COMPARISON OF CHANGES IN GROUNDWATER STORAGE USING GRACE DATA AND A HYDROLOGICAL MODEL IN CALIFORNIA'S CENTRAL VALLEY

Amber Kuss, San Francisco State University
William T. Brandt, California State University, Monterey Bay
Joshua Randall, Arizona State University
Bridget Floyd, University of California, Berkeley
Abdelwahab Bourai, Cupertino High School
Michelle Newcomer, San Francisco State University
Cindy Schmidt, Bay Area Environmental Research Institute
J.W. Skiles Ph.D., NASA Ames Research Center

DEVELOP NASA Ames Research Center
M.S. 239-20 Moffett Field, California 94035
Amberjean.m.kuss@nasa.gov
Joseph.Skiles@nasa.gov

ABSTRACT

The Gravity Recovery and Climate Experiment (GRACE) measures gravity anomalies on earth to estimate changes in total water storage (TWS), and may be a useful tool for calculating changes in groundwater storage for California's agriculturally productive Central Valley region. Under current California law, well owners are not required to report groundwater extraction rates, making estimation of total groundwater extraction difficult. As a result, other groundwater change detection techniques are used to estimate changes in groundwater storage in the Central Valley aquifer. From October 2002 to September 2009, GRACE was used to measure changes in TWS for the Sacramento River Basin, and the San Joaquin River Basin (including the Tulare Lake Basin), which contain the Central Valley aquifer. Net groundwater storage changes were calculated from the changes in TWS by incorporating estimates for additional components of the hydrological budget including soil moisture, snow pack, and surface water storage. The changes in groundwater storage at the river basin and regional level (the two basins combined) were then compared to modeled values calculated using the California Department of Water Resources' Central Valley Groundwater-Surface Water Simulation Model (C2VSIM). At the regional level (the Central Valley aquifer) it was found that GRACE-derived estimates of groundwater change in storage produced comparable results to C2VSIM. However, at the river basin level (Sacramento and San Joaquin), GRACE-derived estimates were significantly different from those modeled by C2VSIM, highlighting the current limit of GRACE's spatial resolution. This work has the potential to improve California's groundwater resource management at the regional level and in validating existing hydrological models for the Central Valley. The work also underscores the need for higher resolution satellite data that are applicable smaller scale management.

KEYWORDS: GRACE, groundwater storage, Central Valley, remote sensing, hydrological budget, C2VSIM, GIS, soil moisture, and snowpack

INTRODUCTION

The Central Valley aquifer system (52,000 km^2), located in California, is one of the most productive agricultural regions in the world (Faunt et al., 2009). The Central Valley supplies nearly 7 percent of the United States (U.S.) food supply, with an estimated annual value of $21 billion dollars (California Department of Food and Agriculture, 2010). Additionally, the Central Valley aquifer is the second most heavily pumped in the U.S., supplying nearly 20% of the Nation's groundwater demand (Kenny et al., 2009). California law does not regulate groundwater extraction at the state level; rather groundwater management is implemented at the local level and includes groundwater monitoring, basin and sub-basin management, and restrictions in the development and use of water (California Department of Water Resources, 2003). Also, variations in climate, such as the 2007–2009 drought have also affected groundwater availability in California, with increased demand on the Central Valley aquifer.

The California Department of Water Resources (DWR) has developed an analytical tool, the Central Valley Groundwater-Surface Water Simulation Model (C2VSIM), to assess the groundwater resources and alternative groundwater management strategies in the Central Valley. C2VSIM is a finite element hydrologic model that can calculate change in groundwater storage on an element by element basis. The calculated change in groundwater storage can be aggregated for each of the 21 subregions that define the Central Valley in the model. The change in storage can also be aggregated for the three hydrologic regions (the Sacramento River Basin, the San Joaquin River Basin, and the Tulare Lake Basin) as well as the entire Central Valley. C2VSIM-simulated change in groundwater storage is the residual value from a groundwater budget equation that incorporates variables such as precipitation, streamflow, reservoir storage, evapotranspiration (ET), soil moisture, surface water diversions, land use parameters, hydraulic conductivity, and aquifer properties (Brush et al., 2008).

NASA's Gravity Recovery and Climate Experiment (GRACE) satellite has improved the ability to estimate components of the hydrological budget for many large-scale basins throughout the world (Rodell and Famiglietti, 2002; Han et al., 2005; Yirdaw et al., 2008; Zaitchik et al., 2008; Leblanc et al., 2009; Famiglietti et al., 2011). Since its launch in March 2002, GRACE has recorded gravity anomalies at monthly time intervals using twin satellites that travel 220 km apart in identical orbits. Variations in the distance between the two satellites indicate deviations in the earth's gravitational field, which can be attributed to variations in total water storage (TWS) over a specific area (NASA, 2002).

Groundwater storage changes are difficult to estimate given the spatial and temporal limitations of obtaining complete and accurate groundwater level measurements for large geographic regions. However, the TWS anomalies measured by GRACE are representative of variations in snow and ice cover, surface water storage, soil moisture, and groundwater storage (NASA, 2002). As a result, changes in groundwater can be estimated by subtracting changes in storage for snow pack, surface water storage, and soil moisture from TWS.

The goals of this study were first, to calculate changes in groundwater storage for, the Sacramento River Basin, the San Joaquin River Basin, and the Central Valley using GRACE TWS anomalies and additional water storage components; and second, to compare changes in groundwater storage estimates from GRACE to estimates derived from C2VSIM.

Figure 1. The study area, highlighting the Central Valley region and the Sacramento Hydrologic Region (HR) which corresponds to the Sacramento River Basin, and the San Joaquin River (including the Tulare Lake) HRs are combined as part of the San Joaquin River Basin. The Central Valley aquifer is outlined in black and is the study area for which, C2VSIM calculates groundwater storage changes.

Study Area

The Central Valley aquifer of California (on average 80 km wide and 650 km in length) is a structural trough filled with marine and continental sediments (Planert and Williams, 1995). The aquifer is bounded on the west by the Coast Ranges and the east by the Sierra Nevada and is composed of sand and gravel, with significant amounts of silt and clay (Planert and Williams, 1995). The Central Valley aquifer is contained within three hydrologic regions–the Sacramento River Basin, the San Joaquin River Basin, and the Tulare Lake Basin (Figure 1). For this study, the San Joaquin River Basin and Tulare Lake Basin were combined and throughout this paper will be referred to as the San Joaquin River Basin. The C2VSIM model also incorporates inflow from the hydrologic regions using multiple gauged river inflows into the Central Valley aquifer (Brush et al., 2008). This inflow includes watersheds located in the Sierra Nevada within the defined boundaries of the Sacramento and San Joaquin hydrologic regions, thus incorporating changes within a similar area to GRACE data.

