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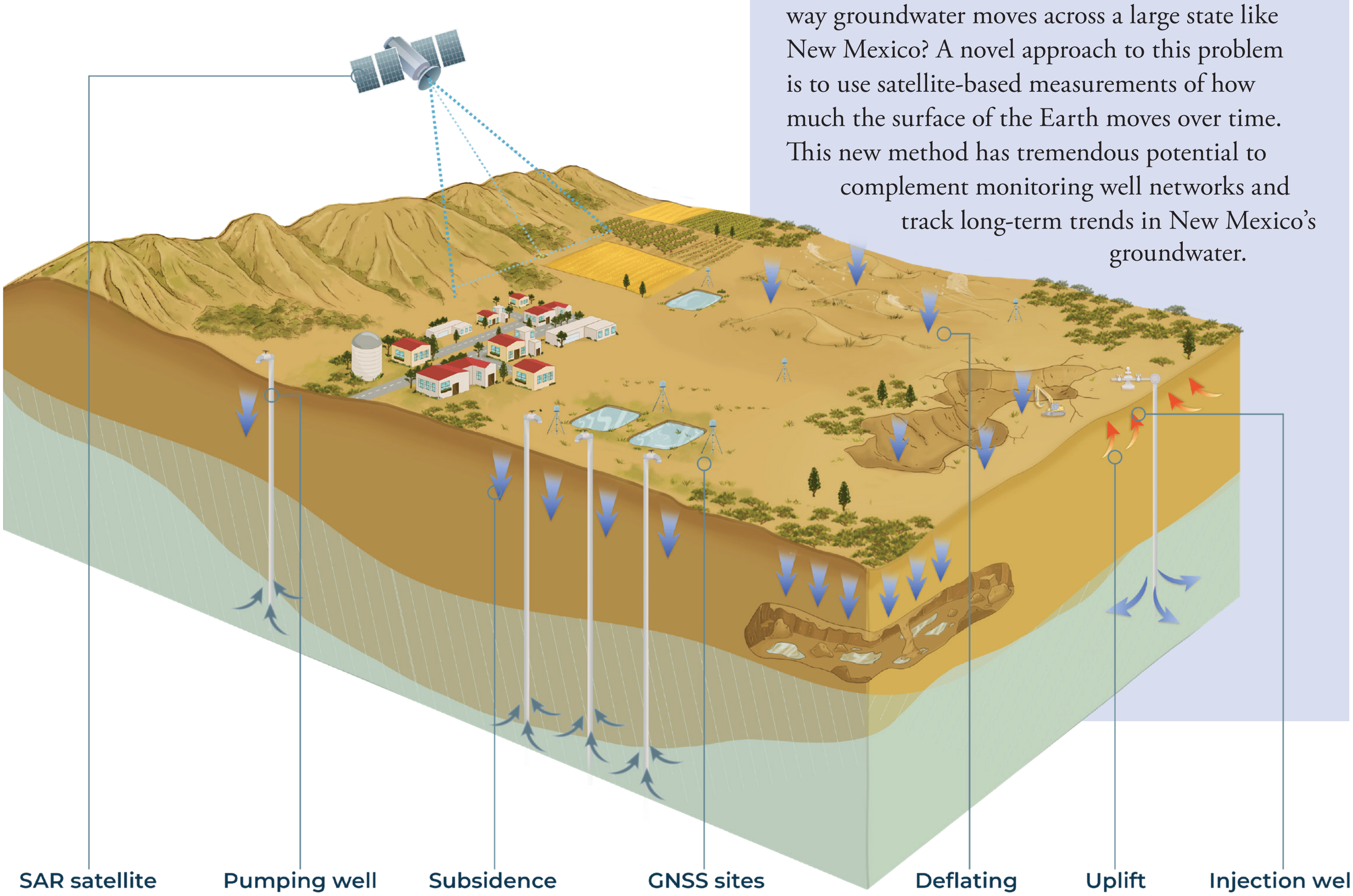
New Mexico Moves: Radar Satellites Record What's Up or Down with Water and More

Water is our most important resource, but much of our state's water is hidden underground. How do we understand the way groundwater moves across a large state like New Mexico? A novel approach to this problem is to use satellite-based measurements of how much the surface of the Earth moves over time. This new method has tremendous potential to complement monitoring well networks and track long-term trends in New Mexico's groundwater.



