Amazing GRACE: A Satellite Mission Helps Us Measure and Track Water Underground

Fresh water is essential to life on Earth. People, plants, and animals require it to survive. Modern society relies on it for a host of important activities, such as irrigating crops, running sanitation systems, and supporting a vast number of industrial processes. Consequently, tensions between water supply and demand are of increasing concern in the United States and around the world, especially as climate change makes the supply of fresh water less reliable.

"Water availability is one of the main issues for global security," says Isabella Velicogna, a geophysicist at the University of California, Irvine (UCI). Indeed, in a 2014 piece in *Nature Climate Change*, hydrologist Jay Famiglietti, executive director of the Global Institute for Water Security at the University of Saskatchewan, cautioned that "further declines in groundwater availability may well trigger more civil uprising and violent conflict in the already water-stressed regions of the world, and new conflict in others."[1]

Fresh water includes the surface water in rivers, lakes, streams, and reservoirs as well as groundwater—water reserves found underground. Worldwide, nearly 2 billion people depend on this underground supply as their primary source of fresh water, and much of the world's agriculture relies on groundwater as well. While groundwater is not the main source of fresh water for most of the United States, "it's an insurance policy for many key human activities," says Nick Brozović, policy director at the Daugherty Water for Food Global Institute at the University of Nebraska. That insurance policy is seeing a greater number of claims as surface water supplies become unreliable. In some areas of the country, 1,000-year-old underground fresh water is being used to irrigate crops and provide drinking water to farms, homes, and businesses as well as to support industry and mining and help fight fires in local communities.

As withdrawal of this precious resource increases, land in some regions is sinking, wells have to be drilled deeper, and tapped aquifers' ability to provide for communities downstream is diminishing. The question looms: Are we at risk of depleting these groundwater reserves faster than they can be replenished?

In many places, it has been a difficult question to answer. Groundwater is hidden under the Earth's surface, in some cases in deep aquifers far below ground. For more than a century, groundwater levels have been determined by drilling monitoring wells and surveying land subsidence associated with groundwater withdrawals. These techniques, still in use today, yield

[1] Famiglietti, J. 2014. The global groundwater crisis. *Nature Climate Change* 4:945–948. https://doi.org/10.1038/nclimate2425 (accessed February 4, 2020).

accurate information, but they are time consuming and can be expensive to use across large areas. In the United States, state managers have often relied on limited measurements of how much water they have pumped out of an aquifer to estimate what might remain—if they measured groundwater at all. In some developing countries, groundwater monitoring has been simply out of reach. And some aquifers are in such remote, hard-to-access areas that monitoring is impractical. For these reasons, getting a regular, comprehensive, and accurate picture of groundwater withdrawal in large aquifers around the world has been nearly impossible. Scientists have had no reliable way to measure changes in groundwater levels over time.

Then, in the late 1990s, a new perspective on this global issue became possible. Scientists and engineers in the United States and Germany embarked on an ambitious initiative to map the Earth's gravity. They wanted to see—with extraordinarily high precision—how the Earth's gravity changed over time. They predicted that two satellites working in tandem could do just that. The data collected would allow them to infer large-scale movements of mass, such as ocean circulation patterns and changes in ice sheets. In addition, they hypothesized that the data could also point to important changes in terrestrial water storage—the sum of groundwater, soil moisture, surface waters, and snow and ice.

How would this mission work? The satellite pair, called the Gravity Recovery and Climate Experiment (GRACE), would circle the Earth at the same altitude, but about 137 miles (220 km) apart. They would use microwave signals to measure, within a hair's width, any change in the distance between them. For example, as the first satellite moved over a mountain, the landmass would strengthen the Earth's gravitational pull on the satellite, causing it to accelerate. The microwave ranging system would track the change in the distance between the two satellites as the first one sped ahead and then slowed once it moved beyond the gravitational pull from the landmass below. Then, as the second satellite passed over the same landmass, the change in distance would be detected again. Global positioning system (GPS) instruments would identify where above the Earth the satellites were traveling. With each orbit, the corresponding maps from the combined microwave and GPS data would show how the gravity of the world physically changed, if it changed at all. It would be the first measurements from space of gravity variations over time and the data would be available to anyone.

