Introduction

NASA’s Gravity Recovery and Climate Experiment (GRACE), which is a joint mission of the United States and Germany, uses a pair of coupled satellites to measure spatial and temporal changes in the Earth’s gravity field. From these data, estimates of changes (time-variable anomalies) in mass are derived. In turn, the mass changes are attributed primarily to changes in water content (Tapley et al. 2004; Tiwari et al. 2009; Rodell et al. 2009; Famiglietti and Rodell 2013). Changes in water mass can arise from several hydrologic components, including soil moisture, surface water, snow and ice, and groundwater storage. Surface water and snow water equivalent contributions to total mass changes are estimated using auxiliary datasets and models and subtracted from GRACE-derived estimates of change in water mass. The residual is attributed to subsurface water storage changes. Assuming that soil moisture changes (trends) are negligible or can be estimated allows volumetric groundwater storage depletion to be identified (noting that fluid density provides a straightforward linkage between water mass and water volume).

GRACE has provided useful information about global groundwater depletion. In particular, the GRACE results have been highly effective in getting large numbers of people to start thinking about groundwater and the sustainability of its use. GRACE’s color-coded maps show at a glance where groundwater is being rapidly depleted around the globe. At the same time, oversimplifications in the interpretations of GRACE results have promulgated some misperceptions about groundwater resources. We address these misperceptions and discuss how, with appropriate caveats on their limitations, GRACE results can be placed in a stronger hydrogeologic context.

GRACE Provides a One-Dimensional Indicator of the Status of a Large Three-Dimensional Groundwater Body: It Is Not a Management Tool

GRACE data provide precise monthly estimates of total change in water storage (accuracy of 1.5 cm equivalent water height) over a large footprint—a resolution on the order of 200,000 km² (Famiglietti and Rodell 2013). Many aquifers that play a critical role in meeting human needs, however, occur at scales of 100s or 1000s of km², much smaller than the GRACE footprint. The low spatial resolution of GRACE limits its ability to provide groundwater depletion data at a scale appropriate for water managers to use effectively. As such, claims that GRACE is a water management tool (e.g., Famiglietti and Rodell 2013) should be made with great modesty. GRACE does provide a “big picture” view that might be appropriate input for setting broad regional or national policies. It also provides compelling evidence of the need for better groundwater management.

Famiglietti and Rodell (2013) recommend that the next-generation missions (beyond the GRACE Follow-On mission planned for 2017) aim for a finer resolution, on the order of 50,000 km². This is still a coarse resolution relative to water management. Neither the present nor next-generation resolutions seem adequate to support using GRACE-derived estimates as replacements for direct observations of groundwater levels in monitoring networks. This is akin to other debates about satellite vs. ground-based measurements (e.g., Famiglietti et al. 2015; Fekete et al. 2015). Of course, where no or minimal monitoring networks exist, GRACE-derived data can provide some valuable regional insight and assessments (e.g., Hu and Jiao 2015).

Many Key Issues Associated with Groundwater Pumping Are Not Addressed by GRACE Data

Among the issues not addressed by GRACE are saltwater intrusion, land subsidence, how streams and other surface water bodies are being affected by groundwater
pumping, and how water quality is changing. For example, capture is societally and hydrologically more important than reductions in groundwater storage in many areas, because it directly affects surface water and causes streamflow depletion (Konikow and Leake 2014). Addressing these concerns requires much more detailed data from wells, springs, streams, geophysical surveys, and other sources.

GRACE data do not provide any information about changes in groundwater flow systems. GRACE is unable to decipher flow directions or velocities, their changes over time, or actual drawdowns. Because large head changes in confined aquifers may be associated with very small volumetric depletions, GRACE would rarely be useful in monitoring or evaluating head changes in such confined aquifer systems. Nor can it distinguish elastic (recoverable) storage from nonelastic (nonrecoverable) storage and releases.

Analysis of GRACE Data Cannot Assess or Apportion the Contributory Factors Causing Groundwater Depletion

Not all groundwater depletion arises from well pumpage. In some aquifers, long-term drainage and water-table declines resulting from climate change—perhaps thousands of years ago—can cause depletion under predevelopment conditions. For example, in the extensive Nubian aquifer system in North Africa, the natural rate of groundwater depletion was about $2.7 \text{ km}^3/\text{year}$ in the mid to late 20th century (Voss and Soliman 2014).

A more common contributory factor is normal baseflow recession, which occurs naturally after precipitation events or wet weather periods end, or during periods of extended drought. This can cause areally extensive water-table declines over time periods of weeks to months that result in volumetrically significant storage depletion. This depletion is typically recoverable as weather cycles change.

In using GRACE data to assess groundwater depletion in the Colorado River Basin during the 9-year period from December 2004 through November 2013, Castle et al. (2014) found that groundwater accounted for $50.1 \text{ km}^3$ of the total $64.8 \text{ km}^3$ of freshwater loss, with the rate of depletion of groundwater storage averaging $5.6 \text{ km}^3/\text{year}$. They attribute all of the groundwater depletion to overallocation of the Basin water supply. Castle et al. (2014) do not indicate that baseflow recession (and its accompanying water-table decline) may be responsible for some or even most of the depletion during this extended drought period. They report that in the Lower Basin, which includes Arizona and small adjacent parts of Nevada and New Mexico, groundwater losses during February 2010 through November 2013 averaged $5.8 \text{ km}^3/\text{year}$. For comparison, the total reported groundwater withdrawal in Arizona and the Las Vegas valley of southern Nevada was just $3.6 \text{ km}^3/\text{year}$ in 2010 (Maupin et al. 2014; Guillory 2012). The estimated total groundwater depletion of $50.1 \text{ km}^3$ is equivalent to a total loss of about $8 \text{ cm}$ (3 inches) of water over the area of the entire Colorado River Basin (an average water-table decline of about $0.5 \text{ m}$, assuming an average specific yield of 0.15).

