Satellites Measure Recent Rates of Groundwater Depletion in California's Central Valley

Article *in* Geophysical Research Letters · February 2011

DOI: 10.1029/2010GL046442

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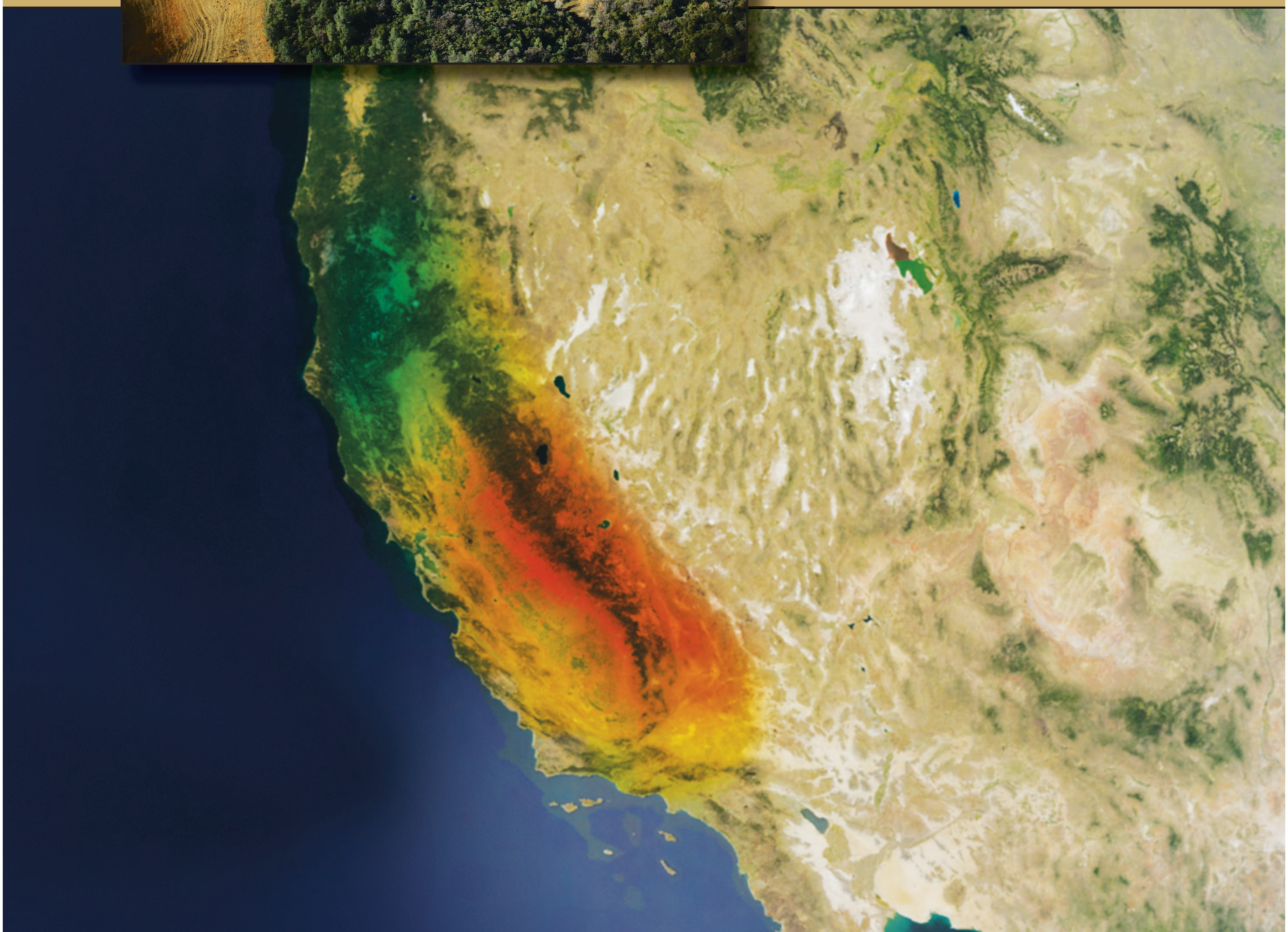
Geophysical Research Letters

16 FEBRUARY 2011
Volume 38 Number 3
AGU American Geophysical Union



Groundwater depleting rapidly in California's Central Valley
• New method to assess coral reef health • Sediment records suggest El Niño variability will continue in warmer world

Satellites measure recent rates of groundwater depletion in California's Central Valley

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Received 8 December 2010; revised 29 December 2010; accepted 4 January 2011; published 5 February 2011.