GRACE data were obtained in hydrologic basin boundaries that were predefined by the Cooperative Institute for Research in Environmental Studies (CIRES) at the University of Colorado (CU). Monthly TWS estimates were calculated using the Design of Total Runoff Integrating Pathways (TRIP) model and were found to be representative of the DWR hydrologic regions 5 (Sacramento River Basin), 6 (San Joaquin River Basin), and 7(Tulare Lake Basin) with 6 and 7 being combined into one region (Oki and Sud, 1998). While the hydrologic regions (combined area of 152,254 km^2) differ significantly in size from the DWR modeled Central

Valley aquifer (52,000 km^2), it was assumed that groundwater changes outside the aquifer would be minimal given that the Sierra Nevada mountain range is not conducive to groundwater storage (Famiglietti et al., 2011).

METHODOLOGY

Monthly GRACE TWS anomalies ($TWS_{\alpha,GRACE}$) were obtained for the Sacramento River Basin and the San Joaquin River Basin (including the Tulare Lake Basin) in 84 monthly time intervals from October 2002 to September 2009 (CU, 2011). Values were converted from totals into anomalies by subtracting the mean of the time series from each monthly value. To validate GRACE, monthly changes in TWS anomalies were calculated and compared to a separate water budget equation for the Central Valley (hydrologic regions 5, 6 and 7). The monthly changes in GRACE TWS anomalies were calculated using the equation:

Equation (1)

$$\Delta TWS_{\alpha,GRACE} = TWS_{\alpha,GRACE}(t_2) - TWS_{\alpha,GRACE}(t_1)$$

where:
$\Delta TWS_{\alpha,GRACE}$ = change in total water storage anomalies derived from GRACE
$TWS_{\alpha,GRACE}(t_1)$ = total water storage anomaly at time period one
$TWS_{\alpha,GRACE}(t_2)$ = total water storage anomaly at time period two

An independent water balance equation was then constructed for the Central Valley using a hydrologic input minus output approach where ΔTWS_{Budget} is the TWS change over the study period:

Equation (2)

$$\Delta TWS_{Budget} = P - (ET + Q)$$

where:
ΔTWS_{Budget} = change in total water storage
P = total monthly precipitation
ET = total monthly evapotranspiration
Q = total monthly surface water discharge

$\Delta TWS_{\alpha,GRACE}$ was then compared with ΔTWS_{Budget}:

$$\Delta TWS_{\alpha,GRACE} \leftrightarrow \Delta TWS_{Budget}$$

To calculate groundwater storage anomalies (GW_α), auxiliary datasets for soil moisture, surface water storage, and snowpack were required. Monthly anomalies for soil moisture (SM_α), surface water (SW_α) and snow pack (SP_α) were then subtracted from monthly $TWS_{\alpha,GRACE}$ values to calculate monthly GW_α for the Central Valley, the Sacramento River Basin, and the San Joaquin River Basin:

Equation (3)

$$GW_\alpha = TWS_{\alpha,GRACE} - (SW_\alpha + SM_\alpha + SP_\alpha)$$

where:
GW_α = groundwater storage anomaly
TWS_α = total water storage anomaly
SW_α = surface water storage anomaly
SM_α = soil moisture storage anomaly
SP_α = snowpack storage anomaly

Changes in storage were then calculated for each of the anomalies TWS, SW, SM, SP, and GW over the length of the study period. Anomalies were plotted and a trend line was fitted. The slopes of the graphs were then converted into a total volume (in km^3) of water lost or gained over the course of the study period.

Data Sets

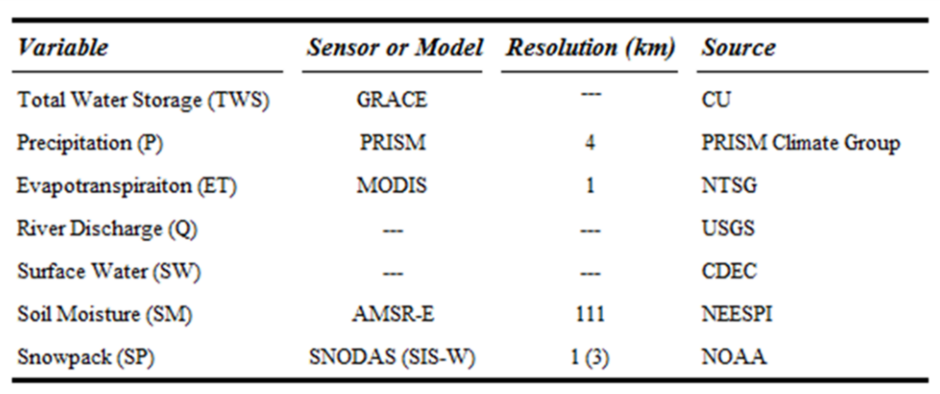
Data were obtained for TWS, SM, SP, SW storages and for P, ET, and for Q from various satellites and *in-situ* sensors and then converted into anomaly values (Table 1).

GRACE. For the study period, 84 months of level 3 destriped GRACE data were obtained from the University of Colorado's (CU) GRACE Data Analysis Website in millimeters of equivalent water thickness over the Sacramento and the San Joaquin River Basins (CU, 2011). Pre-processing of the GRACE data was performed by the Center for Space Research (CSR) at the University of Texas, and the release code was CSR RL04-DS. Additionally, the Jet Propulsion Laboratory (JPL) created validation datasets.

In brief, the GRACE processing consisted of transforming the raw distances between the twin satellites into sets of gravity field solutions which were truncated to degree 60 (Wahr et al. 2004). From each monthly solution the time-mean gravity was then removed and the solutions were converted into millimeters of equivalent water thickness corresponding to $TWS_{\alpha,GRACE}$. The data were then regionally averaged for the Sacramento and the San Joaquin River Basins as defined by the TRIP model (Oki and Sud, 1998). To remove the noise that is inherent in intermediate and short wavelength gravity, a Gaussian filter is often applied by the user upon downloading. However, as this step removes noise but also dampens the actual geophysical signal amplitudes, the gravity signals have to be rescaled to pre-smoothing magnitudes with an appropriate scaling factor (Whar et al., 1998; Whar et al., 2004; Landerer and Swenson, In Press). The scaling factor is a function of the smoothing radii (CU, 2011).

