Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering. Vol. XII, 2023
Print ISSN 2285-6064, CD-ROM ISSN 2285-6072, Online ISSN 2393-5138, ISSN-L 2285-6064

SAR-BASED SUBSIDENCE MONITORING IN URBAN AREAS DUE TO GROUNDWATER WITHDRAWAL FOR AGRICULTURE: A REVIEW WITH DEMOGRAFIC INDICATORS ASSESSMENT

Alina RĂDUȚU, Maria-Ioana VLAD-ȘANDRU

Romanian Space Agency, 21-25 Mendeleev Street, District 1, Bucharest, Romania

Corresponding author email: alina.radutu@rosa.ro

Abstract

Intensive groundwater withdrawal is one of the main causes leading to land subsidence in the natural and urban environments. The overexploitation of groundwater in urban areas comes mainly in the context of rapid urbanization, expansion of industrial and agricultural activities, and in some cases, climatic changes. Sustainable urban planning and detection of potential hazards involve the use of adequate instruments such as the continuous monitoring of land subsidence. The satellite remote sensing Synthetic Aperture Radar Interferometry (InSAR) techniques offer the opportunity for early detection and continuous monitoring of land subsidence for wide areas, including urban centres. Considering various aspects, a review of scientific contributions where urban subsidence due to the intensive groundwater withdrawal for agricultural purposes is monitored based on InSAR techniques, is presented. As land subsidence in urban areas has a direct impact on the quality of life, the review is completed with demographic indicators assessment, followed by analysis on the dynamics of the population in some urban areas affected by land subsidence.

***Key words**: InSAR, groundwater-related subsidence, urban, agriculture, demographic indicators.*

INTRODUCTION

One of the main degradation forms affecting land surface and having a variety of effects on the natural and anthropogenic environments is represented by land subsidence (Ahmad et al., 2017; Bawden et al., 2003; Burkett et al., 2003; Sneed et al., 2014; Bitelli et al., 2015). As a result of various natural or anthropogenic factors (Orellana et al., 2022), this phenomenon is characterized by sinking or settling of the land surface (Allaby, 2013).
Intensive groundwater withdrawal is one of the anthropogenic factors leading to subsidence in urban areas (Galloway & Burbey, 2011). This comes in the context of rapid urbanization and industrial development (Poland, 1984; Ruiz-Constan et al., 2016), leading to the progressive use of groundwater resources in industry, various urban needs and activities, and agriculture (Ezquerro et al., 2020).
Globally, agriculture is using almost 70% of all groundwater withdrawals, reaching in some developing countries up to 95% (Meza-Gastelum et al., 2022). Unless in many cases the groundwater withdrawal for agricultural purposes is not the main cause of land subsidence in urban environment, this phenomenon was or it is still present in significant urban centres. Some urban areas may be prone to subsidence due to the presence of some geological and hydrogeological particularities as well as climatic aspects (Ahmad et al., 2022).
As the land subsidence due to groundwater withdrawal is often a slow process not prominent until its effects are visible (Orellana et al., 2022), measuring and monitoring of this phenomenon is necessary for a sustainable urban planning and for the disclosure of potential hazards (Chen et al., 2016). In this context, various methods and techniques are being used for measuring land subsidence (Galloway & Burbey, 2011), since the beginning of the 20th century, when the subsidence phenomena due to groundwater withdrawal was identified in U.S.A. (USGS, 2017).
Precise levelling and extensometry are the most accurate subsidence monitoring methods, reaching sub-millimetre accuracies (Radutu & Gogu, 2018). Following the technological evolution, since the 1980s, the GNSS techniques started to be used, reaching millimetre accuracy (Bitelli et al., 2015). In the last decades, considering different constraints of each of these methods (Karila et al., 2013), the evolution of

the remote sensing techniques and of the radar satellite missions, the Synthetic Aperture Radar Interferometry (InSAR) techniques started to be used successfully for the continuous land subsidence monitoring and for early detection over wide areas (Raucoules et al., 2007). The complementarity use of different monitoring methods may have the best results.

