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GLOBAL LAND SUBSIDENCE: IMPACT OF WATER RESERVOIR OVERUSE AND RIVER FLOW ON URBAN STABILITY

Introduction. – A quiet death, land subsidence is caused by a number of factors, including a sharp decline in groundwater (GW) levels. Land subsidence has emerged as a significant global challenge, particularly in urban areas where human activities such as groundwater extraction and water reservoir overexploitation accelerate ground deformation. A variety of natural or man-made factors can cause subsidence, which is the lowering of the Earth's land surface. However, solid or fluid mobilization underground is the primary source of subsidence, a potentially disastrous danger[1]. Groundwater depletion-induced subsidence is a slow, gradual process that occurs over long time periods (months to years). It causes a progressive loss of land elevation (centimeters to decimeters annually) over very large areas (tens to thousands of square kilometers) and varies in its effects on agricultural and urban areas across the globe. Subsidence ruins buildings and civil infrastructure, creates earth fissures, raises the danger of flooding, and permanently lowers the storage capacity of aquifer systems.

Over the coming decades, the world's population and economy will continue to grow, increasing demand for groundwater and the resulting groundwater depletion. Droughts will likely make this worse, increasing the likelihood of land subsidence and the associated damages or impacts[2]. Assessing possible global subsidence brought on by groundwater depletion in order to increase awareness and guide decision-making. This is a crucial first step in developing efficient land-subsidence policies,

[1] Sharifi A. et al., "Can river flow prevent land subsidence in urban areas?", *Science of The Total Environment,* 2024, 917, pp. 170-557.

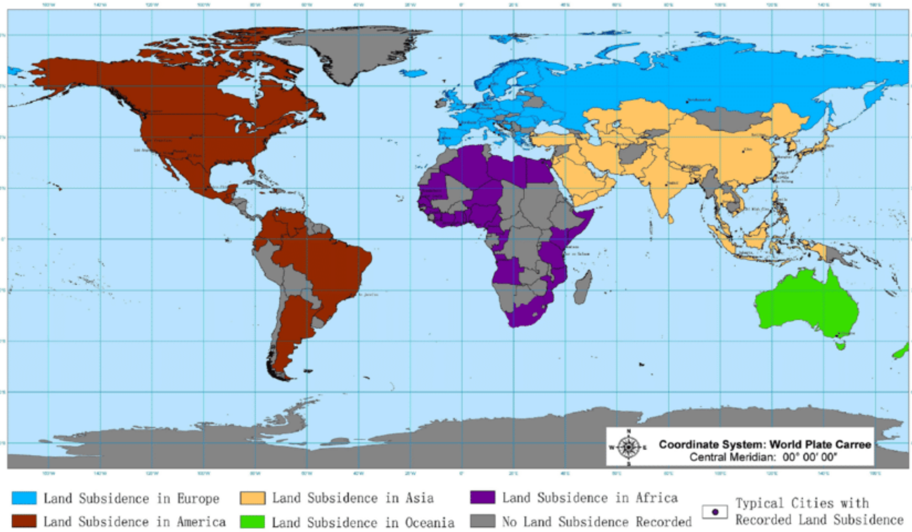
[2] Richard G. Taylor et al., "Ground water and climate change", *Nature Climate Change,* 2013, 3, 4, pp. 322-329.

which are absent in the majority of nations globally. «Land subsidence is a global problem, and its occurrence is often linked to human activities, particularly groundwater extraction, which leads to irreversible ground deformation and significant socio-economic consequences».

Global Distribution and Impact of Land Subsidence. – According to research, GW depletion-induced subsidence has been seen in 200 areas in 34 nations, but little is known about the effects and mitigating measures. However, information on the repercussions is limited, mitigating measures were only put in place in a few areas, and the amount of subsidence is only known for one-third of these records. In China, towns built in the major sedimentary basins are impacted by extensive subsidence. Government officials in Indonesia are considering relocating the capital to the island of Borneo due to the extreme coastline subsidence in Jakarta. Subsidence occurred in a number of Japanese cities throughout the 20th century, notably Tokyo, which experienced more than 4 meters of subsidence until groundwater management techniques prevented more sinking. As a result of uncontrolled groundwater pumping, Iran now has some of the world's fastest-sinking cities (25 cm year--1).

Subsidence has the biggest effect in Europe in the Netherlands, where it is largely to blame for 25% of the country's elevation below mean sea level and elevated danger of floods. Thirty percent of the Italian population is presently at risk due to subsidence in the Po River Plain, which began in the second half of the 20th century and causes frequent coastal flooding in Venice during extremely high tides. From the Central Valley of California, which has seen up to 9 meters of subsidence in the last century, to the Atlantic and Gulf of Mexico coastal lowlands in the United States, where subsidence is raising the danger of floods, severe groundwater depletion causes subsidence throughout North America. Mexico has one of the greatest rates of subsidence in the world (up to 30 cm per year), which has a significant but unrecognized economic impact on the tiny, structurally regulated intermontane basins where the major metropolitan centers grew.