The data were smoothed using a Gaussian filter at multiple smoothing radii to assess the effects of the filter size on the GW storage changes at the Central Valley and river basin scales (discussed below). Groundwater storage estimates were calculated with GRACE TWS values smoothed to 1000 km, 750 km, 300 km, 100 km, and 1km. It was decided *a priori* that the most appropriate smoothing radius for the study area was 300 km. This radius exemplified variations in the TWS while limiting the error.

Table 1. Variables used for this study, with data resolution and source.



Variable	*Sensor or Model*	*Resolution (km)*	*Source*
Total Water Storage (TWS)	GRACE	---	CU
Precipitation (P)	PRISM	4	PRISM Climate Group
Evapotranspiraiton (ET)	MODIS	1	NTSG
River Discharge (Q)	---	---	USGS
Surface Water (SW)	---	---	CDEC
Soil Moisture (SM)	AMSR-E	111	NEESPI
Snowpack (SP)	SNODAS (SIS-W)	1 (3)	NOAA

Precipitation. PRISM (Parameter-elevation Regressions on Independent Slopes Model) data for precipitation were derived from the Oregon State University's climate research initiative known as the PRISM Climate Group (PRISM, 2011) (Table 1). The PRISM dataset is a knowledge-based system that creates a digital grid of monthly climatic estimates based on point measurement of precipitation, temperature, and other parameters at a spatial resolution of 4 km (PRISM, 2011). Data were obtained and spatially averaged for the three hydrologic regions (The Sacramento River Basin, the San Joaquin River Basin, and the Tulare Lake Basin) using a Geographical Information System (GIS). Pixel values were then extracted, converted, and averaged monthly for the Sacramento and San Joaquin River Basins and the Central Valley and used to validate GRACE ΔTWS estimates.

Evapotranspiration. Evapotranspiration data were developed through the MODIS Global Evapotranspiration (MOD16) project of the Numerical Terradynamic Simulation Group (NTSG) at the University of Montana (Table 1) (Mu et al., 2011). The MOD16 project was funded by the NASA Earth Observing System (EOS) in an effort to provide a data set that estimated global evapotranspiration using an algorithm to convert surface reflectance into evapotranspiration (Mu et al., 2011). The data were processed into 1 km gridded monthly averages and consisted of a representative value for evapotranspiration that included evaporation from soil, rain water intercepted by plants, and plant transpiration (Mu et al., 2011). Additionally, an ArcGIS tool, developed by the Center for Research in Water Resources located at the University of Texas-Austin was used to format the data (CRWR, 2011). The data were then used to calculate monthly summations of evapotranspiration over the Sacramento and the San Joaquin River Basins and the Central Valley, and used to validate GRACE ΔTWS estimates.

Discharge. Real time daily mean discharge data were obtained from the U.S. Geological Survey (USGS) National Water Information System (NWIS) for both the Sacramento River at Verona (11425500) and the San Joaquin River at Vernalis Gages (11303500) (USGS, 2011). Gages were selected based on their proximity to the Sacramento-San Joaquin River Delta in an attempt to record maximum runoff for the Sacramento and the San Joaquin River Basins, with limited tidal interaction. Discharge data in ft^3 s^{-1} were converted to km^3 mo^{-1}, and monthly totals were used in the water balance equation to validate GRACE ΔTWS estimates.

Surface Water. Total storage estimates from the 20 largest reservoirs located within the Central Valley region were obtained from the DWR California Data Exchange Center (CDEC) (CDEC, 2011). The monthly average storage values (acre-ft) were sorted based on capacity and location, and then summed to obtain monthly totals. The change in storage values were then calculated from the difference between the current and previous months, which represented the total change in all reservoirs for the Central Valley region. Changes in surface water were averaged and the mean was removed to obtain surface water anomalies that were then used to calculate GW_{α}.

Soil Moisture. The AMSR-E sensor, on the EOS-Aqua satellite, was used to generate monthly changes in soil moisture at a 1 degree spatial resolution for the top 1 cm of the soil. Data were obtained from the National Snow and Ice Data Center (NSIDC), with units of g cm^{-3} of soil moisture (Njoku, 2009). Preprocessing included applying an algorithm to convert surface reflectance into soil moisture estimates, which were then averaged over approximately 12,300 km^2 (Njoku, 2009). These estimates were then downscaled to the Central Valley region and the river basins and the monthly averages were calculated and converted into km^3. Accuracy estimates were on average ± 0.06 g cm^{-3} (Njoku, 2009). In order to estimate the amount of soil moisture throughout the unsaturated zone, a simple depth to water estimate of approximately 15 m was assumed (Faunt et al., 2009), and the value obtained for the top 0.01 m was applied to the entire unsaturated zone. Although there are inherent errors with this assumption, soil moisture can be a significant contributor to TWS. As a result, when calculating GW_{α} using equation 3 it is important to use representative values of changes in soil moisture occurring in the entire unsaturated zone of the aquifer and not just the top 0.01 m. Finally, changes in soil moisture were then averaged and the mean removed to obtain soil moisture anomalies that were then used in calculating GW_{α}.

Snowpack. Snowpack data, obtained as snow water equivalent (SWE), are a product of the NOAA National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC) (NOAA, 2011). The model output combines data sets from airborne and satellite platforms with *in-situ* measurements in a comprehensive model beginning on 1 October 2003. The NOHRSC SWE products were downloaded via the National Snow and Ice Data Center (NSIDC) with a 1 km spatial resolution and 24-hour temporal resolution. To minimize the downloading time for the 7-year time period, the 15th of every month was used as a representative SWE with the assumption that SWE would not vary extensively within months. Data were then clipped to the Sacramento and the San Joaquin River Basins using a GIS. Individual pixel values were then multiplied by the area of the pixel and the values summed across the Central Valley and the two river basins. Finally, changes in snow pack were then averaged and the mean removed to obtain snow pack anomalies that were then used to calculate GW_{α}.