A conceptual sketch of a land surface and subsurface aquifer with a synthetic aperture radar (SAR) satellite overhead, which is generating radar waves that come down to the ground and reflect back to the satellite. Repeat scans measure how far up or down the ground moves. GNSS, or GPS, sites measure deformation at points. Different water uses, such as agricultural or municipal wells, and other processes that produce measurable surface deformation, such as wind-driven sediment movement and surface or subsurface mining, are also illustrated. Blue arrows represent surface subsidence and red arrows represent surface uplift. Visit **geoinfo.nmt.edu/publications/periodicals/earthmatters** to view a zoomable PDF version of this issue of *Earth Matters*.

The term "groundwater" likely evokes an image of a wellhead, maybe with someone standing next to it, taking a measurement or turning on a pump. This is, in fact, accurate—nearly everything we know about groundwater comes from information gathered from wells, such as water level measurements and water chemistry samples. Compared to the size of an *aquifer,* a term used for a volume of sediments and rocks in the subsurface that holds fresh water, the size of a single well is as tiny as a pinprick in a pillow.

Aquifers usually stretch for miles or even hundreds of miles in all directions. Classic examples include the Ogallala Aquifer of the High Plains of eastern New Mexico, the Santa Fe Group Aquifers along the Rio Grande in New Mexico, and the Central Valley Aquifer in California.

While a single pumping well can impact water levels in an aquifer locally—up to hundreds of yards away from the well site—in reality, there is rarely only a single well removing water from an aquifer. Farms typically have wells to pump groundwater for crops and livestock, and larger municipalities may have multiple wells. Additionally, water from streams and rivers drains into and out of shallow aquifers at various locations along the stream's length. All of this can lead to a mismatch between the small spatial scale at which we **monitor** groundwater—at one or several points, like wells—and the much larger spatial scale, that of the entire aquifer, at which we **manage** groundwater. Making the challenge harder is the fact that we often don't realize until it's too late that our local-scale monitoring observations have an inherent spatial bias that may not accurately reflect the large-scale changes that need to be managed in a given aquifer.

However, subsurface changes in an aquifer impact the Earth's surface over time and can be observed as small but measurable upward (uplift) or downward (subsidence) movement of the ground level. Over the past two decades, scientists have leveraged this phenomenon to develop better technologies to measure and monitor groundwater through ground movements. To help us overcome the scaling issue and develop a more holistic view of aquifers, traditional small-scale, well-based measurements of groundwater levels and storage in aquifers have begun to be supplemented by broader-scale measurements of changes at the ground surface.

Technologies from *geodesy*—the science of measuring Earth's shape, orientation, and gravitational field—have been successfully applied to link changes in land surface elevation (i.e., the ground) and the gravity field with aquifer depletion or recharge on scales ranging from a few to hundreds of miles. Historically, these measurements were extremely labor-intensive, but with the introduction of satellite-based techniques, increased computational capacity, and improved power and telemetry systems, measurements of surface elevation have become more automated and streamlined. Modern technologies include radar satellites that estimate changes in surface elevation and permanent, high-precision Global Navigation Satellite System (GNSS) stations, including the GPS constellation of satellites.

In this issue of *New Mexico Earth Matters*, we'll present examples from two recently completed, NASA-funded studies that utilized these techniques and that illustrate the power of satellite-based geodesy. One is a New Mexico-wide inventory of surface deformation using InSAR analysis of data from 2018 to 2020, which shows the promise of these tools for understanding groundwater trends in small aquifers from space. The other is focused on a single injection well that leaked water into a water-bearing rock layer in southeastern New Mexico between 2016 and 2019.