[1] In highly-productive agricultural areas such as California's Central Valley, where groundwater often supplies the bulk of the water required for irrigation, quantifying rates of groundwater depletion remains a challenge owing to a lack of monitoring infrastructure and the absence of water use reporting requirements. Here we use 78 months (October, 2003–March, 2010) of data from the Gravity Recovery and Climate Experiment satellite mission to estimate water storage changes in California's Sacramento and San Joaquin River Basins. We find that the basins are losing water at a rate of 31.0 ± 2.7 mm yr^{-1} equivalent water height, equal to a volume of 30.9 km^3 for the study period, or nearly the capacity of Lake Mead, the largest reservoir in the United States. We use additional observations and hydrological model information to determine that the majority of these losses are due to groundwater depletion in the Central Valley. Our results show that the Central Valley lost 20.4 ± 3.9 mm yr^{-1} of groundwater during the 78-month period, or 20.3 km^3 in volume. Continued groundwater depletion at this rate may well be unsustainable, with potentially dire consequences for the economic and food security of the United States. **Citation:** Famiglietti, J. S., M. Lo, S. L. Ho, J. Bethune, K. J. Anderson, T. H. Syed, S. C. Swenson, C. R. de Linage, and M. Rodell (2011), Satellites measure recent rates of groundwater depletion in California's Central Valley, *Geophys. Res. Lett.*, *38*, L03403, doi:10.1029/2010GL046442.

1. Introduction

[2] Nearly 2 billion people rely on groundwater as a primary source of drinking water and for irrigated agriculture [*Alley et al.*, 2002]. However, in many regions of the world, groundwater resources are under stress due to a number of factors, including salinization, contamination and rapid depletion [*Wada et al.*, 2010]. When coupled with the pressures of changing climate and population growth, the stresses on groundwater supplies will only increase in the decades to come.

[3] In spite of its importance to freshwater supply, groundwater resources are often poorly monitored, so that a consistent picture of their availability is difficult and sometimes impossible to construct. Moreover, water withdrawals from pumping wells are often unrestricted and unmonitored, further complicating attempts to estimate rates of groundwater consumption. In short, no comprehensive framework for monitoring the world's groundwater resources currently exists.

[4] Satellite observations of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) mission [*Tapley et al.*, 2004] may ultimately provide an important component of such a monitoring framework. Recent studies have clearly demonstrated that GRACE-derived estimates of variations of total water storage, TWS (all of the snow, ice, surface water, soil water and groundwater in region), when combined with auxiliary hydrological datasets, can provide groundwater storage change estimates of sufficient accuracy to benefit water management [*Yeh et al.*, 2006; *Zaitchik et al.*, 2008]. Most recently, the GRACE-based approach has been applied to estimate rates of groundwater depletion in northern India, a vast agricultural region that relies heavily on unmonitored groundwater withdrawals for its irrigation water supply [*Rodell et al.*, 2009; *Tiwari et al.*, 2009].

[5] In this study we use 78 months of GRACE data, from October, 2003 through March, 2010, to examine water storage changes in California's Sacramento and San Joaquin River Basins (~154,000 km^2) (Figure 1), which encompass the Central Valley (~52,000 km^2) and its underlying groundwater aquifer system. The Sacramento Basin and San Joaquin Basin, which includes the internally-draining Tulare Basin, are home to California's major mountain water source, the snowpack of the Sierra Nevada range. The Central Valley is the most productive agricultural region in the U. S., growing more than 250 different crops, or 8 percent of the food produced in the U. S. by value [*Faunt*, 2009]. It accounts for 1/6 of the country's irrigated land and supplies 1/5 of the demand for groundwater in the United States. As the second most pumped aquifer in the U. S. after the High Plains aquifer, the Central Valley offers a compelling example of the importance of groundwater as a resource, as well as the need to manage its use for sustained availability and productivity.

