Public Health, Socioeconomic and Environmental Impacts of Urban Land Subsidence

Laureline Josset,[1] Upmanu Lall,[1] Divya Prakash,[2] Ariel Dinar[2]
[1]Columbia University, New York City, USA
[2]University of California, Riverside, USA

Abstract

Land subsidence (LS) due to groundwater pumping has been the subject of many studies at various spatial scales, dimensions of impacts and degrees of economic characterization. Recent progress in remote sensing has led to assessments at the planetary level, with an emphasis on the city-impacts. In this paper we first conduct a review of recent economic assessments of LS impacts and evaluate their potential to inform decisions and to be applied in other urban environments, from which we derive desirable characteristics for future assessments. Then we propose a framework and methodology specific to the urban context, but applicable to any city, considering availability of appropriate data. The approach attempts to categorize levels of impacts on the built and natural infrastructure and propagates its consequences for public health, socio-economic and the environment. From its application to the context of Jakarta, we conclude with recommendations regarding methodology, data, and governance level for the international community to support local actors. In addition to monitoring plans and regulatory interventions, we reaffirm the need of multidisciplinary teams to address the complex issue of the infrastructural risk of LS and its impacts.

Acknowledgement

A previous version of this working paper was prepared as a background paper to the World Bank study (World Bank, June 2023) “The Hidden Wealth of Nations: Groundwater in Times of Climate Change”[1], and was partially funded by the World Bank.

JEL Codes: D62, Q24, Q25, O18, R14

Keywords: land subsidence, urban groundwater, assessment framework, critical infrastructure, data availability, data gap, InSAR.

[1] https://www.worldbank.org/en/topic/water/publication/the-hidden-wealth-of-nations-groundwater-in-times-of-climate-change

1 Introduction

Land subsidence (LS) is the phenomenon of sudden or gradual sinking of the land surface in response to either natural processes, such as oxidation and vaporization of organic soils, or human activities, including oil mining or groundwater extraction (Zoccarato et al. 2018). Subsidence occurs throughout the globe, mostly studied and recognized, to different extents, in association with groundwater over-pumping of unconsolidated alluvial aquifers composed of a substantial fraction of fine-grained sediments.

LS inflicts significant damage on local communities and on the environment as assessed in Dinar et al. 2021; Herrera et al., 2021; Kok and Costa, 2021, and others cited below. Damages include infrastructure collapse, soil fracture leading to loss in life in some cases, reduced performance of hydrological structures, with irreversible loss of aquifer storage capacity, and malfunctioning of drainage systems, to name a few. As such, identifying the types of damages and quantifying their physical and economic impacts, whether direct or indirect and in the short- and long-term, is essential to assess risks, inform responses and determine stakeholders.

LS impacts infrastructure, and, consequently, cities. Trends in building heights, buried infrastructure, urbanization, and reliance on groundwater contribute to increasing LS risks. LS also affects the agricultural sector via impacts on water conveyance infrastructure and drainage systems. However, there is a need to characterize LS implications specifically in urban zones, where immediate social impact and extent may be much greater than in rural areas.

The motivation for focusing on cities is the combined effect of LS and floods. Cities experience pluvial and fluvial floods, and storm surges at increased rates and intensities. Because LS impacts ground elevation, runoff, and recharge rates, in addition to the structural integrity of flood-mitigation infrastructure, LS accentuates flood risks.

Cities often do not have the capacity to perform assessments of LS and its impacts, and these are challenging to accomplish from a global perspective. Recent advances in LS monitoring through remote sensing permit studies beyond the most documented cases, e.g., Mexico City, Bangkok, or Beijing. In parallel, global demographic and environmental data sets and mapping tools are now available. Combining both allows for a first order assessment of LS risks and their implications to inform further local regulators.

This working paper is centered on characterizing the public health, socio-economic, and environmental impacts of LS in cities. Recognizing that data on land subsidence extent and on the damages inflicted by LS are both scant and partial, we focus our efforts on developing a standardized approach that leverages global data availability and defines a multi-dimensional Land Subsidence Geospatial Risk Index (LSGRI) to inform actions on the risks faced by cities.

This paper is structured as follows. First, we present the state of research on socio-economic frameworks that evaluate LS impacts and latest attempts at quantifications. We also examine gaps at the public health and environmental impacts, and derive the characteristics of a multidimensional index, the LS Geospatial Risk Index (LSGRI), to inform decision-makers (Part A). Part B consists of a detailed description of our approach to quantify GW-over-pumping induced LS impacts in urban environments, detailing the framework, data considerations and methodology to build the LSGRI. Part C applies the proposed approach to the city of Jakarta as an illustrative example. Last, we end this working paper with our conclusions on current limitations in LS impact assessments, and provide recommendations to monitor, prevent, and mitigate land subsidence and the resulting environmental, socio-economic, and public health impacts.

2 Part A: State of research and literature review

2.1 Economic and social assessment of LS challenges

Several authors developed general frameworks for analysis and assessment of the impact of LS. Kok and Costa, 2021)—suggested short- and long-term, direct and indirect, market and non-market valued considerations. Dinar et al. 2021—suggested an index for assessment of the extent of LS impacts (in the absence of economic values of LS impacts) across affected regions. While these works are not specific to the urban environment, we review their contribution for the city context.

LS can lead to direct damage to public and private infrastructure such as roads, bridges, water pipes, creating accidents, loss of life, and requiring expensive repairs. Some of the costs affect private dwellings, either manifest through structural damages that are associated with repair costs (Mulas et al., 2003), or due to loss of market value to residential homes (Yoo and Perrings, 2017; Willemsen et al., 2020). Repair costs are ad-hoc and relatively easy to estimate, once repairs have been undertaken (Mulas et al., 2003). However, datasets with such costs are scant or even nonexistent. In the case of loss in market value of residential dwelling, existing studies (Yoo and Perrings, 2017, Willemsen et al., 2020) have used hedonic approaches where values of residential homes around fissures and sites with land subsidence were determined by distance from such locations. However, data on residential market prices in large urban centers may not be available over time in developing (or even in developed) countries, which are subject to significant population growth, increased need for groundwater supply, and thus increased likelihood of LS impact. Therefore, such studies are of limited use to inform response and prevention by decision-makers globally.

In the absence of specific LS-related damage data on various aspects of economic and social activities in urban areas, the approach in Dinar et al. (2021) proposes to count the categories of LS impacts so that the corresponding score reflects the dimensional range of LS impacts. They identified 10 categories of LS impacts in published literature. Of the ten attributes listed, several, such as the socio-economic impacts, the environmental damages affecting drainage system, hydrogeological damages that result in groundwater storage loss, and groundwater contamination, to explain the extent of damages of LS in the context of the urban sector. A summary of the index and its application are presented in the next section.

2.2 The LS Impact Extent (LSIE) Index

Use of indicative indexes to assess environmental health status has been practiced by many national and international agencies (OECD, 2003; EEA—Gabrielsen and Bosch, 2003; EPA—Fiksel et al, 2012). Use of indexes allows comparison across states and geographical regions (OECD, 2003). The use of indicative indexes can provide useful trajectories in the case of lack of more detailed damage/impact data.

The analytical framework leading to the LSIE is as follows: An exhaustive review of LS-related literature provided indication of different types of land subsidence impacts in each site (Dinar et al. 2021). The LSIE development relied on 183 published scientific works, covering 113 locations in 35 countries, and indicated up to 10 LS impact types in the various analyzed sites. If a certain type is identified, a score of 1 is assigned to that category. If this type of impact has not been documented, a score of 0 is assigned. LSIE is calculated by averaging the values (0 or 1) assigned to each of the 10 impacts. A higher LSIE value means that the location is exposed to more categories of impacts. The LSIE development process used data from 183 scientific works published in the professional literature. The data used pertains to 113 locations in 35 countries. Table 1 presents the LSIE for several major cities affected by LS.

Table 1: Presence of 10 types of LS impacts and the corresponding LSIE score for 8 megacities around the world.

	Tianjin	Mexico City	Ho Chi Minh City	Bangkok	Jakarta	Manila	Shanghai	Beijing
1 Socio-economic impacts such as structural damages to buildings and infrastructures	1	1	1	1	1	1	1	1
2 Environmental damages such as malfunctioning of drainage systems	1	1	1	1	1	1	1	1
3 Geological-related damages: Effects on underground lateral water flows	1	1	1	1	1	1	1	1

4 Environmental damages such as reduced performance of hydrological systems	1	1	1	1	1	0	1	1
5 Environmental damages such as wider expansion of flooded areas	1	1	1	1	1	1	1	1
6 Hydrogeological damages that result in groundwater storage loss	1	1	1	1	1	1	1	1
7 Impact on adaptation ability to climate change, such as the loss of the buffer value of groundwater in years of scarcity	0	1	1	0	1	1	1	1
8 Groundwater contamination	1	1	1	1	1	1	1	0
9 Loss of high value transitional areas (e.g., saltmarshes)	1	0	1	0	1	1	0	0
10 Shift of land use to poorer activities	1	0	0	0	1	1	0	0
LSIE	0.9	0.8	0.9	0.7	1	0.9	0.8	0.7

Source: Authors' elaboration using raw data from Dinar et al. (2021).

However, the lack of detailed information of the impact of LS of different study cases can lead to a bias in the evaluation of the index. Another caveat of the LSIE is that a subsidence event could occur with only one type, but severe impact, and could be seen as less important. For example, the case of Iran or Mexico, where subsidence occurs inland and sea-level-rising related flooding effects are unlikely or even impossible, but the intensities of the other impacts of LS are very harmful. In that respect LSIE does not provide a good quantification of the LS impact, but rather a measure of its extent (or scope) through the accounting for various LS-impact components.

2.3 Quantification of economic and social impacts of LS, and lessons learned

Land subsidence can cause severe environmental, economic, and social losses in urban areas as is discussed in the remainder of this section. Although economic damages caused by LS are relatively acknowledged, the social and environmental costs are equally enormous. As per the existing local and national damage reports, the LS related expenses are estimated to be billions of dollars globally (Kok and Costa, 2021; See also citations in Appendix 1).

With the rapid pace of urbanization and increasing economic expansion, the adverse impact of LS in terms of economic losses in urban centers is becoming more evident and associated with significant cost. However, the assessment of both direct and indirect economic damages and their costs are complex (Deltares, 2015).

Most of the existing LS studies are focused on measuring, modeling, and monitoring subsidence and assessing its extent in terms of loss in elevation (Kok and Costa, 2021). Few studies have performed an economic assessment of the impact of LS in given localities (Warren et al., 1975; Lixin et al., 2010; Hu et al., 2013; Borchers, J. W. et al., 2014; Yoo and Perrings, 2017; Wade et al., 2018; Willemsen et al., 2020). We are not aware of any research that has formulated a standardized framework for the cost assessment of LS, except Kok and Costa (2021), which address any negative environmental externality, including but not limited to LS. As such the specific characteristics of LS, such as public health, socio-economic and environmental aspects (Table 1) have not been addressed.

A broad spectrum of studies estimates the economic impact of natural disasters.[2] Some of these methods have been extensively used to calculate both direct and indirect economic effects of LS, for example, market-based, non-market-based, or both types of valuation approaches (Kok and Costa, 2021). The direct costs could be calculated using market-based valuation techniques based on production functions or cost-based approaches (such as damage repair, engineering, or lifecycle costs). To estimate the non-market effects of a disaster, stated or revealed preference methodologies are commonly used, like adverse health effects, environmental losses, or social upheaval (Pascual, U. et al., 2010). It is observed that the hedonic pricing methods (the revealed preferences approach) and cost-based (market-based) approaches are the most often used methodologies for economic cost assessment of LS. A summary of key papers offering cost estimations of direct and indirect LS impacts is presented in Appendix I.

The adverse effects of subsidence are disregarded until they pose expensive and life-threatening problems, such as flooding or significant infrastructure damage, resulting in prolonged economic, and, sometimes, life losses. In most places, only the physical effects of land subsidence have been considered; however, the economic costs, which might be in the billions of dollars, have not been calculated (Kok and Costa, 2021). Additionally, with the burgeoning urbanization and economic growth, there could be a noticeable rise in the likelihood of economic damage, specifically in places vulnerable to subsidence.

2.3.1 Comparing estimations of LS damages

The estimated cost of LS impacts from the thirteen studies summarized in the appendix are presented in Table 2. The cost estimates have been adjusted to the 2021 dollar value using the Consumer Price Index from the U.S. Bureau of Labor Statistics (Bureau of Labor Statistics, 2022).

[2] Column 5 presents the current monetary values of the LS damage in US Dollars (USD) as used in the original studies. Column 6 presents these damages in constant 2021 USD for better comparison.

Table 2: Economic Damage Values from Land Subsidence in the urban sector in various locations at 2021 prices.

(1) Author(s)	(2) Year of Analysis	(3) Damaged Sector	(4) Country/Region	(5) Actual Value in Paper	(6) Value in 2021
Hallegatte, S. et al	2013	Exposed Assets	136 largest coastal cities	USD 665 billion	USD 773.5 billion
McFarlane	2012	Exposed properties	Virginia, USA	USD 9 to 26 billion	USD 10.6 to 30.7 billion
Erkens et al.	2015	Damage to infrastructures	Netherlands	USD 4.8 billion	USD 6.5 billion
Erkens et al.	2015	Indirect damages	China	USD 1.5 billion	USD 1.8 billion
Lixin et al.	2010	Infrastructure and physical features	China's Tianjin region	USD 18.19 billion	USD 23.8 billion
Erkens et al.	2015	Infrastructure and physical features	Shanghai, China	USD 2 billion	USD 2.4 billion
Warren et al.	1975	Historical costs and property losses	Texas, USA	USD 113.6 million	USD 624.3 million
Borchers, J. W. et al.	2014	Infrastructure and physical features	San Joaquin Valley, California	USD 1.3 billion	USD 1.5 billion
Borchers, J. W. et al.	2014	Infrastructure and physical features	Santa Clara Valley, California	USD 756 million	USD 879.4 million
Saputra et al.	2019	Adapt to damage costs	Indonesia	USD 172 per household	USD 182.3 per household. In total[a], USD 60,159.
Willemsen et al.	2020	Residential properties	Rotterdam and Gouda, Netherlands	17 billion euros	USD 20.3 billion
Yoo and Perring	2017	Residential properties	Maricopa County, Arizona, USA	$24,570 and $27,646 (Properties with existing land subsidence) $18,329 and $19,399 (Properties with future LS)	In total,[b] USD 607.3 million for properties with existing land subsidence and USD 984.9 million for properties with future land subsidence.
Herrera et al.	2021	Exposed Assets	34 countries	USD 8.17 trillion	USD 8.17 trillion

[a]Note: In Saputra et al. (2019) there are a total of 330 households in the sample.

[b]Note: In Yoo and Perring (2017) there are 16,874 property transactions with existing land subsidence beyond 500 meters of an earth fissure; 1324 property transactions with existing land subsidence beyond 500 meters of an earth fissure; and 18,198 property transactions with future land subsidence. For more details see Appendix 1.

The estimates in column 6 (except for the last row) of Table 2 reach nearly USD 865 billion. A different estimate of negative effects of LS by Herrera et al. (2021) in the last row of Table 2 reaches USD 8.17 trillion and could already account for the previous global estimate of USD 856 billion. The latter value is an estimate of global exposure to LS damage, while the prior value is an estimate based on specific studies conducted arbitrarily in specific locations around the globe. In either case, the economic implications are staggering and suggest that LS is a negative externality in need for policy intervention. The few estimated LS cost/damage values in Table 2 show a lack of consistency among the few attempts to quantitatively estimate damages inflicted by LS. The different methods used, extent of affected areas, the varying time spans, the inconsistent use of discount rates and time horizon for the analyses forbid comparisons across studies and challenge the total cost estimate presented above. Rather, they should be considered merely for an illustrative purpose (Dinar et al., 2021).

