WRITTEN TESTIMONY OF
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HEARING ON PERSPECTIVES ON CALIFORNIA WATER SUPPLY: CHALLENGES AND OPPORTUNITIES

BEFORE THE
SUBCOMMITTEE ON WATER AND POWER
COMMITTEE ON NATURAL RESOURCES
U.S. HOUSE OF REPRESENTATIVES

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Chairwoman Napolitano, Ranking Member McClintock, and other members of the subcommittee: thank you for the opportunity to provide testimony on the state of our water supply and water supply monitoring in California, including groundwater resources.

My name is James Famiglietti. I am a hydrologist and Professor on the faculty at the University of California, Irvine, with appointments in the Department of Earth System Science and the Department of Civil and Environmental Engineering. I am the Founding Director of the new UC Center for Hydrologic Modeling. My research group uses satellite remote sensing to track water availability on land, and has been working for many years towards improving hydrological prediction in regional and global weather and climate models. I am also the former Director of the UCI Institute of Geophysics and Planetary Physics and the past Chief Editor of the interdisciplinary Earth science journal Geophysical Research Letters. I am currently in the last year of a three-year term as Chair of the Board of Directors of CUAHSI, the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. It is on the strength of nearly 25 years of research, teaching and service to the water science and engineering community that I offer the following testimony.

INTRODUCTION

Groundwater -- the water stored beneath the land surface in aquifers -- accounts for nearly 30 percent of global freshwater resources. Today, some 2 billion people rely on groundwater as a primary source of drinking water and for irrigated agriculture. However, in many regions of the world, groundwater resources are under stress due to a number of factors, including groundwater depletion (when withdrawal rates exceed recharge rates), salinization and contamination. When coupled with the pressures of changing climate and population growth, the stresses on groundwater supplies will only increase in the decades to come.

In many regions in the United States, including the Ogallala Aquifer of the High Plains, the Colorado River Basin, California, and its Central Valley, groundwater plays an essential role in supporting agricultural activity, as well as in domestic and industrial use. In some regions in the U.S., groundwater provides the sole freshwater source, while in others, it is used to supplement surface water supplies, which can vary with swings in weather and climate. For example, until recently, the cities of Fresno and Visalia depended entirely upon groundwater for their domestic supply; and in my own hometown of Irvine, roughly 50 percent of the water supply is drawn from local aquifers beneath Orange County.

Nearly 80 percent of the fresh water used in the United States is for agriculture (though more recent statistics on water use for power generation underscore the importance of that sector). In regions such as the Central Valley and the Ogallala, groundwater provides the majority of the irrigation water requirements. The Central Valley offers a compelling example of the importance of groundwater, as well as the need to manage its use for sustained availability and productivity. The Central Valley is one of the most productive agricultural regions in the world, producing more than 250 different crops worth \$17 billion per year (2002 dollars), or 8 percent of the food produced in the U. S. by value; it accounts for 1/6 of irrigated land in the U.S.; and it supplies 1/5 of the demand for groundwater in the U.S. In short, it the second most pumped aquifer in the United States.

The current water crisis in California places additional stress on Central Valley groundwater resources. Continued drought has resulted in decreasing surface water allocations to the southern valley, triggering an increased reliance on groundwater, in a region where groundwater dependence is already high. The crisis is being exacerbated by the ongoing drought, since less rainfall results in less groundwater recharge. Under these conditions, groundwater use rates exceed replenishment rates, and the groundwater supply and the water table drop. Likewise, climate change and its impact on the decreasing snowpack in the Sierras and the Rockies poses its own set of challenges to reliable water supply in California. Decreasing snow in the Sierras may well lead to additional reductions in Central Valley groundwater recharge, while the diminishing snowpack in the Colorado River basin may well result in decreasing surface and groundwater availability there. Hence monitoring groundwater availability in the Central Valley is critical to help manage California's water crisis, its impact on the state's economy and the Nation's food production