Would that approach really allow researchers to track changes in water storage? In 1997, a National Research Council report, *Satellite Gravity and the Geosphere,*[2] concluded that a GRACE-type mission could indeed estimate changes in water storage over spatial scales of several hundred miles. Research teams at The University of Texas at Austin (UT Austin), where Byron Tapley, the principal investigator for GRACE, was a professor, and at the Jet Propulsion Laboratory, where Mike Watkins was the project scientist, developed more refined models of how this research could work.

[2] National Research Council. 1997. *Satellite Gravity and the Geosphere: Contributions to the Study of the Solid Earth and Its Fluid Envelopes*. Washington, DC: The National Academies Press. https://doi.org/10.17226/5767.

Matthew Rodell, chief of the Hydrological Sciences Laboratory at the NASA Goddard Space Flight Center in Greenbelt, Maryland, was a graduate student at UT Austin at the time the GRACE mission was in development. He and Famiglietti, who was then Rodell's Ph.D. supervisor at the university, published two reports in the American Geophysical Union's *Water Resources Research* journal in 1999[3] and 2001[4] predicting that GRACE would likely detect changes in water storage in areas of at least 77,220 square miles (200,000 km^2). Soil moisture represented the largest component of month-to-month terrestrial water storage variations, followed by changes in groundwater. Could the data distinguish between the two? In a report published in April 2002, Rodell and Famiglietti concluded that GRACE could detect groundwater storage specifically, and that GRACE could be used to quantify changes in aquifer storage.[5]

One month prior to that report's publication, on March 17, 2002, the two GRACE satellites reached orbit. A joint mission between NASA and the German Aerospace Center, the twin satellites were nicknamed Tom and Jerry after the cartoon cat and mouse.[6] They took 30 days to complete their global coverage and start again on a new gravity map of the world, offering monthly snapshots of the Earth's gravity profile.

The first surprising discovery did not involve groundwater. Researchers used the GRACE data to estimate how fast the ice sheets on Greenland and Antarctica were melting and realized the rates were in terms of gigatons of water per year.[7,8] Scientists knew the ice sheets were thinning, but "they did not know how to measure it precisely and comprehensively," says Velicogna, who led that research.

"The next big discovery was the massive groundwater depletion in northern India," Rodell says. Rodell worked with Velicogna and his former adviser, Famiglietti (now, like Velicogna, at UCI) to evaluate the data from GRACE over the large porous aquifers of northern India in a 2009 paper in *Nature*.[9] The Indian government was aware that the irrigation of rice fields and other crops with groundwater from the region had lowered the water table. "But they had no idea that the

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[3] Rodell, M., and J. S. Famiglietti. 1999. Detectability of variations in continental water storage from satellite observations of the time dependent gravity field. *Water Resources Research* 35(9):2705–2723. https://doi.org/10.1029/1999WR900141 (accessed February 4, 2020).
[4] Rodell, M., and J. S. Famiglietti. 2001. An analysis of terrestrial water storage variations in Illinois with implications for the Gravity Recovery and Climate Experiment (GRACE). *Water Resources Research* 37(5):1327–1339. https://doi.org/10.1029/2000WR900306 (accessed February 4, 2020).
[5] 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. https://doi.org/10.1016/S0022-1694(02)00060-4 (accessed March 9, 2020).
[6] See https://grace.cnes.fr/en/grace-0 (accessed June 5, 2019).
[7] Velicogna, I., and J. Wahr. 2005. Greenland mass balance from GRACE. *Geophysical Research Letters* 32(18). https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2005gl023955 (accessed October 4, 2019)
[8] Velicogna, I. 2009. Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophysical Research Letters* 36(19). https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2009GL040222 (accessed October 4, 2019)
[9] Rodell, M., I. Velicogna, and J. S. Famiglietti. 2009. Satellite-based estimates of groundwater depletion in India. *Nature* 460:999–1002. https://doi.org/10.1038/nature08238 (accessed March 9, 2020).