In this context, the paper presents an analysis of urban areas worldwide, where InSAR techniques are used for monitoring land subsidence due to groundwater withdrawal for agriculture purposes. Different aspects, such as benefits, limitations, particularities are highlighted, considering this type of specific area of interest.

As human resources are vital for the development of each economic sector including agriculture and at the same time land subsidence in urban areas can have a great impact on the quality of life, some demographic characteristics are highlighted having in mind the dynamics of the population for two urban centres from Spain.

MATERIALS AND METHODS

Scientific contributions investigating urban subsidence due to the groundwater pumping for agriculture purposes are analysed.

Different parameters are taken into account, such as history, monitoring methods, geology, climatic conditions and demographic characteristics.

This section presents the InSAR techniques applied for monitoring different areas affected by subsidence, followed by the description of the demographic indicators.

InSAR techniques for monitoring urban subsidence due to groundwater pumping for agriculture

InSAR techniques became popular at the beginning of 1990s when the ERS-1 (European Remote-Sensing Satellite-1) mission was launched (ESA, 2023), providing data with enough high spatial and temporal resolution for generating interferograms. The displacements are encoded in the phase difference between the two coregistered SAR images used for computing the interferogram (Galloway & Hoffman, 2006) along the Line of Sight (LOS) of the satellite (Colesanti & Wasowski, 2006). The day and night operational capabilities regardless the weather conditions of InSAR techniques (Ferretti et al., 2007), the ability to measure the subsidence with a relative low cost and to perform precise ground monitoring (Chaabani & Deffontaines, 2020) are some of the advantages of these techniques, addressing the limitations of the classical methods.

Two classes of InSAR techniques are being used over time:

- the conventional approach, using single interferometric processing, known as **conventional InSAR** (Bamler & Hartl, 1998), and
- the differential approach, or **conventional DInSAR** (Crossetto et al., 2016; Ruiz-Constan et al., 2015), when multiple SAR scenes with the same geometry are used over the same study area at different time moments (Ferreti et al., 2007). As DInSAR technique might be affected by atmospheric influences and temporal and spatial decorrelations when measuring ground displacements (Chaabani & Deffontaines, 2020; Chen et al., 2016; Cianflone et al., 2022), more advanced DInSAR techniques are being developed, named the Multi-Temporal Interferometry techniques (**MTI**) or Advanced-Differential SAR Interferometry techniques (**A-DInSAR**), such as Persistent-Scaterrer Interferometry (**PSI**) (Ferretti et al., 2001; Crossetto et al., 2016; Espiritu et al., 2022) and Small Baseline Intereferometry (**SBAS**) (Berardino et al., 2002).

Further, to compensate some of the MTI techniques' limitations, the temporal decorellation on vegetated or bare soil areas (Galloway & Burbey, 2011), new MTI techniques from the PSI and SBAS families, or combinations of the two techniques were proposed, such as Wavelet Based InSAR (**WabInSAR**) (Miller & Shirzaei, 2015), Parallel Small Baseline Subset (**P-SBAS**) (Cigna & Tapete, 2022; Orellana, et al., 2022), **SqueeSAR** (Ezquerro et al., 2020), Coherence Pixel Technique (**CPT**) (Ezquerro et al., 2020), **StaMPS-MTI** (Ruiz-Constan et al., 2016).

Demographic assessment

Human beings have a powerful effect on the environment quantified in demographic factors regarded as one of the primarily global drivers of human-induced environmental change, in addition to biophysical, economic, socio-political, technological factors (Boberg, 2005). Demographics variability and effects on the environment are emphasised by the population growth and the natural increase rate, information which can be used in many ways to discover the generalities of a particular population.

