

The many faces of anthropogenic subsidence

Shallow and deep human subsurface activities contribute to the total subsidence

By **Thibault Candela** and **Kay Koster**

Human-induced subsidence clearly causes social problems, is costly, and poses flooding and damage threats (1). Less evident is how much each spatially and temporally superimposed human subsurface activity contributes to total subsidence. Subsidence is often caused by an accumulation of multiple shallow and deep subsurface activities, such as groundwater withdrawal and hydrocarbon extraction (2). This complex challenge is well known but has not been properly addressed. A turning point has now been reached at which advanced monitoring strategies and physics-based models can be used in concert to clarify the subsidence contribution of each human intervention. Identifying these causal relationships between human interventions and subsidence helps to establish overarching responsibilities and to better develop science-based site-specific prevention and mitigation strategies.

Multiple human interventions spanning a wide range of depth can cause subsidence. The main documented superimposed subsurface activities causing subsidence are shallow groundwater withdrawal and deep hydrocarbon extraction. The Netherlands is a typical coastal area where research efforts have considered shallow and deep human interventions that cause subsidence as isolated boxes. Studies of the subsidence caused by deep gas production at the Groningen field (3) disregard the potential contribution of groundwater management. In parallel, multiple studies have documented subsidence that is induced by groundwater management (4), disregarding the potential contribution of hydrocarbon extraction. A similar picture emerges in other coastal areas, such as the Mississippi Delta, where most of the attention has been focused on the effects of groundwater withdrawal (5) and little attention has been given to the abundantly present nearby hydrocarbon fields (6). However, the superimposition of human-controlled sources of subsidence is not only occurring in the Netherlands and the Mississippi Delta. For some cases, the combination of groundwater withdrawal at

relatively shallow levels and deep gas extraction contribute to the total subsidence, such as the Northern Adriatic coastland, including Venice lagoon, the Niger delta, and Indonesia (2). For other cases, such as the Mekong delta (7), local subsidence is caused by groundwater management at multiple depths. For example, the extraction of groundwater from shallow-depth and mid-depth aquifers for domestic and industrial uses, respectively.

For deep hydrocarbon and shallower groundwater withdrawal, lowering of ground surface elevation occurs in cases when producing fluid from the subsurface decreases pressure in the pore space of the rock that leads to subsurface compaction (see the figure) (2). Additional human intervention at even very superficial depth can lead to subsidence. For example, when draining very superficial groundwater, organic rich soils (peat) can be exposed to the air and trigger microorganisms to deteriorate the organic carbon, ultimately leading to severe greenhouse gas emissions and subsidence (4). In the Netherlands, this process has already been identified and extensively studied. In other parts of the world, such as the Mississippi Delta, the importance of the very shallow soil layer only recently has been recognized in the overall total

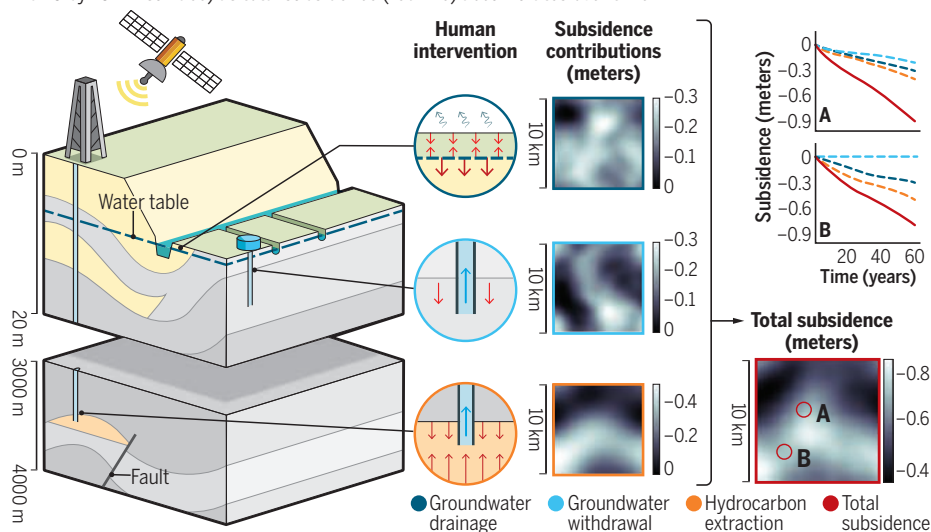
subsidence budget (8). Voosen (8) recently reported that many river deltas are sinking faster than previously believed because of the failure to account for the compaction of these very shallow soil layers.

Monitoring and ultimately deconvolving the different contributions of subsidence is challenging. Using conventional geodetic techniques, the measurement of the compaction of very shallow soil layers is notoriously difficult because of the scarcity of fixed benchmarks installed in such soft soil. Hoyt *et al.* (9) overcame this challenge and demonstrated that satellite-based interferometric synthetic aperture radar (InSAR) measurements can monitor compaction of very shallow soil layers over the Southeast Asian peatlands. Chaussard *et al.* (10) demonstrated that by further post-processing the InSAR measurements with statistical tools (independent component analysis), separation of the multiple components of the total subsidence signal is possible, as well as the linking of each component to a specific subsurface activity.