At present, many countries' regulatory bodies and local water management organizations have not given LS the required preventive attention (Dinar et al., 2020). A better assessment of the potential effects of LS could be made possible by widespread monitoring. Future research is needed to estimate the cost of the damage done by historical and contemporary subsidence. The development of a more accurate economic evaluation of damages is needed to design cost-effective countermeasures.

Such economic evaluation of the impact of LS on urban dwelling values is possible using the hedonic approach. Several studies, presented below, have used the hedonic approach to estimate reduction in residential home values as a result of LS impact.

2.3.2 Using the Hedonic Approach to estimate economic damage from LS in the residential sector.

In the presence of economic data on damage, more comprehensive estimates can be produced. One impact of LS could be on residential houses, leading to a reduction in their market value. If data on houses' sale values in regions affected by LS is available, the "Hedonic Approach" can be applied, as it is done in the case of air or noise pollution on the value of residential homes located at different perimeters from the center of the pollution source (Tang and Niemeier, 2021; Egbenta et al., 2021). Recent works (Yoo and Perrings, 2017; Willemsen et al. 2020) applied the hedonic approach to estimate the economic effect of LS on property values in the town of Mariposa, Arizona, and in the Netherlands, respectively.

The hedonic pricing method has been used to estimate the economic value of an ecosystem or environmental services that are affected by any type of pollution (e.g., noise, air, water), or other negative or positive effects of the environment (e.g., water, parks, recreational sites, land subsidence). It is most commonly applied to variations in housing prices that reflect the value of local environmental attributes of the properties.

The basic principle of the hedonic pricing method is that the price of a market good is related to its characteristics, or the services it provides. For example, the price of family homes reflects the characteristics of that property (e.g., distance from the center of the town, pool, style, neighborhood). Therefore, we can value the individual characteristics of a home or other good by looking at how the price people are willing to pay for it when those characteristics change.

A basic model could look like the following: Home price = f(housing variables, neighborhood variables, environmental variables, …), where housing variables include: age, size, fireplace, pool; neighborhood variables may include: crime levels, schools, proximity to beach; and environmental variables may include PM Ozon, visibility, LS. By controlling for all attributes but one, we can isolate the impact of that one variable on the dependent variable. In the case of estimating impact of LS on residential home value, measures of LS and distance from a LS 'site' of a given home are included. Some of the published works (e.g., Yoo and Perrings, 2017) used also distance from land fissures that are a result of LS, in addition to the LS sinking level.

2.4 Drawbacks of available assessment approaches

2.4.1 Reconciling frameworks and data

There is a dissonance between the scale of proposed analytical frameworks and the limited data availability, resulting in a large number of aspects that remain unassessed. Indeed, frameworks such as those proposed by Kok and Costa (2021) mention nature-induced LS and impacts on the water cycle. However, we have found no description nor quantification of such impacts. In contrast, the fact that data is available in certain locations and for specific LS aspects results in over-assessment. This is particularly the case for real estate impacts, which can only be performed in areas of certain wealth and may ignore public health impacts on poor neighborhoods that require specific attention and policy interventions.

2.4.2 Navigating general approaches, global assessment, and location-specific studies

The mismatch between frameworks and data availability is particularly manifest when one examines the geographical domain of past quantifications. To each mechanism of subsidence correspond regions of specific geological characteristics, which need to be interfaced with the infrastructural, environmental, socio-economic, and demographic dimensions of the area of concern. Therefore, domains of relevance, their spatial extent, and the information of interest are contextual to the dimensions of the framework that are considered. For example, groundwater-led subsidence, which is anthropogenic by nature, cannot occur in areas without abstraction of large volumes of groundwater, which do not occur in granite formation or other hard rock subsurface. For human induced LS, it is imperative that detailed geological characterization and information on the spatial distribution and intensity of pumping be considered. This needs high resolution data within the city scale, rather than global maps of land subsidence that are not appropriately constrained by the local conditions at the spatial resolution of impact. Information on geology and pumping should be used even at a screening stage to consider which locations need further investigation.

2.4.3 Prioritization and actionable information

Another consideration is the relevance of the assessments that are performed. The risks are two. First, the information that is derived from the assessment should be useful, pertinent, and actionable for the stakeholders it is communicated to. In the case of groundwater-led LS in the urban context, the stakeholders include local residents and workers, owners and operators of businesses and industries, the construction and real estate sectors, and city officials, which include regulators, policymakers, elected officials, environmental agencies, urban developers, and critical services providers. Beyond the scale of the city, such derived information on LS and the subsequent impacts are of relevance to:

- National officials in charge of financial support, regulation and monitoring;
- Private and public sectors which may suffer from supply and distribution disruptions;
- NGOs acting in defense of critical services access to population, safe housing, and protection of natural spaces; and
- International organizations charged with monitoring of LS-related damages from space or in situ, or offering financial support for mitigation and adaptation.

Furthermore, a key aspect to consider are the changes in flood exposure due to, or reinforced by LS, which is of concern for all stakeholders listed above.

2.5 Developing the LS Geospatial Risk Index

Considering data constraints and our urban focus, we propose that a multi-dimensional Land Subsidence Geospatial Risk Index (LSGRI) is developed to identify and prioritize groundwater-led impacts to inform decision-making at the city, country, and international levels. Starting from a general framework as comprehensive as possible, we identify dimensions of relevance in the urban context driven by groundwater extraction and cross these dimensions with data availability.

The LSGRI allows screening for risks of LS, by identifying areas of potential public health, socio-economic and environmental impacts. However, no global study can supplement itself to local investigations. Our intent is thus to raise awareness for cities that are or may be facing groundwater-led LS, and equip them with a framework that ranges from the drivers, vectors, direct and indirect impacts. This would encourage a holistic consideration of LS, including its compounding effect from flooding.

Beyond the city-level actions, the index can be used to create regional concentrations of hotspots to support monitoring of LS and its impacts, as they depend on remote sensing and national and supra-national networks of gauges.

3 Part B: Framing and quantifying groundwater-led land subsidence in the urban context

Our objective is to propose a methodology that is replicable for cities throughout the world by relying on readily available global datasets. We focus solely on LS resulting from groundwater pumping in the urban environment. Part B of the report presents the conceptual framework supporting the methodology, then it follows with the data consideration associated with the framework, and finally, it describes the resulting methodological steps. Part C presents an illustration for the city of Jakarta, Indonesia, for which processed InSAR data was provided by Wu et al. (2022).

3.1 Conceptualizing groundwater-led land subsidence in the urban context

Land subsidence is in effect compacting the subsurface over time and therefore it is measured in units of depth (representing *severity*) over a specific domain (representing *extent*). This is established via elevation measurements over time across the urban zone. For groundwater-led LS, the compaction of the subsurface depends on three types of parameters: i) the aquifer and soil characteristics, ii) the groundwater present within that aquifer, and iii) the pumping rate at which water is extracted. Indeed, clay or silt layers within a confined aquifer can get reorganized and take less space when the pressure drops due to abstraction of groundwater (Galloway et al., 1999). Therefore, aquifer composition, i.e., the presence of clay or silt lithologies, the type of aquifer, i.e., confined and layered, and its extent, will determine the zone where LS may occur. Groundwater levels indicate the state of pressurization of the fabric of the clay layers, while pumping location and depth together with recharge rate determine where there are risks of depressurization, and thus rearranging of clay or silt (Galloway et al., 1999). Figure 1 presents a diagram of drivers and impacts of land subsidence in the urban setting.

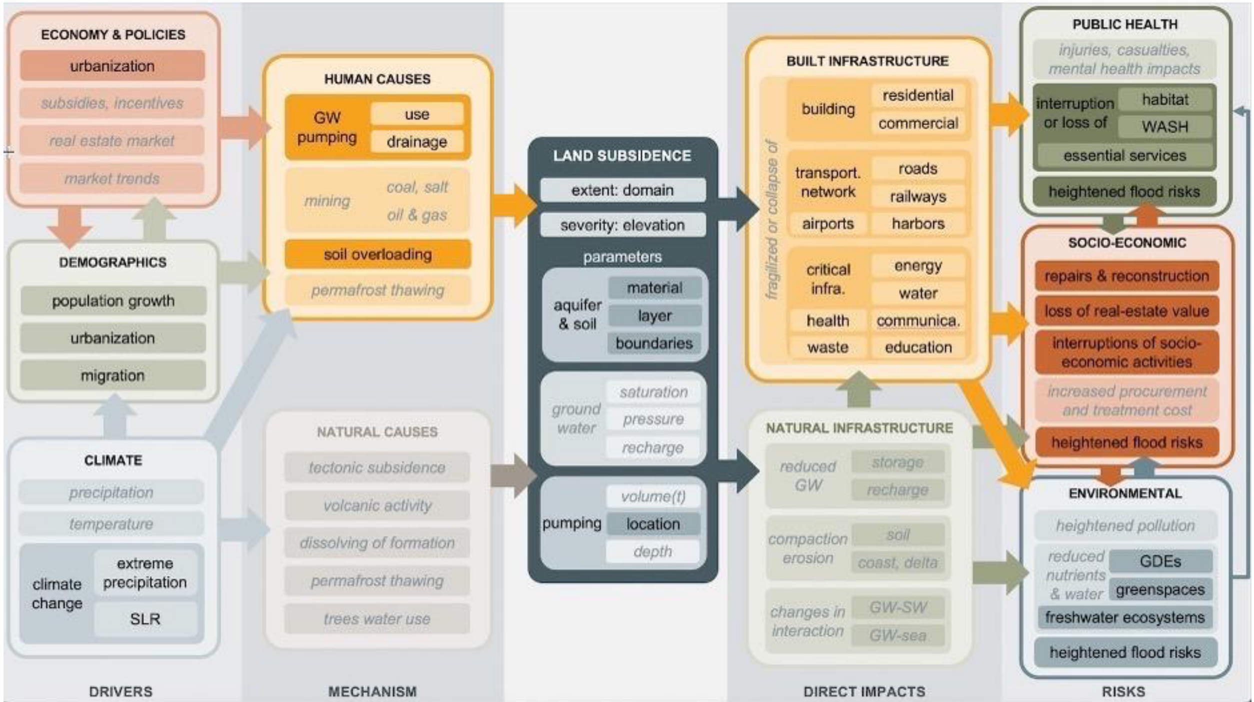


Figure 1: Diagram of drivers and impacts of land subsidence in the urban setting. Dimensions highlighted in black are considered in the present framework through direct estimates or proxy information, while dimensions in fade colors are not considered due to a lack of available data or because being out-of-scope.

Source: Elaborated by authors.

The left panel of the diagram in Figure 1 presents the drivers and vectors of LS in the urban context. The emphasis here is on human-caused, and specifically groundwater-led subsidence. In the urban context, groundwater is pumped to meet water demands for household and essential needs, commercial and industrial usage, and peri-urban agriculture. Groundwater pumping for draining is a common occurrence in some urban settings to render wetlands suitable for construction and limit flood risks of foundations. We highlight here another prominent effect in the urban sector: soil overloading from the weight of the built infrastructure. While other factors lead to LS as represented in Figure 1, whether natural or anthropogenic, they are less common for metropolitan areas.

Factors determining groundwater withdrawals are the water demand due to demographics, climatic and economic settings, in addition to incentives, and pervasive policies and regulations. Climatic conditions are relevant, especially where agricultural demand competes with urban demand over the same water sources. Precipitation predominantly determines recharge rates that determine the safe abstraction rates limiting LS.

Urbanization leading to demographic and economic changes together with sprawling (the city boundaries) and densification (increasing soil overloading) are key drivers to consider for quantifying both the risks of LS and, mainly, the resulting socio-economic risks.

The right panel of the diagram in Figure 1 presents the direct and indirect impacts of LS in the urban context. Direct impacts of LS are felt on the built and natural infrastructure. Regarding the first, we distinguish between impacts on buildings (residential housing or commercial structures), transportation networks and hubs (e.g., roads, railways, stations, harbors, airports), and critical infrastructure. Critical infrastructures considered are the ones necessary for energy, water, communication, health, education, and waste. Note that transportation is also often considered as critical infrastructure, however, we make the distinction between the two to map the resulting public health and socio-economic risks accordingly.

Direct impacts on the natural infrastructure include the effects on the aquifer itself and the natural features that depend on it and affect it. These include damage to groundwater-dependent ecosystems, reduced groundwater storage capacity, decreased recharge effectiveness, erosion of soils, and changes to interaction between subsurface water flows and surface water stocks (fresh or saline).

The resulting societal risks are arranged in three categories: public health risks, socio-economic risks, and environmental risks. The risks are developed in Table 3 below. The indirect risks may cascade one with another as indicated by the arrows in Figure 1.

Heightened flood impacts are present for each of the categories. Flood risks may result from direct LS impacts alone because of increased elevation differential and reduced storage capacity of the aquifer, but may also compound with additional climate stressors from climate change. LS compounds with flood risks in four ways:

- Heavy-precipitation flood events are intensified by reduced recharge and groundwater storage capacity. LS may also change the relative elevation profile thus modifying flood zones. Stormwater infrastructure may get impacted by LS, reducing or interrupting their proper functioning.
- Fluvial and lake flooding induced by changes in climate patterns may result in different and/or more intense flooding because LS modifies the elevation profile of the area.
- In coastal areas, sea-level rise impacts are increased by LS lowering ground elevation.
- Similarly, in coastal areas, storm surges intensified by climate change may result in modified/more severe flooding due to LS-induced changes in ground elevation.

Table 3: LS direct impacts on infrastructures and the corresponding indirect health, socio-economic and environmental impacts.

	Public health risks	**Socio-economic risks**	**Environmental risks**
		Built infrastructure	
Residential housing and commercial buildings	Injuries from collapse of buildings, mental health impact from insecurity	Repair costs leading to reduced earnings, loss of value	N/A
Water and wastewater piping network	Interruption or reduced quality of water services for household usage	Costs of repairs, interruption of socio-economic activities due to water interruptions or reduced quality	Leakages in wastewater pipes, stormwater infrastructure, leading to pollution of the subsurface
Transportation (roads, bridges, railways, harbor)	Loss of access to critical infrastructure (ambulances, firetrucks), loss of public transportation	Disruption in workplace access, disruption in supply and distribution chains	Collapse of transportation infrastructure can come with pollution risks to the surrounding water bodies
Hospital, schools, and other urban critical infrastructure	Interruption of critical services to the public health of the urban population	Decrease in real estate value due to interruption/unreliable services	Potential leakages of polluting substances with fragilized storage
Energy generation or distribution	Pollutants involved in energy generation may enter water resources if integrity of infrastructure is affected by LS	Interruptions in electricity may lead to interruption of socio-economic activity	Pollutants involved in energy generation may enter the ecosystems and water resources if integrity of infrastructure is affected by LS
Storage of toxic product, waste storage, landfills	Pollutants may enter the ecosystems, water resources and air if storage integrity is affected by LS	Loss of storage infrastructure, repair and cleaning cost, license to operate might be challenged	Pollutants may enter ecosystems if storage integrity is affected by LS
		Natural infrastructure and ecological services	
Reduced storage of groundwater for usage	Reduced municipal, community, household GW supply for usage	Reduced groundwater availability in terms of quantity leading to additional cost for procurement and treatment	Impacts on irrigation-dependent urban greenspaces
Compaction and erosion of upper soil	*Public health impacts result from environmental impacts*	*Impacts may result from environmental impacts*	Reduced nutrients and water access for root systems in urban and peripheral ecosystems (e.g., mangrove)
Reduced recharge and drainage inducing flooding	Temporal loss of habitat, proliferation of water-borne disease, WASH impacts	Cost of temporary interruption, relocation, cleaning, repair, replacement	Drowning of ecosystems, flooding-related pollution of ecosystems
Changes in GW-SW interactions	*Public health impacts result from environmental impacts*	Reduced surface water availability in terms of quantity and quality leading to additional cost for procurement and treatment	Impacts on Groundwater Dependent Ecosystem (GDE) Impacts on river lowflows and freshwater ecosystem, progression of the salt front

Changes in GW-seawater interactions	Saline intrusion may jeopardize household or community wells	Saline intrusion may lead to additional treatment cost, loss assets and additional procurement costs	Saline intrusion may lead to impacts on GDE
Coastal and delta land compaction or/and collapse	Reduced protection from SLR at the household level, seawater-flooding of wells for household water usage	Reduced value due to potential increased exposure to SLR and flooding risks	Drowning of ecosystems, reduced nutrients and soil for peripheral ecosystems (e.g., mangrove)

Source: Elaborated by authors.