The natural increase rate in the total population refers to the difference between the number birth rate and the death rate occurring in a year, divided by the mid-year population of that year, multiplied by a factor (usually 1,000) (Dumitrache & Erdeli, 2009). For birth rate evaluation it is considered the number of people born in a population in a given amount of time, while the death rate is represented by the number of deaths, per year, varying, due to differences in living standards and economic conditions.

The natural increase rate indicator is determined for Murcia and Madrid, two regions from Spain where groundwater usage is contributing significantly to Spanish agricultural and regional development.

RESULTS AND DISCUSSIONS

The current review, based on an extensive scientific literature inquiry on the urban areas affected by land subsidence due to groundwater withdrawal for agriculture, are taking into consideration different aspects, considering the domain of interest. Therefore climate, geology, hydrogeology, InSAR monitoring techniques, satellite SAR missions, management of hydrological resources, demographic dynamics, or urbanisation might give a glimpse on where and how overexploitation of groundwater resources for agriculture purposes might affect urban areas.

History of groundwater pumping for agriculture in urban areas

- First half of 20th century

U.S.A.

Looking on the history aspect, groundwater pumping for agriculture has enabled the San Joaquin Valley of California, U.S.A. to become one of the world's most productive agricultural regions (Galloway & Riley, 1999).

For Santa Clara Valley, Coachella Valley, San Joaquin Valley, California, agriculture was the predominant activity in the first half of the 20th century, with a rapid urban and industrial development after the World War II (Galloway & Hoffman, 2006; Sneed et al., 2014; Galloway & Riley, 1999), and the extraction rate of groundwater continuing to increase (Schmidt & Burgman, 2003). Same situation is specific for Phoenix, Arizona (Miller & Shirzaei, 2015). Therefore, since 1970s, the water in many wells declined from 15 m (Sneed et al., 2014) up to 90 m in the deep confined aquifers, while large areas from these regions were affected by land subsidence reaching up to 8 m subsidence (Galloway & Riley, 1999). For Santa Clara Valley, the decrease of rainfalls in the first part of the 20th century contributed to the increase of groundwater needs for agriculture (Schmidt & Burgman, 2003).

As a consequence of the water increase demand, the necessity to preserve the groundwater resources and to prevent severe damages, various measures were taken in the U.S.A. Thus, in the Coachella Valley, California, in 1949 water from Colorado River started to be imported, a recovery of the groundwater levels being registered until 1970. However, since late 1970s, the water demand increased leading to the increase of groundwater pumping (Sneed et al., 2014). As a consequence, the subsidence process continued until today, in the 2000s, in Palm Desert a 4 cm/year subsidence being registered (Sneed et al., 2014).

The import of surface-water has been used also in Santa Clara valley for supplementing the water demand and to recharge the declining groundwater system (Galloway & Hoffmann, 2006). Favourable rainfalls contributed to the recovery, so that in the 1990s InSAR measurements indicated up to 6.4 mm/year uplift North to Sunnyvale (Schmidt & Burgman, 2003). Unless highly urbanised, these areas are still major agriculture regions in the U.S.A, relying heavily on the groundwater resources. Therefore, in San Joaquin Valley, a long-term land subsidence is present, due to the compaction of fine-grained aquitard layers within the aquifer system, reaching in the 2000s up to 25 cm/year subsidence (Liu et al., 2019). As a consequence, aqueducts, levees, bridges and roads are at risk of damage (NASA, 2017), potentially affecting the quality of life of the population from the region.

China

Found on a different continent, land-subsidence due to groundwater over-exploitation is present in Beijing, China, since 1935 (Chen et al., 2016). As groundwater is the main water source for industry, agriculture and domestic use in the area, and considering the great impact of the land subsidence, more than 25 studies on this subject are available for Beijing (Hu et al., 2019; Bai et al., 2022). Nowadays, the values of land-subsidence are greater than 10 cm/year (Chen et al., 2016).