2. Data and Methods

[6] We use 78 months of GRACE gravity coefficients from Release-04 computed at the Center for Space Research at the University of Texas at Austin. The temporal mean was removed to compute gravity anomalies, and each field was

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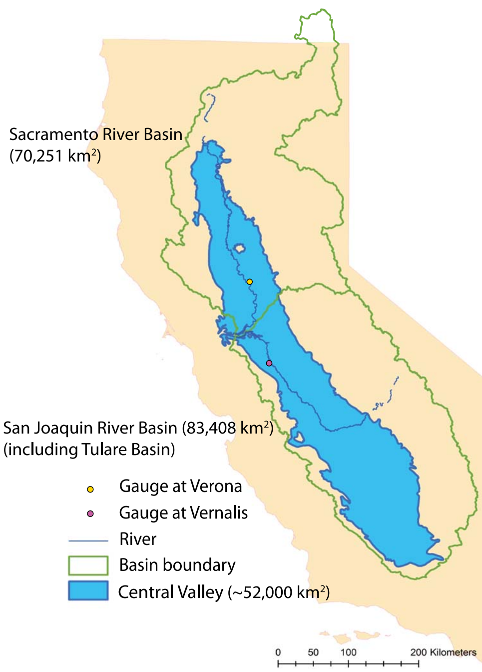

Figure 1. The Sacramento and San Joaquin river basins, including the Tulare basin and the Central Valley in California.

filtered to reduce noise [*Swenson and Wahr*, 2006] and then converted to mass in units of equivalent water height. We then used the method of averaging kernels [*Swenson and Wahr*, 2002] convolved with the GRACE coefficients to estimate the average water storage change for the combined Sacramento and San Joaquin River Basins. In order to restore power of the signal reduced by the truncation of the gravity coefficients (at degree and order 60) and filtering, the original estimate of GRACE TWS was scaled by a factor of 2.35 in order to recover an unbiased mass change estimate for the region [*Velicogna and Wahr*, 2006].

[7] Precipitation (P) data from the PRISM system [*Daly et al.*, 2008], satellite-based evapotranspiration (E) [*Tang et al.*, 2009] and U. S. Geological Survey (USGS) streamflow (Q) measurements at the Verona and Vernalis gauging stations (see Figure 1) were used in a water balance to assess the accuracy of the GRACE data (see Results).

[8] Snow, surface water and soil moisture data were required to isolate the groundwater contribution to TWS changes. Snow water equivalent (SWE) data were obtained from the National Operational Hydrologic Remote Sensing Center, and were determined from a combination of remote, field survey and *in situ* observations assimilated into an operational snow simulation model [http://www.nohrsc.noaa.gov/technology/]. Surface water storage data were compiled for the 20 largest reservoirs in the river basins, which accounted for the bulk of the observed surface water changes, and were obtained from the California Department of Water Resources [http://cdec.water.ca.gov/reservoir.html]. Soil moisture content is largely unmeasured in the United States. Consequently, we estimated soil moisture storage using the average of three different soil moisture simulations [*Rodell et al.*, 2009] for the corresponding time period taken from land surface models [*Ek et al.*, 2003; *Koster and Suarez*, 1992; *Liang et al.*, 1994] included in the NASA Global Land Data Assimilation System [*Rodell et al.*, 2004a].

