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GEOSCIENCE

Mapping the global threat of land subsidence

Nineteen percent of the global population may face a high probability of subsidence

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Subsidence, the lowering of Earth's land surface, is a potentially destructive hazard that can be caused by a wide range of natural or anthropogenic triggers but mainly results from solid or fluid mobilization underground. Subsidence due to groundwater depletion (1) is a slow and gradual process that develops on large time scales (months to years), producing progressive loss of land elevation (centimeters to decimeters per year) typically over very large areas (tens to thousands of square kilometers) and variably affects urban and agricultural areas worldwide. Subsidence permanently reduces aquifer-system storage capacity, causes earth fissures, damages buildings and civil infrastructure, and increases flood susceptibility and risk. During the next decades, global population and economic growth will continue to increase groundwater demand and accompanying groundwater depletion (2) and, when exacerbated by droughts (3), will probably increase land subsidence occurrence and related damages or impacts. To raise awareness and inform decision-making, we evaluate potential global subsidence due to groundwater depletion, a key first step toward formulating effective land-subsidence policies that are lacking in most countries worldwide.

A large-scale systematic literature review reveals that during the past century, land subsidence due to groundwater depletion occurred at 200 locations in 34 countries [see supplementary materials (SM)]. However, subsidence extent is only known for one-third of these records, information on the impacts is scarce, and mitigation measures were implemented only in a few locations. In China, widespread subsidence affects cities developed in the main sedimentary basins. In Indonesia, coastal subsidence in Jakarta is so severe that government authorities are planning to move the capital to the island of

Borneo. In Japan, subsidence affected several cities during the 20th century, including more than 4 m of subsidence in Tokyo, before groundwater management practices mitigated further subsidence. Iran currently hosts some of the fastest-sinking cities in the world (25 cm year⁻¹) because of unregulated groundwater pumping. In Europe, the greatest impact of subsidence occurs in the Netherlands, where subsidence is primarily responsible for placing 25% of the country below the mean sea level and increasing the flooding risk. Subsidence in the Po River Plain in Italy started during the second half of the 20th century and currently threatens 30% of the Italian population, contributing to recurrent coastal flooding during extreme high tides in Venice. In North America, intense groundwater depletion triggers subsidence from California's Central Valley, with as much as 9 m of subsidence in the past century, to the Atlantic and Gulf of Mexico coastal plains in the United States, where subsidence is increasing flooding risk. In México, subsidence rates are among the highest worldwide (as much as 30 cm year⁻¹), affecting small structurally controlled intermontane basins where the main urban centers developed, causing an important but unaccounted economic impact.

Spatial analysis of subsidence locations identified in our global database (see SM) reveals that subsidence has preferentially occurred in very flat areas where unconsolidated sediments accumulated in alluvial basins or coastal plains, and where urban or agricultural areas developed in temperate or arid climates characterized by prolonged dry periods. Land subsidence has generally occurred in water-stressed basins, where the combination of groundwater withdrawal and natural groundwater discharge outpaced groundwater recharge, resulting in groundwater storage losses, groundwater depletion, and compaction of susceptible aquifer systems. In the affected basins, land subsidence mainly occurred in highly populated areas, with half of documented occurrences in ar-

reas susceptible to flooding. In coastal zones, the combined effects of absolute sea-level rise and land subsidence contribute to relative sea-level rise (4). The contribution from land subsidence may exceed the contribution from absolute sea-level rise by a factor of 10 or more and could be especially critical for 21% of the geographic locations identified in our database, where land elevation is less than 1 m above the mean sea level.

