

**Editor’s Note:** one year ago New Orleans was suffering from the effects of Hurricane Katrina. As was widely discussed at the time the prolonged flooding that inundated much of the City was due to the fact that most of the City sits below sea level, and that anthropogenetically-induced subsidence has caused the City to gradually sink even lower, making the flooding worse than it would otherwise have been.. An unquantified, but likely significant portion of this subsidence, is due to years of groundwater withdrawals from the underlying aquifer. This article is the first in a series of four that review the role that groundwater can play in various geological hazards and catastrophic events that have occurred, and may occur again.

## Ground Subsidence and Groundwater

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Until Hurricane Katrina few people were aware of the threat that land subsidence can pose to humans. However, land subsidence has been a perennial problem across the United States for most of the last century. As of 1999, more than 17,000 square miles in 45 states have been impacted by land subsidence (Galloway, et. al., 1999). Economic losses, even before Katrina, have been in the billions of dollars. Many places in the United States face continued threats from subsidence, and new places will likely be impacted by it as increased demands are made on vulnerable aquifers.

While a variety of causes can lead to land subsidence and cause considerable damage (Figure 1), the three most common are mining of groundwater, drainage of organic soils, and collapsing cavities. The first cause is clearly a function of changes in groundwater conditions (withdrawals of groundwater beyond the recharge capacity of an aquifer system with a compressible matrix). The

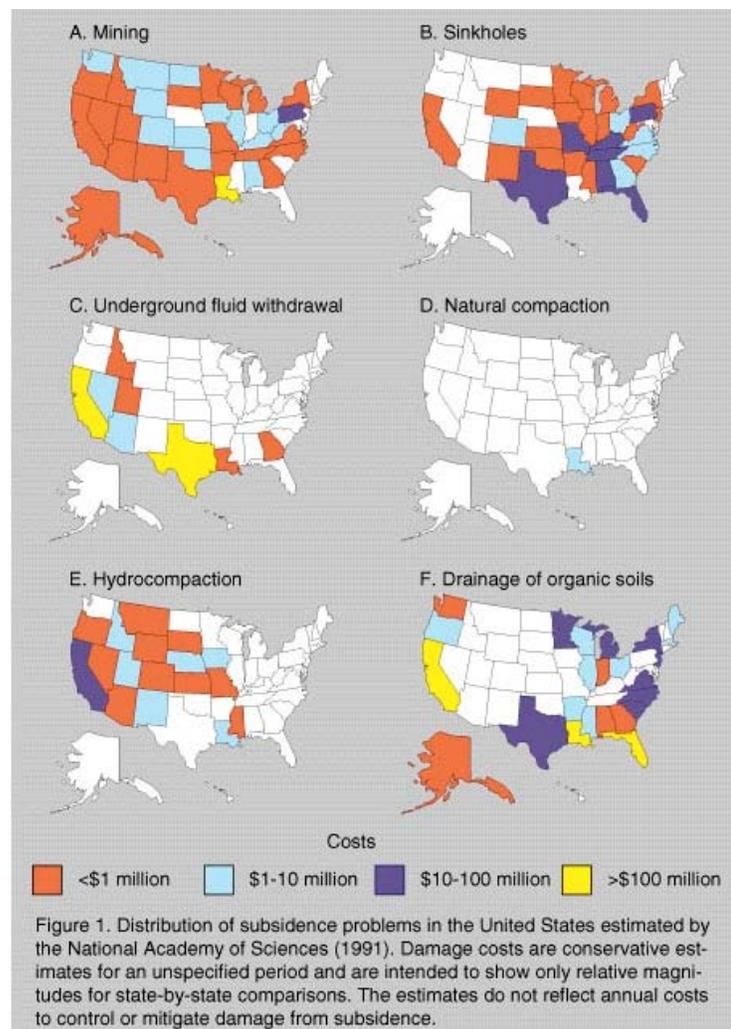


Figure 1 – Types, distribution, and costs of subsidence in the United States (after Leake, 2004).

second cause is generally not related to groundwater, but rather is due to surface water drainage of wetland areas that allows highly organic soils and peat deposits to oxidize and compact. The third cause is typically the result of karstification

processes and can occur in the absence of human activities, but can be accelerated by artificial withdrawals of groundwater. While there are other causes of land subsidence, such as oil and gas withdrawals, mine collapses, and neo-tectonic subsidence, more than 80 percent of land subsidence in the United States is attributed to withdrawals of groundwater (Galloway, et. al., 2000). The first and third most common causes are reviewed in more detail in this article.