[9] GRACE TWS monthly errors are 45.3 mm, which is the sum of the leakage error [*Swenson and Wahr*, 2002] and the residual error in the filtered, scaled GRACE data. Since no published error estimates for the monthly surface water and SWE were available, we assumed an error of 15 percent of the mean absolute changes in each, i.e., 4.0 mm for surface water and 7.0 mm for snow. Soil moisture error was estimated as the mean monthly standard deviation of the three model time series, or 11.9 mm. These errors combine to yield a monthly error in our groundwater estimate of 47.5 mm. Uncertainties in the GRACE TWS, SWE, and surface water trends were estimated using a least squares fit, and then propagating errors from the monthly data using the covariance matrix. We find trend errors of 2.7 mm yr^{-1}, 0.4 mm yr^{-1}, and 0.2 mm yr^{-1} for GRACE TWS, SWE, and surface water respectively. Error in the soil moisture trend was computed as the standard deviation of trends from the three models, which is 2.8 mm yr^{-1}. The total error estimate for the groundwater trend, 3.9 mm yr^{-1}, combines these values and assumes that the individual errors are uncorrelated.

3. Results

[10] To assess the accuracy of our GRACE-derived water storage estimate for the combined river basins, we compared its time derivative, *dS*/*dt*, to that determined from an independent water balance for the region ($dS/dt = P - E - Q$). Figure 2a shows the monthly-averaged *P*, *E*, and *Q* data. Figure 2b shows that the observed water balance agrees well with the storage changes observed from GRACE, giving confidence that the GRACE data accurately capture the storage changes in the basins and can be used to estimate groundwater storage trends. The blue shading in Figure 2b represents the error in the GRACE *dS*/*dt* of 63 mm month^{-1}. The red shading represents the uncertainty in our water balance estimate of *dS*/*dt*, calculated after *Rodell et al.*

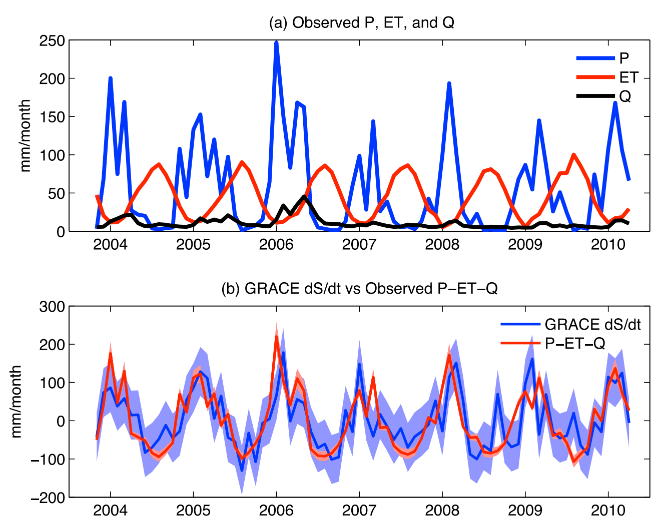

Figure 2. (a) Precipitation (P), evapotranspiration (E), and streamflow (Q) (mm/month) from October 2003–March 2010. (b) Comparison between observed total water storage change (*dS*/*dt*) and that from GRACE. Blue shading shows GRACE *dS*/*dt* errors. Red shading shows uncertainty in the observed water balance estimate of *dS*/*dt*.

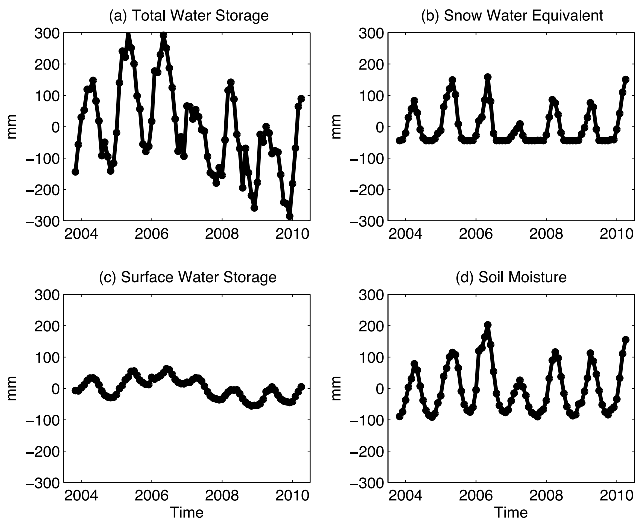

Figure 3. Monthly anomalies of (a) total water storage; (b) snow water equivalent; (c) surface water storage; and (d) soil moisture for the Sacramento and San Joaquin River Basins in mm from October 2003 to March 2010.