3.2 Data needs, availability, and constraints

The analytical framework detailed in Figure 1 is an attempt at a comprehensive representation of land subsidence, considering the drivers, mechanisms, direct impacts and resulting risks. However, for the purpose of conducting an assessment of groundwater-driven LS in the urban context, certain dimensions deemed secondary are dropped as highlighted by a grayer shade in the various parts in Figure 1 and as specified in Table 4.

3.2.1 Data requirements

From the analytical framework illustrated in Figure 1, one can derive the data needs and related key attributes. Table 4 details the requirements for each dimension. This exercise is conducted specifically for the urban context with the intent of considering public health, socio-economic and environmental impacts from groundwater-led LS. The domain and resolution are thus defined considering both the actual variable and its usage to quantify the impacts. For instance, if one is to understand the impact of LS on the built infrastructure, the spatial resolution of LS at the scale of a building would be relevant.

Table 4: Data requirements and scale of relevance for each of the elements of the diagram depicted in Figure 1.

	Variables of interest	Temporal	Spatial	
			Domain	Resolution
Drivers and compounding effects				
Economy & policies				
Urbanization	Population, building types and density trends, socio-economic and demographic characteristics	Yearly	City	Zone, neighborhood
Subsidies and incentives	Insurance, loans, tax credits		City-nation	City, neighborhood
Real estate market	Price and value		City	
Market trends	Commercial and real estate trends		City-nation	
Demographics				

Population growth	Population, socio-economic and demographic characteristics	Yearly	City	Neighborhood
Urbanization	Population, building types and density trends, socio-economic and demographic characteristics			
Migration	Population, socio-economic and demographic characteristics			City
Climate				
Precipitation	Volume, intensity, frequency	Monthly-seasonal	Recharge area	
Temperature	Impact on water demand	Daily-seasonal	City	
Climate change	Extreme precipitation	Daily/yearly, historical/projection	City	
	Sea-level rise	Yearly-projection	City, coast	
Mechanisms				
Human causes				
GW pumping for usage or drainage	Volume, depth, location	Monthly-seasonal	Aquifer	Well
Mining	*Ignored as rare in large metropoles prioritized for this assessment but may be relevant in some cases*			
Soil overloading	Building (weight, height, material)	Concurrent, historical	Intersection between urban and aquifer	Building or zone
Permafrost thawing	*Ignored as rare in the urban context and the latitudes of most cities*			
Natural causes	*Ignored here as focus is on GW-led subsidence, but may compound in further LS*			
Land subsidence				
Extent	Surface area, boundaries	Year-decade	City/aquifer	Building
Severity	Depth, slope	Year-decade	City/aquifer	Building
Parameters				
Aquifer	Material (in particular clay and silt) Layer (number, thickness, depth) Boundaries	Year-decade to static	Aquifer	Building
Groundwater	Saturation (soil-aquifer interface) Pressure (confined/unconfined, piezometric levels) Recharge (location and volumes)	Monthly-seasonal		Well
Pumping	Volume (abstracted, returned) Location (latitude, longitude) Depth (with respect to layers)	Monthly-seasonal		Well, layers
Direct impacts				
Built infrastructure				
Buildings	Residential (number of residents, demographics, real estate value) Commercial (usage/sector, real estate value)	Concurrent, historical	Intersection between urban and LS delineation	Building or zone

	Building (weight, height, material)			
Transportation	Buildings (station, airport) Networks (rail, road, metro lines)	Concurrent		Building/roads
Critical infrastructure	Buildings (energy, water and waste plants, hospitals and clinics, schools, data centers, antennas and relay towers) Networks (energy, water, wastewater, communication)			Building
Natural infrastructure	*Ignored as limited at the urban-scale and lack of information prevents characterization*			
Risks				
Heightened flood risks				
Types	Elevation and terrain, distance to water bodies, land coverage	Historical-projection	City	Building, neighborhood
Mitigation	Built (e.g., levees) and natural (e.g., mangrove, green spaces) infrastructure, warning and monitoring systems, maps	Concurrent		
Impacts	Built and natural infrastructure, public health, socio-economic, environmental	Concurrent		
Public health				
Injuries, casualties, mental health	Affected population, location	Historical-concurrent, yearly	City	Building, neighborhood
Interruption or loss of habitat	Affected population, location, relocation	Historical-concurrent, daily-weekly		
Interruption or loss of WASH activities	Drinking and household water source, quality, distribution, sanitation facilities and wastewater treatment			
Interruption or loss of other essential services	Location, served population and neighborhood, related impacts			
Socio-economic				
Repairs and reconstruction	Cost, location, amount	Historical	City	Building, neighborhood
Loss of real estate value	Market valuation, reputational cost			Zone, neighborhood
Interruption of socio-economic activities	Sector affected, timing, duration, reputational cost/impacts			
Increased procurement and treatment cost	Back-up solution, added cost, capex	Projection	Within or beyond city limit	City, neighborhood
Environmental				
Heightened pollution	Vulnerable ecosystem location and dependent fauna and flora, services	Concurrent, seasonal	Urban, peri-urban	Ecosystem

Reduced nutrients and water for	GDEs, greenspaces, freshwater ecosystems, location, distance to source of risk, fluxes of water			

Source: Elaborated by authors.

Measuring LS extent and severity

When focusing on the infrastructural impacts of LS, the resolution of interest is at the building level and the dimensions of relevance are the area where LS is occurring. The severity of LS determines the impacts. It may be a regional lowering of the ground or a phenomenon of smaller extent. However, impacts on buildings inducing fragility in the infrastructure stem from a gradient in the LS. Therefore, the differential, the slope of LS is of particular interest.

Recent progress in remote sensing allows the detection of changes in surface elevation through Interferometric Synthetic Aperture Radar (InSAR) at the relevant scale and resolution. Interpretation of InSAR data requires GPS stations in the vicinity of the zone of interest in addition to a digital elevation model (DEM) (Wu et al. 2022). We discuss in Section 3.2.2 and in Box 2 in Part C the sources of uncertainties, difficulties, and possibilities associated with InSAR derived LS rates.

Assertion of LS occurrence requires additional knowledge of the local hydrogeological context listed under parameters in Figure 1 and Table 3. Several confounding factors and attribution may arise. Depth of pumping wells, aquifer composition and geometry may lead to variations in spatial distribution of LS. General datasets on aquifer characteristics, geological information, and soil composition may facilitate interpretation. Further information on the aquifer geometry and composition may refine assessment of the evolution of LS and the subsequent risks. These include boundaries, presence of layers and thickness. For instance, we know that if groundwater is pumped from an aquifer that underlies a thick clay layer, we have a significant opportunity for LS, since the clay is what compacts as it is depressurized due to water withdrawal. The compaction is differential based on the surface loading (higher with a tall building than with a road) even if the clay thickness and the depressurization due to groundwater extraction is the same. The LS dropdown cannot exceed the thickness of the clay layer, since that layer only is subject to compaction.

Hydrogeological information of relevance also includes groundwater levels to assess pressurization and risk of compaction, recharge patterns that may offset certain withdrawals depending on their location, depth of water table, and intensity of pumping. This information is necessary to establish the stage of LS whether it is at the stage of susceptible, early onset, ongoing, or stabilized. The limited available data on monitoring and extraction wells, groundwater usage, and drainage, prevent a direct identification of causation. However, remote sensing imagery can facilitate the identification of groundwater usage through its infrastructure (e.g., well pumps location, size, or the intended use through the building and spaces around it).[3]

From a global perspective, where groundwater induced subsidence is of interest, we can then limit screening of potential locations to one with known sedimentary aquifers with thick clay layers. Thus, places in South India that suffer significant groundwater drawdowns, but have fractured hard rock aquifers would not be a concern for groundwater induced LS, while places that are known to have multi-layered sedimentary aquifers (e.g., the Indo-Gangetic plains and Bangladesh Delta) would be of special concern, especially as they are in the process of getting access to mechanized pumping and deep well drilling, which goes to deeper sandy layers beneath thick clay deposits.

Quantifying the impacts of LS

As per the framework presented above, the impacts are arranged in three overarching categories: public health, socio-economic, and environmental. The direct impacts of LS are predominantly infrastructural (built or natural), whereas indirect impacts are the consequences of the infrastructural impacts.

For the built infrastructure, LS stages of severity lead to different levels of impacts ranging from fragilizing the infrastructure and leading to reparations, to complete collapses. For direct impacts, the datasets of relevance are surveys of building integrity and costs of repair, replacement, or displacement such as in Borchers, J. W. et al. (2014) or Saputra et al. (2019). Market valued impacts are difficult to assess due to a lack of available data on housing sale values and the impact of intervention policies on the price signal, together with the importance of the informal housing market for areas and population characteristics of interest. We instead focus on the variables discussed below.

Affected population

To infer the number of people that may be impacted in the LS area, available population density datasets can be used, although at a scale that is larger than the building scale, permitting the derivation of the number of individuals exposed. Additional demographics statistics are becoming available at this scale, with a recent and for only specific location, efforts to map slums (Blaze, 2021). OpenStreetMap has building contours, while remote sensing data is gradually providing information on building roofs, which, when combined with DEM, allows to determine their heights and infer population density. See section 3.3.2 for a discussion on the role of remote sensing.

[3]There are several cases where stock of GW in aquifers is monitored using satellites. For example, Bastiaanssen and Hellegers (2007) describe the use of satellite to measure and regulate groundwater level in Pakistan, Mexico, and Saudi Arabia. The U.S. National Science Foundation (2018) reports use of satellite by scientists to measure vital underground water resources.

Critical infrastructure

Beyond assessing the number of people that are affected, a thorough assessment of impacts requires to narrow on the impacts on critical infrastructure. A recent dataset at the gridded scale of 0.10 × 0.10 and 0.25 × 0.25 degrees has been constructed worldwide (Nirandjan et al., 2022). The critical infrastructure data is classified in seven categories: energy, transportation, telecommunication, water, waste, health and education. Additionally, OpenStreetMap, from which the dataset was derived, has explicit layers for road systems, airports, railways, and also energy generation and distribution, storage structures, etc. The exactitude and completeness may vary from city to city.

Specific high-resolution datasets are available from remote sensing image processing, such as road networks. Additional products include distance to roads and waterways, which may be of relevance as covariates to estimate potential impacts, including flooding.

Regarding health infrastructures, which have their own identifier in OpenStreetMap, the World Health Organization is in the process of collecting this information for distribution (WHO, 2022). It may become available in the next couple of years.

The subsurface infrastructure, in particular water piping, remains largely unavailable. However, these tend to follow roads, which can be used as a proxy for their location. City level, and country level presence of underground piping may indicate a risk when combined with soil information on clay content for instance. Metro, subways, and underground train infrastructure can be considered with the location of lines and stations in OpenStreetMaps.

Commercial and industrial activities

At the building level, similar datasets in OpenStreetMaps and Google maps can be used to assess buildings and infrastructures at risk. Impacts from the critical infrastructure (in particular on water, energy and transportation) have an impact on the economic activities, thus propagating beyond LS focus. Two indices can be computed to (1) reflect numbers and density of commercial activities directly at threat from building integrity, and (2) their compounding with critical infrastructure. For (2), this includes impacts from lack of electricity, lack of water, and interruption in transportation networks (roads, railways, and harbor). Impacts on loss of production and consumers are not assessed.

Spatial analysis of the risks on natural infrastructure

Quantifying the impacts of LS on the subsurface medium is a challenge: Aquifer mapping remains imperfect and groundwater monitoring networks are limited. Nonetheless, UN-IGRAC aggregated available information into a groundwater network of monitoring wells. When available, this information might help assess impacts on groundwater storage capacity and recharge. However, it is fair to assume that when compaction is detected, it is already an indicator of impacts on groundwater resources.

The groundwater-surface water dynamics are of such complexity that assessing the impact of LS on this interaction would require dense and specific monitoring, beyond what is currently available for most cities.

Regarding the impacts on groundwater-seawater interactions and delta dynamics, while underground processes are difficult to assess, some changes in dynamics can appear in remote sensing imagery. Distinguishing them from other processes at play remains a challenge and global datasets are not currently available to perform a first estimate.

On the contrary, groundwater dependent ecosystems (dependent on groundwater directly or not, such as brackish and saline front line) mapping is widely available. Multiple datasets exist on mangroves, marshes, peatlands, etc. Furthermore, remote sensing imagery processed dataset on the presence of greenspaces within the urban environment, and specifically with trees are available.

Drivers of LS

Examining the drivers of land-subsidence is necessary to understand the spatial and temporal evolution of LS, but also to serve as a proxy of the quantification of the extent and severity of the direct and indirect impacts. Furthermore, they are oftentimes at the origin of compounding and confounding impacts. This is particularly the case for precipitation, a lack of which leads to intensified pumping and thus likely LS, while storm surges may lead to consequential flooding due to reduced drainage. Equally important, monitoring the drivers is key to identifying early-onset of LS and deployment of mitigation strategies before impacts are irreversible. Focus here is placed on demography and climate. A third component is pervasive policy as a driver of LS. For instance, subsidies and incentives for energy have led to tremendous groundwater depletion. In parallel, regulations or lack thereof on groundwater usage may dominate demographic factors. Lastly, city-level management of flooding risks (e.g., levees, drainage) are key to establishing the flooding risk profile of a city. While many maps have been produced at various scales on coastal exposure, SLR, or flood maps, datasets on levees and other mitigation strategies remain absent. This is particularly a problem as flood mitigation infrastructure (natural or built) may be fragilized by LS.

3.2.2 The role of remote sensing and its limitations

Thorough reviews of InSAR technologies can be found in the peer-reviewed literature discussing the merits and limitations of various InSAR data products (Raspini et al., 2022; Guzy and Malinowska, 2020), some of which focus specifically on land subsidence. Most recent instruments developed and operated by the European Space Agency, namely Copernicus Sentinel-1 and Sentinel-2, provide publicly available high-resolution imagery and radar information permitting never-before attained assessment of changes in elevation. One example is the DLR data product for Germany at the sub-building level, providing a detailed view and height assessments at the building level. This information is not yet available for the entire globe but may soon become readily available. We indicate once more that the quality of InSAR products is conditional on GPS stations, and that validation with in-situ aquifer measurements should not be neglected. Furthermore, high resolution remote sensing LS data exists only since the late 2000s. While concurrent information is key, historical trends and long time series are of importance to assess past compaction, differentiate actual land subsidence from seasonal variations, and monitor rate of LS evolution (stabilization or acceleration).

The availability of high-resolution imagery with world-wide time series coverage, such as DLR/EOC Copernicus Sentinel Data, is of use on two aspects beside the direct measurements of changes in elevation. First, significant progress in image classification and pattern recognition (such as link) provides an avenue to obtain data beyond what is officially reported, aggregated and/or disclosed. Second, reluctance to adopt open data principles due to privacy do not necessarily hold and may encourage data sharing. Therefore, any infrastructure and impact that can be identifiable from remote sensing imagery may soon become available information at great accuracy and completeness. We note that this information is already widely available thanks to the tremendous effort and open contribution of OpenStreetMap and the community behind that project.

However, groundwater, aquifer characteristics, and subsurface infrastructure are by nature hidden, and thus not measurable from space. Although attempts have been made to measure groundwater using GRACE, the resolution of the data products are irrelevant in the urban context. We therefore discourage its use. Assessment of groundwater usage and presence of wells may however be estimated from remote sensing imagery.