Errors

GRACE satellite data possess two types of errors: the measurement error, which is intrinsic in the twin satellites, and the leakage error. The monthly measurement error and the leakage error were obtained from the GRACE Tellus website as a separate geospatially referenced raster (Swenson and Whar, 2006). For both the measurement and leakage error, the values were averaged over the Sacramento and the San Joaquin River Basins and the Central Valley. It should be noted that this was a best-estimate approximation of the errors, and recent studies suggest that the errors for smaller regions are correlated and may be larger than currently reported errors (Landerer and Swenson, In Press). Thus, for simplistic approximation of the errors in this study, the average error was used, although this is an area intended for further study. The combined measurement and leakage error are also a function of the smoothing radius, which is used in reducing noisy short-wavelength gravity during the pre-processing steps for TWS. For this study, the combined measurement and leakage error was found to be 1.01 km^3, 1.00 km^3, and 1.00 km^3 for the Sacramento River Basin, and the San Joaquin River Basin, and the Central Valley, respectively. Additionally, an error of 15% was assumed for each of the hydrologic variables (surface water, soil moisture, and snow pack).

In order to establish the error involved with the groundwater estimates, the propagation of uncertainty rule for sums and differences was used (Meyer, 1975). This rule establishes the combined uncertainties of each variable in the calculation of changes in groundwater storage using the equation

Equation (4)

$$S_{GW} = \sqrt{(S_{TWS})^2 + (S_{SW})^2 + (S_{SM})^2 + (S_{SP})^2}$$

where
S_{TWS} = standard error of total water storage
S_{SW} = standard error of surface water storage
S_{SM} = standard error of soil moisture
S_{SP} = standard error of snow pack

These errors are then applied to the total changes in groundwater storage for GRACE-derived estimates. To compare C2VSIM to the GRACE-derived groundwater estimates, an error of 15% was also applied to the C2VSIM-derived groundwater estimates.

C2VSIM Model

C2VSIM was developed by DWR, and is a finite-element hydrologic model built to estimate water storage in the Central Valley aquifer (Brush et al., 2008; Miller et al., 2009). The model utilizes various parameters which include, but are not limited to precipitation, stream flow, evapotranspiration, subsidence, and beginning and ending groundwater storage for each month. Groundwater storage changes were first calculated and then converted to anomalies using the equation below:

Equation (5)

$$GW_{\alpha} = \overline{GW} - GW$$

where
GW_{α} = groundwater anomaly
$\overline{GW}$= average groundwater storage value over the entire time period
GW = groundwater storage for the month in consideration

A linear trend was then applied to the anomalies, and the slope used to calculate total groundwater storage change over the study period for the Central Valley region and the Sacramento and San Joaquin River Basins.

RESULTS

Hydrological Budget

A hydrological budget was used to assess the accuracy of GRACE TWS estimates for the Central Valley region (Figure 2). Change in TWS was calculated using equation 1, and is represented in units of km^3 month^{-1} to compare with change in volume estimates from the hydrologic budget equation. Both the magnitude and the seasonality of the data for ΔTWS_{GRACE} and ΔTWS_{Budget} agreed well, with significance at an $\alpha = 0.05$. As a result, GRACE TWS values were shown to be representative of TWS changes within the system. This finding is in agreement with the data presented by Famiglietti et al. 2011. The hydrological budget (ΔTWS_{Budget}) was calculated using precipitation, evapotranspiration and discharge; the results for these individual data sets are discussed below. The trends of the variables within the hydrological budget equations are examined as indication of the variations in climate associated with the study period.

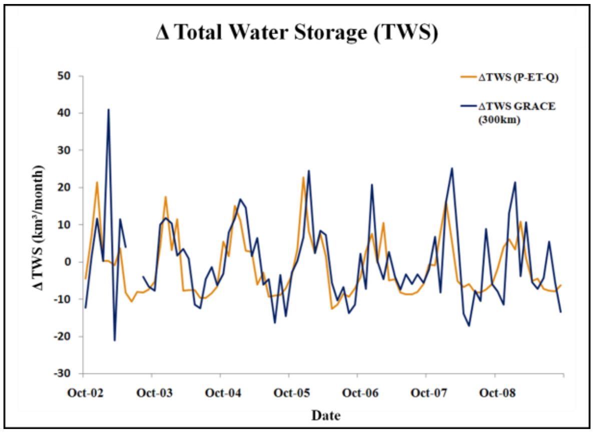


Figure 2. A comparison of ΔTWS_{GRACE} for the 300 km smoothing radius and ΔTWS_{Budget} from the hydrological budget equation.

Precipitation was consistently the largest contributor to ΔTWS_{Budget}. The Sacramento River Basin exhibited the largest amount of precipitation. Strong seasonal trends in both river basins were apparent, with the largest amount of precipitation occurring between

December and April during the region's winter storm period with a range of 14.54 km^3–25.83 km^3. These results reflect the drought period from 2007–2009 following the above average precipitation year of 2006. The Sacramento River Basin experienced the largest loss in total evapotranspiration followed by the San Joaquin River Basin. As would be expected, evapotranspiration exhibited seasonal trends with the largest evapotranspiration values occurring in late spring to early summer (May, June, and July), and the lowest values during the winter months (December and January). The Sacramento River Basin, in comparison with the San Joaquin River Basin, consistently produced greater discharge. Discharge also exhibited seasonal trends that peaked between February and April (in occurrence with snow melt from the Sierras) before steadily declining through the months of June and December. The range of discharge varied from 1.63–6.89 km^3 in both the Sacramento and San Joaquin rivers.