- Second half of 20th century

Mexico

Unless land-subsidence due to groundwater extraction was observed in Mexico City since 1920, it was in the 1980s when subsidence started to be observed and monitored in other cities from central Mexico, such as Morelia or Celaya (Suarez et al., 2018), where agriculture is one of the important activities for which groundwater exploitation is necessary (Cigna et al., 2022; Chaussard et al., 2014). In the Metropolitan Area of Morelia, 47% of the groundwater wells are for agriculture, the yearly subsidence rate between 2014 and 2021 reaching up to 9 cm. Celaya, Silao and Leon cities are characterised by a rapid, local-scale subsidence due to groundwater withdrawal for agriculture, reaching up to 8 cm/year from a SAR subsidence monitoring conducted between 2007 and 2011 (Chaussard et al., 2014).

Spain

Alto Guadalentin Basin from Southeast Spain, is a fertile basin cultivated since the Arabic ages (800 B.C.), agriculture being traditionally the most important economic activity in the area (Ezquerro et al., 2017). However, in the 1960s the agricultural development involved the use of groundwater resources, helping to the revitalization of this economic sector in the 1980s, but leading to temporally overexploitation in 1987 (Boni et al., 2015; Ezquerro et al., 2017). After this moment, the transfer of water resources from Tajo River and Segura River helped the recovery of the aquifer system, but the droughts periods from 1990 to 1995 and from 2005 to 2007 led again to the intensive use of groundwater resources (Boni et al., 2015). Unless urban and touristic activities progressively entered the economic activity, agriculture still has an important impact over groundwater resources, studies using SAR data revealing a continuous deformation pattern with greatest values in Europe, higher than 10 cm/year (Gonzales & Fernandez, 2011). This dynamics comes in the context of continuous increase of population, in Lorca and Puerto Lumbreras cities reaching more than 100,000 inhabitants in 2012, an increase of almost 50% from 1960. Land subsidence and the increase of population make the structures and infrastructures from the area vulnerable, considering also the important geological risk of the region (Ezquerro et al., 2017).

City of Murcia, found in the neighbouring of Alto Guadalentin valley, is also part of the South-Eastern regions of Spain known and being monitored due to the over-exploitation of groundwater for domestic, agricultural and industrial needs (Rigo et al., 2013). The drought period from the 1990s led to the groundwater overexploitation that generated land-subsidence accompanied by damages to over 150 buildings and other structures. During the drought period from 2004 to 2008, new wells were drilled for maintaining water supply for population and agriculture needs (Tessitore et al., 2016).

Unless not having the same importance as in Alto Guadalentin Basin, agriculture and groundwater pumping for agriculture are present also in the Metropolitan area of Madrid, 32% of the land-use from this region being arable for annual crops (Copernicus, 2018). Agriculture is more important here for the smaller municipalities, correlation coefficients between displacements and piezometric time series having values higher than 85% for all the wells, for a cumulated value of subsidence over almost 20 years of 8 cm (Ezquerro et al., 2014).

Montellano, Spain, is another town where land subsidence is present due to intensive exploitation of groundwater for agricultural and urban purposes, the particularity of this area being that aquifer was not exploited before 1990s the use of water from river being more common.

The changes in agricultural practices from non-irrigated to irrigated land and the severe droughts since 1990s favoured intensive groundwater exploitation and a cumulated value of 33 mm subsidence for almost 20 years, since 1992 (Ruiz-Constan et al., 2016).

Italy

The economic boom of Italy after the World War II led to extensive exploitation of groundwater for agricultural and industrial use in the Plain of Po River Delta, making it a historically land-subsidence affected area (Solari et al., 2018). This resulted in a territory very difficult to be managed, as large areas were part of the land reclamation projects from the end of 19th century, when the territory was largely increased for usable crop production (Corbau et al., 2019). Unless this is a poorly urbanised area, this is an example of successful policies applied since the 1950s, as subsidence was estimated to 300 mm/year in the period from 1950 to 1957. Therefore, since 1960, anthropogenic withdrawals were suspended and other specific works have been done, leading to the decrease of land subsidence to values of 4.5 mm/year nowadays (Fabris et al., 2022), which are mainly related to the natural consolidation of the compressible Holocene deposits (Corbau et al., 2019).

