Often driven by human activity, subsidence is a problem worldwide

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Earth's surface is ever changing. Sinkholes swallow neighborhoods, river deltas slowly slide beneath the waves, and fertile fields lose elevation as farmers draw large amounts of water for irrigation from underlying aquifers. Whether gradual and subtle, or sudden and dramatic, these phenomena are known as subsidence —the lowering of the ground's surface owing to the subterranean movement of material.

Many instances of subsidence stem from natural processes. For instance, the same flows of groundwater that dissolve limestone to form caves far below ground can also operate at shallower depths, sculpting caverns that grow until their roofs can no longer support overlying strata. When those roofs collapse, a sinkhole can form.

But now, researchers are finding that subsidence more often results from human activity. According to the US Geological Survey, in the United States, more than 80 percent of the known subsidence—which together covers an area that's nearly 17,000 square miles and spread across 45 states—stems from groundwater use. Worldwide, almost one-fifth of the planet's population lives in areas where subsidence driven by groundwater withdrawals is a major threat, a new analysis finds.

Humans cause subsidence in other ways, too. The sheer weight of large cities can depress Earth's crust several centimeters—a substantial threat for coastal cities now that sea level is on the rise. Most types of anthropogenic subsidence are not reversible, meaning that prevention is the best remedy. Fortunately, satellites offer a convenient way to monitor wide swaths of landscape, allowing scientists to not only measure subsidence over time but to gain "lessons learned" and preclude future problems. Even so, sinking ground is likely to be a serious concern in the decades ahead.

Headed for a Fall

Where rivers meet the sea, loads of suspended sediment settle to form river deltas. As that material accumulates, it traps large amounts of water. As newer layers of sediment accumulate, water is squeezed out of the underlying deposits, causing them to compact and the land surface to sink.

As farmers pump out water to irrigate crops, ground water levels drop and massive sinkholes can form, such as this one in Dover, FL, that formed after a freeze event in January of 2010. Image credit: USGS/Ann Tihansky.

That process works in reverse as well: When humans pump large amounts of water out of underground aquifers, the sediments left behind—no longer supported by the nearly incompressible water—will densify, especially if they haven't fully hardened into rock. That sort of subsidence, long recognized by geologists, is a growing problem for both agricultural and urban areas worldwide, says Gerardo Herrera-García, a geoscientist at the Spanish Geological Survey in Madrid.

Subsidence can be extreme. In some intermountain basins in Mexico—where, coincidentally, some of that nation's main urban centers arose—subsidence rates are as high as 30 centimeters per year (1). Iran hosts several cities where the ground subsides at 25

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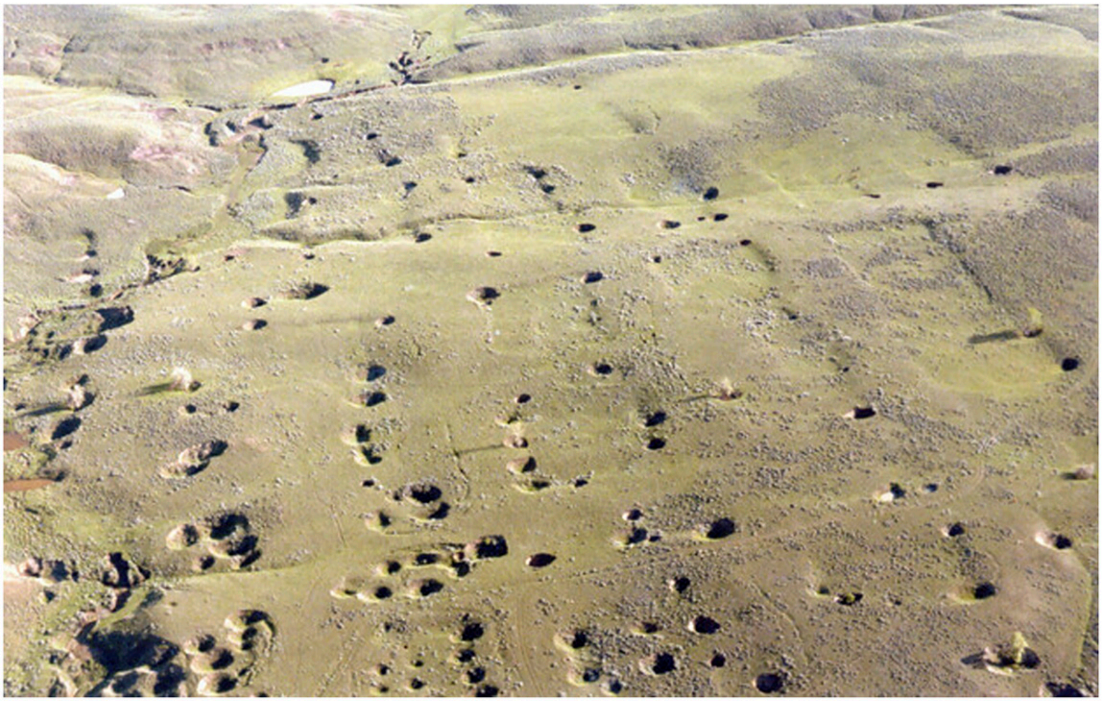