A big difference between storage depletion from pumping and baseflow recession is the latter is more readily recoverable. In fact, baseflow recession and its accompanying water-table decline are normal cyclical phenomena, though intensified during extended droughts.

Total Volume of Groundwater Is Much Less Important Than Many Other Attributes of a Groundwater System and Is Meaningless for Many (Most) Aquifer Systems

GRACE results have led to calls for investing major resources to assess the total volume of groundwater in storage (e.g., Famiglietti 2014; Richey et al. 2015a; Postel 2015). In our opinion, numerous other information needs are of much higher priority.

The interest in the total volume of groundwater stems from a desire to place GRACE estimates of storage depletion in a total storage context. Yet, the total volume of groundwater storage is almost invariably a misleading indicator of groundwater availability. Aquifer permeability, water quality, cost of drilling wells, and cost of lifting water all limit the volume of water that is economically recoverable and usable in practice. In many confined aquifer systems, the mass and volume of depleted groundwater is relatively small, yet declines in water levels are very large and severely impact water productivity.

In addition to considerations about the economic recoverability of groundwater, depletion of just a small part of the total storage volume (in some cases, only a few percent) can cause harmful land subsidence and surface water depletion. These external effects can become the limiting factors to development of the groundwater resource much sooner than the storage depletion itself. For example, the Central Valley of California and Houston, Texas, have vast groundwater resources, yet land subsidence caused expensive conversions to partial reliance on surface water after only a relatively small depletion of the total groundwater resource. Alley (2007) gives examples of well-known areas in which the effects of groundwater pumping on surface water resources and aquatic ecosystems have become limiting factors to groundwater development after only a small percentage decrease in total groundwater storage.

Different Indicators from GRACE Results Apply to Renewable vs. Nonrenewable Aquifers

A common indicator of the degree of stress imposed by groundwater withdrawal upon groundwater resources is the ratio of annual groundwater use to average annual recharge, often expressed as a percentage. This ratio is referred to as the renewable groundwater stress (RGS) indicator by Richey et al. (2015b). Traditionally, values for “use” in the numerator of this ratio were based on
estimates of groundwater withdrawals. GRACE data allow substitution of the estimated rate of groundwater depletion (dGW/dt) for the “use” term (Richey et al. 2015b). This more appropriately reflects consumptive use rather than withdrawals. Using either definition of use, the indicator is applicable only to aquifers with renewable groundwater (Margat and van der Gun 2013). Even then, the RGS indicator is based on a flawed concept that the degree of aquifer stress is determined by comparison of use to average annual recharge. Withdrawals are balanced by capture, as well as by storage depletion, and not by average annual recharge. Such indicators are thus susceptible to the “water-budget myth” (Bredheoef et al. 1982).

The GRACE results are perhaps most easily interpreted for nonrenewable aquifers in arid climates, as this is more analogous to a groundwater mining situation where changes in other hydrologic stocks are relatively minor. Even for nonrenewable aquifers, however, water levels are almost invariably a more limiting factor than total volume. The decline of water levels may reach several hundreds of meters in confined aquifer systems after having withdrawn only a small fraction of the total water volume. Some nonrenewable aquifers also have critical surface water features at oases and springs (Voss and Soliman 2014).

One can envision a groundwater model analysis of a nonrenewable aquifer based on appropriate data on heads, hydraulic properties, and boundary conditions that estimates an acceptable overall change in groundwater volume (so-called exploitable storage) for a given scenario. GRACE data that track overall groundwater depletion could then supplement measurements of water levels and other hydrologic monitoring to evaluate aquifer status over time. The key point is that a hydrogeologic analysis that goes well beyond estimating groundwater storage characteristics is needed to make meaningful interpretations and management decisions, even in the case of nonrenewable aquifers.

Concluding Remarks

Groundwater is being severely depleted in many areas, but the world is not running out of groundwater. Even aquifers with severe depletion are unlikely to dry up—depletion rates will eventually slow down due to both economic and hydraulic principles. Nevertheless, depletion of groundwater stocks is a serious problem in many areas.

Given the media attention to GRACE results that highlight areas of groundwater depletion, it is important not to convey the impression that all future groundwater development is bad. There are areas, such as sub-Saharan Africa, where increased groundwater use could make substantive improvements in human well-being. Moreover, groundwater “mining” is inherently unsustainable, yet might be beneficial and appropriate for extended periods of time, depending on local and regional economic and social considerations (Foster and Loucks 2006). Hydrogeologic analyses and monitoring are critical for developing a rational and beneficial water policy.

GRACE is among the latest “tools in the toolbox” available to hydrogeologists to evaluate groundwater resources. Planned improvement in the resolution of satellite-based gravity measurement technology will certainly increase the value and utility of this tool. But all hydrologic “tools” have their strengths and limitations. GRACE, a powerful tool in some respects, is no exception to this rule.

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