Storage Anomalies

GRACE TWS anomalies exhibited similar trends for the Sacramento River Basin, the San Joaquin River Basin, and the Central Valley region. Storage anomalies increased after the winter rains and rapidly decreased throughout the drier summer months (Figure 3A). The Central Valley region produced the largest standard deviations about the mean (0.72 km^3 ± 19.05) followed by the San Joaquin (0.35 km^3 ± 9.86) and Sacramento (0.37 km^3 ± 9.55), respectively. Surface water storage anomalies demonstrated similar seasonal trends (Figure 3B). In general, surface water storage anomalies increased between 2002 and 2006, before decreasing at the onset of the drought period beginning in 2007. Soil moisture storage anomalies also exhibited seasonal trends that increased during the winter months and decreased during the drier summer months (Figure 3B). In general, the Sacramento and San Joaquin River Basins and the Central Valley displayed similar values (both in magnitude and seasonality) throughout the length of the study. Snowpack storage anomalies exhibited pronounced winter and summer variations (Figure 3C). The winters between 2004 and 2006 produced the largest snowpack totals during the study period. Interestingly, the Sacramento and San Joaquin River Basins exhibited conflicting anomaly trends with anomaly values increasing for the Sacramento River Basin through the duration of the study period (with the exception of the winter in 2006–2007) (Figure 3D). However, in the San Joaquin River Basin, snowpack anomalies increased until the winter of 2005–2006 before exhibiting a sharp and notable decrease for the rest of the study period. The Central Valley and the San Joaquin River Basin exhibit the largest seasonal fluctuations and differ significantly from the Sacramento

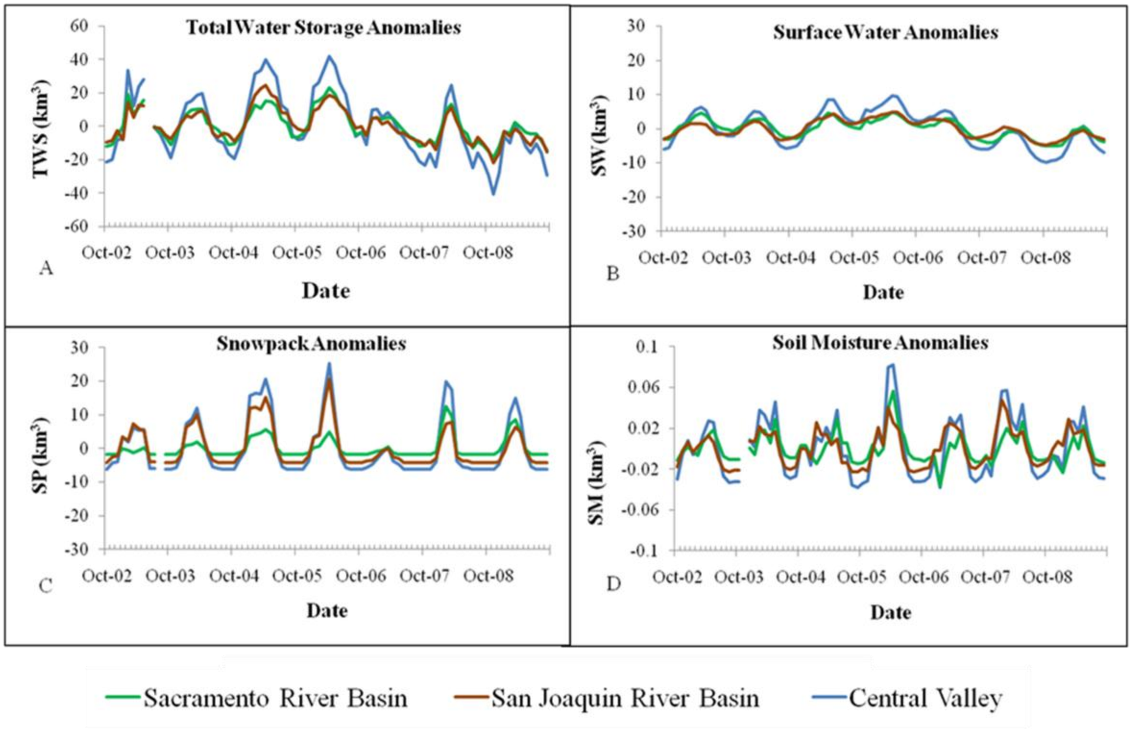


Figure 3. Hydrologic variable anomalies. (A) TWS anomalies from GRACE, (B) surface water storage anomalies from CDEC, (C) soil moisture storage anomalies from AMSR-E, and (D) snow pack anomalies from NOAA.

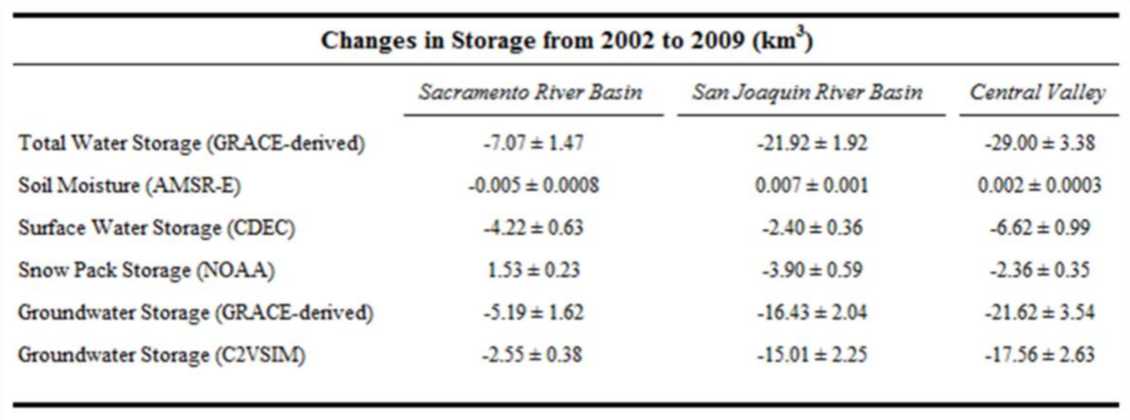
groundwater storage anomalies. The onset of the drought period beginning in 2007 is especially visible in the San Joaquin River Basin, but difficult to discern in the Sacramento River Basin.

The San Joaquin River Basin exhibited the largest loss in TWS, snowpack and groundwater storage anomalies (Table 2). In contrast, the Sacramento River Basin displayed the largest loss in surface water storage. Soil moisture storage values, however, remained relatively unchanged throughout the study period in both regions. The results presented here are consistent with the results presented by Famiglietti et al. 2011 and Faunt et al. 2009.