3.2.3 Selected datasets

Datasets that are available at the global scale are privileged so that the methodology can be applied to any city. However, resolution, completeness, and accuracy of the data may vary from one city to another. Leveraging supplemental information may be necessary to augment the resolution, refine the assessments or allow to fill gaps on dimensions that are otherwise uncharacterized. Furthermore, consultations with city officials and local experts are of crucial importance as no dataset can replace the knowledge acquired through experience. Present assessment methodology may help prioritize and guide engagement. Table 5 presents the data requirements and scale of relevance for each of the elements of the diagram depicted in Figure 1, which were discussed above.

Table 5: Data requirements and scale of relevance for each of the elements of the diagram depicted in Figure 1.

	Name	Year	Resolution	Ref
Drivers and compounding effects				
Economy & policies, and Demographic				
Urbanization	DLR World settlement footprint evolution	2019, 1985-2015	100m x 100m	Link, link
Demographic	Urban Center Database R2019A	2020	1km x 1km	Link
	NASA gridded population of the world	2000-2020	1km x 1km	Link
Climate				
Climate change	Extreme precipitation	Varies	Varies	Link
	Sea-level rise	1970-2017, 2040-2100	2.5Km x 2.5km	Link, Link
Mechanism				
Human causes				
GW pumping	*Assessed from InSAR image analysis correlated with OpenStreetMap information*			
Soil overloading	*Assessed from remote sensing imagery correlated with OpenStreetMap information*			
Land subsidence				
Extent Severity	Processed InSAR data	2015-2021		Wu et al. (2022)
	GPS stations network	Concurrent	Station	Link
Parameters				
Lithologies	Global Lithological Map V1.0	Static		Link
Karstic aquifer	World karst aquifer map WHYMAP	2017		Link
Monitoring well	UN-IGRAC Global Groundwater Monitoring Network	Concurrent, historical	Station	Link
Susceptibility	Potential global subsidence map	Static		Link
Direct impacts				
Built infrastructure				
Critical infrastructure	OpenStreetMaps	Concurrent	Building	Link
	A spatially-explicit harmonized global dataset of critical infrastructure	2022	0.25 × 0.25, 0.1 x 0.1	Link
Risks				
Heightened flood risks				
DEM	DLR DEM90	Concurrent		Link
Flood vulnerability	NASA Low Elevation Coastal Zone, urban-rural population and land area estimates	Concurrent		Link
SLR	NASA/IPCC sea level projection tool	2020-2150	Selected coastal cities	Link
Distance to waterways	Distance to OpenStreetMaps major waterways	2016		Link
Environmental				
GDEs and delta ecosystem	CIFOR global wetlands	2017		Link

Groundwater resources	UN-IGRAC groundwater resources of the world	Static		Link

Source: Elaborated by authors.

3.3 Proposed methodology

3.3.1 Overview

Trading off between a holistic consideration of the socio-economic impacts, data availability constraints, and objectives of replicability, we propose a methodology to consider the socio-economic impact of groundwater-induced land subsidence in the urban context. The overall procedure is illustrated in Figure 2, and Figure 3 provides the details of the steps from the spatial analysis of LS to the computation of the LSGRI. A step-by-step description of the methodology to follow for each city and the underlying motivations and constraints are described in the following section.

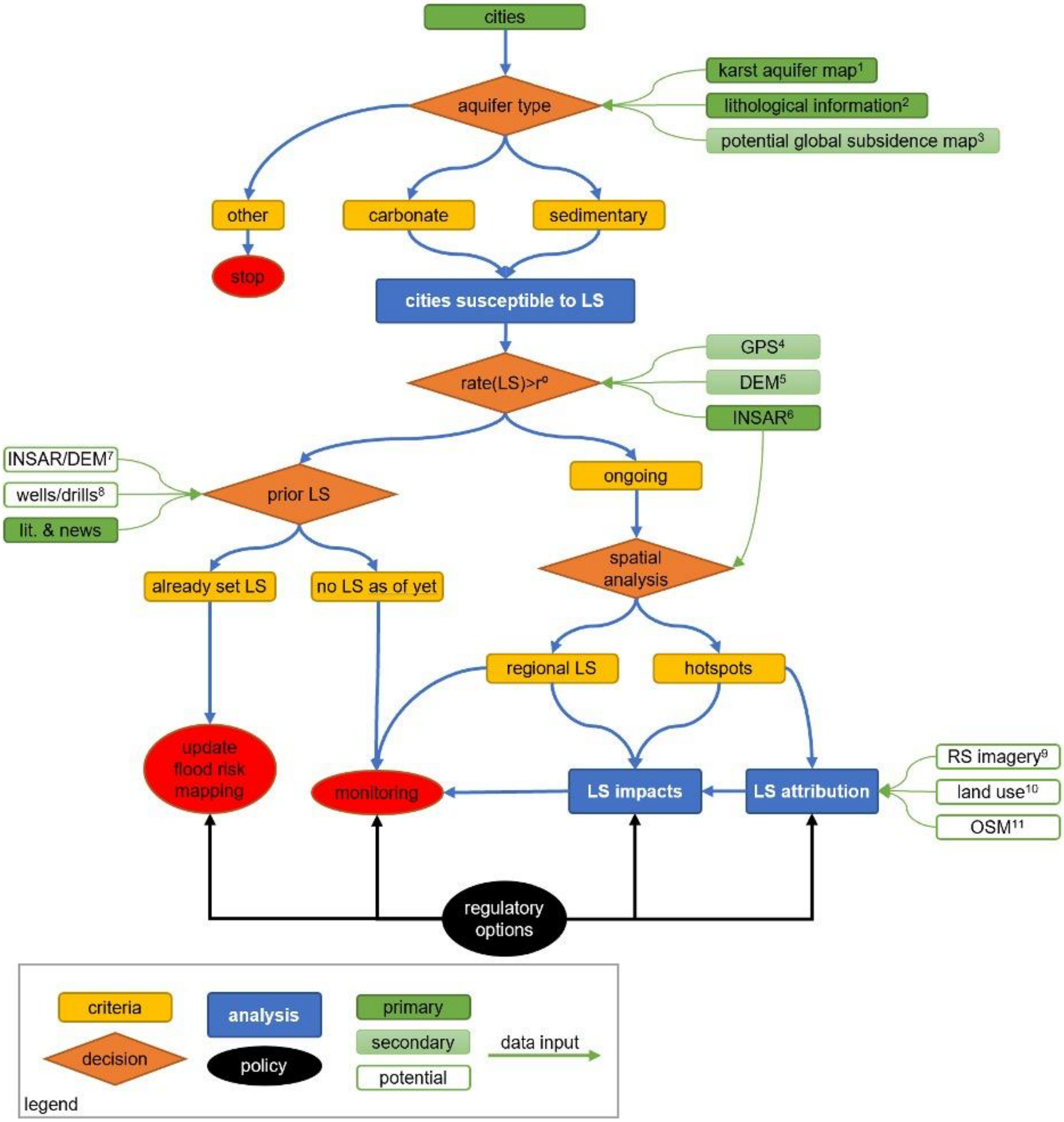


Figure 2: Overall workflow for the determination of groundwater-led LS socio-economic impacts for urban areas. Details of the quantification of LS impacts are represented in Figure 3.

Data sources and acronyms: [1] WHYMAP, [2] GLimP, [3] Herrerra (2018), [4] GPS station from the Nevada Geodetic Laboratory Networks Map, [5] Digital Elevation Model, [6] InSAR image analysis from 2015-2021 using Wu et al. 2022, 4 and 5, [7] InSAR data from years anterior to 6, as in Raspini et al. (2022) such as NASA, [8] IGRAC monitoring well network augmented with local information if found, [9] High resolution Copernicus Sentinel imagery, [10] OpenStreetMap

Source: Elaborated by authors.

3.3.2 Step by step description of the methodology

Identifying groundwater-led LS susceptibility of cities

The first step is to determine whether the geological characteristics beneath the city are susceptible to land subsidence. Initiation screening is performed based on lithological information and karstic aquifer map. If the rock formation is not sedimentary or carbonate in nature, the city is assessed as not susceptible to land subsidence. The screening process is validated/compared with the potential groundwater subsidence map.

InSAR data initial assessment

Relying on InSAR data processing presented by Wu et al. (2022), trends are derived at the spatial resolution of 30m for the 2015-2020 period relying on openly available Sentinel data. Precision is determined by proximity of GPS stations openly available as represented here. The presence of a GPS stations within the city vicinity at a 5km radius is used to evaluate the accuracy of the InSAR delineation. The level of accuracy however should highlight ongoing LS and may permit detection of early onset LS.

If the detected rate is inferior to $r^0 = \Delta$ mm/year, where Δ is a predetermined value identified for a sufficient area of each city or aquifer, it is assumed that no ongoing LS of relevance for impact assessments. Given the limited timeframe, already settled LS would need to be distinguished from its potential occurrence. Peer-reviewed literature and news articles are then considered to assess this. In the case of already settled LS, update of flood maps might be necessary in case DEM used were not up to date. Additional surveys of structural integrity might be conducted. In the case of no documentation of LS phenomenon, a monitoring plan should be considered.

LS delineation and attribution

InSAR data can be noisy because of its high sensitivity to elevation. Although the processing methods consider DEM and building heights, mischaracterization may remain. The initial screening step prevents focusing on areas where geology would not permit its occurrence, at least at a rate that would lead to socio-economic, public health and environmental impacts.

However, there is a need to identify zones of occurrence and confirm its drivers by attempting to attribute causality. This is performed by image analysis of InSAR data. Using a combination of spatial interpolation and wavelet analysis, delineation of regional subsidence and hotspots are identified ($r > r^0$). This corresponds to an inverse problem where we may have a high spatial resolution LS map that shows significant heterogeneity in its pattern. By correlating location and pattern identification with OpenStreetMaps, satellite imagery and additional local aquifer information, locations of major production wells (typically those used by industry and by a municipal water supplier) are located. We expect significantly higher extraction rates in the case of major production wells than for private wells. The associated cone of depression of the groundwater piezometric level, would then translate into a corresponding hotspot of LS. Conversely the generalized pumping by many private wells, each pumping a much smaller amount of water would emerge as a “smoother” spatial depression and hence in LS. Thus, the InSAR data on LS and the original topographic data from a source such as SRTM, in conjunction with generalized geological data from the city and some information on where the major groundwater wells are located, based on well permits, would be sufficient for an initial identification of the nature of the groundwater-LS relationship in a place of interest. Obviously, the more local information that is available, the better such a characterization would be, and the better the information to subsequently design a policy that is more effective to limit the impacts of LS in a spatially specific way. This would allow a consideration of both the overall extent of LS as related to the total estimated groundwater pumping or water level drops, but also the spatially specific pumping impacts that lead to critical urban impacts because of their confluence with build infrastructure or natural infrastructure.

Quantifying risk of fragilized infrastructure

As represented in Figure 3, we distinguish between two modes of compaction: regional lowering may not fragilize the built infrastructure directly, but rather increase susceptibility to flood (see dedicated section below). Less smooth subsidence, such as in the case of hotspots or on borders of regional subsidence may lead to a spatial gradient in land deformation r_g that jeopardize structural integrity. Depending on the slope, this may affect only road and other network infrastructure, but if above a certain threshold, would affect buildings. Therefore, the InSAR image analysis is separate in distinct or overlapping layers:

- Areas A_{flood} below a certain threshold including regional and hotspots are assumed to be zones of potential heightened flood risks because of LS
- Areas $A_{network}$ with a slope gradient superior to $r_{g\_network}$ are identified as zones of potential impacts on network infrastructure
- Areas $A_{building}$ with a slope gradient superior to $r_{g\_building} > r_{g\_network}$ are identified as zones of potential impacts on network infrastructure

Spatial analysis of the risks to buildings

Intersecting $A_{building}$ with population and urbanization datasets, quantification in km^2 of residential and commercial areas, and exposed population can be estimated.

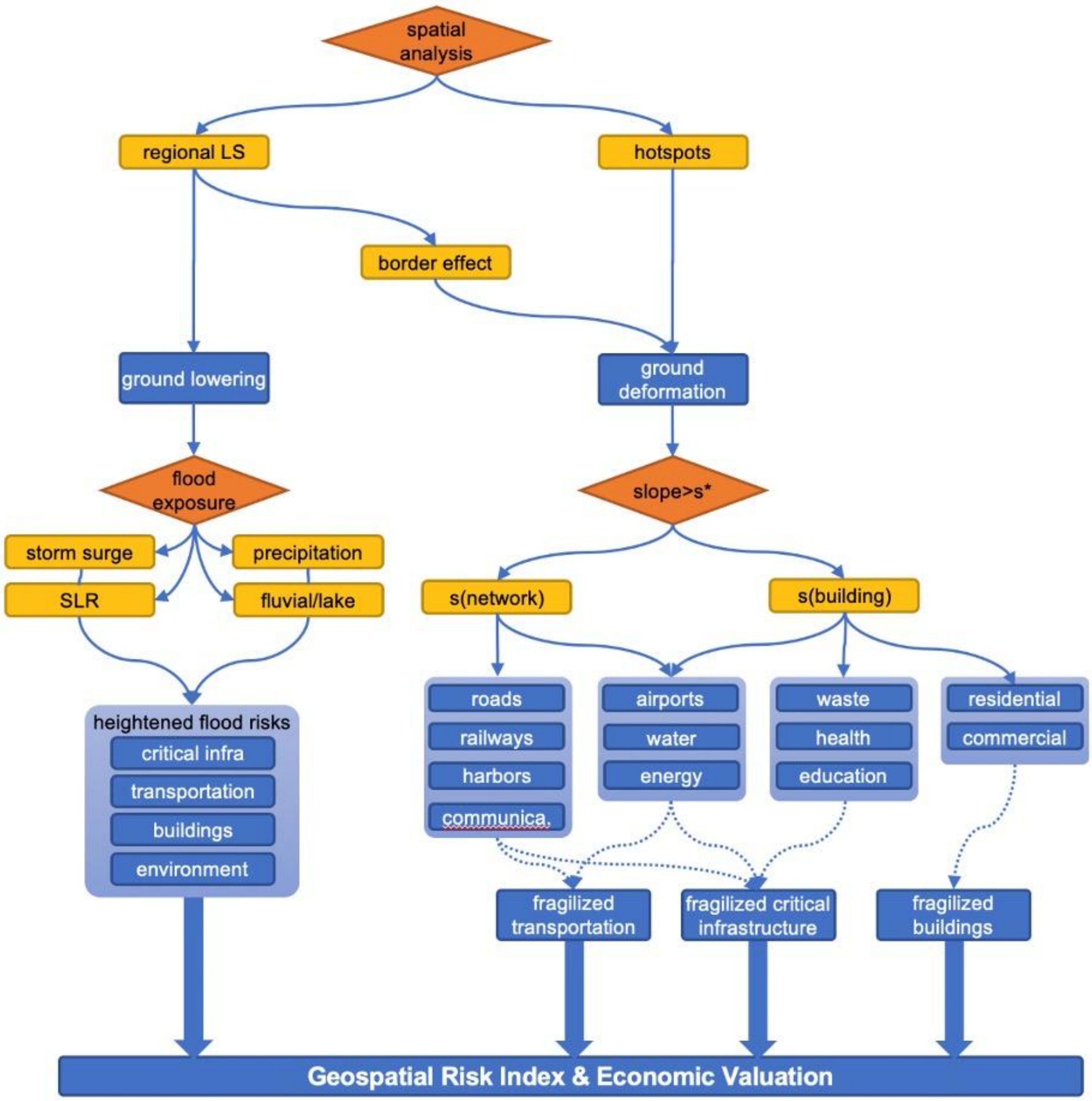


Figure 3: Workflow for the spatial analysis of land subsidence impacts

Source: Elaborated by authors.