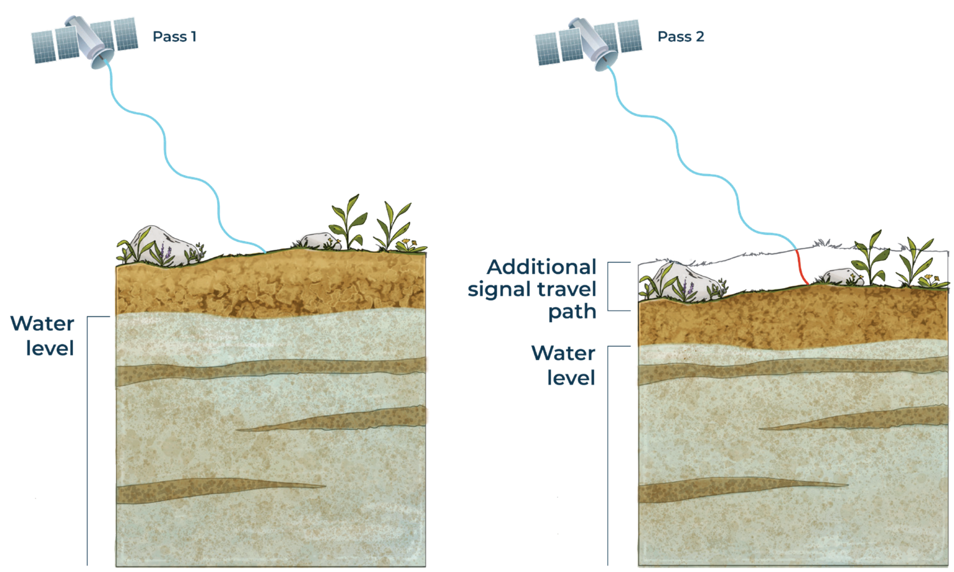
Introduction to InSAR Analysis

Several satellites carry synthetic aperture radar (SAR) systems as they orbit Earth. SAR observations have, for instance, been used to construct elevation maps for the entire globe and to monitor crops, forests, and changes in sea ice. These instruments send out radar signals that bounce off the Earth's surface, then record the radar energy reflected back to the satellite. Because the signals can penetrate clouds, SAR data are useful for observing ship traffic or changes in sea ice, simply by looking at how much of the signal bounces back, which is referred to as the signal amplitude, or strength. The satellites also record the phase of the reflected signal. Because the signals are waves, the comparison of phase signals between two or more passes of a SAR satellite over the same patch of ground is known as "interferometry" (interferometric SAR, or InSAR). When this comparison reveals a phase shift, it tells us the ground is either moving toward or away from the satellite. The details of such analyses are complicated by different noise sources, such as water vapor in the troposphere or ionospheric activity. Furthermore, substantial changes to the land surface, such as the growth of vegetation in agricultural fields and forests, result in too many uncorrelated phase changes, meaning that we cannot get useful information in these areas when applying InSAR.

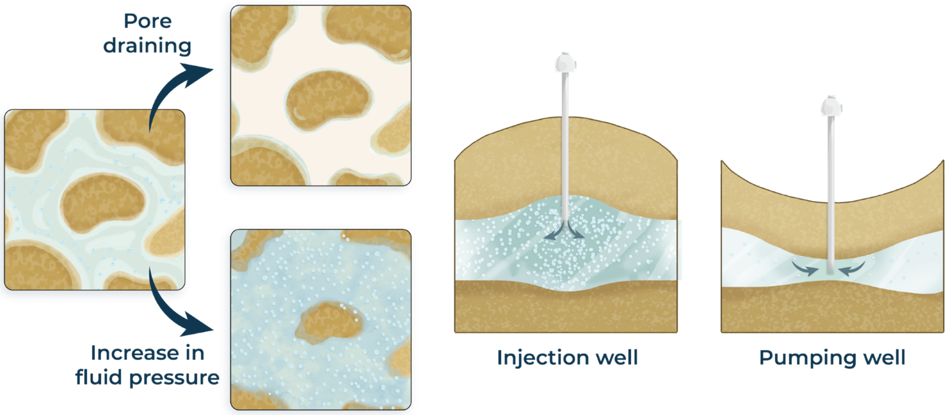
Geodesists have worked to streamline these analyses, allowing for relatively routine measurements of average deformation rates of greater than 5 mm/yr (less than a quarter of an inch per year) over a footprint of a football field.