C2VSIM Change in Storage

C2VSIM calculated change in groundwater storage exhibited seasonal variability and a negative overall trend (Figure 4). The net change in storage for the Central Valley aquifer was -17.56 ± 2.63 km^3 (-14.24 ± 2.13 million acre-feet). The San Joaquin River Basin exhibited a loss of -15.01 ± 2.25 km^3 (12 million acre feet) and the Sacramento River Basin exhibited a net decrease of -2.55 ± 0.38 km^3 (2 million acre-feet). The largest positive change in groundwater storage occurred in December 2005 (0.35 ± 0.05 km^3) and January 2006 (0.34 ± 0.05 km^3). The largest negative change in groundwater storage occurred in July 2008 (-0.45 ± 0.07 km^3) followed by July 2009 (-0.44 ± 0.07 km^3).

Table 2. Change in storage from October 2002 to September 2009 for total water storage, soil moisture, surface water storage, snow pack storage, and groundwater storage.



Changes in Storage from 2002 to 2009 (km^3)			
	Sacramento River Basin	*San Joaquin River Basin*	*Central Valley*
Total Water Storage (GRACE-derived)	-7.07 ± 1.47	-21.92 ± 1.92	-29.00 ± 3.38
Soil Moisture (AMSR-E)	-0.005 ± 0.0008	0.007 ± 0.001	0.002 ± 0.0003
Surface Water Storage (CDEC)	-4.22 ± 0.63	-2.40 ± 0.36	-6.62 ± 0.99
Snow Pack Storage (NOAA)	1.53 ± 0.23	-3.90 ± 0.59	-2.36 ± 0.35
Groundwater Storage (GRACE-derived)	-5.19 ± 1.62	-16.43 ± 2.04	-21.62 ± 3.54
Groundwater Storage (C2VSIM)	-2.55 ± 0.38	-15.01 ± 2.25	-17.56 ± 2.63

DISCUSSION

GRACE and C2VSIM groundwater storage anomalies exhibited similar trends for the Central Valley region from October 2002 through September 2009 (Figure 4). This finding is important as it validates the usefulness of GRACE at scales of ≥ 150,000 km^2. It should be noted that GRACE and C2VSIM groundwater anomalies display marked differences during the seasonal peaks and troughs. GRACE is more variable and covers a larger geographic area which may include changes in water storage outside the Central Valley aquifer. This characteristic may be a due to the coarse spatial resolution of GRACE. Small spatial scales combined with small changes in TWS may make separating the differences between noise and short gravitational wavelength's difficult. Regardless, both methods clearly document the California drought period beginning in 2007 with the data taking on a distinctive negative trend.

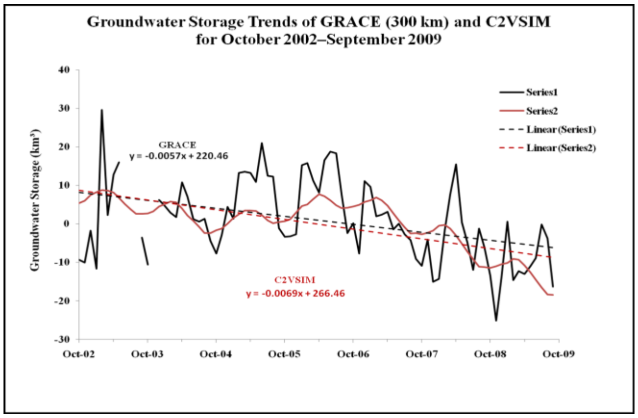


Figure 4. Groundwater storage anomalies from GRACE and C2VSIM with linear trendlines. Of note is the significant decrease in ΔGW at the onset of the California wide drought beginning in 2007.

Both GRACE and C2VSIM produced comparable results for change in groundwater storage over the study period for the Central Valley region; however, results were significantly different for the Sacramento and San Joaquin River Basins (Figure 5). At the Central Valley aquifer scale, GRACE estimated change in groundwater of -14.47 ± 1.45 km^3 compared to C2VSIM's estimate of -17.56 ± 2.63 km^3. While, the estimates are different (by about 18%), they are within the accepted errors and therefore comparable. However, at the river basin scale both GRACE and C2VSIM produced very different results when using the 300 km smoothing radius. The GRACE-derived estimate for total change in groundwater storage for the Sacramento River Basin was -7.70 ± 1.49 km^3; whereas C2VSIM estimated losses of -2.55 ± 0.38 km^3. For the San Joaquin River Basin, GRACE estimated losses of -6.76 ± 1.45 km^3 and C2VSIM estimated a loss of -15.01 ± 2.25 km^3. These data highlight the resolution limitations of GRACE, especially in small basin or sub-basin analyses.

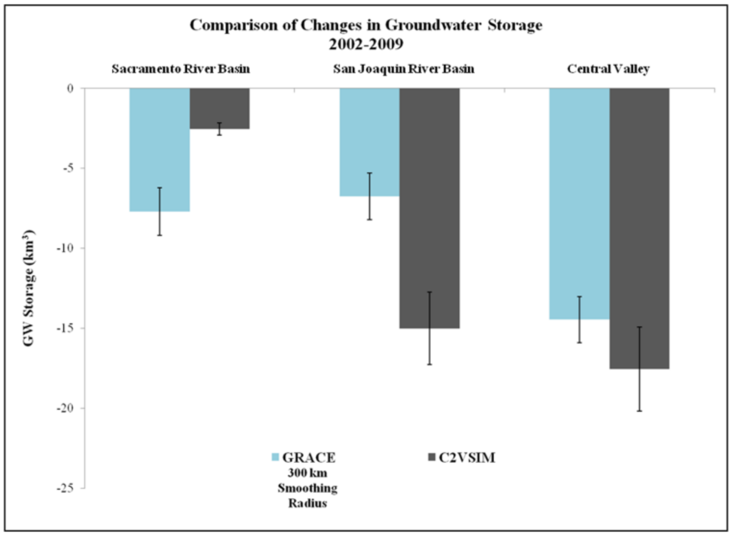


Figure 5. Changes in groundwater for the Sacramento River Basin, the San Joaquin River Basin, and the Central Valley aquifer for GRACE and C2VSIM.