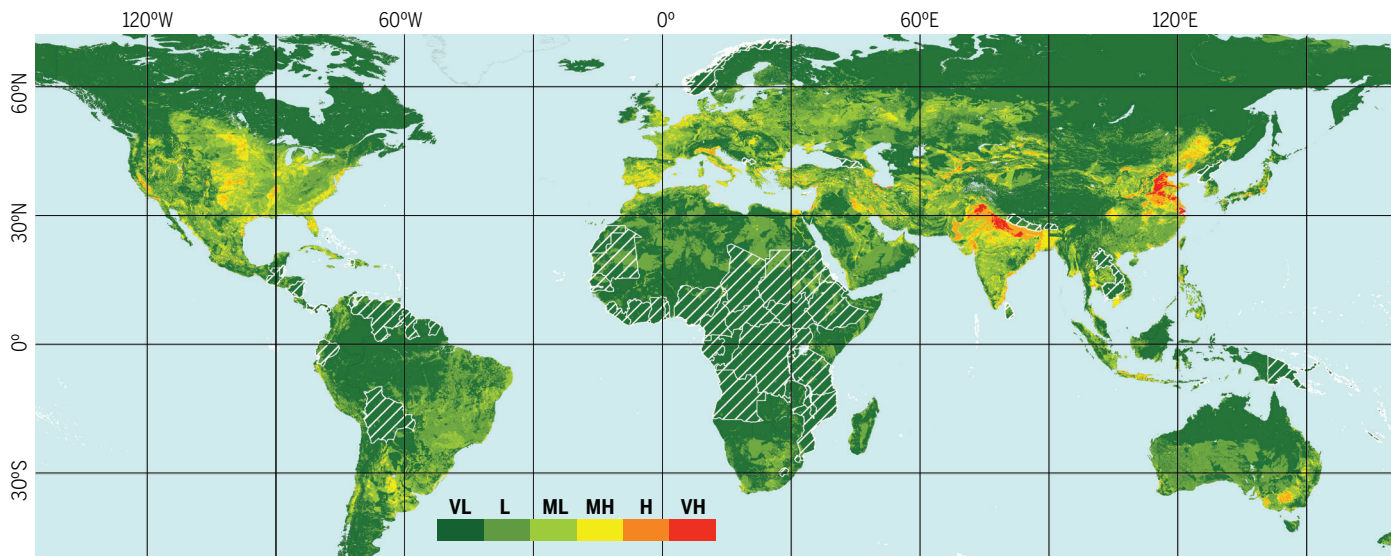
On the basis of the spatial analysis findings, a global model is proposed to combine the main variables influencing subsidence to identify environmental settings favoring land subsidence and the anthropogenic factors leading to groundwater depletion (see SM). Statistical analyses of lithology, land-surface slope, land cover, and Koppen-Geiger climate classes are used to predict global subsidence susceptibility at a spatial resolution of 1 km². The probability of groundwater depletion is estimated by identifying urban and irrigated areas suffering water stress and where groundwater demand is high.

The analyses do not consider subsidence magnitude and rate, owing to the lack of this information at a global scale. Hence, the combination of subsidence susceptibility and the probability of groundwater depletion is used to predict a "proxy" of subsidence hazard, which permits identification of exposed areas where the probability of land subsidence occurrence is high or very high. Even though these results do not necessarily translate to direct impacts or damages, they are useful for identifying potential subsidence areas where further local-scale analysis is necessary. The comparison of our model predictions with an independent validation dataset reveals a 94% capability to distinguish between subsidence and nonsubsidence areas, according to the value of the area under the receiver operating characteristic curve (see SM). The global exposure to potential subsidence is evaluated by calculating the number of inhabitants living in potential subsidence areas, i.e., subsidence hazard proxy, and the equivalent gross domestic product (GDP). This "proxy" of exposed assets is calculated assuming that GDP per capita is homogeneous within each country. Finally, the evolution of potential global subsidence and the related exposure is pre-

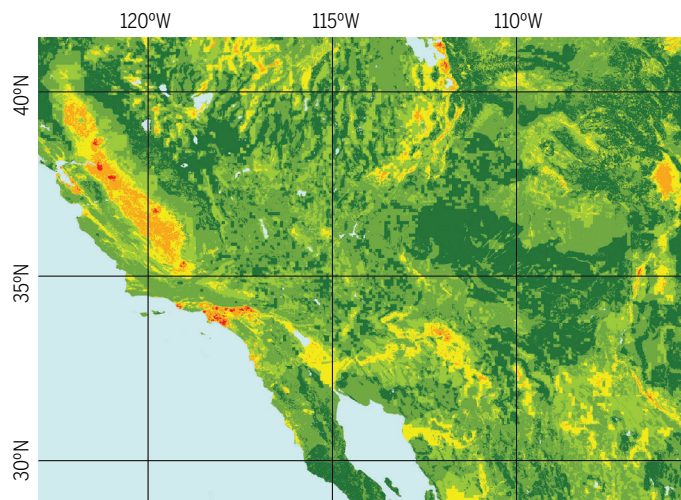
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Potential global subsidence