Coal mining is one major cause of subsidence. As seen at this site near Sheridan, WY, depressions and pits often form above abandoned mines. Image credit: Science Source/US Geological Survey.

centimeters per year, largely a result of unregulated pumping of groundwater, he notes. In Indonesia, coastal subsidence in Jakarta has measured more than 2 meters in just the past two decades (2)—a rate so severe that governmental authorities are planning to move the capital, a rapidly growing city of more than 10 million, across the Java Sea to the island of Borneo.

As part of a recently published analysis (1), Herrera-García and his colleagues used data gained at more than 200 locations in 34 countries to develop a computer model that can assess the threat of subsidence at other sites that might be caused by groundwater withdrawals. That model incorporates information such as the geology, climate, and land use at a site, as well as the rate of groundwater pumping there. For example, the presence of farmland in an area that's typically dry and remote from sources of surface water boosts the likelihood that water for irrigation would be pumped from underlying aquifers, thus increasing the risk of subsidence.

The team's results are sobering. Almost 1,600 of the world's major cities have at least a 50–50 chance of experiencing subsidence, and more than half of them are also located in flood-prone areas. Worldwide, areas that add up to about 2.2 million square kilometers (slightly larger than Greenland) have a high risk of subsidence. Often, those locales are typically concentrated near urban and irrigated areas, home to 1.2 billion people, where demand for groundwater is high, says Herrera-García. And these regions collectively account for 12 percent of the world's gross domestic product—a whopping $8.19 trillion.

If policymakers pay heed, says Herrera-García, they could better anticipate future problems and shift sources of groundwater to help minimize local subsidence—but researchers have known this all along. "There's nothing new to discover here," he notes.

The Weight of Civilization

Groundwater pumping aside, development exacerbates subsidence in a number of ways. Extracting oil and natural gas can cause the strata they're found in to collapse. In some places, particularly in The Netherlands, groundwater pumping has a slightly different effect: The removal of water from peaty soils, a move intended to create farmlands, exposes the soil's organic matter to oxygen, which in turn enables its decomposition. Once the soil is aerated, as much as 95 percent of it simply rots away—which helps explain why nearly a quarter of The Netherlands lies below average sea level.

Building heavy structures such as homes, skyscrapers, and even entire cities also can trigger subsidence, explains Tom Parsons, a geophysicist at the US Geological Survey in Moffett Field, CA. Recently, he used computer simulations to estimate the effect of San Francisco and its metropolitan area—where he and 7.75 million other people reside—on Earth's crust. The immense weight of a city—including pavement, pipes, concrete, steel, and other building materials, not to mention food, fuel, water, and vehicles—can depress broad areas in a similar but less-widespread version of the effect that massive ice sheets have during Ice Ages, he notes.