GRACE-derived change in groundwater storage estimates exhibited high variability depending on the Gaussian smoothing radius used. When using a smaller smoothing radius, the differences between the Sacramento and San Joaquin River Basins become more pronounced and seemingly more accurate given the results from C2VSIM. Additionally, the monthly GRACE groundwater storage anomalies for smaller smoothing radii were found to be more characteristic of the variations in climate, such as the onset of the drought in 2007. Although the groundwater storage estimates derived with a smaller smoothing radius are closer to previously reported values, the error involved is currently unknown. It is assumed that the error would increase significantly with a decreasing smoothing radius, therefore producing unclear results. However, an interesting trend in change in groundwater storage for various smoothing radii suggests that an equilibrium point is approached with progressively smaller radii (Figure 6). For example, there is a difference of 6.41 km^3 between the groundwater storage estimate with a smoothing radius of 750 km and 300 km, but there is only a 0.49 km^3 difference between 100 km and 1 km smoothing, due to use of degree 60 data, which produces little difference in 100 km and 1km groundwater storage estimates. These findings prove helpful in downscaling efforts to smaller areas similar to that of the river basins.

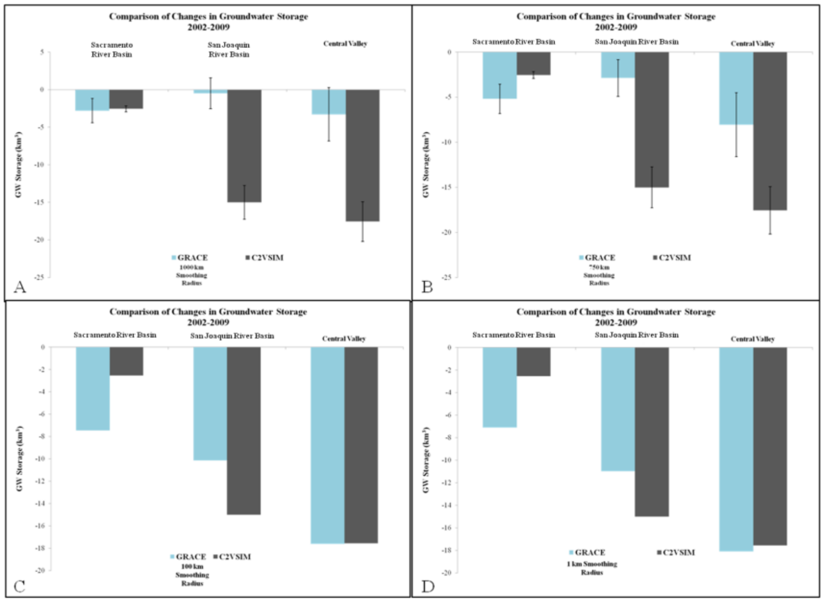


Figure 6. GRACE-derived groundwater storage estimates for the study period with different smoothing radii for A) 1000 km, B) 750 km, C) 100 km, and D) 1 km. It is important to note the large swings in ΔGW for the river basins; especially above a 100 km smoothing radius.

Although both GRACE and C2VSIM estimate significant declines in groundwater storage, the period of record is an important factor in the results presented here. Periods of increased or decreased precipitation due to natural climate variability will affect changes in groundwater storage in the Central Valley aquifer. This study period included a moderate drought, which greatly affected the groundwater depletion trends. Prior to the onset of the 2007–2009 drought, there were no significant changes in groundwater storage, as also noted by Famiglietti et al. 2011. Thus, it is important to generate trends in groundwater storage over a long enough time period to identify natural variability in climate. GRACE and C2VSIM data display these trends and therefore are useful tools for groundwater storage monitoring and management in the Central Valley aquifer.

CONCLUSION

The goals of this study were to 1) calculate the change in groundwater storage for the Sacramento River Basin, the San Joaquin River Basin, and the Central Valley using GRACE TWS anomalies and additional water storage components; and 2) to compare total change in groundwater storage estimates for both GRACE and C2VSIM. In order to address the first goal of this study, GRACE TWS anomalies were used to calculate change in groundwater storage. This was calculated by subtracting the monthly anomalies of water storage (surface water, soil moisture, and snowpack) from the monthly GRACE TWS anomaly. Additional water storage anomalies were calculated from reservoir storage data from CDEC (surface water), soil moisture values from AMSR-E and an integration of soil moisture throughout the unsaturated zone, and from snowpack data from NOAA. A linear trend of monthly groundwater storage anomalies was used to estimate total change in groundwater storage for the study period (October 2002–Spetember 2009). To address the second goal of the study, groundwater storage anomalies from C2VSIM were also calculated from modeled outputs and a trend was used to estimate total change in groundwater storage.

A major factor in calculating change in groundwater storage estimates from GRACE data was the ability to use a variety of smoothing radii. The processing of GRACE data can greatly affect change in groundwater storage estimates, and different smoothing radii produced dramatically different results. For this study, a smoothing radius of 300 km was chosen due to the size of the study area and the acceptable level of associated error. However, it should be noted that smoothing radii of 1,000 km, 750 km, 100 km, and 1 km were also used to report total change in groundwater storage. The change in groundwater storage estimates for smaller smoothing radii produced results similar to C2VSIM and previously reported values, although the associated error is unknown. Due to the unknown errors for the 100 km and 1km smoothing radii, discretion at larger scales is recommended. Thus, GRACE proved effective at estimating change in groundwater storage at the Central Valley region scale. However, at smaller scales the satellite is not sensitive enough to separate the differences occurring at the river basin level.

For the 300 km smoothing radius, both GRACE and C2VSIM produced comparable results for the Central Valley region exhibiting a net loss in change in groundwater storage of -14.47 ± 1.49 km³ and -17.56 ± 2.63 km³ for GRACE and C2VSIM, respectively. This loss occurred over the 7-year study period (October 2002–September 2009). However, the two methods differed in their estimates of change in groundwater storage loss at the basin scale when using a smoothing radius ≥ 300 km. This result emphasizes the usefulness of GRACE for large-scale basins greater than or equal to basins of 150,000 km^2 and also highlights the limits of the satellite for water resource management at basin or sub-basin scales. It was found that GRACE data at finer spatial scales must be processed and evaluated differently through the assimilation of GRACE-data into hydrologic models. This study shows that current water resource management practices provide the most accurate estimates of change in groundwater storage at the basin and sub-basin scale. GRACE data are an effective water resources management tool for large basins equal to or greater than the size of the Central Valley aquifer.

ACKNOWLEDGEMENTS

We thank the Department of Water Resources, notably the people who supported us throughout this project, Mary Scruggs, Abdul Khan, Charles Brush, Bill Brewster, and Chris Bonds. We also thank Stephen Kashiwada for the tour of the California State Water Project. We also thank Kings River Conservation District, notably David Orth, Eric Osterling, and Cristel Tufenkjian, for the insight into local water management and the tour of the Pine Flat Dam.