How Do Changes in Groundwater Levels and Other Processes Change Surface Elevations?

Many processes can drive changes in the elevation of particular parts of the Earth's surface. The easiest to interpret are those related to surface processes, such as the accumulation of blowing sands, landslides,



Schematic of how InSAR works on a subsiding surface, depicting dry soil (brown) and a subsurface aquifer in layered sediment (pale blue). The left panel shows the initial pass of a satellite capturing a radio image of the surface, which includes both the strength of the reflected signal (amplitude) and the phase of the signal as it returns, conceptualized by a blue sine wave. The right panel shows a subsequent radar pass after the water level below the surface has dropped, which lowered the ground surface (indicated by the outline of the original ground surface). This means the radar pulse now takes longer (red part of the sine wave) to reach the surface, resulting in a different phase measurement. The difference between the phase observations is equivalent to the amount the land surface moved away from, or toward, the satellite.



Conceptual diagrams of how changes in groundwater storage lead to surface deformation on the pore scale (left) and the aquifer scale with a pumping well (right). The pumping well diagrams depict an extremely exaggerated case of what happens when water is injected into (left panel) or pumped out of (right panel) a confined aquifer (an aquifer sandwiched between less-permeable rock layers), depicted as such in order to illustrate the physical processes taking place. In reality, these displacements are less than a centimeter—thousands of times smaller than the horizontal scale shown here. As a reminder, the water-bearing layer is filled with both sediment and water.

or human excavations for mines, landfills, and other features. However, subtler changes also occur due to changes in underground fluid pressure and stresses, such as those that might happen in an aquifer. The underground changes can either be reversible (elastic) or irreversible (inelastic).

Irreversible changes occur when something causes the grains of sediment or rock to move in bulk. This usually happens when water is drained out of pore spaces, which are the spaces between grains of sediment. When the pores are filled, the pressure of the water pushes against the grains, helping to support the sediment. When water is removed, that force is removed, and the pores between grains can collapse because the sediment cannot support the weight above it. When this happens, the grains are irreversibly compacted, resulting in a loss of storage space. Even if the aquifer is refilled with water, the grains will not return to their original positions. At the scale of an aquifer, this can lead to *subsidence,* a process characterized by the irreversible downward movement of the surface. This is most common in sediment that contains clay. The clay is weaker than sand grains and is less able to bear a load. Clay-rich sediment is common in lakes, dry playa lakebeds, ocean deltas, and areas called alluvial fans, where sediment is washed out of mountain canyons.

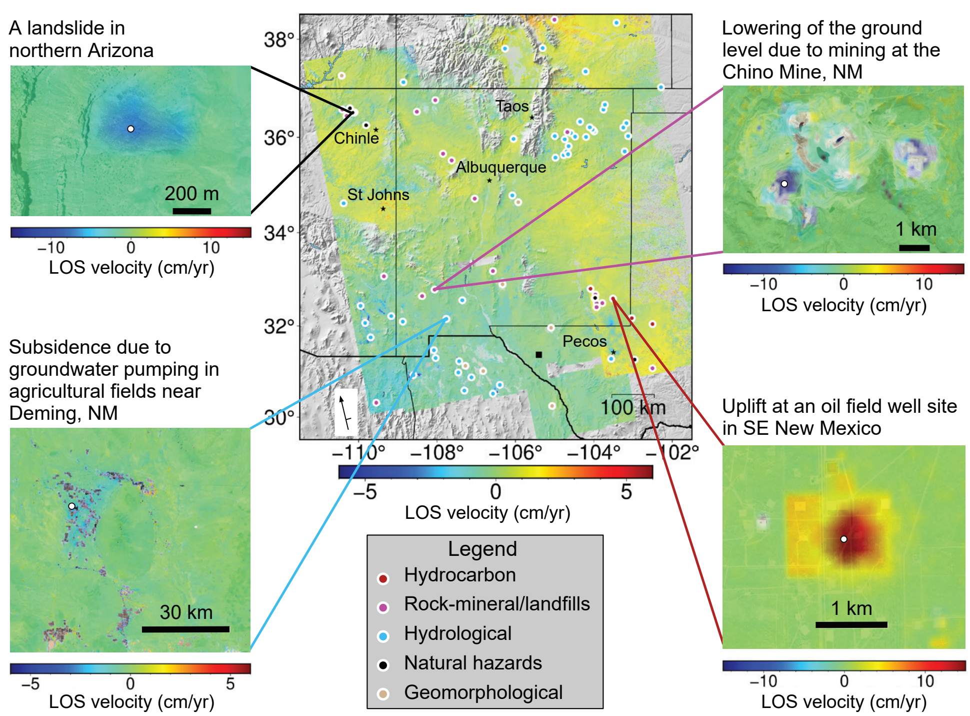
Most famously, the Central Valley of California has subsided by almost 30 feet since the 1950s, largely due to groundwater pumping. However, subsidence driven by groundwater extraction is occurring increasingly across the Basin and Range Province of the American West, as well as in urban areas on deltas worldwide.