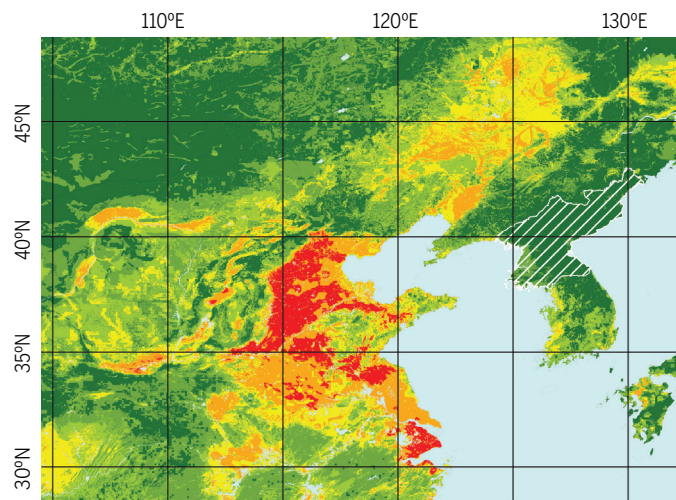
The color scale indicates the probability intervals classified from very low (VL) to very high (VH), for every 30-arcsec resolution pixel (1 km by 1 km at the Equator). The white hatched polygons indicate countries where groundwater data is unavailable, and the potential subsidence only includes information on the susceptibility. See maps of other regions in supplementary materials.



North America



East Asia



dicted for 2040 for a global change scenario based on steady population growth and increasing greenhouse gas emissions (Shared Socioeconomic Pathways 2, Representative Concentration Pathway 8.5), which accounts for the greatest sea-level rise projections.

Our results suggest that potential subsidence threatens 12 million km² (8%) of the global land surface with a probability greater than 50% (MH to VH in the figure). Potential subsidence areas are concentrated in and near densely urban and irrigated areas with high water stress and high groundwater demand, overlying some of the largest and most depleted aquifer systems (5) in Asia (e.g., North China Plain) and North America (e.g., Gulf of Mexico coastal plain);

coastal and river delta areas worldwide (e.g., Vietnam, Egypt, or the Netherlands); and inland sedimentary basins of México, Iran, and the Mediterranean countries. Potential subsidence is lower in Africa, Australia, and South America, owing to the lower groundwater depletion (6). In central Africa, potential subsidence only includes information on the susceptibility, as groundwater depletion is unknown. In this region, subsidence susceptibility (see fig. S6) could be useful to prevent subsidence impacts on developing cities that during the next decades could rely more on the available groundwater resources.

To evaluate the exposure to potential subsidence, we focus on areas where the potential subsidence probability is high or very

high (see the figure). The cumulative potential subsidence area amounts to 2.2 million km², or 1.6% of the land; includes 1.2 billion inhabitants, or 19% of the global population; and has an exposed GDP of US\$ 8.19 trillion, or 12% of the global GDP. High-income countries account for 62% of the global exposed GDP but only 11% of the global exposed population, whereas low-income countries account for 54% of the global exposed population and 12% of the global exposed GDP. It is expected that the capability of low-income countries to implement the political, regulatory, and socioeconomic measures necessary to prevent and mitigate subsidence impact will be less than that for high-income countries.

Potential subsidence threatens 484 million inhabitants living in flood-prone areas, 75% of whom live in fluvial areas and 25% of whom live near the coast. This number of threatened inhabitants corresponds to 50% of the global population exposed to flooding hazards according to previous estimates (7), demonstrating the importance of considering potential subsidence in global flooding risk analyses.