### Groundwater Mining

Groundwater mining induced subsidence is one of the most widespread and damaging forms of land subsidence in the United States (Figure 2). Subsidence can occur when withdrawals of groundwater from an aquifer with a non-rigid matrix exceed the recharge capacity of the aquifer.

The impacts of this process can be gradual, almost imperceptible, or they can be dramatic. Gradual subsidence may be manifested as an overall decrease in the land surface, or as the gradual formation of surface fissures and faults. While this type of land subsidence typically is in the range of only a few feet, groundwater-withdrawal

induced subsidence in the San Joaquin Valley of California has resulted in what has been described as the largest “human alteration of the Earth’s surface” (Galloway, et. al.,

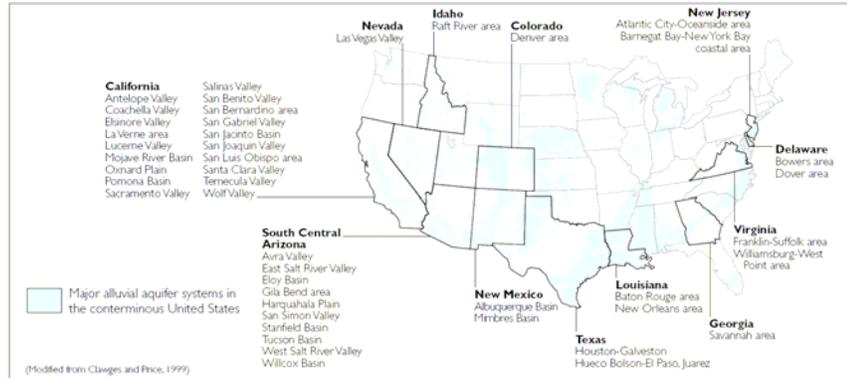


Figure 2 – Areas in the United States where land subsidence has been attributed to groundwater withdrawals (after Galloway, et. al, 1999).

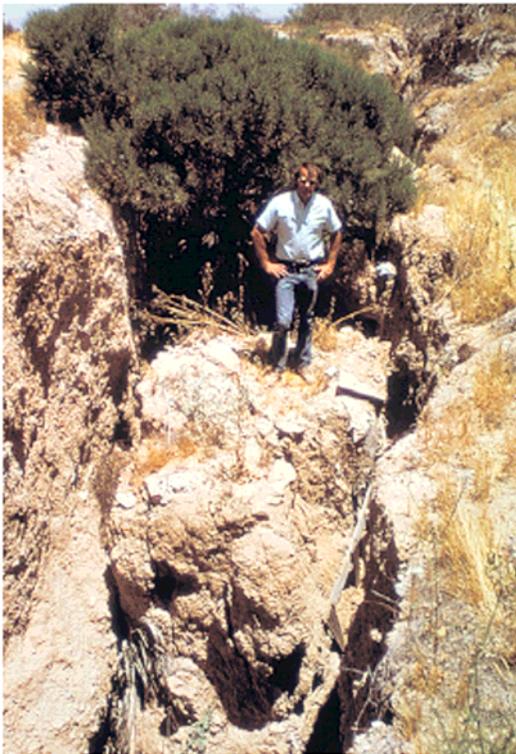


Figure 3 – Groundwater withdrawals over approximately 50 years resulted in over 28 feet of land subsidence near Mendota, California (after Galloway, et. al, 1999).

1999). Over half of the San Joaquin Valley has subsided as the result of groundwater withdrawals. In one part of the Valley, groundwater subsidence near Mendota, California resulted in 28 feet of subsidence (Figure 3). This subsidence required expensive modifications to two major Central California water projects (Holzer, 1991).