Spatial analysis of the risks to critical infrastructure and essential services

Intersecting $A_{building}$ with location of critical building infrastructure as represented in Figure 3, quantification in number of facilities. When combined with intersecting of $A_{network}$ with mapping of critical infrastructure, an identification of potential interrupted sector can be performed.

Spatial analysis of the risks for transportation

Similarly, intersecting network and building risk areas with location of transportation network and building, allows for the identification of the types and scale of transportation that are at LS risks. Further mapping can be performed to assess affected population and socio-economic activities.

Spatial analysis of the risks for commercial and industrial activities

Intersecting $A_{building}$ with zoning information on commercial and industrial activities, if available, can provide an estimate of the sectors at risk and the risk value.

Spatial analysis of the risks on natural infrastructure

Intersecting A_{flood} with peat-body information provides an estimate in types and surface area of affected GDEs. A similar course is followed for urban greenspaces.

Spatial analysis of heightened flood risks

Intersecting A_{flood} with sea-level rise projection information and DEM permits the delineation of an area prone to LS-heightened SLR. Similarly, distance from coast leads to the quantification of area susceptible to storm surge, distance from waterways leads to the quantification of LS-heightened fluvial flood risk area. Combining DEM with A_{flood} with extreme precipitation data can help an initial evaluation of precipitation-induced flooding area heightened by LS.

Computing the LS Geospatial Risk Index (LSGRI)

The LS Geospatial Risk Index comprises the various dimensions computed above. The dimensions of the LSGRI and the corresponding units in which they are quantified are listed in Table 6. Sensitivity analysis on InSAR LS data thresholds is required to assess parameter sensitivity.

Table 6: Dimensions of the LSGRI. Indicators marked with X mean that they can be computed within this framework and for the selected datasets, while indicators marked with (X) notes that an assessment may be possible but requires additional processing.

Dimension	Presence	Affected areas (km2)	Population at risk	By type/sector
Residential	X	X	X	(X)
Critical infrastructure (non-transportation)	X	-	(X)	X
Transportation	X	-	(X)	X
Commercial and industrial activity	X	(X)	-	(X)
Natural infrastructure	X	X	-	X
Heightened flood risks	X	X	(X)	X

Source: Elaborated by Authors.

The LSGRI is in essence multidimensional to support the computation of metrics as a function of the stakeholders they intend to inform (see 2.4.3). At the city-level, an interactive map of the areas of subsidence with the infrastructure at risks and summary statistics would be relevant for the residents and workers, owners and operators of businesses and industries, the construction and real estate sectors, and city officials, which include, among others, regulators, environmental agencies, and critical services providers. This requires a first examination of the LSGRI to validate with local data and regional and sectoral experts. Even prior to the inclusion of local data and further refinement to adapt to the local context, the LSGRI can serve as a support for a cross-sectoral or neighborhood discussion on LS risks and to define areas of priority or data and expert knowledge needs.

Beyond the city-scale, the information of relevance to the decision-makers require aggregation. For each of the categories identified in 2.4.3, we provide an illustrative example of the dimensions and subsequent actionable indicators:

- National officials: the department of transportation could be interested in the length of road at risk to assess maintenance cost.
- Private and public sectors: a company may be interested in potential impacts on their supply chain due to damage to road, harbor, or railways.
- An NGO might want to identify cities priorities by comparing population exposed numbers, and to distribute funds, inform on the ground actors and advocate to local authorities.
- International organizations could leverage the LSGRI to identify critical cities needing improved InSAR data through better calibration and/or additional GPS stations.

4 Part C: Megacity Case study – Jakarta

As an illustration, we apply the methodology to the city of Jakarta, where subsidence has been documented for many years (Wu et al., 2022). The proximity of the city to the ocean and the intensity of rainfall have led to increased flooding risks in areas with high subsidence. The magnitude of the impacts has led to population displacement. Jakarta is used in our working paper as a case study for several reasons:

- Land subsidence is ongoing in different parts of the city;
- Local information and documentation are available to compare and contrast with the results of the proposed methodology (Part B), which rely exclusively on global datasets;
- Despite the extensive documentation of LS in Jakarta, gaps remain in the characterization of socio-economic, public health and environmental impacts.

This case study is, therefore, a 'work in progress' assessment of LS health, socio-economic and environmental risks in Jakarta, that, although it serves only as an illustration in this working paper, could be expanded, maintained and tested with local stakeholders.

4.1 InSAR data as a measure of ongoing subsidence

Extracting ongoing rates of land subsidence from InSAR is a formidable endeavor that requires expertise and assumptions. Indeed, the InSAR data points are not direct observations of vertical compaction, but rather estimates of Line Of Sight (LOS) rate of change. These values are subject to many uncertainties (Box 2), which require further benchmarking with local information to allow robust exploitation of the data. Because our methodology and its application aim to produce indicators and screening tools for local and international stakeholders to act on, the InSAR-derived LOS rates are assumed to be indicative of the rate of subsidence.

In the present case, we rely on a dataset (covering the period 2015-2020) for the region of Jakarta by Wu et al. (2022). The data was first analyzed and showed no significant hotspots as detailed in Part B. The data was therefore aggregated at the grid level (see Appendix 1).

Box 2: Sources of uncertainties in the input InSAR data

Although InSAR has been refined extensively over the last decades, sources of uncertainties remain and some depend on the local context, be it volcanic activity, calibrating data availability and transparency, and land coverage. This uncertainty is to weigh with respect to the finesse of the InSAR datasets (accuracy versus precision) and the rates of importance as a function of what is characterized. This is a strenuous task. We only list here a few factors that are sources of uncertainties to illustrate this complexity.

For instance, InSAR estimates the Line Of Sight (LOS) change rate in mm/year, a small nuance that reflects the fact that the satellites are not directly above the point they measure. Though it can be corrected, a challenge with great geographical variability is taking into account the lateral deformation. Jakarta is a region of important tectonic movements, which may complicate the separation between vertical compaction and overall deformation (Indonesian permanent GNSS stations network: the current status). The impacts on the quality of the InSAR derived vertical rates are unknown to us.

An accuracy of around 2mm/year is expected if calibrated via a GNSS station (Wu et al., 2022). In the present case, one station outside of Jakarta was used (black circle in figure A1.a). However, GNSS stations have missing data. When this is the case, calibration is performed relying on an unbuilt area of 5km in radius outside of the city limits (the pink triangle in figure A1.a marks its center). Comparison of values in GNSS and InSAR LOS estimates by Wu et al. (2022) led to errors of 5mm/year. There are 3 GPS stations within the city center of Jakarta installed in 2007, which could improve the calibration of InSAR data and overall understanding of the occurring LS, however their data are not publicly available.

Another critical element contributing to uncertainty is the urban environment, the very objective of our study. Surface elevation estimates from Sentinel 1 data detect building constructions due to the fine horizontal resolution: an apartment building of 20m built over the course of a year exceeds any compaction signal at the 1cm/year. Separating these effects while taking into account lateral deformation robustly across an urban environment remains a challenging exercise.

InSAR data are not only subject to spatial challenges, but also temporal ones: InSAR data vary seasonally due to changing moisture content in the atmosphere, leading to systematic and stochastic delays that result in uncertainty (Fattehi and Amelung, 2015; Chen et al., 2022). In the present dataset, the trends were derived from bi-monthly data (5 images per year). Further investigation of seasonal effects would be interesting given the specificity of the Indonesian climate; however, the high frequency of imaging together with the derivation of a yearly rate averaged over 5 years should limit and average out their impacts.

These sources of uncertainty may explain the apparent positive and negative trends in LS for certain zones. The adequate transformation of the signal to apply in terms of rate and offset is an ongoing challenge that deserves further investigation.

4.2 Identifying groundwater-induced LS susceptibility of cities

Subsidence rates greater than 20mm/year in the Jakarta region are used to identify zones with ongoing subsidence (Figure 4). The threshold is chosen considering the indicated level of uncertainty in the InSAR data and the minimum rate that may lead to infrastructural impacts, and would require monitoring and potential regulatory interventions. As indicated earlier, groundwater pumping-induced subsidence is expected where there are thick clay layers in a stratified sedimentary aquifer, or where dissolution features emerge in a limestone or similar aquifer. The Jakarta region has such lithologies, but an initial examination of the InSAR data showed high subsidence rates over an area indicated to have volcanic rocks in the lithology maps. This would suggest an error in the InSAR or in the lithology maps. Since we have no quick way of verifying that disagreement between the two sources, for the case study we chose to screen out volcanic rock areas (GLiM), and a map of ongoing subsidence areas is produced (Figure 4) with summary statistics of natural and municipal infrastructure reported in Table 7.

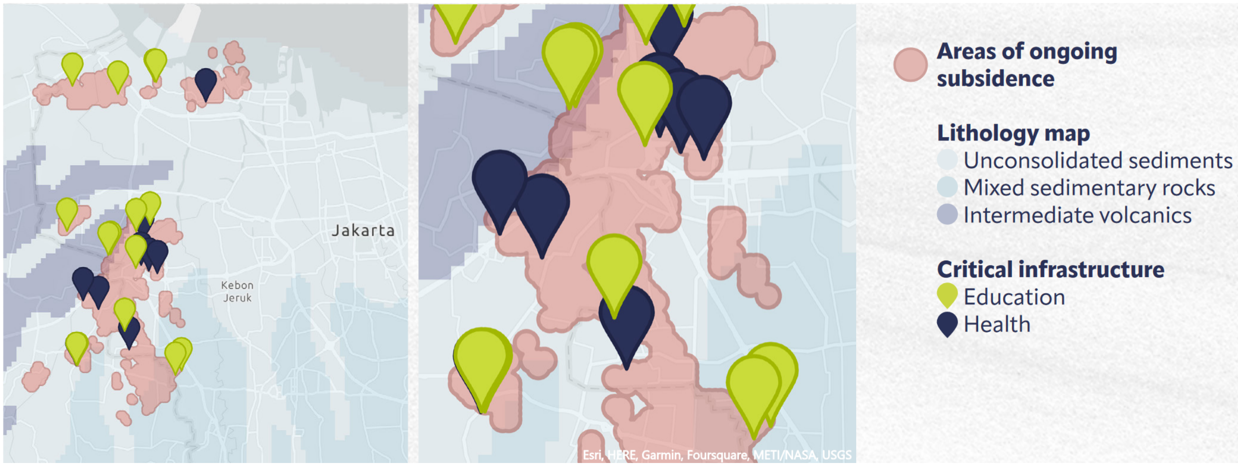


Figure 4: Regional and close-up map of Jakarta with delineated areas in red representing areas of ongoing subsidence above 20mm/year. The location of educational and health infrastructure within the areas is indicated with light and dark marks. Lithological information for the city of Jakarta was obtained from the ESRI dataset available in the following link. Unconsolidated sediments are particularly prone to subsidence, mixed sedimentary rocks are less, but possible, while intermediate volcanics are not subject to subsidence where subsidence rates are greater than 20mm/year as was mentioned in the beginning of the section (For more context see World Bank, 2023).

Source: Elaborated by authors.

4.2 Exploring the attribution of groundwater-Induced subsidence

An exploration of the business attributes using mapping services (e.g., Google maps) may permit a tentative identification of the kinds of actors to which the LS could be attributed to. Initial investigations have revealed the presence of industries (e.g., sugar processing factories, oil refineries), recreational activities (e.g., water parks, stadiums), or utilities (e.g., water treatment plants, hospitals). However, local knowledge of water sourcing, withdrawal permit holders' locations and volumes is necessary to evaluate these results. The initial map permits the identification of areas of risks that can be prioritized for further investigations, regulations and mitigations of induced risks.

4.3 Quantifying risks of fragilized infrastructure

As per the European Land cover classification for the year 2020, using Sentinel data, the areas of ongoing subsidence are quantified in acres per category (Table 7). 348,000 acres of built areas may be at risk, amongst which 12 health-related buildings and 15 schools. Further analysis is required to evaluate the impact on energy and water plants, and on network infrastructures (e.g., public transportation and roads).

We put forward that assessments of risks in units of surface area, length, or in number of buildings, can directly inform actions and interventions, such as assessing survey needs, finding regulatory permits, or changing land classification. Additional analyses are needed, not only to perform a more systematic assessment, but also, and maybe more importantly, the need for a response by neighborhood and city decision-makers. Direct engagement of stakeholders is necessary to validate the LSGRI approach.

Table 7: Areas in Jakarta (acres per category), and health and education infrastructures (category count) within the zones of ongoing LS.

Land classification	Area (Acres)
Built area	**347,548**
Natural land	**93,198**
Tree Cover	*55,149*
Grass and shrub land	*27,952*
Bare or sparse vegetation	*10,097*
Water	**19,683**
Permanent water bodies	*18,333*
Herbaceous wetland	*1,350*

Critical infrastructure	Count
Health	**12**
Hospital	*1*
Clinic	*6*
Pharmacy	*5*
Education	**15**
Kindergarten	*11*
School	*4*

Source: Elaborated by authors.

5 Part D: Conclusion and policy implications

○ 5.1 Summary of approaches and findings: limitations, and next steps

This working paper attempts to estimate the economic and social cost of LS with focus on the urban sector. We started with a review of several existing studies with focus on economic estimates of damages from land subsidence in the urban sector. We remark a misalignment between assessment frameworks and economic quantifications. The existing economic work is very scant and biased towards a limited number of aspects of LS damage as well as lacking a comprehensive actionable analytical framework that can be applied in many locations and serve to inform remediation actions.

The inconsistencies between the scales and dimensions of published analytical frameworks can be explained by the lack of available data for doing so. For instance, while comprehensive frameworks such as Kok and Costa (2021) detail nature-induced LS and impacts on the water cycle, we have found no quantification of these impacts. The fact that data is available in certain locations and for specific dimensions of LS impacts result in over- or under-assessment. This is particularly the case for real estate impacts, which can only be performed in areas of certain wealth and real-estate markets with documented selling prices. This bias may mask several important aspects of LS impacts, such as public health consequences, damages in poor neighborhoods' housing or transportation systems, and interruption of water and electricity supplies, to name a few.

All the above led us to move away from the original objective of performing a detailed economic impact assessment, and instead prioritize quantifications that are informative to municipal stakeholders and while leveraging globally available datasets. (Below are several recommendations to improve local LS monitoring and response plans in hotspots around the world.)

Instead, we propose to conceptualize and quantify the health, social and environmental risks of LS in a multi-dimensional index—The LS Geospatial Risk Index (LSGRI), which offers the necessary flexibility to inform municipal-to-national risks assessments.

In part B, we first developed a framework that links the LS drivers, the resulting infrastructural impacts and the related public health, socio-economic and environmental risks. We then performed a detailed comparative study of the data needs and availability. We then propose a workflow to compute the LSGRI, that focuses on the potential risks and leverages available data sets. Some of the included dimensions cannot be observed directly and are estimates or proxy information. Some of the dimensions in this framework are still impossible to include due to a lack of available data. In part C, a partial application of the LSGRI to the case of

Jakarta, Indonesia, illustrates the limitations of remote-sensing of LS detection and the importance of data calibration, completeness and standardization.

5.2 Recommendations

In the process of investigating possible data on LS, and LS impacts, we realized that data is not readily available and thus, does not support an actionable quantification of the health, social and environmental cost of LS. We arrived at several recommendations that touch upon various issues we faced and identified. Below we provide observations at the framework level, suggesting interventions to address the lack of data, and suggesting next steps for using the available data.

5.2.1 Investing in monitoring groundwater-led LS

- Data-level: LS is a local phenomenon that can simply be measured through the changes in groundwater pressure in aquifers susceptible to compaction. Given that large impactful pumping is most often subject to regulations, the collection of information for monitoring and improving local groundwater regulation models is possible. Additionally, each time a well is drilled, information on clay layers thickness could be measured to improve the spatial resolution of the aquifer data.
- Potential intervention: The local knowledge of zones-at-riss is often present. What might be lacking is the capacity to regulate, install monitoring systems and aggregate this information. Financial support from international agencies could be necessary for cities and countries, both developed and developing, to pursue this effort in a way that serves the local needs. Furthermore, although remote sensing provides a tangible avenue to monitor LS, it is only valid if properly calibrated locally. Encouraging countries to share their GPS station information would significantly improve remote assessments, beyond the context of LS.

