SUBSIDENCE

Urban Geology, March 2011
Facts and figures from Holzer and Galloway (2005)

- Approximately 26,000 km\(^2\) of land in US permanently lowered
- Largest area – San Joaquin Valley, CA; at least 45 other areas in 12 states
- Maximum none elevation change – 9 meters
Fast or slow; small or large

- Isostatic adjustment
- Earthquakes
- Human activities
- Loss of water in organic soils
- Dissolving of subsurface rock
- Thawing permafrost
- Natural compaction of soils
- Expansive soils
Human activities

- Gas and oil extraction
- Water removal
  - US – cause for 80% of subsidence
- Underground mining
- Draining organic soils (e.g., wetlands) and diverting sediment replenishment through flooding
- Oil/gas and water removal discussed largely in Holzer and Galloway (2005)
Possible consequences

Groundwater extraction in the basin of Mexico exceeds recharge, lowering the water table by 0.1-1.5 m/yr, reducing pore fluid pressure in the aquifer and overlying acquitard, and leading to compaction of lacustrine shales and surface subsidence.

Source: http://water.usgs.gov/ogw/pubs/fs00165/
Possible consequences

- Changing topography and water movement
- Flooding
- Structural damage
- Ground water pollution
- Increased erosion and land loss
- Mass wasting
- Faults and fissures
- Reduced capacity of aquifers to store water

Source: http://water.usgs.gov/ogw/pubs/fs00165/
Faults and fissures

Arizona fissure

http://water.usgs.gov/ogw/subsidence.html

Arizona fissure

Figure 3. Some of the areas where subsidence has been attributed to the compaction of aquifer systems caused by ground-water pumpage.
What’s happening underground?

- Fluid removed from porous materials
- Fluid pressure decreases
- Effective stress increases, stress from grain to grain
- Increase pressure on solid components
- Reduction of pore space
Aquifer-system compaction

Aquitard Drainage and Aquifer-System Compaction
The Principle of Effective Stress

This principle describes the relation between changes in water levels and deformation of the aquifer system.

\[ \sigma_T = \sigma_e + \rho \]

For any arbitrary plane below the water table, the total stress represented by the weight of the overlying rock and water is balanced by the pore-fluid pressure and the intergranular or effective stress.

“...the term aquitard has been coined to describe the less-permeable beds in a stratigraphic sequence. These beds may be permeable enough to transmit water in quantities that are significant in the study of regional ground-water flow, but their permeability is not sufficient to allow the completion of production wells within them.”

—Freeze and Cherry, 1979
Prolonged water removal

PROLONGED CHANGES IN GROUND-WATER LEVELS INDUCE SUBSIDENCE

Prior to the extensive development of ground-water resources, water levels are relatively stable—though subject to seasonal and longer-term climatic variability.

During development of ground-water resources, water levels decline and land subsidence begins.

After ground-water pumping slows or decreases, water levels stabilize but land subsidence may continue.

The weight of the overlying rock and water is balanced by the pore-fluid pressure and the intergranular or effective stress.

Ground-water withdrawal from confined aquifers reduces fluid pressures ($p$). As the total stress ($\sigma_T$) remains nearly constant, a portion of the load is shifted from the confined fluid to the skeleton of the aquifer system, increasing the effective stress ($\sigma_e$) and causing some compression.

Under the principle of effective stress, the compaction of a thick sequence of interbedded aquifers and aquitards can proceed only as rapidly as pore pressures throughout the sequence can decay toward equilibrium with reduced pressures in the pumped aquifers. Most of the land subsidence occurs as a result of the permanent compaction of the aquitards, which may be delayed due to their slow drainage.
Aquifers and Aquitards

When water levels drop, due mainly to seasonal increases in ground-water pumping, some support for the overlying material shifts from the pressurized fluid filling the pores to the granular skeleton of the aquifer system.

When ground water is recharged and water levels rise, some support for the overlying material shifts from the granular skeleton to the pressurized pore fluid.

Long-term pumping: irreversible consequences

When long-term pumping lowers ground-water levels and raises stresses on the aquitards beyond the preconsolidation-stress thresholds, the aquitards compact and the land surface subsides permanently.

Organic soils

- Mainly in cold-region wetlands
- Drained for agriculture
  - Increases decomposition
  - Organic carbon to CO$_2$ and H$_2$O
  - Compaction, desiccation, and erosion

Figure 6. Most organic soils occur in the northern contiguous 48 States and Alaska
Sinkholes

- Occur in areas with carbonates (e.g., limestone and dolomite), evaporites (e.g., salt and gypsum)
- Occur more frequently when water table is lowered such as during droughts

Source: http://ga.water.usgs.gov/edu/sinkholes.html
Areas in the US with sinkholes

Source: http://ga.water.usgs.gov/edu/sinkholes.html
Types of sinkholes

- Dissolution
  - Downward migration of acidic water
  - Common
- Collapse
  - Collapse into underground cavern

> FIGURE 7.4 FORMATION OF SINKHOLES (a) Initial dissolution of soluble bedrock takes place along vertical and horizontal fractures, and some fractures become small caves. (b) Over geologic time, dissolution continues to enlarge fractures and some caves become caverns with roofs partly supported by groundwater. (c) Subsequent lowering of the groundwater table removes the cavern roof support and it falls into the cave to form a collapse sinkhole. Collapse may occur only a few years after the groundwater table has lowered. The heavily fractured area of bedrock is dissolved to create a solutional sinkhole.
Texas Gulf Coast aquifer system

- Evangeline aquifer most used
- Salt water encroachment exacerbated by ground water removal

Source: http://pubs.usgs.gov/circ/circ1182/pdf/07Houston.pdf
Houston subsidence

- Mainly from water removal, but also oil and gas
- 1906-1943, subsidence of >1.6 feet
- 1943-mid 1970s, up to 6 feet
- Subsidence arrested since then; surface water primary
- 1975 legislation
Wetlands were lost to inundation resulting from subsidence in the lower reaches of the San Jacinto River.
San Joaquin Valley

- Valley: a trough formed by collision of the Pacific and North American Plates.
- Marine sediments overlain by continental sediments, in some places thousands of feet deep.
- Streams draining the mountains, and partially in lakes that inundated portions of the valley floor from time to time.
- More than half the thickness of the continental sediments is composed of fine-grained (clay, sandy clay, sandy silt, and silt) stream (fluvial) and lake (lacustrine) deposits susceptible to compaction.

Source: http://pubs.usgs.gov/circ/circ1182/pdf/06SanJoaquinValley.pdf