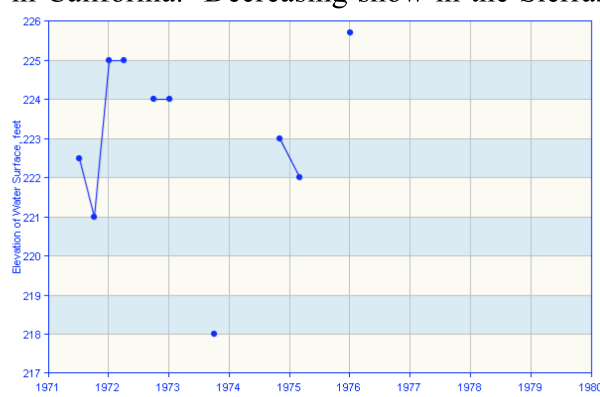

***Figure 1**. A typical well record of groundwater elevation from the Central Valley in California. Note the infrequent and discontinuous nature of the measurements.*

Surprisingly, in spite of its importance to freshwater supply, groundwater resources are often poorly monitored, so that a consistent picture of its availability is difficult and sometimes impossible to construct. Typical groundwater monitoring relies on tracking water levels in a network of wells. However, existing monitoring wells are often sparse, measurement records are frequently discontinuous (Figure 1), and wells are often monitored by different agencies, at different time intervals, and record lengths often vary. Well measurements from different local, state and federal agencies are often archived at different locations, stored in different formats, and may not be easily or freely accessible. The recent U. S. Geological Survey report on "Groundwater Availability of the Central Valley Aquifer, California," which was several years in the making, underscores the major effort required to assemble a comprehensive picture of changing groundwater availability. It is not clear that such an effort can be sustained as part a routine monitoring program.

The main goal of this testimony is to share with committee members recent advances in satellite technology that now enable routine groundwater monitoring from space, including in the Central Valley. The satellite mission of interest today, the Gravity Recovery and Climate Experiment, or GRACE, has already been successfully applied to track monthly groundwater storage changes in several large aquifer systems around the world. It is our hope that the information that advanced technologies such as GRACE can provide will ultimately be incorporated into the information stream that supports environmental decision making. I will also appeal to you for your help. Unfortunately, hydrological model development and water observing networks have lagged far behind the increasingly urgent need to address pressing issues of national significance. We cannot make the necessary progress in areas such as water, energy and food security without your leadership and support.

BACKGROUND

The GRACE mission was launched in March 2002. It consists of two satellites that orbit around Earth each month. The primary measurement is not of Earth's surface, but rather, of the distance between the two satellites, which is perturbed by changes in gravity from place to place