First, Parsons used satellite data to estimate the size and weight of all of the buildings (and their presumed contents) in the San Francisco metro area, all 965,000 or so of them. According to his model, those structures collectively weigh about 1.6 billion metric tons (3). Then, he modelled how the shallow layers of soil, as well as the top 10 kilometers of the underlying crust, would react to the heft of those structures.

Near the surface, Parsons found, buildings would compress the soil anywhere from 5 to 80 millimeters over the course of roughly a century. Because his model didn't include the weight of roads, bridges, and utilities, the results of his analysis are likely an underestimate, he notes. Add in any subsidence caused by groundwater pumping, and the results are disturbing, especially because other studies suggest that sea level may rise between 20 and 30 centimeters in the San Francisco Bay by the year 2050 (4).

The combination of sea level rise, the migration of humans into coastal and urban areas, and subsidence caused by various factors are a "perfect storm" that could exacerbate flooding in those areas, says Parsons. "The results of subsidence," he adds, "are almost always bad."

Sinkage from Space

Solutions are not easy to come by. During the 20th century, Tokyo sank more than 4 meters before improved groundwater management largely arrested the subsidence. But although it's possible to raise the surface of the ground by pumping water back into underground aquifers, those partially collapsed sediments don't fully swell, or "inflate" in the parlance of geologists, to reverse the subsidence that has occurred.

Take, for example, California's Santa Ana basin, which lies southeast of Los Angeles. There, as in many spots elsewhere in the region, water managers pump groundwater from aquifers to meet increased demand during the dry season. But when demand is low, they collect rainfall—as well as water diverted from the Colorado River and from sources in the northern part of the state—and pump it into the ground to store it rather than let it run out to sea. GPS data and radar observations from satellites show that parts of the basin rise and fall by as much as 5.5 cm as seasons come and go (5). The same analysis reveals, however, that over longer intervals the ground there subsides at an average rate of 1.2 centimeters per year.

Many studies of subsidence have focused on relatively small areas for relatively short periods of time. But now, Europe is getting ready to launch a program that will allow researchers—as well as government agencies and members of the public—to tap into a database devised to monitor subsidence across the continent.

That trove of information will include radar data and images gathered by two polar-orbiting satellites operated by the European Space Agency, says Dag Anders Moldestad, a remote sensing specialist at the Norwegian Space Agency in Oslo. Analyses of the radar data can discern long-term vertical movements as small as a few millimeters, he notes. Also, using the database could reduce the number or length of field studies required to do the same job, thus saving money.

Some countries in Europe, including Norway and Germany, already have databases that cover their entire mainland areas. Other countries on the continent are in the process of developing their own such version. But by the end of this year, the European Union's Copernicus land-monitoring program will have compiled a set of observations that will serve as a baseline for future analyses, Moldestad and his colleagues reported last June (6).

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>
> **—Tom Parsons**

Such analyses will not only provide insight into subsidence, they'll enable researchers to monitor natural phenomena such as volcanoes (which tend to swell as molten rock rises inside them) as well as areas where geologists, at the behest of oil companies and governments keen on carbon capture and storage, are pumping carbon dioxide-bearing fluids into the ground for long-term storage. Geologists could also check for minuscule movements that could presage future rockslides, potentially saving lives by providing early warning. And they could uncover landslides that have already happened in remote areas, offering greater insight into what types of terrain are prone to such events. In the first few months after Norway launched its national database in 2018, scientists identified more than 100 landslides that hadn't been spotted previously in satellite data.

Furthermore, the database will help researchers monitor subsidence of everything from hefty buildings and infrastructure to the ground's surface in areas as small as individual neighborhoods, Moldestad says. "We'll be able to monitor subsidence before, during, and after construction, which will let us know when the ground stabilizes," he notes. "That, in turn, will help us learn where it's difficult to build and teach us how to build smarter."

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