In Gioia Tauro Plain, an important urban industrialised and coastal agricultural area from the Southern part of Italy, the groundwater pumping for agricultural purposes is present since the 1970s. A significant drop of the piezometric level of the shallow aquifer was registered between that period and 2021 (Cianflone et al., 2021). Unless the main towns of the plain (Gioia Tauro, Rosarno, Nicotera, Taurianova, and Citanova) are stable, an increasing subsidence rate of up to -5mm/year was observed in the town of Polistena (Cianflone et al., 2022). The farming system from the area with hundreds of individual small plots, despite the public water supply network, leads to the presence of uncontrolled drilled water wells (Raspini et al., 2012). Another particularity of the area is related to the land use changes in the last two decades, with intensive and ongoing kiwifruit farming, requiring a high-water supply, almost doubled, compared to the previous citrus and olive crops (Cianflone et al., 2022).

Part of the Firenze-Prato-Pistoia plain, Pistoia is a city with instability phenomena documented since the 1960s (Ceccatelli, 2020). From the early 1990s, Ezquerro et al. (2020), states that land subsidence is occurring in the Firenze-Prato-Pistoia basin, due to intensive groundwater withdrawal for agriculture. More specifically, Pistoia is known for the tree nursery activities, and the presence of soft sediments subsiding due to groundwater withdrawal (Del Soldato et al., 2018), the maximum deformation measured during 2014-2018 being of 1.7 cm/year (Ezquerro et al., 2020).

Using SAR interferometry, severe land subsidence was detected in the last two decades in the Sele and Volturno Plain, being stated that land subsidence is present due to groundwater overexploitation for agricultural use, inducing coastal inundation (Solari et al., 2018). The plain is characterised by an increased concentration of infrastructure and inhabited areas, such as Castelvolturno, Mondragone, or Capua cities, with known farming, agricultural and cheese production activities (Matano et al., 2018).

Turkey

Konya Plain, with its urban areas Konya, Ismil, Cumra, Hotamis, or Eregli, it is a known area in Turkey for intensive groundwater pumping for covering the agricultural, urban and industrial needs (Calo et al., 2017). The rapid groundwater withdrawal and vertical displacements have been observed during the last 3-4 decades, with an intensification of the groundwater pumping in the last years (Ustun et al., 2018), in the context of an increase of irrigated land, for crops as sugar beet and corn. Water needs for irrigation led to uncontrolled groundwater withdrawal, and as a consequence of groundwater withdrawal, sinkholes appeared, leading to damages to infrastructures and of some villages. Vertical deformation of up to 10 cm during 8 years of monitoring were detected in the area (Calo et al., 2017).

Iran

At the Iran country level, 90% of the groundwater consumption is used for agricultural purposes (Haghshenas Haghighi & Motagh, 2021). The old and inefficient farming methods are one of the factors prone to higher need for groundwater (Pirouzi & Eslami, 2017). Shariar area, situated in the west of Tehran plain, faced over-exploitation of groundwater resources few years after the construction of a dam in the area in the 1960 (Khodapanah et al., 2011). In the Kerman Province, subsidence due to extensive groundwater withdrawal is present since the 1980s (Toufigh et al., 2004). As agricultural regions are spread all over the country, many urban areas, or neighbouring of urban areas are affected by land subsidence, such as Tehran city (Pirouzi & Eslami, 2017), Neyshabour City (Dehghani et al., 2009), Rafsanjan and Anar cities situated in the Iran's center of Pistachio plantation, Mashhad city (Haghshenas Haghighi & Motagh, 2021), Ardabil, Khalilabad, and Araloyebozorg (Ghorbani et al., 2022), Ashkane city (Rafiei et al., 2022). In many areas affected by land subsidence, the vertical displacements have values higher than 10 cm/year, which can lead in the near future to significant economic losses such as structural damage and high maintenance costs for roads, railways, dikes, pipelines, and buildings (Rajabi Baniani et al., 2020). Several roads located in the agricultural area to the southwest of Tehran are already affected by land subsidence (Haghshenas Haghighi & Motagh, 2021), while field research in the city of Ashkhane and neighbouring areas showed the presence of damages such as cracks in the walls (Rafiei et al., 2022).