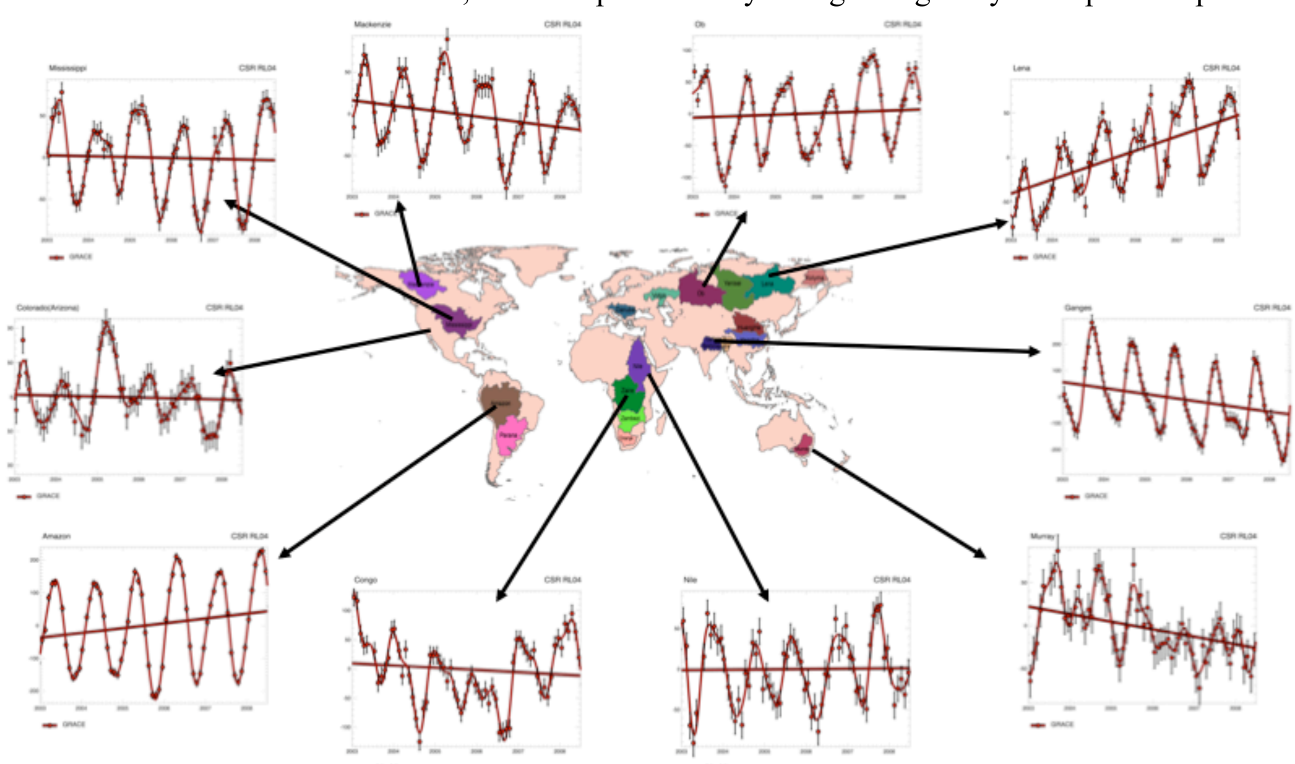

Figure 2. *Water storage changes (in mm water equivalent, i.e. volume divided by basin area) in the world's major river basins from GRACE, 2002-2008. Shown as anomalies (deviations from the mean). Note that scales change between graphs. Straight lines are trends.*

as the pair orbit around the globe. The mission collects millions of these inter-satellite distance measurements, which are exceptionally accurate (to the sub-micron level), and uses them to produce a map of our planet's gravitational field. Taking the difference between these maps yields the time-variable component of the gravity field. The major topographic and geologic features of Earth do not change on a monthly basis: their contribution to Earth's gravity field is static. Consequently, owing to the fact that water is one of the heaviest materials on Earth, the time-variable component of the gravity field is largely a reflection of changes in water storage each month. Hence the measurements of this time-variable component of the gravity field are used to estimate the corresponding changes in water mass stored on land and in the oceans. GRACE cannot measure the total (absolute) amount of water stored in a river basin, an aquifer or any other region of interest. It can only tell us the change between successive measurements of the gravity field.

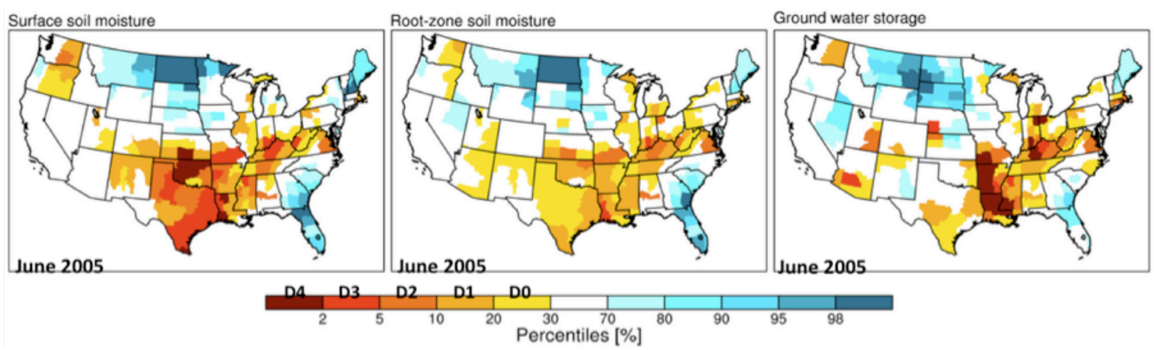

Figure 3. *GRACE data incorporated into the U.S. Drought Monitor. Surface soil moisture (left), root-zone soil moisture (middle) and groundwater storage (right) as percentiles. Orange and red colors indicate the severity of drought conditions.*

GRACE data have been successfully used to measure changes in the Greenland and Antarctic ice sheets, the Alaskan glaciers, and the Patagonian glaciers in Chile. Our research group at UC Irvine has focused on hydrologic applications of GRACE. We have demonstrated how GRACE data can be used to track water storage changes (Figure 2), to estimate evapotranspiration and to estimate streamflow from the world's major river basins. We also incorporate GRACE data in computer models of hydrology to improve prediction of surface and groundwater storage changes. GRACE data are now an input data stream into the operational U.S. Drought Monitor (Figure 3). After nearly 8 years of GRACE data, we are now able to identify trends in water storage that result from both natural and anthropogenic forces (Figure 4).