REFERENCES

Brush, C.F., E.C. Dogrul, M.R. Moncrief, J. Galef, S. Shultz, M. Tonkin, D. Wendell, T.N. Kadir, and F.I. Chung. 2008. *Estimating hydrologic flow components of the Central Valley hydrologic flow system with the California Central Valley Groundwater-Surface Water Model*. In CF Brush and NL Miller, eds. Proceedings of the California Central Valley Groundwater Modeling Workshop, July 10-11, 2008, Lawrence Berkeley National Laboratory, Berkeley, California. California Water and Environmental Modeling Forum, Sacramento, CA.

California Department of Water Resources. 2003, *California's Groundwater Bulletin 118, Update 2003.* Sacramento, CA. 265 pp.

CDEC, 2011, Reservoir Data Summary, 1964 to 2011, Department of Water Resources California Data Exchange Center (CDEC), http://cdec.water.ca.gov/reservoir.html, Sacramento, CA, (Updated daily).

CRWR, 2011, MODIS 16 GIS Tool, 2000 to 2011, The Center for Research in Water Resources at the University of Texas at Austin, http://data.crwr.utexas.edu/blog/news/historical-evapotranspiration-data/, Austin, TX.

CU, 2011. Real-Time GRACE Data Analysis Site, 2002 to 2009, University of Colorado Cooperative Institute for Research in Environmental Sciences. http://geoid.colorado.edu/grace/grace.php, Boulder, CO.

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*, *38*, L03403, doi:10.1029/2010GL046442.

Faunt, C. C., R.T. Hanson, K. Belitz, W. Schmid, S.P. Predmore, D.L. Rewis, K. McPhearson, 2009. *Groundwater availability of the central valley aquifer, California*, US Geological Survey, Professional Paper 1766, 225 pp.

Han, S. C., C. K. Shum, C. Jekeli, and D. Alsdorf. 2005. Improved estimation of terrestrial water storage changes from GRACE, *Geophys. Res. Lett*, *32*(7). L07302, doi:10.1029/2005GL022382.

Kenny, J. F., N. L. Barber , S. S. Hutson, K. S. Linsey, J. K. Lovelace, and M. A. Maupin. 2009. Estimated Use of Water in the United States in 2005. Reston, VA: U.S. Geological Survey Circular 1344. 52 pp.

Landerer and Swensen, In Press. Accuracy of scaled GRACE terrestrial water storage estimates. *Water Resources Research*. 27pp.

Leblanc, M. J., P. Tregoning, G. Ramillien, S. O. Tweed, and A. Fakes. 2009. Basin-scale, integrated observations of the early 21st century multiyear drought in southeast Australia, *Water resources research*, *45*(1).

Meyer, S.L., 1975, Data Analysis for Scientists and Engineers. John Wiley and Sons, Hoboken, New Jersey.

Miller, NL, LL Dale, CF Brush, SD Vicuna, TN Kadir, EC Dogrul, and FI Chung, 2009. Drought resilience of the California Central Valley surface-groundwater-conveyance system. Journal of the American Water Resources Association. doi: 10.1111/j.1752-1688.2009.00329.x.

Mu, Q., M. Zhao, and S. W. Running. 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm, *Remote Sensing of Environment*. *115*. 1781–1800.

NASA. 2002. *Studying the earth's gravity from space: The Gravity Recovery and Climate Experiment (GRACE)*, National Areonautics and Space Adminstration, Greenbelt, MD.

Njoku, Eni. 2009, updated daily. *AMSR-E/Aqua L2B Surface Soil Moisture, Ancillary Parms, & QC EASE-Grids V002*, October 2002–September 2009, Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

NOAA, 2011, National Snow Data, 2002 to 2011, National Operational Hydrologic Remote Sensing Center, http://www.nohrsc.nws.gov/, Chanhassen, MN, (Updated daily).

Oki, T., and Y. C. Sud. 1998. Design of Total Runoff Integrating Pathways (TRIP)—A Global River Channel Network, *Earth Interact.*, *2*(1), 1-37, doi:10.1175/1087-3562(1998)002<0001:DOTRIP>2.3.CO;2.

Planert, M., and J. Williams (1995), Ground water Atlas of the United States-California, Nevada, in *Ground water Atlas of the United States*, USGS, Washington, D.C.

PRISM, 2011. Near-Real-time Monthly High-Resolution Precipitation Climate Sate Set for the Conterminous United States. 1997 to 2011. The Prism Climate Group at Oregon State University. http://prism.oregonstate.edu, Corvallis, OR. (Updated daily).

Rodell, M., and J. S. Famiglietti. 2002. The potential for satellite-based monitoring of groundwater storage changes using GRACE: the High Plains aquifer, Central US, *Journal of Hydrology*, *263*(1-4), 245–256.

Swenson, S., and J. Wahr, 2006, Post-processing removal of correlated errors in GRACE data, *Geophys. Res. Lett.*, *33*(8), doi:10.1029/2005GL025285. [online] Available from: http://grace.jpl.nasa.gov/data/gracemonthlymassgridsland/ (Accessed 7 June 2011).

USGS, 2011, Real-Time Water Data for the Nation: Daily Streamflow Conditions, National Water Information System (NWIS), http://waterdata.usgs.gov/nwis/rt, Washington, DC, (Updated daily).

Wahr, J., M. Molenaar, and F. Bryan. 1998. Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, *103*(B12), PP. 30,205-30,229, doi:199810.1029/98JB02844.

Wahr, J., S. Swenson, V. Zlotnicki, and I. Velicogna. 2004. Time-variable gravity from GRACE: First results, *Geophys. Res. Lett*, *31*(11), L11501.

Yirdaw, S. Z., K. R. Snelgrove, and C. O. Agboma. 2008. GRACE satellite observations of terrestrial moisture changes for drought characterization in the Canadian Prairie, *Journal of Hydrology*, *356*(1-2), 84–92.

Zaitchik, B. F., M. Rodell, and R. H. Reichle. 2008. Assimilation of GRACE Terrestrial Water Storage Data into a Land Surface Model: Results for the Mississippi River Basin, *J. Hydrometeor*, *9*(3), 535-548, doi:10.1175/2007JHM951.1.