Philippines

Subsidence due to groundwater withdrawal in East Asia has as one of the main cause the expanding of coastal aquaculture and the presence large crops of rice, especially for Manila Bay, where the biggest crops of rice across the East Asia are found. Subsidence due to groundwater use is known since 1965 (Rodolfo & Siringan, 2006). The Metropolitan Manila, including Manila, Caloocan, Malabon, Navotas and Valenzuela cities, is affected by land subsidence with rates between 1 and 2 cm/ year, studies showing that subsidence is the cause of floods worsening in the recent years. This comes in the context of an area exposed to multiple natural hazards, such as earthquakes, landslides, volcano eruptions, and typhoons, endangering buildings, houses and underground facilities (Espiritu et al., 2022).

- The 21st century

Pakistan

Pakistan has at the moment the highest speed of urbanization in South Asia. As an example, the urban area of Lahore city doubled between years 1999 to 2011 (Ahmad et al., 2021). As the only source of water for the city, due to the uncontrolled urbanization, the intensive groundwater extraction led to land subsidence (Farhat et al., 2018; Hussain et al., 2022), with values up to 11 cm/year (Ahmad et al., 2022). Although the highest rate of groundwater pumping is for the domestic use, agriculture still has an important role and impact in the groundwater balance of Lahore city, 23% of the discharge being for agricultural purposes, more than for the industrial and commercial use (Ahmad et al., 2022). Field surveys confirmed the results of the InSAR analyses, damages of buildings and other infrastructures taking place in areas affected by subsidence (Ahmad et al., 2022; Hussain et al., 2022). In the actual context, for a sustainable development, proper strategies of urban planning considering the land use and land cover classes, including agricultural lands, should be developed (Farhat et al., 2018).

Chile

Found in a vulnerable area with the most seismically active subduction zones in the world, the Metropolitan Area of Santiago de Chile is affected by ground instability due to natural factors and anthropic factors, such as the groundwater overexploitation. As a result of climate changes and influenced by the intensive agriculture, Paine city, part of Grater Santiago, experienced in the recent years more noticeable deformations, considering the exploitation and compaction of the aquifer (Orellana et al., 2022).

Tunisia

Situated in North Africa, Tunisia is one of the Mediterranean countries which relies on deep aquifers for fulfilling the water needs for agriculture, domestic use and industry, as surface waters are scarce and irregular (Mokadem et al., 2018). Since the 1960s, a significant agricultural and industrial boom was registered in the coastal northern Tunisia. Therefore, the groundwater exploitation speed from the unconfined aquifer increased from 280 l/s in 1971, to 600 l/s in 1999 (Charef et al., 2012).

As a consequence, in the last two decades land subsidence is producing in Tunis City and the Mornag plain with values up to 19 mm/ year, leading to numerous failures of buildings, considering also the highly compressive deposits from the area. Also, due to agricultural and industrial activities, in the peri-urban area of Mornag plain, drinking water resources is under substantial pressure (Chaabani & Deffontaines, 2020).