One of the key hydrologic contributions of GRACE is that it has enabled satellite observation of groundwater storage changes. Our group has pioneered these techniques, beginning over a decade ago with our pre-launch feasibility study of the potential of GRACE to monitor groundwater storage changes in the Ogallala Aquifer. Since then we have used GRACE data to explore groundwater storage changes in the Mississippi River basin, and in aquifers in Illinois, Oklahoma and Australia. Figure 5 shows a figure from our recent study of rapid rates of groundwater depletion in northwestern India, an agricultural region like the Central Valley that is heavily dependent on groundwater for its irrigation demands.

It is critical to recognize the contribution of the GRACE mission to observing the changing hydrology of the continents. Figures 2, 4 and 5 display information on the behavior of water storage on land that is essentially brand-new: before the GRACE mission, this information was simply not available. For example, the ups and downs of river basin water storage shown in

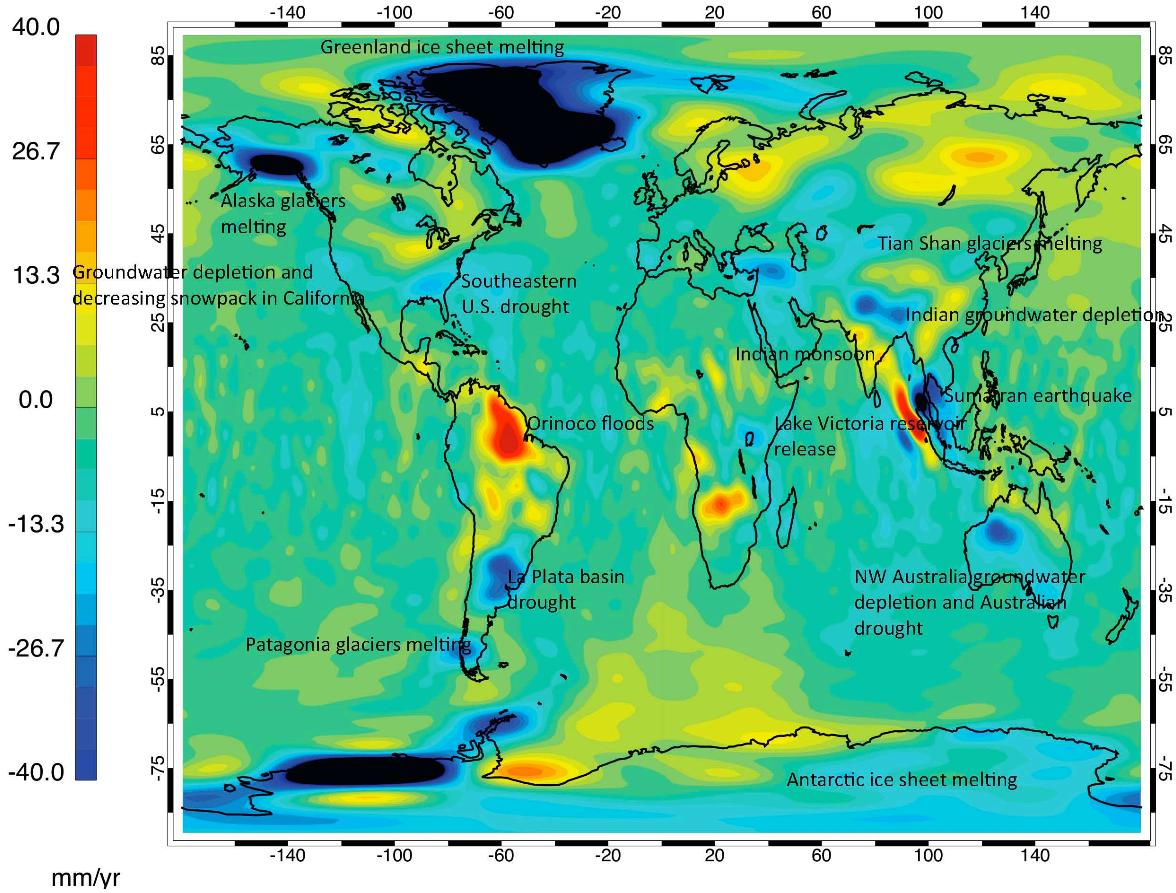

Figure 4. *Trends (mm/yr) in water storage for the globe. Major trends identified to date are labeled. Negative trends imply water loss, and positive trends indicate increasing water storage.*

Figure 2 were simply not known: likewise the pattern of water storage trends in Figure 4. In particular, remote sensing of groundwater was regarded as a 'Holy Grail' in the hydrologic community. In addition to the several reasons described in my introductory testimony, since groundwater is located below the Earth's surface, it is not 'visible' by traditional, optical satellite missions. GRACE has effectively allowed us to 'see' beneath the surface, by 'weighing' groundwater storage changes from space.