Fig. 1 – *Map of global land subsidence distribution*[3]



Source: Yan X. et al., "Sustainable development of coastal cities through control of land subsidence: activities of IGCP Project 663 in Jakarta", *Episodes*, 2021 (DOI: 10.18814/epiiugs/2021/021014)

Causes and Mechanisms of Land Subsidence. – Generally speaking, land subsidence has happened in water-stressed basins where natural groundwater flow and groundwater extraction exceeded groundwater recharge. This led to compaction of vulnerable aquifer systems, groundwater depletion, and losses in groundwater storage. Land sinking in the impacted basins mostly happened in densely inhabited regions, with half of recorded incidents occurring in flood-prone locations. Relative sea-level increase in coastal areas is a result of both land subsidence and sea-level rise.

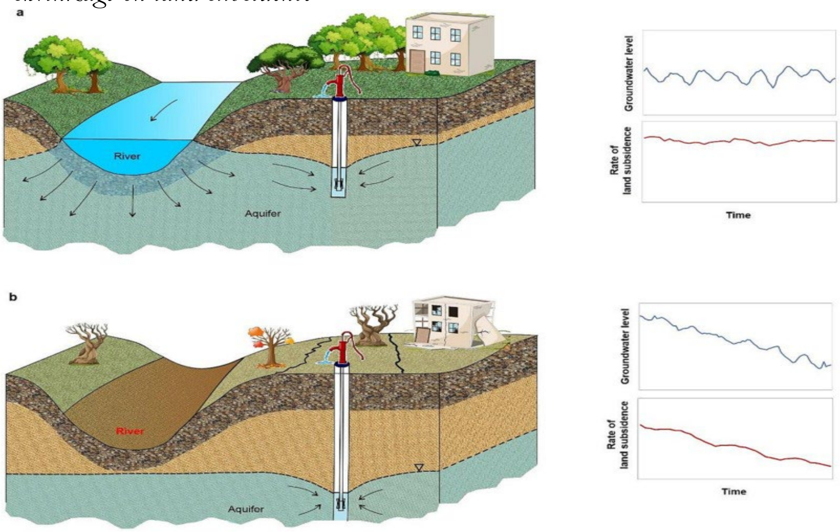
Groundwater and Surface Water Interactions. – There has been much research and documentation on the relationship between land subsidence

[3] Nearly 90 nations with land subsidence records globally were selected based on the statistical findings of historical papers and documents, and a country map of land subsidence distribution was created (fig. 2). A more thorough map at the regional and local levels has been intended to be developed in addition to the global land subsidence mapping. According to the findings of the global subsidence mapping collaboration with UNESCO's Land Subsidence International Initiative (LaSII) and IGCP641, 19% of the world's population may be at high risk of subsidence (Herrera et al., 2021). Additional details are available on the LaSII website (https://www.landsubsidence-unesco.org/maps/).

and GW depletion. But little focus has been placed on the function of surface water (SW) in this process, particularly in areas where low GW tables and inadequate rainfall preclude direct GW recharging from precipitation. For instance, studies conducted to examine the connection between land subsidence reducing groundwater recharge from the river system and rainfall brought on by human activity in deltaic regions that are closely related to fluvial and marine processes[4].

In riparian zones, where proximity to rivers greatly affects GW levels, groundwater (GW) and surface water (SW) interact intimately. The effect of SW on GW diminishes with increasing distance from the river. An abundance of river water stabilizes GW levels and lowers the likelihood of soil subsidence by replenishing it. GW depletion speeds up and increases subsidence when there is insufficient SW. As long as the river maintains sufficient water levels, urban areas next to it stay stable; but, when river levels fall, GW tables decrease as well, accelerating subsidence.

Fig. 2 – *The schematic view of the interaction between the river and GW and the effect of SW shrinkage on land subsidence*



Source: Sharifi A. et al., "Can river flow prevent land subsidence in urban areas?", *Science of The Total Environment*, 2024, 917, pp. 170-557

[4] Golian M. et al., "Consequences of groundwater overexploitation on land subsidence in Fars Province of Iran and its mitigation management programme", *Water and Environment Journal,* 2021, 35, 3, pp. 975-985.

Socio-Economic Consequences. – On top of some of the largest and most depleted aquifer systems in Asia (such as the North China Plain) and North America (such as the Gulf of Mexico coastal plain); coastal and river delta areas worldwide (such as Vietnam, Egypt, or the Netherlands); and inland sedimentary basins of Mexico, Iran, and the Mediterranean countries, potential subsidence areas are concentrated in and near densely urban and irrigated areas with high water stress and high groundwater demand. Due to less groundwater depletion, there is less potential for subsidence in South America, Australia, and Africa. Since groundwater depletion is unknown in central Africa, prospective subsidence merely provides information on vulnerability.