Most of the global population exposed to potential subsidence live in Asia (86%), which is about 10 times the combined exposed population of North America and Europe (9%). The results indicate that 97% of the exposed global population is concentrated in 30 countries (see SM). India and China share the top two rankings of potential subsidence in terms of spatial extent and exposed population. Egypt and the Netherlands have the largest populations living in potential subsidence areas that are below the mean sea level. The greatest population densities in potential subsidence areas occur in Egypt and Indonesia, whereas the relative exposure per country, measured as the exposed population normalized by the total population, is greater than 30% for Egypt, Bangladesh, Netherlands, and Italy. The United States ranks first in terms of GDP exposed to potential subsidence, owing to its high GDP per capita.

Combination of the aforementioned metrics permits derivation of a potential subsidence index ranking (see SM). Seven of the first ten ranked countries have the greatest subsidence impact, accounting for the greatest amount of reported damages (Netherlands, China, USA, Japan, Indonesia, México and Italy).

During this century, climate change will cause serious impacts on the world's water resources through sea-level rise, more frequent and severe floods and droughts, changes in the mean value and mode of precipitation (rain versus snow), and increased evapotranspiration. Prolonged droughts will decrease groundwater recharge and increase groundwater depletion, intensifying subsidence. The global potential subsidence is predicted for 2040 using the same subsidence metrics and available global projections of water stress, water demand variations, climate, and population (see SM). Although predicted potential subsidence areas increase only by 7% globally, the threatened population is predicted to rise by 30%, affecting 1.6 billion inhabitants, 635 million of whom will be living in flood-prone ar-

eas. These changes will not be homogeneous. Between 2010 and 2040, the predicted population exposed to potential subsidence increases more than 80% in the Philippines, Iraq, Indonesia, México, Israel, Netherlands, Algeria, and Bangladesh. The increase will be moderate, less than 30%, for China, the United States, Italy, and Iran. Potential subsidence is forecasted to decrease in Japan and Germany, owing to effective groundwater management policies and population declines. Finally, potential subsidence is predicted to emerge in high-latitude northern countries like Canada and to increase in extent in Russia or Hungary, where climate change will favor longer dry seasons.

Further advancements in the global evaluation of subsidence can be made when a global historical database on subsidence rate, magnitude, and extent has been compiled, which could be largely sourced from continental monitoring of surface dis-

placements using satellite radar imagery (8). Widespread continuous monitoring of subsidence will permit better evaluation of the potential impact of land subsidence, especially in countries like Indonesia, México, and Iran, where local studies revealed the highest subsidence rates worldwide, but the national dimension of subsidence is still unknown. Further research also is necessary to evaluate the cost of damage caused by current and historical subsidence worldwide. The combination of damage information with hazard estimates will permit improved assessments of potential loss and design of cost-effective countermeasures. Presently, annual subsidence costs are only published for China (US\$ 1.5 billion) and the Netherlands (US\$ 4.8 billion) (9). The greater subsidence costs in the Netherlands owe to the exposed population below the mean sea level and the large investments made to prevent flooding. Our model, which does not yet consider mitigation measures, likely overestimates potential subsidence exposure in the Netherlands and Japan, where groundwater management has effectively controlled subsidence over the past decades (10).

Our results identify 1596 major cities, or about 22% of the world's 7343 major cities that are in potential subsidence areas, with 57% of these cities also located in flood-prone areas. Moreover, subsidence threatens 15 of the 20 major coastal cities ranked with the highest flood risk worldwide (11), where potential subsidence can help delimit areas in which flooding risk could be increased and mitigation measures are necessary.

Overall, potential global subsidence results can be useful to better define the spatial extent of poorly documented subsidence occurrences, discover unknown subsiding areas, prevent potential subsidence impacts wherever groundwater depletion occurs, and better identify areas where subsidence could increase the flooding risk. In any of these scenarios, an effective land-subsidence policy should include systematic monitoring and modeling of exposed areas, evaluation of potential damages, and cost-benefit analyses permitting implementation of adequate mitigation or adaptation measures. These measures should consider groundwater regulation and strategic long-term measures, such as the development of alternative water supplies and the protection and (or) enhancement of natural or artificial recharge of aquifers.

Considering that the potential subsidence may affect 635 million inhabitants living in flood-prone areas in 2040, it is of prime importance that potential subsidence is quantified and systematically included in flood risk analyses and related mitigation strategies.

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SUPPLEMENTARY MATERIALS

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