[2004a, 2004b] assuming relative errors of 15 percent in P [*Jeton et al.*, 2005] and E [*Tang et al.*, 2009], and 5 percent in Q [*Rodell et al.*, 2004b].

[11] Figure 3a shows the GRACE-based estimate of TWS variations for the combined Sacramento-San Joaquin Basins. The regional drought conditions, which persisted from 2006 through the end of the study, are evident. During the 78-month period beginning in October, 2003, total water storage declined at a rate of 31.0 ± 2.7 mm yr^{-1} equivalent water height, which corresponds to a total volume of 30.9 km^3 for the study period.

[12] In order to isolate groundwater storage variations from the GRACE TWS estimate, water mass variations in snow, surface water and soil moisture were estimated and subtracted from the total. Below-average SWE (Figure 3b) during the winters of 2006/07 through 2008/09 is apparent, consistent with the regional drought conditions, as are above-average conditions before and after that time period. These data show a slight decrease of 1.6 ± 0.4 mm yr^{-1} equivalent water height, which corresponds to 1.5 km^3 of water loss in 78 months. Figure 3c shows that surface water storage has been declining slightly since 2006. Over the length of the study period, surface water storage decreased at a rate of 8.8 ± 0.2 mm yr^{-1}, accounting for 8.7 km^3 of water loss. The loss of soil moisture (Figure 3d) was not significant during the study period. The trends for total water storage, SWE, surface water, soil moisture, and groundwater, along with the corresponding total volume changes for the October, 2003–March, 2010 period, are summarized in Table 1.

[13] Subtracting the snow, surface water and soil moisture components from GRACE TWS for the combined basins yields the groundwater storage variations shown in Figure 4. Over the course of the study period, groundwater storage decreased by 20.4 ± 3.9 mm yr^{-1}, which corresponds to a volume of 20.3 km^3 of water loss, or two-thirds of the total water storage loss in the river basins. We assume in this work that nearly all of the groundwater loss occurs in the Central Valley, and that the other major geological features in the

Table 1. Trends in Water Storage for the Combined Sacramento-San Joaquin River Basins[a]

	Trend (mm yr^{-1})	Volume Lost (km^3)
Total Water Storage	−31.0 ± 2.7	30.9 ± 2.6
Snow Water Equivalent	−1.6 ± 0.4	1.5 ± 0.3
Surface Water Storage	−8.8 ± 0.2	8.7 ± 0.1
Soil Moisture	−0.2 ± 2.8	0.1 ± 2.7
Groundwater Storage	−20.4 ± 3.9	20.3 ± 3.8
Groundwater Storage (2003/10–2006/03)	−1.4 ± 12.7	0.5 ± 4.8
Groundwater Storage (2006/04–2010/03)	−38.9 ± 9.5	23.9 ± 5.8

[a]Trends and volumes are for October, 2003–March, 2010 unless otherwise noted.

combined basins, that is, the mountain ranges surrounding the Valley, have limited capacity to store groundwater. Based on separate water budget analyses of the Sacramento and San Joaquin basins (not shown) we estimate that over 80 percent of the 20.3 km^3 of groundwater loss occurred in the San Joaquin river basin, including the Tulare basin, which is consistent with a recent USGS report on groundwater availability in the Central Valley [*Faunt*, 2009]. The San Joaquin portion of the Valley has always relied on groundwater more heavily than its Sacramento counterpart because its drier climate results in more limited natural surface water availability.