While the subsidence in the San Joaquin Valley has impacted principally lightly-populated agricultural areas, a number of large metropolitan areas have also been affected by subsidence, including New Orleans, Baton Rouse, Houston, Las Vegas, San Jose, Phoenix, Tucson, and Denver.

The Houston area has probably been affected more by subsidence than any other metropolitan area (Galloway, et. al., 1999). Damages have included losses of residential structures, extensive impacts to industrial and transportation infrastructure, and loss of wetland habitat. Land containing more than 400 homes near Galveston Bay settled as much as 10 feet resulting in its submergence (Johnson, A. Ivan, 1998). Subsidence in the Houston area has been manifested both as overall subsidence of the land surface and the formation of surface faults, which have damaged roads, utilities, homes, and other structures.



In the Southwestern United States, particularly the Central Valley of Arizona, groundwater withdrawals have resulted in the formation of spectacular earth fissures (Figure 4). They often start out as seemingly inconsequential hair-line cracks of less than an inch in width, and tens or hundreds of feet in length. But they can expand to become fissures and gullies of more than 30 feet in depth and width and thousands of feet, or several miles, in length. One fissure had a measured depth of 82 feet, and it has been speculated that fissure depths may reach as much as 300 feet based on indirect evidence (Galloway, et. al., 1999).

Figure 4 – Earth fissure formed in south-central Arizona (after Galloway, et. al. 2000).

Earth fissures have caused and can pose a number of problems. They have damaged highways, railroads,

sewers, canals, aqueducts, buildings, and

flood-control dikes. They can pose a threat to grazing livestock, farm workers, vehicles, hikers, and wildlife. They can exacerbate the risk of aquifer contamination by channeling surface releases of hazardous materials into the deep subsurface.

Houston, like New Orleans, has also experienced some of the more dramatic, short-term impacts of land subsidence. When Hurricane Alicia struck Houston in 1983, several areas

experienced severe flooding as a result of prior land subsidence. Extensive subsidence-related flooding from Alicia near Houston resulted in a lawsuit that led to a historic reinterpretation of common-law related to groundwater usage (Holzer, 1991). The court ruled that groundwater users no longer had an unlimited right to withdraw groundwater and could be held liable for damages related to future withdrawals.

Studies of the causes of land subsidence related to the withdrawal of groundwater and other subsurface fluids resulted in the development of a model called the aquitard-drainage model (Holzer, 1991). In thick, unconsolidated sediments, drainage of subsurface fluids can lead to a decrease in fluid pressure increasing the effective stress exerted on the aquifer matrix. If the transfer of overburden stress to the sediment matrix exceeds the maximum level of stress that the matrix has been previously exposed to, the matrix undergoes collapse (Figure 5). The initial matrix compaction is elastic, and will recover if the aquifer is recharged. However, once the matrix collapse exceeds the elastic