groundwater losses were so severe," Rodell says. A similar paper published around the same time in *Geophysical Research Letters* confirmed their findings. The data helped show that India had been conducting the largest groundwater withdrawal in human history. "These papers were largely responsible for both alerting the world to the dangerous situation in India and making scientists aware of just how valuable a tool GRACE was for hydrology," Rodell says.

GRACE data proved to be most effective in areas with large groundwater depletion—or its opposite, recovery. They have shown how changes in water usage can help overburdened aquifers replenish, even when the surface is hard. Some aquifers can recharge quickly if, for example, the surface layers are porous gravel and sand. In other areas where the surface layers are granite or other hard rock or if the aquifers are deep, it takes a long time for them to replenish.

Such is the case in the western and southern regions of India. In contrast to the findings in the north of India, where groundwater was being depleted, satellite data confirmed ground observations showing that aquifers in the western and southern regions of India were replenishing[10] despite the hard surface above them. This was largely due to the implementation of government policy changes at the state level, which had grown from community efforts to change groundwater usage approaches.[11]

Models of water storage in a region, another critical method for assessing water availability, need to take into account all of the sources of fresh water—surface water, snow cover, soil moisture, and groundwater. "The aquifer is a series of complicated paths from the surface to deep underground and if the soil is saturated in the first place, there will be runoff that can lead to flooding of rivers, but if there is a little rain every day the aquifer can slowly recharge," Tapley says. GRACE data have helped here, too. "Earlier models didn't include groundwater in the Amazon basin, for example, and then once GRACE aquifer data were included the model became better."

Though the GRACE mission ended in 2017, 15 years after its launch and 10 years past its expected lifetime, that's not the end of GRACE's story. A new pair of satellites, GRACE Follow On, or GRACE-FO, launched aboard a SpaceX Falcon 9 rocket on May 22, 2018.[12] The pair is extending the data record begun by its predecessor, tracking changes in underground water storage as well as water levels in large rivers and lakes, soil, ice sheets, and glaciers. At the same time they are testing new technology that researchers hope will improve the precision of

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[10] Bhanja, S. N., A. Mukherjee, M. Rodell, Y. Wada, S. Chattopadhyay, I. Velicogna, K. Pangaluru, and J. Famiglietti. 2017. Groundwater rejuvenation in parts of India influenced by water-policy change implementation. *Scientific Reports* 7:7453. https://www.nature.com/articles/s41598-017-07058-2 (accessed February 4, 2020).

[11] Mukherjee, A., and S. N. Bhanja. 2019. An Untold Story of Groundwater Replenishment in India: Impact of Long-Term Policy Interventions. In *Water Governance: Challenges and Prospects*, edited by A. Singh, D. Saha, and A. Tyagi. Springer Water. Springer, Singapore. https://link.springer.com/chapter/10.1007/978-981-13-2700-1_11 (accessed February 4, 2020).

[12] See https://www.nasa.gov/missions/grace-fo/overview (accessed February 4, 2020).

GRACE's measurements.

The GRACE mission's work remains critically important. As the availability of fresh water changes in response to natural and human-made pressures, we need to understand what levels of use on the surface and underground are sustainable.[13] GRACE-FO is providing data that will help assess the status of this resource that is so essential to life. Then we can make informed decisions, striving to ensure its availability for future generations.

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[13] Richey, A., B. Thomas, M. Lo, J. Reager, J. Famiglietti, K. Voss, S. Swenson, and M. Rodell. 2015. Quantifying renewable groundwater stress with GRACE. *Water Resources Research.* https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015WR017349 (accessed February 4, 2020).