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Coastal subsidence and relative sea level rise

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Abstract
Subsurface fluid-pressure declines caused by pumping of groundwater or hydrocarbons can lead to aquifer-system compaction and consequent land subsidence. This subsidence can be rapid, as much as 30 cm per year in some instances, and large, totaling more than 13 m in extreme examples. Thus anthropogenic subsidence may be the dominant contributor to relative sea-level rise in coastal environments where subsurface fluids are heavily exploited. Maximum observed rates of human-induced subsidence greatly exceed the rates of natural subsidence of unconsolidated sediments (∼0.1–1 cm yr⁻¹) and the estimated rates of ongoing global sea-level rise (∼0.3 cm yr⁻¹).

Keywords: subsidence, groundwater, coastal

In their article, Laura Erban and colleagues (Erban et al 2014 Environ. Res. Lett. 9 084010) assess the role of groundwater pumping in ongoing subsidence of the Mekong Delta, Vietnam and Cambodia. Over geologic time, natural subsidence of deltaic sediments is compensated by delivery of new sediments, so that the land-surface elevation remains near sea level. Erban and colleagues point out that much of the Mekong Delta is <2 m asl. Because of their rich soil and abundant water, many of the major river deltas of the world are densely populated, and the Mekong Delta is no exception: its current population density is >400 persons km⁻², similar to that of the Netherlands, whose national area consists largely of the Rhine–Meuse–Scheldt delta. The Dutch experience shows that large human populations can be sustained near or even below sea level, given sufficient engineering expertise and capital investment.

Erban et al (2014) use satellite-radar interferometry (InSAR) to document recent subsidence rates of 1–4 cm yr⁻¹ over large parts of the Mekong Delta, and show that this widespread subsidence is likely caused by groundwater pumping and associated water-level declines. They project ∼0.9 m of human-induced subsidence by 2050, versus ∼0.1 m of expected sea-level rise. Their study underscores the importance of ground-truth data to constrain interpretations of InSAR-derived ground-displacement measurements (e.g. Galloway and Hoffmann 2007).

In some areas of the world, the obvious and expensive damage caused by anthropogenic coastal subsidence has prompted concerted efforts to arrest and reverse groundwater-level declines, often by importing additional surface water. For instance in the greater Houston (USA) area, nearly 3 m of coastal subsidence due to aquifer-system compaction caused billions of dollars in damage and in 1975 prompted establishment of a Subsidence District with regulatory authority (Galloway et al 2003). Anthropogenic coastal subsidence in the Houston area is now carefully monitored and greatly reduced. Large reductions in groundwater pumping have been facilitated by the construction of dams, canals, and pipelines.
to import and distribute surface water. However, aquifer-system compaction is essentially irreversible (inelastic), so that some of its deleterious effects are permanent, including increased flood risk, storm-water management complicated by altered drainage, and loss of established wetlands (figure 1: two photos of the abandoned Brownwood subdivision).

Figure 1. The fate of the Brownwood subdivision of Baytown, greater Houston area, affords a dramatic example of the dangers of coastal subsidence. Brownwood was constructed beginning in the 1930s as an upper-income residential subdivision on wooded lots along Galveston Bay. At that time the area was generally <3 m above sea level. By 1978 more than 2 m of subsidence had occurred. (a) In 1983 Hurricane Alicia, with >3 m of storm surge, dealt a final blow to Brownwood and (b) all homes in the subdivision were permanently abandoned; the ~2 km² area now comprises the Baytown Nature Center and is home to 317 species of resident and neo-tropical migratory birds (http://en.wikipedia.org/wiki/Baytown_Nature_Center) – minor compensation for the subsidence-related loss of more than 100 km² of established wetlands around Galveston Bay.

The Santa Clara Valley (‘Silicon Valley’), California, is another example of successfully arrested coastal subsidence (Ingebritsen and Jones 1999). Historical human-induced subsidence of up to ~4 m lowered an area of ~50 km² at the northern end of Silicon Valley below mean high tide level. The direct costs of land subsidence in Silicon Valley were recently estimated at >$756 M (Borchers and Carpenter 2014), and include the cost of constructing levees around the adjacent southern end of San Francisco Bay and the bayward ends of stream channels, raising grades for railroads and roads, enlarging or replacing bridges, enlarging sewers and adding sewage pumping stations, and constructing and operating
storm-drainage pumping stations in areas that have subsided below the high-tide level. The successful arrest of subsidence in Silicon Valley, and effective subsidence management, depend upon delivery of high-quality surface water from massive diversion facilities in the southern part of the Sacramento–San Joaquin Delta. These California Delta diversion facilities themselves are threatened by another form of anthropogenic subsidence—the peat-soil oxidation that is the inevitable consequence of drainage of organic soils (e.g. Deverel and Rojstaczer 1996, Ingebritsen and Ikehara 1999). Because much of California relies on large-scale inter-basin water transfers, subsidence and water quality issues in many parts of the State are complexly interrelated. And in Silicon Valley, as in Houston, there are permanent economic and environmental consequences of historical subsidence.

The three examples of sustained and reasonably successful management of coastal subsidence that we highlight here—Houston, Silicon Valley, and the Netherlands—all involve wealthy countries or regions, relatively localized subsidence, effective governance, and large capital investment. Each of these examples also entails a large degree of protective armoring of the coastline with dikes, levees, and stormwalls, and sophisticated stormwater-drainage systems that include active pumping to protect the subsided areas from internal flooding.

Localized armoring of the coast to protect subsided landscapes is technically and economically feasible, but the extensive perimeter of the Mekong Delta may not be defensible. Thus its long-term fate may prove somewhat analogous to that of the wetlands of the Mississippi River Delta in southern Louisiana, USA. Between the 1930s and 1990s Louisiana lost about 20% of its total coastal wetland area to submergence (Britsch and Dunbar 1993), and the mean rate of land loss was \( \sim 75 \text{ km}^2 \text{ yr}^{-1} \) (Williams and Sellenger 1992). The remaining wetland area has become both less habitable and less able to mitigate storm-surge flooding of urbanized areas. A complex variety of causes drives the ongoing shrinkage of the Mississippi Delta (e.g. González and Törnqvist 2006), the most important of which may be sediment starvation (Blum and Roberts 2009)—another anthropogenic driver. Many of the world’s largest deltas are becoming increasingly vulnerable to flooding and conversion of land to open water as a result of the combined effects of accelerating global sea-level rise, sediment starvation, and subsurface fluid extraction (Syvitsky et al 2009).

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