5.2.2 Addressing the drivers of LS: groundwater pumping and urbanization

- Framework-level: Given the dynamic (both spatial and intertemporal) nature of urbanization, expansion of urban centers may be expected over time, which leads to new urban development over possible LS hot spots. This would be expected to increase the level of risk to urban dwelling and to urban infrastructure and services. Incorporation of such risk into calculations of urban sprawl (that also includes climate-driven rural to urban migration) becomes a necessary policy requirement.
- Potential intervention: Minimizing LS effects on future urban development over LS-risked aquifers could take place by introducing appropriate regulations starting with appropriate pumping and building standards over such areas, and even banning new urban

developments, in case the risk index to dwelling, public infrastructure and services is above a certain level.

5.2.3 Mitigating the public health, socio-economic and environmental impacts

- Framework-level: Given existing evidence of indirect and secondary impacts to public health, socio-economic costs, and environmental degradation, such values have to be factored to the calculations of the Risk Index in each location, using the data needed for such calculations available in each location.
- Potential intervention: As indicated in section 5.2.1 (Investing in monitoring groundwater-led LS), international efforts led by multilateral agencies such as UNEP, UNDP, World Bank, and regional banks of development could develop projects to fund studies that estimate impacts of LS on public health, socio-economic damages, and the environment. Data from such studies could be used also, as a first proxy, in regions with LS impacts for which data is not available.

5.2.4 Compounding risks: flood risks, loss of aquifer storage capacity

- Framework-level: Flooding risks stem from several variables that are also interacting: an increase in water level from climate change (e.g., increased precipitation, sea level rise), from decrease in ground elevation, and from the ability of the soil to hold water. Therefore, LS may further amplify flood risks due to extreme climates and should be taken into consideration when performing climate impact assessments.
- Potential intervention: While flood risk maps have been developed by several institutions in the past, they do not speak in one language and may not be relevant for decisions on flood fighting and policymaking. International agencies such as UNEP or World Bank could invest in projects located in hotspots, such as coastal cities to produce flood maps that would inform decision-makers regarding the compound risk of high water and sinking grounds.

5.2.5 Addressing data constraints

Identifying needed variables

The study by Kok and Costa (2021) provides a good foundation for the types of variables needed for assessment of LS impacts along the dimensions identified in our work: Residential, Critical infrastructure (non-transportation), Transportation, Commercial and industrial activity, Natural infrastructure, and flood. However, as we realized during our efforts to develop the LSGRI, the data for some of the variables is not readily available and proxies are needed. The nature of such proxies is by itself a critical issue that would benefit greatly from a collaboration among scholars from different relevant disciplines such as hydrology, geography, public health, economics, and others. Developing a mechanism to allow such relevant disciplines to communicate (e.g., periodical workshops, webinars, committees) could help in setting standards that would be followed by the profession.

Developing data collection mechanisms

The development of data collection mechanisms is discussed under the sub-bullet "Mimic water utilities information" below.

Developing data sharing mechanisms

The development of data sharing mechanisms is discussed under the sub-bullet "Mimic water utilities information" below.

- Framework-level: As we indicated in several places in the text, data availability is a major constraint for an analysis of economic and social impacts of LS. In the development of our LSGRI we had to make several by-passes to overcome the lack of appropriate data. Availability of such data could provide more robust results in our analysis and eliminate likely biases due to use of partial data (e.g., data that exists for certain cities, for parts of a given city, for parts of the LS dimensions).
- Potential intervention: As was recommended in previous sections of the Recommendation section, a systematic data collection process funded by international agencies via long-term projects could lead to establishment of dataset accessible freely by researchers and decision makers in their attempts to assess LS impacts in certain locations.
    - Mimic water utilities information: The on-going data collection that was initiated by the World Bank on water utilities performance (https://www.ib-net.org/) and is used for benchmarking worldwide, can be used as a model for establishing data collection on GW-led LS. This will include a network of cities and GW pumping facilities that will provide timely information (GW pumping rates, population consuming GW, InSAR periodical sinking rates, etc… Establishing a network of potential partners to maintain the system and disseminate the data would help involve decision makers and other technical scholars in need of such data.

5.2.6 Promoting studies to assess policy interventions for reducing risk of LS

A final recommendation we provide is related to the role we suggest the World Bank with other international or global bodies, such as GEF (Global Environmental Facility) undertake to address the chronic global problem (global bad) of LS. Given the estimated magnitude of the damages from LS, which are only partial in nature, and given the future water scarcity levels in many parts of the world due to climate change, more local and global studies are needed to allow a better assessment not only of direct but also indirect and compounding impacts. Such solicited studies could be designed and commissioned by a panel of experts that also includes social sciences and public health experts, in addition to the most marginalized and very often forgotten victims of LS in the urban, sub-urban and agricultural context. A good departing point could be the UNESCO Land Subsidence International Initiative https://www.landsubsidence-unesco.org/.

5.3 Concluding remarks

The main conclusion from the work leading to this working paper is that the process affecting land subsidence, and especially, water-extraction-led LS, is very complicated conceptually, quantitatively and across the

Although we firmly believe in the modularity of our proposed LSGRI, it does not provide the identification of a proper policy intervention to prevent or mitigate the damage. Previous studies have modeled policy interventions and shown a quite homogeneous set of outcomes across various studies of LS regulations (e.g., Esteban et al., 2023; Wade et al., 2018). Experimenting policy intervention is outside the scope of this study, but we aim to test the usefulness of our proposed framework, workflow and index within this context to highlight potential rippling effects or blind spots, or to support the design of the metrics to monitor the intervention successes.

Last but not least, our most rewarding take-away is in the undeniable value of an interdisciplinary team to deal with LS and its impact on society, including the environment. We invite all to humbly participate in this endeavor by taking down discipline silos and thriving to center the population and ecosystems at risk.

6 References

Alliance for the Chesapeake Bay, n.d. https://www.allianceforthebay.org/2017/02/slowing-land-subsidence-in-hampton-roads-va-with-wastewater/. Accessed on August 7, 2022.

Bastiaanssen, Wim G.M. and Petra J.G.J. Hellegers, 2007. Satellite Measurements to Assess and Charge for Groundwater Abstraction. In: Dinar, A., S. Abdel-Dayem and J. Agwe (Eds.). The Role of Technology and Institutions in the Cost Recovery of Irrigation and Drainage Projects. Agriculture and Rural Development Discussion Paper 33, Washington D.C., World Bank, February 2007. https://documents1.worldbank.org/curated/en/151361468316133598/pdf/387160Technology0Cost0Recovery01PUBLIC1.pdf.

Borchers, J.W., Carpenter, M., Grabert, V.K., Dalgish, B. and Cannon, D., 2014. Land subsidence from groundwater use in California. California water foundation.

Bureau of Labor Statistics. (2022). Consumer Price Index [Historical Dataset]. United States. Retrieved on September 14, 2022, from https://www.bls.gov/cpi/data.htm

Chateau, J., Rebolledo, C. and Dellink, R., 2011. An Economic Projection to 2050: The OECD" ENV-Linkages" Model Baseline.

Chaussard, E., E. Havazli, H. Fattahi, E. Cabral-Cano, and D. Solano-Rojas, 2021. Over a Century of Sinking in Mexico City: No Hope for Significant Elevation and Storage Capacity Recovery. *Journal of Geophysical Research: Solid Earth, 126, e2020JB020648. https://doi.org/10.1029/2020JB020648*,

Deltares. 2015. Sinking cities: An integrated approach towards solutions. https://www.deltares.nl/app/uploads/2015/09/Sinking-cities.pdf

Dinar, A., E. Esteban, E. Calvo, G. Herrera, P. Teatini, R. Tomás, Y. Li, P. Ezquerro, and Jose Albiac, 2021. We Lose Ground: Global Assessment of Land Subsidence Impact Extent. *Science of the Total Environment*, 786:147415, https://doi.org/10.1016/j.scitotenv.2021.147415.

Dinar, A., Esteban, E., Calvo, E., Herrera, G., Teatini, P., Tomás, R., Li, Y., Albiac, J., 2020. Land subsidence: the forgotten enigma of groundwater (over-)extraction. Paper presented at the AERE/ASSA 2020 Allied Social Sciences Associations Annual Meeting, San Diego, CA, January 3–5, 2020 Retrieved from https://www.aeaweb.org/conference/2020/preliminary/2093?q=eNqrVipOLS7OzM8LqSxIVbKqhnGVrJQMlWp1lBKLi_OTgRwlHaWS1KJcXAgrJbESKpSZmwphlWWmloO0FxUUXDAFTA1AegsS00Gylkq1XDButx4c. Accessed on August 7, 2022.

Egbenta, Idu R., Smart N. Uchegbu, Ejike Ubani, and Okwuchi Juliet Akalemeaku, 2021. Effects of Noise Pollution on Residential Property Value in Enugu Urban, Nigeria. SAGE Open, July-September 2021: 1–12. https://doi.org/10.1177/215824402110321.

Erkens, G., Bucx, T., Dam, R., De Lange, G. and Lambert, J., 2015. Sinking coastal cities. Proceedings of the International Association of Hydrological Sciences, 372, pp.189-198.

Erkens, G., Bucx, T., De Lange, G. and Van Ruiten, C.J.M., 2015. An integrated assessment framework for land subsidence in delta cities. Proceedings of the International Association of Hydrological Sciences, 372, pp.485-491.

Esteban, E., A. Dinar, E. Calvo Calzada; J. Albiac, J. Calatrava, G. H. García, P. Ezquerro, R. T. Jover, P. Teatini, Y. Li, 2023. Modeling the Optimal Management of Land Subsidence Due to Aquifers Overexploitation. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2023.119333.

Fiksel, J., T. Eason and H. Frederickson, 2012. Framework for Sustainability Indicators at EPA. Office of Research and Development, National Risk Management Research Laboratory, U.S. Environmental Protection Agency. Washington DC: EPA.

Fowler, L.C., 1981. Economic consequences of land surface subsidence. Journal of the Irrigation and Drainage Division, 107(2), pp.151-159.

Gabrielsen, P. and P. Bosch, 2003. Environmental Indicators: Typology and Use in Reporting. European Environment Agency Internal Working Paper. Copenhagen: European Environment Agency.

Hallegatte, S., Green, C., Nicholls, R.J. and Corfee-Morlot, J., 2013. Future flood losses in major coastal cities. Nature climate change, 3(9), pp.802-806.

Herrera-Garcia, G., P. Ezquerro, R. Tomás, M. Béjar-Pizarro, J. López-Vinielles, M. Rossi, R. M. Mateo, D. Carreón-Freyre, J. Lambert, P. Teatini, E. Cabral-Cano, G. Erkens, D. Galloway, W.-C. Hung, N. Kakar, M. Sneed, L. Tosi, H. Wang, S. Ye, 2021. Mapping the global threat of land subsidence. *Science*, 371 (6524) :34–36. https://rua.ua.es/dspace/bitstream/10045/111711/5/Herrera-Garcia_etal_2021_Science_preprint.pdf

Hu, B., Zhou, J., Xu, S., Chen, Z., Wang, J., Wang, D., Wang, L., Guo, J. and Meng, W., 2013. Assessment of hazards and economic losses induced by land subsidence in Tianjin Binhai new area from 2011 to 2020 based on scenario analysis. Natural Hazards, 66(2), pp.873-886.

Hasibuan, H.S., R.P. Tambunan, D. Rukmana, C.T. Permana, B.N. Elizandri, G.A.Y. Putra, A.N. Wahidah, and Y. Ristya, 2023. Policymaking and the spatial characteristics of land subsidence in North Jakarta, City and Environment Interactions, 18, 100103. https://doi.org/10.1016/j.cacint.2023.100103.

Kok, S., Costa, A.L., 2021. Framework for economic cost assessment of land subsidence. *Natural Hazards*, 106:1931–1949. https://doi.org/10.1007/s11069-021-04520-3.

Lixin, Y., Jie, W., Chuanqing, S., Guo, J., Yanxiang, J., Liu, B., 2010. Land subsidence disaster survey and its economic loss assessment in Tianjin, China. *Natural Hazards Review*, 11, 35–41. https://ascelibrary.org/doi/10.1061/%28ASCE%291527-6988%282010%2911%3A1%2835%29.

McFarlane, B.J., 2012. Climate Change in Hampton Roads: Phase III: Sea Level Rise in Hampton Roads, Virginia. NOAA/Virginia Coastal Zone Management Program, Report (www. hrpdcva. gov).

Mulas, J., Aragón, R., Martínez, M., Lambán, J., García-Aróstegui, J.L., Fernández-Grillo, A.I., Hornero, J., Rodríguez, J. & Rodríguez, J.M. 2003. Geotechnical and hydrogeological analysis of land subsidence in Murcia (Spain). *Materials and Geo-environment*, 50, 249-252.

Nemati, M., M. Sneed and A. Dinar, Impact of land subsidence on home sales value: Evidence from California. Paper presented at the 2023 APPAM Fall Research Conference Atlanta, Georgia, November 9 - 11, 2023.

Nicholls, R.J., Brown, S., Hanson, S. and Hinkel, J., 2010. Economics of coastal zone adaptation to climate change.

OECD (Organisation for Economic Co-operation and Development), 2003. OECD Environmental Indicators: Development Measurement and Use. Paris: OECD.

Pascual, U., Muradian, R., Brander, L., Gómez-Baggethun, E., Martín-López, B., Verma, M., Armsworth, P., Christie, M., Cornelissen, H., Eppink, F. and Farley, J., 2010. The economics of valuing ecosystem services and biodiversity. The economics of ecosystems and biodiversity: Ecological and economic foundations, pp.183-256.

Roll, R.J. 1967. Effect of subsidence on well fields. Journal of the American Water Works Association 59, no. 1: 80-88.

Saputra, E., Spit, T., Zoomers, A., 2019. Living in a bottomless pit: Households' responses to land subsidence, an example from Indonesia. *Journal of Environmental Protection*, 10:1–21. https://doi.org/10.4236/jep.2019.101001.

Sneed, M. 2023. Economic and Social Impacts of Land Subsidence in the San Joaquin Valley, California. Paper presented at the Rosenberg International Forum of Water Policy, "Economic and Social Impacts of Land Subsidence: Global and local assessments". February 21, 2023 (online).

Tang, W, Z. Xiangjun, M. Motagh, G. Bi, J. Li, M.Chen, H. Chen, and M. Lia, 2022. Land subsidence and rebound in the Taiyuan basin, northern China, in the context of inter-basin water transfer and groundwater management. *Remote Sensing of Environment*, 269, 2022, 112792. https://doi.org/10.1016/j.rse.2021.112792.

Tang, Minmeng, and Deb Niemeier, 2021. How Does Air Pollution Influence Housing Prices in the Bay Area? *International Journal of Environmental Research and Public Health* 18(22): 12195. https://doi.org/10.3390/ijerph182212195.

United States National Science Foundation (2018). News Release 18-053. Scientists Use Satellites to Measure Vital Underground Water Resources. https://www.nsf.gov/news/news_summ.jsp?cntn_id=295988#:~:text=The%20satellites%20continually%20measure%20the,work%20will%20not%20end%20there. Retrieved on February 10, 2024.

Viets, V. F., C. K. Vaughan, and R. C. Harding. 1979. Environmental and economic effects of subsidence: Report prepared by EDAW, Inc. and Earth Sciences Associates for University of California, Berkeley, Lawrence Berkeley Laboratory, Berkeley, California, LBL-8615, app. A-B, 242 p., http://www.osti.gov/bridge/servlets/purl/6113332-7R9bEr/6113332.PDF.