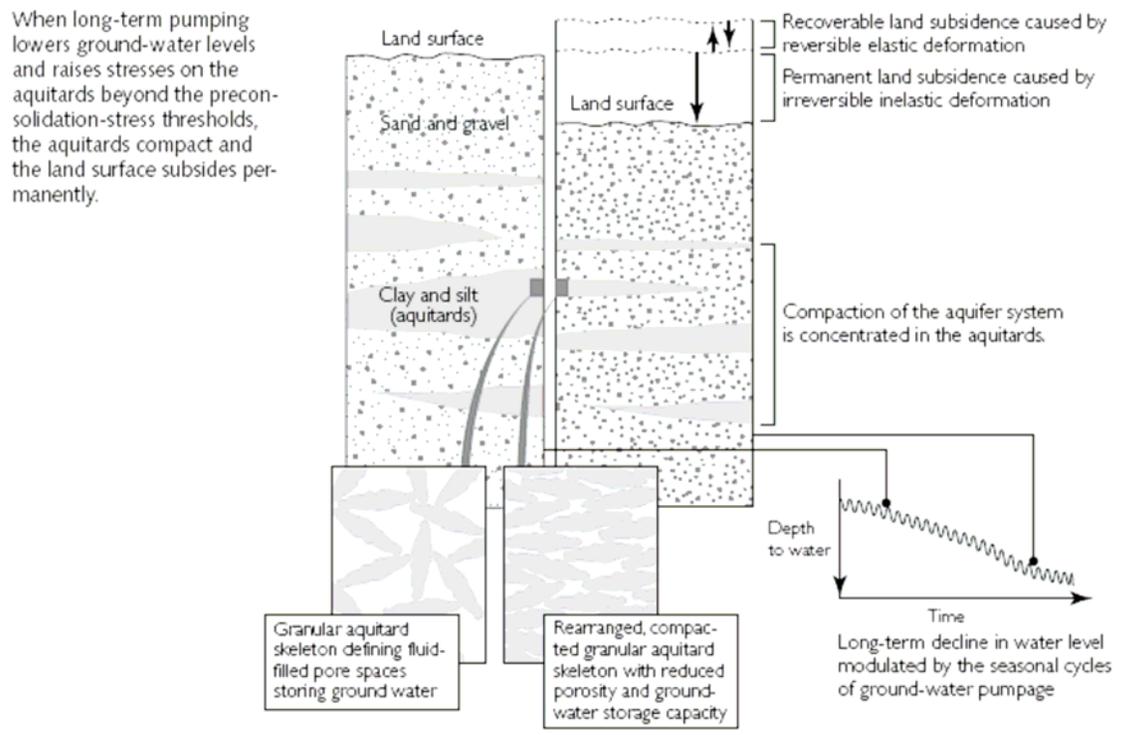


Figure 5 – Illustration of how groundwater withdrawals can lead to land subsidence (after Galloway, et. al, 1999).

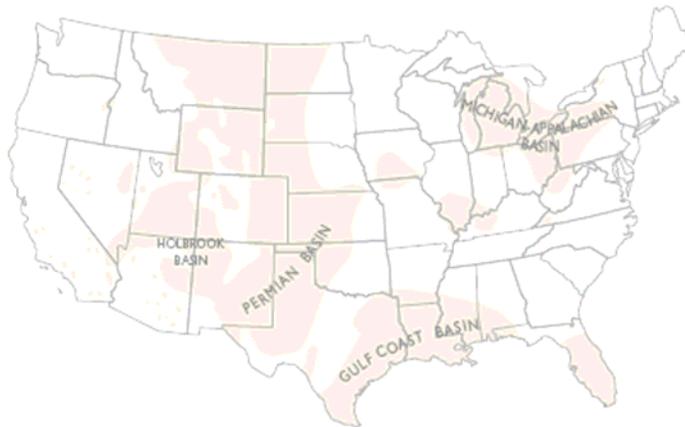
limit of the material, the land subsidence becomes permanent. Most subsidence is related to the expulsion of water from the fine-grained aquitards into the adjacent aquifers because clays have much higher porosities and lower matrix strength than coarse grained sediments. Even so, the compaction of the aquifer matrix can reduce its future storage capacity and production efficiency.

### Groundwater and Cavity Collapses

In the potentially even more dramatic category of subsidences are cavity collapses. Cavity collapses, or sinkhole formation, is a common natural risk in areas underlain by

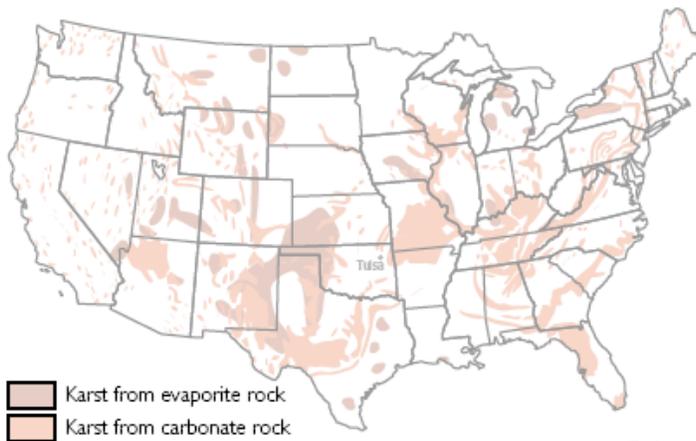
soluble bedrock, such as carbonates or evaporites. Large areas of the United States are underlain by evaporites and carbonates (Figure 6). To date, few human casualties have resulted from these events even though they have cause large economic losses. However, some of these areas, such as Central Florida, are experiencing rapid population growth. Tragic events resulting from cavity collapses are virtually inevitable. This is particularly true given the potential for human activities, such as groundwater withdrawals to accelerate the occurrences of these events. (Author’s note: while visiting central Florida a few years ago a small sinkhole formed under one of the roads leading from Walt Disney World. Fortunately it occurred at night and no one was hurt before it was discovered.)