There are several caveats that must be understood before we discuss the Central Valley example. First, GRACE operates at relatively low resolution in space and time. It can measure monthly changes in water storage, for regions with a minimum area 150,000 km^2, with an accuracy of 1.5 cm of equivalent water height. Its performance improves with increasing area and time period. Second, GRACE measures changes in all of the water stored in a region – that is, it is unable to differentiate among snow, ice, surface water, soil moisture and groundwater. In order to isolate changes in one of these individual storage reservoirs, for example, groundwater, mass changes in the other above-mentioned storages must be estimated and removed. Typically these data come from ground-based observations, advanced hydrological models, or from other satellites. Third, the GRACE mission has a limited lifespan. Barring any unforeseen battery or electronics failures, mission scientists at NASA's Jet Propulsion Laboratory estimate that GRACE will perform reliably for only another 3-5 years.

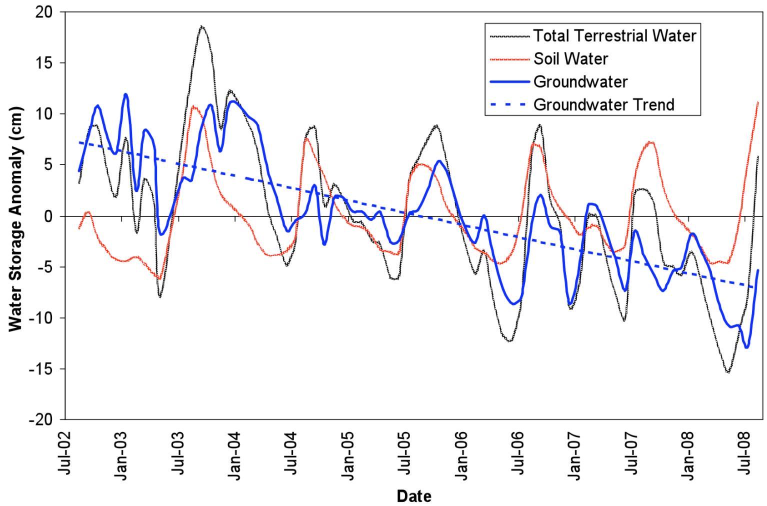

Figure 5. Groundwater depletion in India. Trend is 17.7 km3/yr for the period August 2002-October 2008.

Finally, it is important to note that our goal is not to expose water 'overuse.' In fact, Figure 4 shows that in many land regions, for example, in high-latitude Eurasia, water storage is increasing. Moreover, unpublished research from our group suggests that the continents as a whole show zero storage change, or even a small increase in water storage, during the life of the GRACE mission. Rather, we are committed to developing advanced methodologies to help monitor water storage changes, characterize water availability, and to predict and understand the forces that contribute to regional water stress. As mentioned earlier, it is our hope to share this information with regional water managers, and with state and federal policy and decision makers.

WATER STORAGE CHANGES IN THE SACRAMENTO AND SAN JOAQUIN RIVER BASINS: GROUNDWATER DEPLETION IN THE CENTRAL VALLEY

Our most recent regional study is of the combined Sacramento and San Joaquin River basins in California. This 154,000 km^2 region includes California's major mountain water source, the snowpack in the Sierra Nevada mountain range, as well is its primary agricultural region, the Central Valley (~52,000 km^2). We selected this region for study due to its socioeconomic importance for California and for the Nation. This research shown here was presented in December 2009 at the Fall Meeting of the American Geophysical Union (AGU) conference held in San Francisco. It is currently in preparation for submission to a peer-reviewed journal.

Figure 6 (upper left) shows the change in total water storage (all of the snow, surface water, soil moisture and groundwater) for the combined Sacramento- San Joaquin drainage area. The drought conditions since 2005 are evident in the figure. During the 66-month time period studied (October 2003-March 2009), water storage in the basins decreased by 31.3 km^3, or roughly the volume of Lake Mead.