Wade, C.M., Cobourn, K.M., Amacher, G.S., Hester, E.T., 2018. Policy targeting to reduce economic damages from land subsidence. *Water Resources Research*, 54:4401–4416. https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2017WR022133.

Warren, J.P. and Jones, L.L., 1975. Land Subsidence and Associated Externalities in the Coastal Area of Texas. Journal of Agricultural and Applied Economics, 7(1), pp.111-115.

Willemsen, W., Kok, S. and Kuik, O., 2020. The effect of land subsidence on real estate values. Proceedings of the International Association of Hydrological Sciences, 382, pp.703-707.

World Bank, 2010. The changing wealth of nations: measuring sustainable development in the new millennium. The World Bank. https://issuu.com/world.bank.publications/docs/9780821384886.

World Bank, 2023. The Hidden Wealth of Nations: Groundwater in Times of Climate Change. The World Bank. https://www.worldbank.org/en/topic/water/publication/the-hidden-wealth-of-nations-groundwater-in-times-of-climate-change.

Yoo, J., Perrings, C., 2017. An externality of groundwater depletion: land subsidence and residential property prices in Phoenix, Arizona. *Journal of Environmental Economics and Policy* 6 (2), 121–133. https://doi.org/10.1080/21606544.2016.1226198.

Zoccarato, C., Minderhoud, P.S.J., Teatini, P., 2018. The role of sedimentation and natural compaction in a prograding delta: insights from the mega Mekong delta, Vietnam. Sci. Rep. 8, 11437. https://doi.org/10.1038/s41598-018-29734-7.

7 Appendixes

7.1 Appendix I: Summary of literature on LS economic impact assessment

With growing populations, LS has continued to inflict massive damage across the world. LS has become a worldwide geological crisis and has resulted in substantial economic losses in the short run as well as long run. Currently, the annual subsidence costs are available only for the Netherlands and China. In 2006, over 4.8 billion USD was assessed to be expended annually in the Netherlands on subsidence-related damages (Erkens et al., 2015). On the other hand, China experiences an annual total economic loss from subsidence of about 1.5 billion USD, of which 80–90 percent are indirect costs (Erkens et al., 2015).

Herrera et al. (2021) have shown that in 200 locations across 34 countries, groundwater depletion had caused LS. Additionally, they estimated that it poses a threat to 1.2 billion individuals, equivalent to 19 percent of the global population residing in 21 percent of the world's major cities. Reductions in the global GDP figure could be indicative of the risk potential of LS. By determining the population in probable subsidence zones and the equivalent regional gross domestic product (GDP), global exposure to potential subsidence was assessed. The corresponding exposure to the economy could potentially be as high as USD 8.17 trillion, or 12 percent of the world's GDP. This "proxy" of exposed economic assets is determined under the assumption that GDP per capita within each country is uniform. Finally, for a global change scenario based on steady population growth and rising greenhouse gas emissions, responsible for the most significant sea level rise forecasts, the evolution of potential worldwide subsidence and the associated exposure is forecasted by Herrera et al. (2021) for the year 2040. Therefore, the estimates of the global economic vulnerability could be seen as the lower bound of damage estimates (Dinar et al., 2021; Esteban et al., 2023).

In areas with extensive agricultural activity, we observe significant subsidence due to groundwater pumping. In such situations the eventual policy solution may lead to reduced pumping, fallowing part of the agricultural land which may lead to reduced food production and higher food prices leading eventually to greater food insecurity for the poorer population. While quantifying such chains of events would be difficult, using existing examples from around the world, such as the case of California (Nemati et al., 2023), could help lay out the mechanism. Similarly, extreme dislocation of an urban center – e.g., the Jakarta example (Hasibuan et al., 2023), or the flooding impacts in Mexico City (Chaussard et al., 2021) from modest rainfall events, may be worth exposing as causal diagrams.

Hallegatte, S. et al. (2013) estimate that by 2050, coastal communities would suffer USD 635 billion in yearly flood damage due to subsidence if additional funds are not invested in tackling rising sea levels. The authors used two socioeconomic scenarios to assess future losses:

an OECD-based growth scenario where urban populations increase uniformly across all cities, extrapolating from UN urbanization scenarios, and an OECD-based growth scenario where city populations are limited to 35 million people (Chateau, J. et al., 2011). They presumed that the elevation distribution of existing and future city assets would be the same. The population exposure is taken from Nicholls, Robert J., et al. (2010). Using an estimate of produced capital per inhabitant, exposed assets were converted from the exposed population (The World Bank, 2010).

Research by McFarlane (2012) estimates that property damage due to rising sea levels and land subsidence will be between 9 to 26 billion USD in coastal regions. The authors represented economic implications using two datasets. From Esri's Company Analyst suite, business data was retrieved as a collection of points representing specific business locations. The dataset's needed information includes the number of employees and business locations. The business layer was geographically connected to a locality boundary layer to assign each business a county and city identity. Each sea level vulnerability zone had a data layer on top of it. The total number of firms and employees in the sixteen Hampton Roads towns was computed for each scenario. The entire value of each parcel was used to represent investments in real-estate property, and parcel information was also utilized to indicate economic consequences. Sub-scenarios were employed to determine whether regions would be severely or somewhat impacted by sea level rise. For each sub-scenario, the total value of parcels was aggregated by locality and region.

The economic loss in China's Tianjin region is estimated to be USD 18.19 billion in 2007 prices (Lixin et al. 2010). Following an analysis of the socioeconomic effects of land subsidence on the Tianjin metropolis, the authors divided the total economic loss into eight categories: loss of elevation resources, loss of buildings, damage to urban infrastructure, loss of water conservation projects, secondary disaster loss, loss of industry and agriculture, loss of the environment, and costs associated with disaster prevention and mitigation. Every component of economic loss has an estimate method developed based on understanding its process. Distinct techniques were utilized in the calculation, each with a different level of precision. The cost of disaster prevention and mitigation, infrastructure damage loss, water conservancy damage loss, and secondary-disaster loss are all estimated based on historical records, and they have a comparatively high degree of precision. The results are based on mathematical models for building damage loss, elevation resource loss, industry and agricultural loss, and environmental and economic loss. The analysis done by Lixin et al. (2010) is regarded as the most thorough assessment of the economic damage brought on by land subsidence in Tianjin. In Shanghai, the cumulative loss amounts to over 2 billion USD between 2001 and 2010. In Bangkok, subsidence has seriously destroyed numerous public and private structures, including roads, sidewalks, levees, and subsurface infrastructure (Erkens et al., 2015).

In Texas, the economic loss from LS is estimated to be around 113.6 million USD between 1943 and 1973 (Warren et al., 1975). Regions higher than 25 feet were randomly sampled at a rate of 10%, and selected sample areas were enumerated at a rate of 5%. Since it was predicted that the damage would be more significant at lower elevations, a 20% random sample was taken from those locations, and a 10% enumeration rate was used instead. Property owners were randomly chosen from each stratum for interviews. Thirty public (municipal) and 411 private sector questionnaires were each completed by five student enumerators. These answers gave the data needed for analysis. Interviewers' reports of losses and damages were taken to be typical of what property owners in sample areas of each stratum would have experienced. The sample responses were expanded to estimate the overall economic losses and damages within the sample locations. The total damages and losses for the 300 square mile research region were then evaluated using these figures, presuming that the square mile sample areas were representative.

A recent study (Esteban et al., 2023), using an optimal control approach for optimizing GW extraction under LS-prone conditions, finds economically sustainable paths of groundwater extractions and water table levels under the existence of land subsidence impacts. The model has been applied to the Alto Guadalentín over-exploited aquifer system in the Segura River Basin of Spain. The empirical outcomes indicate that by following the optimal paths, groundwater extractions should be curtailed to avoid reaching the critical water level at which subsidence takes place. Results suggest that regional net present value of welfare over the planning period, under two land subsidence scenarios, is reduced by nearly 1–5%, compared to the no land subsidence scenario. Furthermore, under subsidence, even with relatively small impacts of both types of externalities, groundwater optimal extractions are kept at levels that avoid these externalities.

In the San Joaquin Valley of California, between 1955 and 1972, the economic loss is estimated to be around 1.3 billion USD (Borchers, J. W. et al., 2014). The billing invoices were collected from land surveyors and other contractors and repair estimates from county agencies for remediating damage caused by subsidence between 1955 to 1972 in Fresno and Kings Counties that had subsided more than 1.22 meters (4 feet) between 1925 and 1972. The invoices and repair estimates included costs for periodic field surveys and regrading to allow for proper water flow during flood irrigation, replacing networks of damaged 20 to 25.4 cm (8 to 10 in) ceramic pipes that were buried in trenches to transport irrigation water to fields, and fixing damaged sanitary sewers in urban areas. The damage estimates also considered the expense of repairing or replacing wells damaged by subsidence, the value of structures lost due to condemnation, and decreased property values brought on by zoning changes when subsidence increased the area and depth of floods. By conservatively assigning a cost of $10 million to each of the 18 years from 1955 to 1972 and considering inflation, the total cost in 2013 dollars is estimated to be $1.321 billion for the period. This estimate excludes the costs of repairing damage to canals that is estimated above, as well as indirect costs of land subsidence such as flood damage to flooded farm equipment, long-term environmental effects, and any damage that may have happened in areas where land subsidence from over pumping groundwater was less than 1.22 m (4 ft), damage that occurred before 1955, or damage that occurred after 1972.

In Santa Clara Valley, California, similar estimates are approximately 756 million USD in 2013 prices (Borchers, J. W. et al., 2014). To assess the cost of rehabilitating 1,000 wells in the Santa Clara Valley whose steel casing had been squeezed and collapsed by subsidence, the author used estimations from Fowler (1981). Two million dollars are estimated to have been spent between 1960 and 1965. Well replacement and repair expenditures came to $35 million in 2013 dollars, using Roll's early 1960s and 1967 estimates as a base value. Larger sewer mains or parallel lines had to be built where sanitary sewers' carrying capacities were reduced due to reductions in design grade. Pumping stations had to be built to lift fluids to the bay at the cost of more than $8 million in 1970 (or $48 million in 2013 dollars), excluding the additional yearly costs for electricity and pumping station maintenance (Viets et al., 1979). The extra pumping facilities at the San Jose-Santa Clara Sewage Treatment Plant would have cost $200,000 per year to run in 1970 ($28 million through 2013 in 2013 dollars). By 1975, the cost of grading roads and bridges had increased to $2.8 million ($12 million in 2013 dollars), excluding the expense of flood-related repairs. The first cost of erecting stream channel levees was more than $10 million in 1979 ($32.2 million in 2013 dollars), while the expected cost of building bayfront levees was $58 million in 1973 ($305 million in 2013 dollars). In 1975, a capital outlay of $2.7 million ($12 million in 2013 dollars) was made to construct pumping stations to remove storm runoff. The overall capital expenditure for the building of the plants ($283 million in 2013 dollars) was predicted to be exceeded by the annual operating and maintenance expenses for the pumping facilities. In 1970, it cost $100,000 to raise a Southern Pacific Railroad bridge to match it with rails that had to be relocated to prevent floods (0.6 million in 2013 dollars). More on the cost of LS in California can be found in Box A.

Box A: Observations of LS damages from California.

The main cause of subsidence in California is continued intensive groundwater pumping. The impacts of subsidence include damage to buildings and infrastructure (water canals, roads), increased flood risk in low-lying areas along the pacific coast, and irreversible damage to capacity of groundwater aquifers, their water quality, and damage to aquatic ecosystems. The linkage between groundwater pumping and land subsidence can be seen following the drought periods in California. The years 1955-1977 were a period of intensive groundwater pumping that led to subsidence. The pumping was curtailed during 1975 to 2000 but the subsidence due to the prior period of pumping continued and hence the loss would need to be assessed over the longer period to fit a modeling chain of pumping, leading to subsidence and causing impact. Then post 2000 California has gone through another intensive pumping, due to drought events, leading to subsidence. The San Joaquin Valley is one of the majorly LS-impacted regions in the state of California.[a]

Extensive groundwater withdrawal from the unconsolidated deposits in the San Joaquin Valley, California, caused massive land subsidence during periods since the 1920s. During 2015–22, annual subsidence rates locally exceeded 0.3m at times, resulting in nearly 2m of subsidence during that period. Land subsidence damage has been seen to structures including aqueducts, levees, dams, roads, bridges, pipelines, and well casings. Sociologically important and expensive damages and repairs include the loss of conveyance capacity in canals that deliver water or remove floodwaters; the realignment of canals as their constant gradient becomes variable; the raising of infrastructure such as canal check stations, levees, and dams; the releveling of furrowed fields; and the drilling of new wells. Costs from these damages during 1955–72 have been estimated at $1.3 billion (2013 dollars). Although few data are available to quantify total damages during 2015–22, repair of the Federally-owned Friant-Kern Canal to recover lost conveyance is estimated at $500 million. The impacts of subsidence to smaller water purveyors and the communities they serve are far worse because they possess fewer resources to mitigate such direct impacts. Indirect impacts of subsidence include increased severity of floods (area, depth, and duration) and long-term environmental effects (altered stream gradients, channel courses, water depths, and water temperatures).[b]

Sources: [a]USGS, n.d. https://www.usgs.gov/centers/land-subsidence-in-california, [b]Sneed (2023).

Impact of LS is seen also in the adaptation of individual families affected. Saputra et al. (2019) surveyed three cities in Indonesia, namely Jakarta, Semarang City, and Indragiri Hilir, to determine how households responded to LS and how much was the cost. They found that household expenditure went up in the impacted areas due to the repair cost and adjustment to the damaged house. Additionally, LS impacts households' primary sources of income, further astringing their earning capacity. According to the findings, each household's average income loss in 2015 was around US$ 113, or 5.3% of their average overall annual income (US$ 2,152). Therefore, the afflicted households' reduced earning potential had constrained their range of options. Repairing the damage cost each household on average US$ 107 in 2015, over a quarter (28%) of their average total annual spending (US$ 382). Every household had spent, on average, roughly US$ 172 (32% of their average total expenditure) to accommodate the damage.

Researchers have performed an assessment of the economic impact of LS on property values. Willemsen et al. (2020) studied such impact in the cities of Rotterdam and Gouda in the Netherlands, whereas Yoo and Perring (2017) investigated Maricopa County, Arizona. Both studies have used the revealed preference methodology, also known as the hedonic pricing method. The uniform subsidence of a house and its surroundings has a negative effect on the value of the house. There has been a considerable decline in property values of about 7 percent in Rotterdam and 6 percent in Gouda (Willemsen et al., 2020). The hedonic pricing model was utilized by the authors to evaluate the economic impact of LS on property values. One of the environmental parameters included in the study is the variable "subsistence rate." According to the hedonic pricing theory, purchasers should consider subsidence when buying a house by modifying their bid price since they are assumed to be fully informed about all factors affecting the house value. Since there is frequently little information about subsidence risk, buyers are unlikely to be fully informed. Based on the information accessible to them, the results will reveal whether buyers take subsidence into account. The authors identified three distinct types of subsidence to evaluate the impact of each type on property values: uniform subsidence of the house based on information about the "absolute" subsidence rate of the building, differential subsidence based on information about the building's differential settlement, and subsidence of the surrounding area. The latter includes subsidence of features like sidewalks, yards, and roadways, which is anticipated to cause issues like damaged utility pipes, particularly with "fixed" nearby houses on concrete foundation piles. The Netherlands' damage to houses and infrastructure is estimated at 17 billion Euros by 2050. However, the accurate cost estimates of these damages are still unclear.