The investigation evaluates the danger of land subsidence worldwide, finding 2.2 million km^2 (1.6% of land) as high-risk locations that might impact 1.2 billion people (19% of the world's population) and generate US$ 8.19 trillion in GDP (12% of the world's GDP). Disparities in mitigation capacity are highlighted by the fact that low-income countries account for 54% of the population at risk but only 12% of the exposed GDP, whereas high-income countries hold 62% of the exposed GDP but only 11% of the exposed population[5].

Environmental Impact and Future Projections. – Climate change will significantly impact global water resources through rising sea levels, extreme weather events, and altered precipitation patterns, leading to increased groundwater depletion and land subsidence. By 2040, potential subsidence areas are expected to grow by 7%, but the affected population will rise by 30%, reaching 1.6 billion, including 635 million in flood-prone regions. Countries like the Philippines, Iraq, Indonesia, Mexico, Israel, the Netherlands, Algeria, and Bangladesh may see an 80% increase in exposure, while China, the U.S., Italy, and Iran will experience a moderate rise of less than 30%[6]. Effective groundwater management is expected to reduce subsidence risks in Japan and Germany, while high-latitude countries like Canada, Russia, and Hungary may see new or worsening subsidence due to climate-driven prolonged dry seasons.

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[5] Herrera-García G. et al., "Mapping the global threat of land subsidence", *Science,* 2021, 371, 6524, pp. 34-36.

[6] Taylor R.G. et al., "Ground water and climate change", *Nature Climate Change,* 2013, 3, 4, pp. 322-329.

A global model that analyzes lithology, land-surface slope, land cover, and Koppen-Geiger climate classes at a resolution of 1 km2 is proposed in order to discover natural and human-induced factors that influence land subsidence. The model evaluates urban and irrigated areas experiencing water stress in order to determine the probability of groundwater depletion. It forecasts subsidence danger by integrating susceptibility and groundwater depletion likelihood, but it is unable to evaluate the extent or pace of subsidence due to data restrictions. A 94% accuracy rate in identifying locations susceptible to subsidence is demonstrated by validation. Based on population expansion and high greenhouse gas emissions, 2040 predictions indicate that rising sea levels and climate change would increase the dangers and vulnerability to subsidence[7].

Flood Risk and Urban Stability. – Subsidence contributes to the worldwide flood risk by endangering 484 million people in flood-prone areas, mostly in coastal zones (25%) and river regions (75%). Asia is most exposed (86%), with China and India having the most impacted populations and land. While over 30% of the inhabitants of Egypt, Bangladesh, the Netherlands, and Italy are at danger, the biggest populations below sea level are found in Egypt and the Netherlands. Because of its large per capita income, the United States has the highest GDP exposure. The most impacted countries are ranked by a subsidence index, with the most documented damages occurring in the Netherlands, China, the United States, Japan, Indonesia, Mexico, and Italy (see SM).

Advancements in Subsidence Monitoring and Mitigation. – Progressions in global subsidence evaluation rely on compiling a historical database on subsidence rates, magnitudes, and extents, supported by satellite radar monitoring. Continuous monitoring will improve impact assessments, particularly in highly affected countries like Indonesia, Mexico, and Iran. Estimating the economic costs of subsidence remains a challenge, with only China and the Netherlands reporting annual losses. Subsidence threatens 22% of major cities, including 15 of the 20 most flood-prone coastal cities, emphasizing its role in exacerbating flooding risks (see

[7] Mirabbasi R., Ahmadi F., Jhajharia D., "Comparison of parametric and non-parametric methods for trend identification in groundwater levels in Sirjan plain aquifer", *Iran. Hydrology Research,* 2020, 51, 6, pp. 1455-1477.

SM). Effective mitigation requires systematic monitoring, groundwater regulation, and alternative water supply strategies. Sustainable surface water (SW) management is crucial, as SW sources help stabilize groundwater (GW) levels and reduce subsidence risks, particularly in river-adjacent regions.

Conclusion. – Land subsidence poses a significant threat to urban areas, particularly where groundwater depletion is severe. Integrating systematic monitoring, predictive modelling, and cost-benefit assessments into policy frameworks is essential to mitigate risks. Sustainable groundwater and surface water management strategies must be prioritized to maintain water balance and reduce subsidence impacts. Given that 635 million people in flood-prone areas may be affected by 2040, it is imperative to incorporate subsidence risks into global flood management plans. Proactive planning, regulatory measures, and innovative water conservation strategies will be key in protecting vulnerable regions from the cascading effects of land subsidence.

Subsidenza e urbanizzazione: rischi a scala globale dell'uso incontrollato della risorsa idrica

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