As I mentioned earlier, in order to estimate only the groundwater storage changes in the region, mass changes in the other major water stores (snow, surface water, soil moisture) must be estimated and removed. Soil moisture is largely unmeasured in the United States. Consequently, we estimated and removed the soil moisture signal using the average of three different soil moisture simulations for the corresponding time period, taken from advanced hydrological models, and run at the NASA Goddard Space Flight Center (upper right). The loss of soil moisture during the study period accounted for 1.7 km^3 of the 31.3 km^3 total. Reservoir storage data (lower left) were compiled from the state CDEC website, and accounted for 7.6 km^3 of water loss. The snowpack estimates, or its snow water equivalent (lower right), were obtained from the National Operational Hydrologic Remote Sensing Center (NOHRSC), and are a combination of both observations and advanced simulation models. The NOHRSC data represent the best estimate of the Sierra snowpack currently available. These data show a decrease of 1.7 km^3 during the study period. The results the total water storage, snow, surface water, soil moisture, and groundwater (discussed next) are summarized in Table 1. Note that the trends reported are for the specified time period, which was selected to maximize the overlap among the various datasets used in the study.

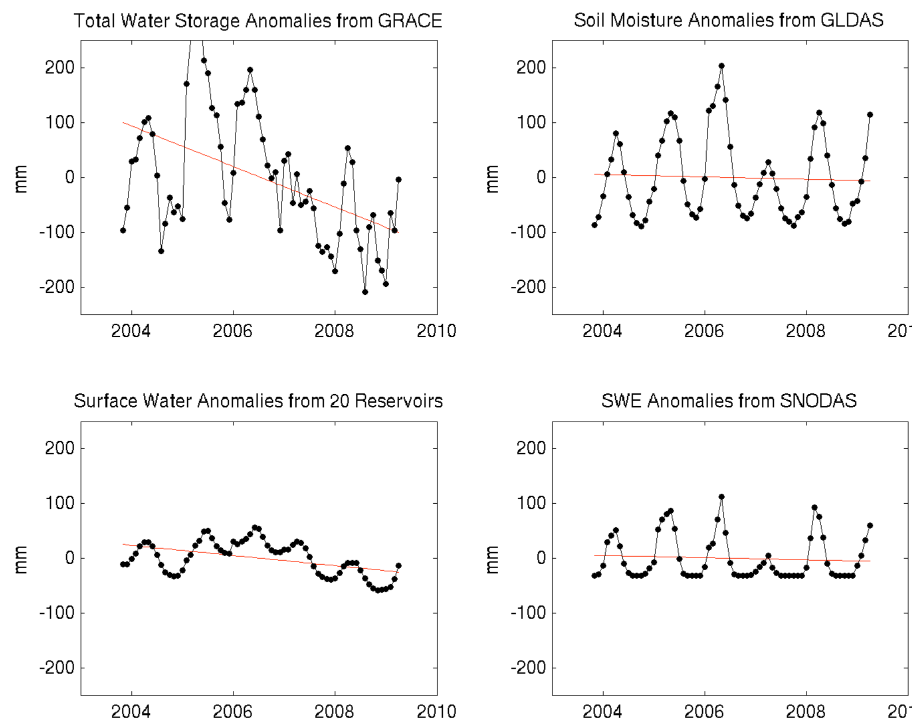

Figure 6. *Upper left: Total water storage change in the Sacramento-San Joaquin River basins from GRACE (anomalies, in mm). Solid line is trend. Upper right: soil moisture anomalies. Lower left: surface water anomalies. Lower right: snow water equivalent anomalies*

Since the total water storage change in the Sacramento and San Joaquin basins is the sum of the snow, surface water, soil moisture and groundwater changes, subtracting the first three of these components from the total (observed by GRACE) yields the groundwater storage change (Figure 7). Table 1 shows that during the study period, groundwater storage changes accounted for 20.3 km^3 of the total water loss. We assume in this work that nearly all of the groundwater loss occurs in the Central Valley, since the other major geological features in the combined basins, that is, the mountain ranges surrounding the Valley, have limited capacity to store groundwater.