Salt and gypsum underlie about 40 percent of the contiguous United States.



(Martinez and others, 1998)

Carbonate karst landscapes comprise about 40 percent of the contiguous United States east of Tulsa, Oklahoma.



(Davies and Legrand, 1972)

Figure 6 – Areas of the United States underlain by evaporites and carbonates (after Galloway, et. al, 1999).

Central Florida is probably the best known location in the United States for this type of subsidence. A review of virtually any topographic map from this area reveals the effects of land subsidence through the presence of numerous semi-circular lakes, ponds, and depressions. These types of subsidences can occur rapidly and almost always without warning (Figure 7).



Under normal conditions these types of subsidences are relatively uncommon. Their formation requires both soluble bedrock and moving water that is undersaturated with respect to the soluble bedrock minerals. In places such as south-central Florida groundwater would normally move slowly through the aquifer and would be saturated with respect to the carbonate. However, excessive pumping of groundwater can increase both the groundwater gradient through the bedrock and expose the bedrock to much larger volumes of undersaturated water. Pumping of groundwater can also disturb the equilibrium of fluid pressure and overburden stress triggering a collapse.

Other cases of collapse have occurred when improperly abandoned oil and gas wells have allowed shallower groundwater to

Figure 7 – Large sinkhole formed near Winter Park, Florida in 1981 (after Galloway, et. al, 1999).

penetrate and dissolve cavities in deeper evaporite layers (Galloway, et. al, 1999).

Even when cavity collapses are due to causes other than groundwater withdrawals they can have serious impacts on groundwater aquifer systems. A collapse of a large mine cavity can cause a confining layer to be breached draining the overlying aquifer into the mine. The collapse of the Retsof Mine, a salt mine in western New York, beginning on March 12, 1994 soon led to serious damage to area groundwater supplies (Galloway, et. al, 1999). Problems included degradation of groundwater quality, and for some groundwater users, a complete loss of their groundwater supply.

### **Groundwater Related Subsidence and the Future**

Groundwater-related subsidence will be a continuing, and likely increasing, problem in the future as more demands are placed on groundwater resources and more people move into subsidence-prone areas. The lack of general public awareness of the issue all but guarantees this. This lack of public awareness partly stems from the fact that the most subsidence has been in predominantly agricultural areas as the results of groundwater pumping for irrigation (S. A. Leake, 2004). However, as groundwater withdrawals increase beneath expanding metropolitan areas, the problem will become an increasingly urban one.

Groundwater-related subsidence is also one of the generally unrecognized risks of climate change. Across the southern United States from the Gulf Coast to Arizona an increasingly drier climate has and will place greater demands on groundwater supplies leading to increased subsidence. For coastal areas subject to subsidence forecasts of continued sea level rise related to global warming (Burkett, et. al., 2003) and potentially more powerful storms spells even greater problems in the future. For southern Louisiana where subsidence and other factors are leading to a loss of the protective wetlands, it is likely only a matter of time before the combination of land subsidence, rising sea levels, and strong storms makes the city of New Orleans essentially unprotectable.

There are a variety of potential measures to prevent or mitigate groundwater withdrawal induced subsidence in most areas subject to groundwater-related subsidence. While it is not possible to reverse the effects of groundwater withdrawal induced subsidences (except in the minor case of elastic aquifer deformation), it can be stopped or slowed. Options include stopping or reducing groundwater withdrawals, carefully managing the placement and production of groundwater supply wells, and using artificial recharge of aquifers. In addition, it may be possible to identify areas that are most likely susceptible to subsidence and limit surface usage to activities that are likely to suffer only minor impacts from subsidence.

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