, and self-organized institutions for governing common-pool resources. Land Econ 70(3):294–317. doi: *http://dx.doi.org/10.2307/3146531*

Sophocleous M. 1997. Managing water resources systems: why "safe yield" is not sustainable. Groundwater 35(4):561–561. doi: *http://dx.doi.org/10.1111/j.1745-6584.1997.tb00116.x*

Theis CV. 1940. The source of water derived from wells: essential factors controlling the response of an aquifer to development. [cited 2015 Sep 02]. Civ Eng 10(5):277–280. Available from: *https://www.eqb.state.mn.us/sites/default/files/documents/Source_of_Water_Derived_from_Wells.pdf*

Wada Y, van Beek LPH, van Kempen CM, Reckman JWTM, Vasak S, Bierkens MFP. 2010. Global depletion of groundwater resources. Geophys Res Lett 37(2):L20402. doi: *http://dx.doi.org/10.1029/2010GL044571*.

Woodside G, Westropp M. 2015. Orange County Water District draft groundwater management plan 2015 update. Fountain Valley (CA): Orange County Water District. [cited 2015 Sept 2];334 p. Available from: *http://www.ocwd.com/Portals/0/News/ReportsPublications/2015/GWMP2015Draft_20150409.pdf*