Yoo and Perring (2017) also find that housing prices in the LS-affected areas have decreased. However, the effects are more noticeable for relatively expensive residences and are negligible for significantly less expensive ones. According to the findings, the value of residential properties in current land subsidence affected areas in Maricopa County is 9.86% lower than the value of homes outside of these affected areas if there are no earth fissures within 500 meters and 11.07% lower if there are fissures within 500 meters from the houses. The value of properties is determined to be 5.38% lower when an earth fissure is within 500 meters and 6.81% lower when properties are in future land subsidence zones presently outside of existing land subsidence areas. Residential properties within existing land subsidence areas saw a capitalized value drop of $24,570 and $27,646 for homes outside and within 500 meters of an earth fissure. Properties within future land subsidence areas or within 500 meters of an earth fissure caused a loss in capitalized value of properties outside of existing land subsidence areas of $18,329 and $19,399, respectively.

7.2 Appendix II: InSAR data initial analysis and treatment

7.2.1 Data processing

The InSAR data processing produced by Wu et al. (2022) for the region of Jakarta (Figure A1.b) is a dataset of 2,048,977 geolocations with the corresponding annual trend in mm/year computed for the years 2015-2020. An interpolation of these points produced by the authors is shown in Figure A1.a. The GPS stations in the vicinity are as plotted in Figure A1.c. They are used for the calibration of the satellite data by Wu et al. (2022). Their sparsity relative to the resolution of the InSAR data product is worth noting.

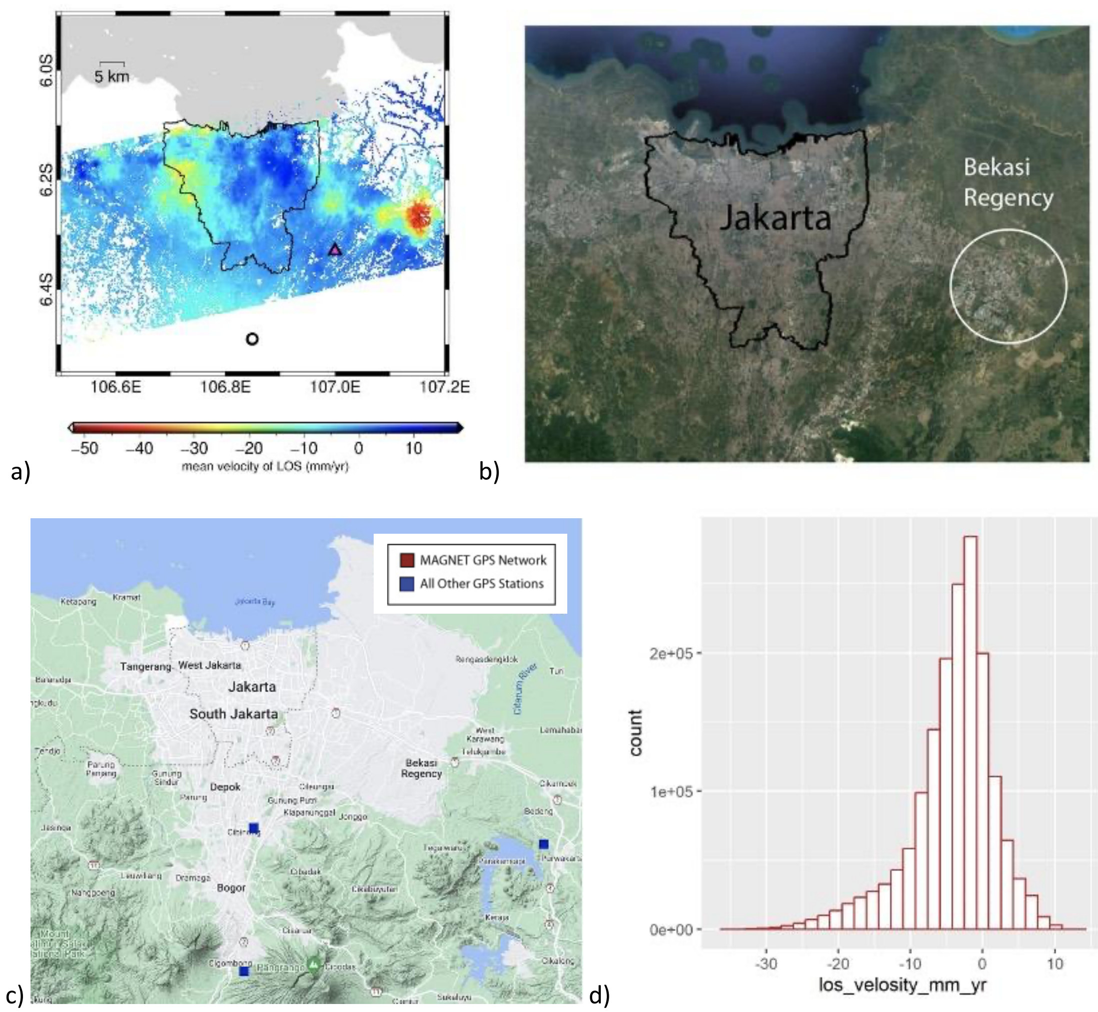


Figure A1: a) Processed InSAR data produced for the region of Jakarta and b) satellite imagery with city boundaries by Wu et al. (2022). c) location of the GPS station openly available around Jakarta (here). d) histogram of input LOS in mm/year.

Sources: a-b) Wu et al. (2022), c) Google maps, and d) elaborated by authors.

Because our focus is the urban environment, we filter the data points to keep only the ones of -6.4 to -6.03 latitude, and longitude 106.56 to 107.07 to capture Jakarta and its outskirts, corresponding to 1’662’757 points of selected InSAR data.

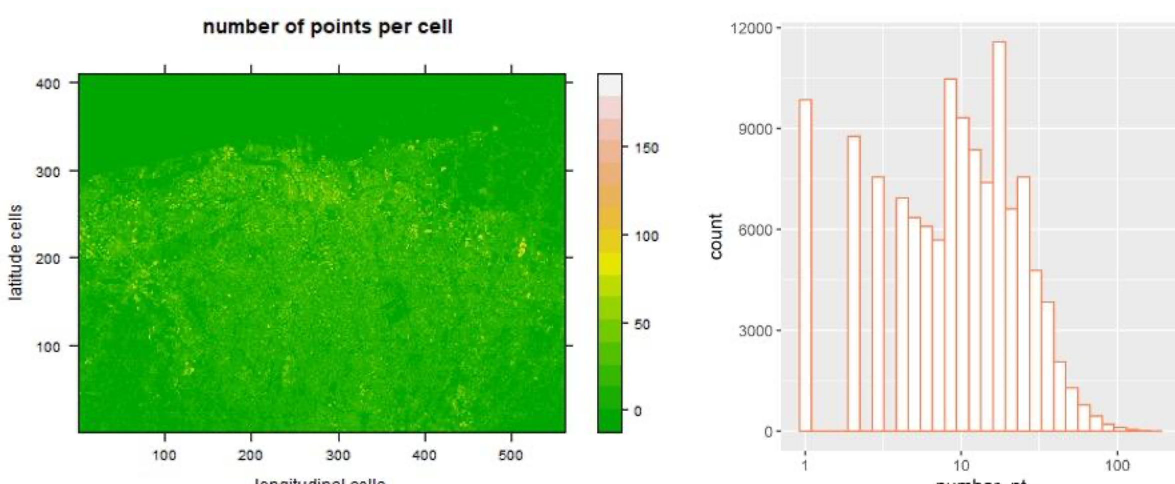
7.2.2 Initial screening of subsidence rate

Subsidence is detected in the input data with 13% of the points above a LOS rate of 10 mm/year, and 2.1% above 20 mm/year (Figure A1.d). The maximum rate in our input data is at 35 mm/year, when historical subsidence rate exceeded 280 mm/year in Jakarta between 1982 and 2010 (Abidin et al., 2011). As mentioned in part B, this situation corresponds to a situation that combines already settled LS, ongoing LS, and yet to happen LS, depending on the locations. A comparison with past studies is therefore necessary.

Nearly 20% of points have positive LOS velocities. Their locations do not align with a natural process that would be occurring. Only 1’099 (0.06%) have values greater than 10mm/year.

7.2.3 LS delineation and attribution

Given the high volume of information and the risks of capturing noise effects, the data is first aggregated on a grid of 410 by 560 cells, each 100m by 100m. Several reasons motivate the choice of scale, such as finding the balance between resolution and coverage as InSAR data are of irregular densities. Indeed, 45% of the cells have 0 points due to the selected frame and band, yet the average number of points per cell is above 7, with a maximum of 179 (see distribution in figure A2).



a) b)

Figure A2: a) Number of points per grid cell and b) histogram of the number of points with log transformation.

Source: Elaborated by authors.

Summary statistics are mapped in figures A3 and A4. Median or mean processing leads to comparable results. Differences between minimum and maximum values within each cell are predominantly under 5mm/year, showing a great uniformity within cells and further justifying the choice of 100m by 100m grid cells. Moreover, 23 cells with differences above 10mm/year were inspected to determine if the differences indicate an artifact or if a hotspot is present in conjunction with location, lithological information, and OSM data.

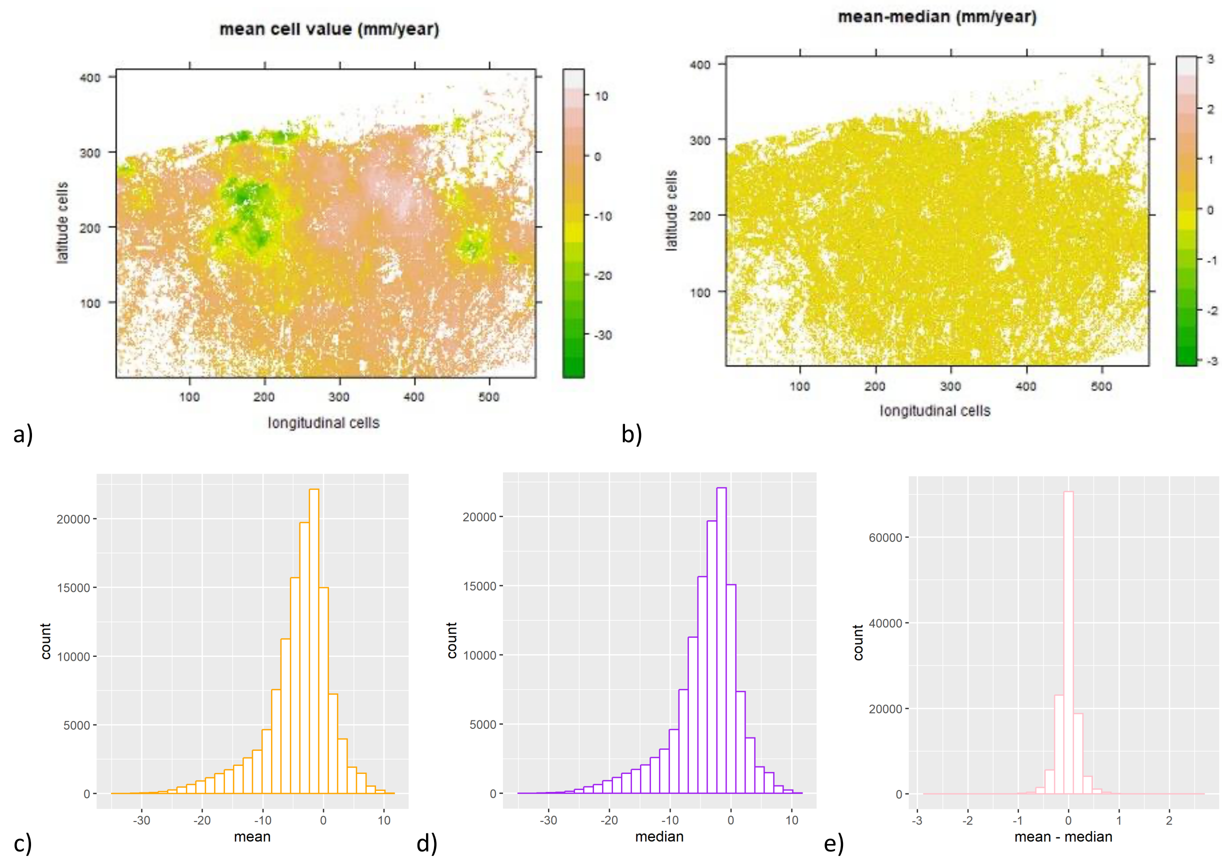


Figure A3: Analysis of sensitivity to aggregation methods comparing mean and median cell values.

Source: Elaborated by authors.

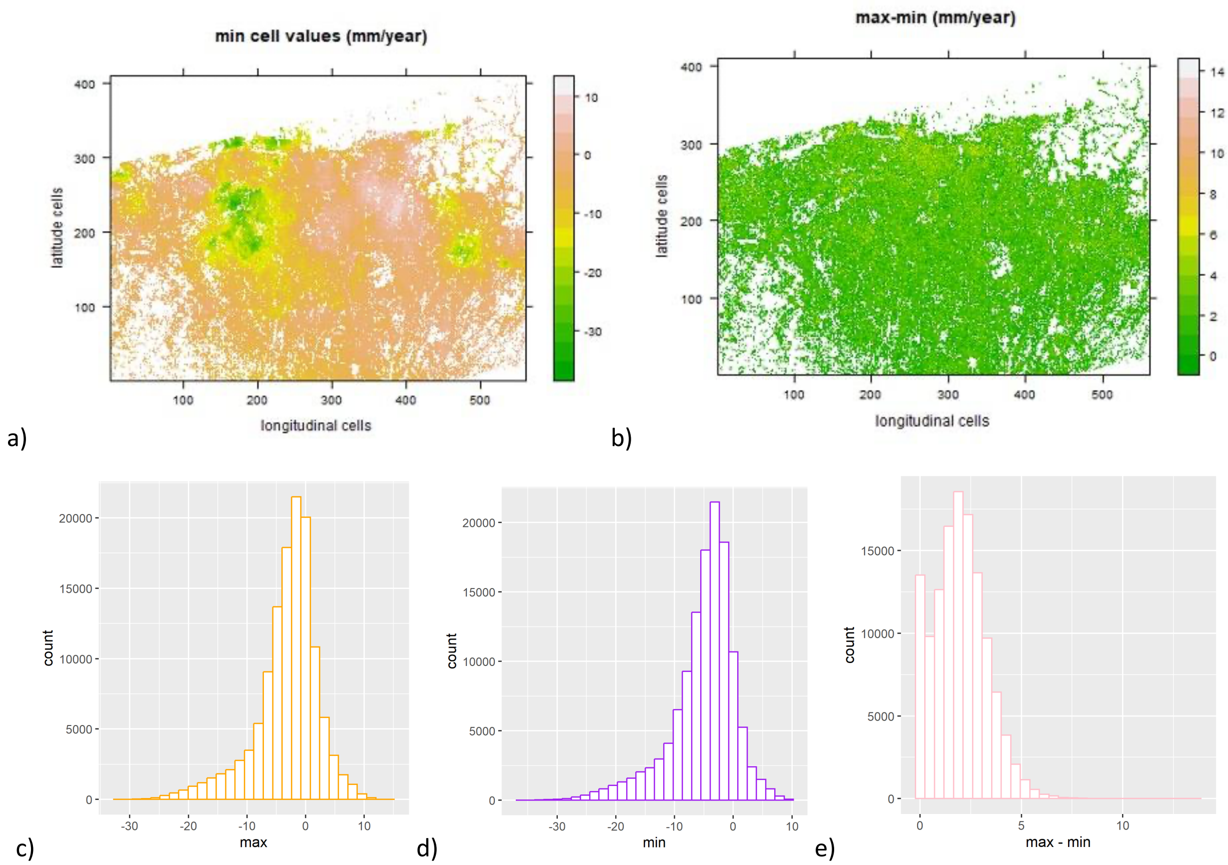


Figure A4: Analysis of within grid cells variations. The histogram e) of differences between minimal and maximal values in LOS rate are under 15mm/year, indicating an absence of infrastructural risks at the sub-grid scale as per the InSAR input data. Furthermore, differences in values do not seem to follow a spatial pattern in b).

Source: Elaborated by authors.