The other type of underground change that can occur, known as reversible or elastic change, is driven by a more complex mechanism. Reversible changes are analogous to filling a bicycle tire with air. When you fill a tire with air, there is already air in the tire, but you are pushing more air into it. Two things happen in this process: the air pressure increases, causing the air to become denser, but the tire also stretches in response to that added force. This can also occur in aquifers. If water is added to an aquifer, leading to an increase in water pressure, the water gets very slightly denser in response. The increase in pressure also causes the grains of sediment to be slightly compressed and become smaller—more pore space opens up! If the pressure is reduced, through a pumping well or another "leak," the water density decreases slightly and the pores close again. In dense rock, the amount of storage resulting from pressure changes in water and changes in pore volume is similar. In sediments, most of the storage change occurs through changes in the volume of pores, not water, because water is much less compressible.

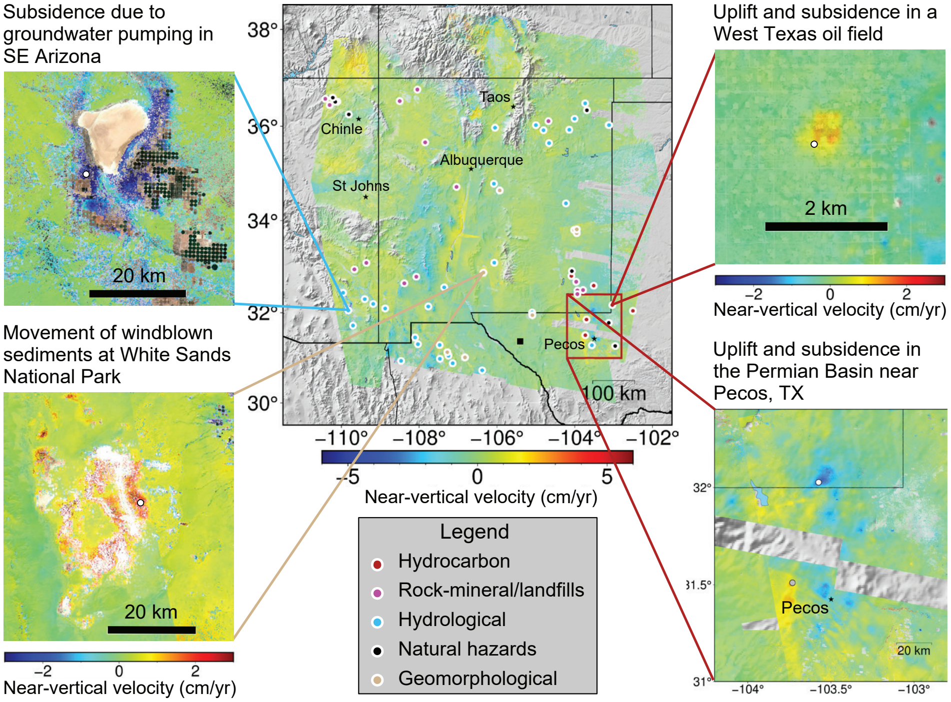
With a tire, we can observe these changes with our eyes and with a tire gauge. In an aquifer, the changes are much smaller. However, over aquifer thicknesses of hundreds of feet, these small changes accumulate until we can measure the changes in surface elevation.