The picture that emerges from this analysis is consistent with the U.S.G.S. study, and extends that study from its end date in 2003 to the present. Our estimated loss trends are similar to those of the U.S.G.S., and the steep decline estimated in our study is similar to the those estimated by the U.S.G.S. in previous drought periods. Furthermore, the results are consistent with our understanding of Central Valley farmers' behavior. Facing significant cuts in surface water allocations, farmers are forced to tap heavily into groundwater reserves to attempt to meet their irrigation water demands. Our research also indicates (not shown here) that nearly 75 percent of the 20.3 km^3 of groundwater loss is occurring in the San Joaquin River basin, including the Tulare Lake basin, which is also consistent with ground-based observations (Figure 8) and other studies.

	Trend (mm/yr)	Volume lost (km^3)
GRACE Total Water Storage	-37	31.3
Snow	-2	1.7
Surface Water	-9	7.6
Soil Moisture	-2	1.7
Groundwater	-24	20.3

Table 1. *Trends in the major water storage components in the combined Sacramento-San Joaquin river basins (left column). Volume lost for the study period (right column).*

WHERE DO WE GO FROM HERE?

As you know, California's water future is highly uncertain. Climate change may drive the Sierra snowpack close to zero by the end of the century, while our population will continue to grow. Unfortunately, the Colorado River basin faces a similar plight (Figure 9). It is not hard to imagine that water may emerge as one of the key political issues in the decades to come. Perhaps that time is now. Will water be the 'oil of the future?'

Maybe.

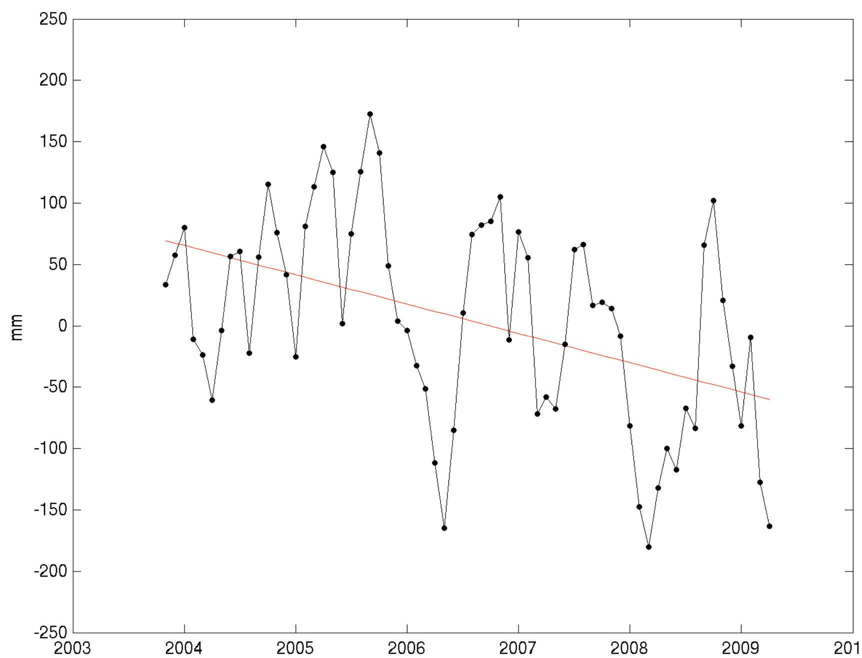

***Figure** 7. Groundwater storage changes in Central Valley. Red line is the trend for the study period (-24 mm/yr). Total groundwater loss of the 66 month period is 20.3 km^3*

Given the importance of water, both now and in the future, the U. S. must significantly accelerate its predictive capabilities in order to address the pressing issues we will soon face. Will we have enough water to supply our growing population? Will there be enough water to sustain agricultural activity? Is there enough water and land to support biofuel production? How will declining snowpack affect hydropower in the American West? How will changes in extreme events such as flooding and drought affect California? How can water management best adapt to these changes in climate, snowpack, population and hydrologic extremes? Agencies like NOAA, the National Weather Service, and NASA, are responding, but slowly given current economic constraints. I contend that a significant investment in hydrologic prediction, observation and research must be made, now, in order to build the intellectual infrastructure to ensure the security of our nation in the decades to come.