Indonesia

Indonesia is one of the countries with rapid increasing of population in urban areas, followed by increasing of water and land needs, considering mainly the industrial needs, followed by the agricultural and housing activities, causing land subsidence (Sidiq et al., 2019). Groundwater exploitation is documented in Indonesia since the first half of 20^{th} century, and it could be revealed the massive increase of groundwater exploitation since 1970, concomitantly with the manufacturing industry development, and the massive urbanisation, consequently. Due to industrial pumpers, the total groundwater abstractions in Bandung basin grew from 18% to 83% during 1950-1990 time period (Braadbaart & Braadbaart, 1997). However, the presence of land subsidence is mentioned since year 2000, when the GPS surveys started to be used for ground motion monitoring (Abidin et al., 2009). As for the SAR monitoring, from 2007 to 2011, for two agricultural areas from Bandung, the land subsidence rate was as high as 5 cm/year (Sidiq et al., 2019). Similar values are registered for two other urban areas, Blanakan and Pekalongan cities, where agriculture has a significant impact on groundwater withdrawal (Chaussard et al., 2013).

SAR techniques and SAR data used for land subsidence monitoring

The capability of SBAS technique of improving conventional InSAR monitoring over agricultural areas (Galloway & Burbey, 2011) is proved by the high number of scientific contributions where SBAS (Chaussard et al., 2013; Sidiq et al., 2019; Chaabani & Deffontaines, 2020; Chen et al., 2016; Calo et al., 2017; Haghighi & Motagh, 2021; Dehghani et al., 2009; Farr & Liu, 2015; Cianflone et al., 2022; Ezquerro et al., 2017) is used as SAR processing technique for subsidence monitoring in the urban areas where agricultural activities have a great importance. This is highlighted in Figure 1, where a statistic of the SAR monitoring techniques is made, considering the consulted scientific contributions available on the topic of this paper. Thus, in 36% of the contributions, the SBAS techniques is used, followed by the PSI technique (Baniani et al., 2021; Fabris et al., 2022; Ezquerro et al., 2014; Espiritu et al., 2022; Ahmad et al., 2022; Boni et al., 2015) with 21% and other InSAR (Galloway & Hoffmann, 2006; Sneed et al., 2014) and A-DInSAR techniques such as P-SBAS (Orellana et al., 2022; Cigna & Tapete, 2022), DInSAR (Liu et al., 2019; Rafiei et al., 2022), InSAR-SB (Chaussard et al., 2014), LiCSBAS (Ghorbani et al., 2022), WabInSAR (Miller & Shirzaei, 2015), SqueeSAR (Ezquerro et al., 2020), or STAMPS-MTI (Ruiz-Constan et al., 2016). If we take into consideration all the techniques which are part of the SBAS family, more than half of the scientific contributions are using an approach based on SBAS technique.

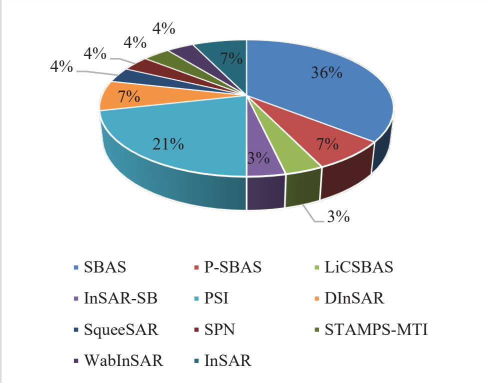

Figure 1. SAR monitoring techniques used in the scientific contributions

Figure 2 presents a statistics on the data sets used in the scientific contributions on the topic of this paper, considering the past and actual launched SAR missions. The figure highlights at a first sight the high number of studies using data from European SAR missions.

This comes in the context of free and open access of the European SAR missions, starting with ERS 1& 2 in the 1990s, the ENVISAT ASAR in the 2000s and the actual European SAR mission, Sentinel-1 mission since 2014. Therefore, almost 80% of the used SAR data are from European missions: the greatest percentage is registered for Sentinel-1 data sets, with 35%, followed by ENVISAT datasets with 24%, and ERS 1&2 with 19%. Other data sets are from the TerraSAR-X mission which was available during the gap period between the retirement of ENVISAT mission in 2012 and the launch of Sentinel-1 in 2014 (Romero, et al., 2020), from ALOS PALSAR and CosmoSkyMed.