Statewide Velocity Analysis

Line-of-sight (LOS) velocities are estimates of the average speed at which a piece of ground is moving toward or away from the SAR satellites. This is a combination of horizontal and vertical motion of the surface relative to the satellite. To estimate near-vertical velocities, we employ different



In the center, we show a map of the LOS average velocity between 2018 and 2020. Blue colors indicate motion away from the satellite (here, predominantly downward), while yellow, orange, and red indicate motion toward the satellite (here, predominantly upward). The LOS velocity map shows deformation related to oil and gas extraction (deep red circles), mining and landfills (pink), changes in groundwater storage (light blue), landslides (black), and wind-blown sediment movement (tan). The zoomed-in panels show the land surface movement changes in detail at selected sites. Deformation changes through time can be determined via repeated observations (adapted from Graves et al., 2025).



The center panel shows a map of the average rate of ground movement, either up or down, between 2018 and 2020. The map is not accurate in areas with steep topography, such as mountains and badlands. The zoomed-in panels show signals and examples of how specific points in the area are moving through time (adapted from Graves et al., 2025).

strategies to correct LOS observations for the satellite viewing angle.

We have developed LOS and near-vertical estimates of the average rate of land surface movement for several areas in New Mexico and Arizona from 2018 to 2020. Below, we highlight several of these areas where we identified ground motion using SAR information. The images we show have undergone minor corrections to focus solely on the deformation associated with the features we are illustrating and to separate this from the average regional motions illustrated in the central panels of the figures.

The figure at the bottom of page 3 shows the following processes in the satellite LOS: a landslide in northern Arizona moving steadily away from the satellite at around 6.5 cm/yr, apparent lowering of the ground level due to mining excavation activity at the Chino Mine in New Mexico at about 20 cm/yr, subsidence of about 1 to 3 cm/yr around groundwater-irrigated fields near Deming, New Mexico, and uplift at rates of more than 10 cm/yr at an oil field well site in southeastern New Mexico, which is different from the case study discussed in the next section.

Recalculating the LOS velocities to near-vertical velocities helps with the interpretation of the surface changes. The figure at the top of this page reveals the sensitivity to the dynamics of windblown sediments downwind of the dune field at White Sands National Park, which affects the signal at about 1.5 cm/yr. We also observe subsidence related to groundwater pumping in the Willcox Basin in Arizona at 12 cm/yr; in a West Texas oil well field 90 km east-northeast of Midland, with complex movement both upward and downward; and around the Permian Basin near Pecos, Texas, with both uplift and subsidence depending on the point examined on the map.

Finding and Understanding a Leaking Well

InSAR analysis over the Northwestern Shelf of the Delaware Basin in New Mexico was able to detect a leaking water-alternating-gas (WAG) injection well used for enhanced oil recovery (EOR). The WAG process involves injecting carbon dioxide (CO_2) and then water into depleted oil fields to first loosen and then sweep oil out of small pores and into pumping wells. This process requires repeatedly pressurizing the rock layer using an injection well. If the injection well is not operating correctly, it can leak fluid into the overlying and possibly water-bearing rock formations.

While conducting an inventory of the region to identify surface changes between 2016 and 2019, we found a "bullseye" roughly 1 km in diameter, indicating a swelling of the land surface, with an injection well at its center. A more careful, month-by-month analysis showed that the swelling occurred between December 17, 2016, and January 10, 2017.

The swelling appears circular at first (January 10, 2017, through February 27, 2017), indicating that pressurization of the rock was occurring equally in all directions. Beginning on April 4, 2017, the feature morphed from circular into an elongated shape along a roughly northwest-trending line. This is what we would expect from an injection plume when the pressure front encounters a low-permeability boundary. This is analogous to blowing up a balloon against a wall—the balloon forms a flat face pressed against the wall. From July 16, 2018, through February 17, 2019, the bullseye became smaller and smaller, which we interpreted as the pressure bleeding off.