Instead of relying only on InSAR measurements, multiple observation techniques are being used in concert at the Mississippi Delta and the Venice Lagoon (11). InSAR measurements are combined with a fit-for-

Subsidence through multiple human interventions

Modern observation can map surface subsidence over an area of concern (left column) and help disentangle the relative contributions from multiple causes (middle column). Disregarding any potential human intervention will risk overestimating the role of others at any point on the surface (for example, points A and B in a 10 by 10 km surface) as total subsidence (red line) accumulates over time.



Geological Survey of the Netherlands, Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO), Utrecht, Netherlands.
Email: thibault.candela@tno.nl

purpose surface elevation table apparatus and with at-depth along-wells optical fiber strainmeters. Following this integrated approach, the along-wells deeper measurements exclusively record the subsidence contribution of deep human interventions. By contrast, the InSAR measurements of the changes in elevation of the ground surface record both deep and shallow contributions. In the Netherlands, combining diverse geodetic techniques (absolute gravity, Global Navigation Satellite System, and InSAR) has allowed separation of the measuring points into two families (7). One monitors deep human interventions such as hydrocarbon extraction, and the other monitors shallow human interventions such as groundwater level changes.

The subsidence footprint of each human intervention can now be measured with tailored monitoring technologies. This development is a major step forward, which helps avoid the tunnel vision that can lead to erroneously attributing the total subsidence to one single human subsurface activity. Because these tailored monitoring technologies are in place, unbiased assessment of the subsidence rate caused by each superimposed human subsurface activity can be deployed.

Connecting the underlying physical causes of subsidence to the observation-based disentanglement allows a full picture of the origin of subsidence. Subsurface modeling is required because of the limited predictive power of observations but allows for establishing causal relationships. After demonstrating that the models can explain the observations, these validated models can be used to test targeted prevention and mitigation strategies for each human intervention.

Data assimilation techniques designed to calibrate physical models with observations, identical to those used for weather forecasting, have recently been successfully deployed for human-induced subsidence forecasting (4, 12). However, these studies have only focused on a single subsurface activity at a time. The natural evolution would be to use the same data assimilation techniques to jointly calibrate, in one go, models of subsidence induced by shallow and deep human interventions. This calibration step will help to discriminate deep-seated causes and shallow-seated causes from the total subsidence signal. By tightly connecting observations and models, physical explanation will support the observation-based disentanglement.

The negative effects of human-induced subsidence are known, especially in terms of financial consequences. City officials of Amsterdam, the Netherlands, for example, estimate their municipality to suffer more than

€60 million per year worth of subsidence-related building damage and infrastructural maintenance costs (13). However, the sense of emergency is difficult to perceive because subsidence is a slow and gradual motion. This results in a passive decision-making process that may be exacerbated by attaching each superimposed subsurface activity to a specific actor. This makes it unclear to what extent an actor may be responsible for the total subsidence. Disentangling the total subsidence into the relative contribution of each human intervention could allow for a more active mode for planning mitigation procedures rather than the more passive method of focusing on adaptation strategies.

Underlying the need for disentangling subsidence source is the recognition that human interventions in the subsurface will be ongoing for the foreseeable future. Large-scale groundwater withdrawal for domestic, industrial, and agricultural use will continue and possibly expand with changing weather patterns and increasing population. Compaction of hydrocarbon reservoirs continues for decades even after production stops, so any decreases in hydrocarbon extraction will not immediately stop the related subsidence. The potential also exists for large-scale human interventions to ramp up for long-term underground CO₂ storage and hydrogen, along with geothermal energy extraction. All of these can lead to subsidence and will need to be individually accounted for by establishing causal relationships (14). The issues are especially crucial because coastal cities are already exposed to the threats of global sea-level rise and collectively affected by subsidence-induced groundwater management (15). New sources of human-induced subsidence put these places in an even more vulnerable position. ■

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CHEMISTRY

Nitriles for the production of various amines

Nitriles functionalize amines and ammonia under catalytic hydrogenation conditions

By Yasunari Monguchi

Amines are commercially important chemicals that are widely used in pharmaceuticals and agrochemicals, with an ever-growing demand for their industrial production (1, 2). Catalytic hydrogenation, which uses hydrogen gas as a reducing reagent, is a well-established industrial process for producing various chemicals. There are many benefits of this method. For instance, the hydrogen gas can be removed by simply opening the reaction vessel; there is no need for removing unreacted reagents and reagent-derived wastes. However, it has been difficult to apply hydrogenation to produce specific amines because the reaction lacks control over selectivity. On page 1433 of this issue, Chandrashekar *et al.* (3) demonstrate a general method to produce various amines using a catalytic hydrogenation condition in a highly selective manner.

Amines are nitrogen-containing compounds that are derivatives of ammonia (NH₃), with one or more hydrogen atoms replaced with carbon substituents from either aliphatic compounds, that is, from the alkyl group, or aromatic compounds, that is, from the aryl group. Amines have traditionally been produced by substituting the hydrogen atoms in ammonia with substituents through chemical reactions. This process is known as alkylation when the substituent is from the alkyl group. However, it is practically impossible to control the number of introduced substituents for each ammonia molecule using this method, resulting in the generation of all substituted amines, that is, ammonia molecules with one (primary), two (secondary), or all three (tertiary) of its hydrogen

Laboratory of Organic Chemistry, Daiichi University of Pharmacy, 22-1 Tamagawa-machi, Minami-ku, Fukuoka 815-8511, Japan. Email: monguchi@daiichi-cps.ac.jp

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