[14] Figure 4 also shows a distinct break in the behavior of groundwater storage variations. Prior to the onset of drought conditions in 2006, there was no significant change in groundwater storage. However, beginning with the drought in 2006, a steep decline in groundwater storage of 38.9 ± 9.5 mm yr^{-1} (6.0 km^3 yr^{-1}) occurred between April, 2006 and March, 2010. Our estimate of the current depletion rate is nearly as large as previous model-based estimates of

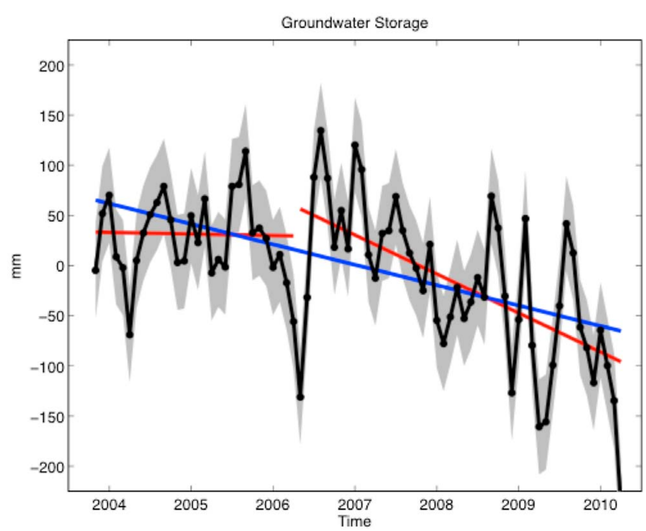

Figure 4. Monthly groundwater storage anomalies for the Sacramento and San Joaquin River Basins in mm, from October 2003 to March 2010. Monthly errors shown by gray shading. The blue line represents the overall trend in groundwater storage changes for the 78-month period. The red lines represent the trends from October 2003 and March 2006 and April 2006 through March 2010.

groundwater losses [*Faunt*, 2009] during the two major droughts of the last 50 years. Reported groundwater losses during those periods were approximately 12.3 km^3 yr^{-1} from 1974–76, and 8.2 km^3 yr^{-1} from 1985–89. Our estimated rate is also slightly larger than the loss of 4.9 km^3 yr^{-1} reported by *Faunt* [2009] for the more recent dry period between 1998 and 2003. Combining the USGS estimates of groundwater depletion between 1998 and 2003 with our GRACE-based estimates for October, 2003 through March, 2010 indicates that nearly 48.5 km^3 of groundwater has been lost from the Central Valley in the 12-year time period.

4. Discussion

[15] The picture that emerges from our GRACE based analysis is in agreement with *Faunt* [2009], and extends aspects of that study from its end date in 2003 to the present. Furthermore, results are consistent with the historical pattern of Central Valley agricultural water use. Facing significant cuts in managed surface water allocations during periods of drought, farmers, in particular those in the drier San Joaquin Valley, are forced to tap heavily into groundwater reserves to attempt to meet their irrigation water demands – this in a region where groundwater dependence is already high. Under these conditions, groundwater use rates exceed replenishment rates, and groundwater storage and the water table drop. Given the naturally low rates of groundwater recharge in the San Joaquin Valley, combined with projections of decreasing snowpack [*Cayan et al.*, 2006] and population growth, continued groundwater depletion at the rates estimated in this study may become the norm in the decades to come, and may well be unsustainable on those time scales.

[16] GRACE-based estimates of groundwater storage changes provide a holistic view of aquifer behavior that may not be otherwise possible, in particular in the developing world. Even in well-instrumented regions, a typical groundwater availability study is a massive undertaking, often several years in the making assembling supporting datasets and implementing numerical groundwater models. While there is no substitute for a dense network of ground-based observations and detailed groundwater model simulations, it is not clear that the major effort required for model-based studies can be sustained as part a routine monitoring program. Satellite gravimetry offers an important complement to both *in situ* observations and modeling studies by enabling independent estimates of groundwater storage changes, and by providing the opportunity to constrain aquifer-scale groundwater model simulations [*Zaitchik et al.*, 2008; *Lo et al.*, 2010].

[17] **Acknowledgments.** This research was funded by grants from NASA's GRACE Science Team, Terrestrial Hydrology and Earth and Space Sciences fellowship program. Claudia Faunt of the U. S. Geological Survey provided critical datasets used in this work. We thank Q. Tang at the University of Washington for providing evapotranspiration data.

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