After identifying the well (API No. 3002524312) from New Mexico Oil Conservation Division records, we discovered that it was an injection well and that a leak had been documented on August 14, 2017, which was eight months after we observed the InSAR deformation signature. The leak was apparently into the *red beds*, or red-colored, clay-rich rocks that contain preserved sandy river channels, which can form aquifers; in this case, however, the red beds are so deep that they are unlikely to contain fresh water. These

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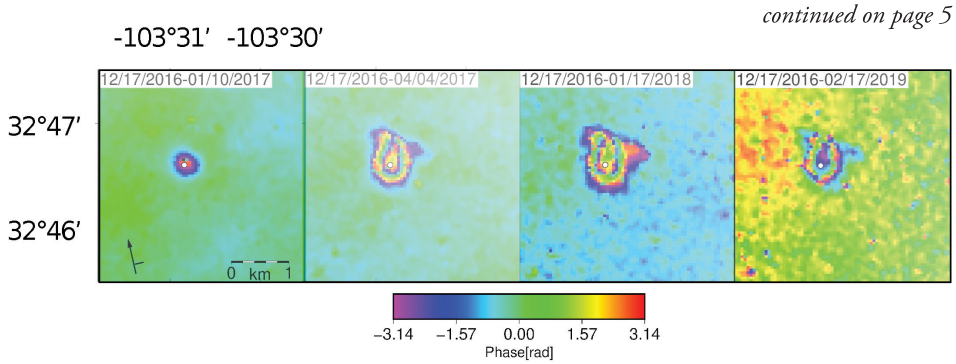

Land uplift around the API No. 3002524312 well site (white circle). A fixed reference image from December 2016 was compared with other images taken between December 2016 and February 2019. The colors indicate phase changes in the radar signal. The fringes show an anomalous uplift of a maximum of 4.3 cm (1.7 inches) over the EOR injection well. The uplift signal grows over time, preferentially moving toward the northwest and encountering a low-permeability barrier (after Graves et al., 2023).

continued from page 4

red beds are located above the sandstones and limestones that form the layer into which the injection was intended to go. After being unable to fix the leak, the well was plugged and abandoned by September 1, 2017—consistent with the timing of our observed maximum extent of deformation.

The next question was whether we could use these observations to determine the permeability of the sand channels in the red beds and the thickness of the aquifer formation. Like modern rivers, preserved river channels can form complicated geometries. Underground, these channels are difficult to locate, let alone measure their shape (thickness and width) or determine how easily water can flow through them (permeability).

We set up a relatively simple pen-and-paper mathematical model that accounted for both water pressure movement *and* the land surface deformation during fluid injection from the well. We then used a computer to compare over 3 million simulations of that model to predict how confident we were about the different model parameters. In fact, we were able to show that the deformation from the leak could be used to predict permeability and prove that the leak was shallow and not just from normal operations. We were also able to estimate the depth of the top of the red beds.

This study is one of a growing number that show the power of satellite-based InSAR analysis to reveal fluid movement and storage changes (pressure changes) at depth. These analyses can supplement the direct measurements provided by monitoring wells and can supply crucial data in areas where no monitoring wells are present.

A Pathway to Understanding Water and the Environment at Operational Scales

Using InSAR analysis combined with local understanding of hydrology and environmental changes has allowed us to "see" a range of processes, including changes of sediments and landslides, changes at mines and subsidence of natural cavities, and underground fluid storage dynamics, such as changes in water storage in aquifers and pressure changes in oil and gas reservoirs.

The addition of satellite-derived deformation information can give a broad spatial view of a number of processes. This can provide insights into well-known signals, such as subsidence in agricultural areas that rely heavily on groundwater pumping, and previously unknown signals, such as dynamic sand dune migration, sinkhole development, and leaking wells. InSAR-based groundwater and environmental studies are growing in number as the methods used become more accessible and a new generation of geodesists begins to focus on these critical issues.