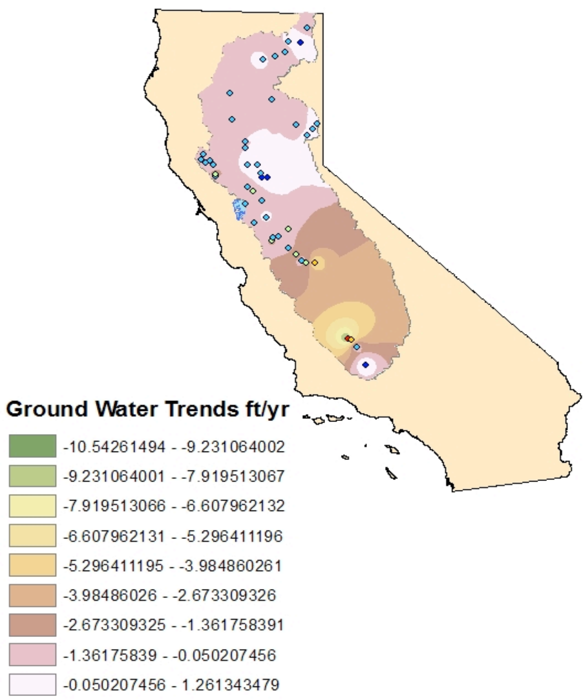

Figure 8. *Observed trends in groundwater storage in the Sacramento and San Joaquin River basins for the 66 month study period.*

My own contribution to this effort is through leadership at the state and national levels. I am the founding director of a new modeling center at UC Irvine called the UC Center for Hydrologic Modeling. Our goal is to develop a very high-resolution hydrological model for the state that includes all major components of the natural (snow, ice, surface waters, soil water, groundwater) and managed (reservoirs, aqueducts, groundwater withdrawals) water cycle that can be used to test solutions and provide answers to the questions above. Another goal is to provide a forum for water managers, practitioners, environmental decision makers, and center researchers, to transfer knowledge, provide training, and develop meaningful collaborations that can advance water management in our state.

I am leading a similar effort at the national level. This activity, called the Community Hydrologic Modeling Platform (CHyMP), is unfunded, but is highly regarded by the National Science Foundation and other agencies such as NASA and NOAA. Both the UC Center and the CHyMP effort will require sustained funding at the state and national levels. Again, I am already devoted to the cause, but I need your help to identify the resources to ramp up and sustain these critical activities. Students must be trained at all degree levels. New modeling paradigms must be developed that can easily accommodate ground-based observations, emerging sensor technologies, and satellite observations like those from GRACE. There is much work to be done.

I hope that I have convinced you that advanced technologies such as the GRACE mission can make an important contribution to the future of water management. I will be happy to work with your staff to spread the word about the potential of GRACE so that it can be fully utilized in water prediction and management. However, recall that GRACE will last, at best, another 3-5 years. The follow-on mission, known as GRACE 2, is not slated for launch until 2020. Assuming the usual delays, we can expect a gap of at least a decade in GRACE water storage data. If your committee believes, as I do, that GRACE is invaluable in order to adapt water management to changing climate, then please do what you can in Congress to help increase the priority of the GRACE 2 mission.

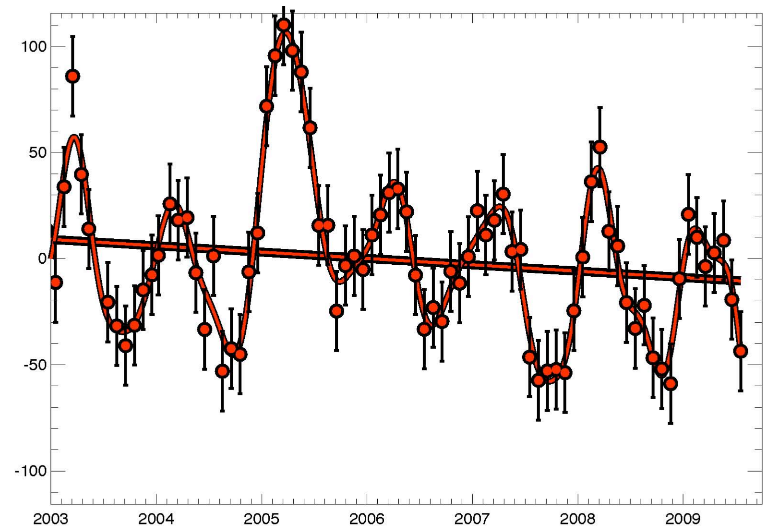

Figure 9. *Water storage changes in the Colorado River basin from GRACE (mm). Straight line shows decreasing trend for the time period.*

I thank you once again for the opportunity to testify.