However, InSAR is just one technology in geodesy. Researchers are beginning to link different geodetic techniques—InSAR, GNSS or GPS, and satellite- and ground-based repeat gravity surveys—with hydrological techniques. Such approaches offer not only a regional understanding of processes but also allow researchers to zoom in on specific, smaller features. This holds the promise of providing information to help monitor and manage aquifers and environmental systems at the scales at which they operate, rather than only at the much smaller scales at which we have traditionally measured.

New Mexico is facing water challenges as it moves into the future, with decreasing supplies even as agricultural and industrial demands remain the same or increase. As this happens, we will have to rely more and more on groundwater to meet New Mexico's water needs—but groundwater will remain difficult to monitor away from urban areas with dense well coverage. The geodetic techniques we have discussed fill a literal gap in space and time between wells and measurement times. Moving forward, they will form a new layer of information for water management, complementing current efforts while also finding new "signals" that are important to us all.

Dr. Alex Rinehart, Dr. Ronni Grapenthin, and Dr. Emily Graves

Dr. Alex Rinehart is an associate professor of hydrology in the Department of Earth and Environmental Science at New Mexico Tech.

Dr. Ronni Grapenthin is a professor of geodesy at the University of Alaska Fairbanks (UAF) and the geodesist for the Alaska Volcano Observatory and Alaska Earthquake Center at the UAF Geophysical Institute.

Dr. Emily Graves recently defended her PhD dissertation at the University of Alaska Fairbanks.

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Bureau News

In Memoriam Mark Leo-Russell

Mark Leo-Russell, our valued friend and colleague, passed away suddenly on November 10, 2025. He was 66. Mark's first association with the Bureau of Geology was as an undergraduate geology major at New Mexico Tech, where he spent several years as the student curator in our Mineral Museum. He rejoined the bureau in 2021 as a database administrator, where he worked on database migration and support, data modeling, systems management, web development, and GIS projects. Mark's bureau colleagues noted his kindness, friendliness, sense of humor, curiosity, passion for geology, and willingness to always pitch in to help his colleagues and their students. He will be greatly missed.

New Hydrogeology Report on New Mexico's Borderlands

A recent publication by New Mexico Bureau of Geology and Mineral Resources emeritus scientist, Dr. John Hawley, and coauthors delves into a detailed hydrogeologic framework of the broad Borderlands Region of south-central New Mexico and adjacent parts of Texas and Chihuahua, Mexico. A wealth of data, along with Hawley's 65 years of experience in the region, has yielded a detailed picture of the subsurface sediments and associated aquifers in the study area, particularly in the Mesilla Basin. The full report (TR363) can be accessed, free of charge, through the Water Resources Research Institute website (**nmwrri.nmsu.edu/publications/technical-reports/tr-reports/tr-363.html**).

Brackish and fresh groundwater aquifers in this region are relied on to support the growing population and business centers of El Paso, Ciudad Juárez, Las Cruces, Santa Teresa, and the Borderland Ports of Entry. Additionally, these same water sources would need to support any industries that are planning to establish new projects in this region. The study provides insight into the structural, stratigraphic, lithologic, and hydrogeologic frameworks within the basins—especially the Mesilla Basin—and estimates the flow, volume, and quality of groundwater available both now and in the near future. The study also examines possible groundwater recharge and locations of low-quality water within the basin that could be targets for desalination, perhaps using solar or geothermal energy.

These models and the assembled data presented in this report will serve as a valuable resource upon which water planners can base future decisions, which can be modified as new data become available. For example, aerial geophysical surveys were conducted across the study area in November and December 2025, sponsored by New Mexico Tech and the Bureau of Geology, which will provide additional data to further improve the three-dimensional models of aquifer systems.

Dr. Les McFadden Receives Earth Science Achievement Award

The 2025 Earth Science Achievement Award for Research and Education was presented to University of New Mexico Emeritus Professor Dr. Les McFadden at the New Mexico Geological Society's annual Fall Field Conference in September. During a career spanning almost four decades—all spent in New Mexico—McFadden's research has increased our understanding of the state's soils, climates (past, present, and future), human histories, land management policies, hydrology, and landscape evolution. Just as significant are his teaching and mentorship of students at the University of New Mexico, which have left an impact on generations of geoscientists in New Mexico and beyond.