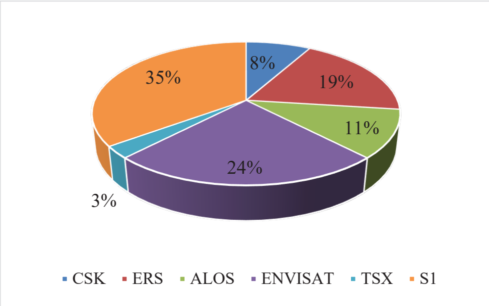

Figure 2. SAR data sets from different SAR missions used in the scientific contributions

Datasets from the different SAR missions covers time intervals starting with the 1990s until the present day. Figure 3 presents the percentages of datasets used in each decade from 1990s, followed by the 2000s and all the datasets since 2010s.

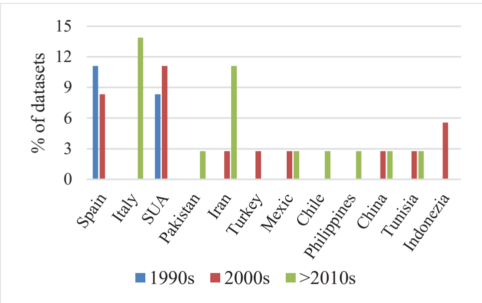

Figure 3. Percentages of SAR data sets used for land subsidence monitoring in different countries

Looking on the graph, the highest percentages of datasets from the 1990s and from the 2000s are used for urban areas from Spain and U.S.A, both countries with long history on groundwater pumping for agricultural activities. For the time interval covering the last decade, Italy has the highest percentage of SAR datasets used for land subsidence monitoring, followed by Iran, one of the countries with high land subsidence problems nowadays. The lack of studies covering the 1990s in some countries where land subsidence is present for more than half of a century, might be explained by the use of other land subsidence monitoring methods, such as precise levelling or GNSS surveillance.
Different numbers of SAR data sets are used in in the consulted scientific contributions for the land subsidence monitoring, the maximum number of data sets from different missions being three. Therefore, Figure 4 presents the percentages of scientific contributions which used data sets from one, two or three SAR missions for land subsidence monitoring.
Most contributions used a SAR data set from a single SAR mission (65%), followed by contributions where data sets from two SAR missions were used (31%). Only 4% of contributions used data sets from three SAR missions.

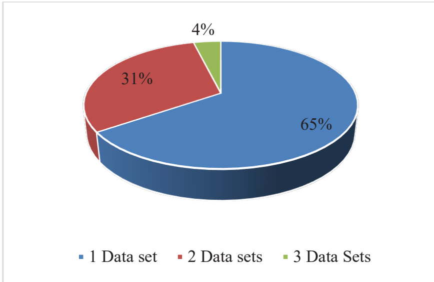

Figure 4. Percentages of scientific contributions using data sets from one or more SAR missions

As for the land subsidence measured using SAR techniques, there were registered values between 1.4 cm/year in Lahore City, Pakistan (Ahmad et al., 2022) and 25 cm/year in San Joaquin, U.S.A. (Liu et al., 2019).
Figure 5 presents the percentages of urban areas from different countries affected by land subsidence due to groundwater withdrawal for agricultural purposes, considering different deformation intervals. It includes areas with land subsidence rates: under 5 cm/year, between 5 and 10 cm/year, between 10 and 20 cm/year and higher than 20 cm/year.
Urban areas where land subsidence has values lower than 5 cm/year are present in Tunisia, Philippines, Iran, U.S.A., Italy and Spain. On the other side, as mentioned above, in U.S.A. is registered also the highest subsidence rate, higher than 20 cm/year. Displacement values between 5 and 10 cm/year are measured by InSAR techniques in Indonesia, Mexic, and Spain, while displacements values between 10-20 cm/year are measured in urban areas from China, Chile, Turkey, Iran, Pakistan, U.S.A., and Spain.

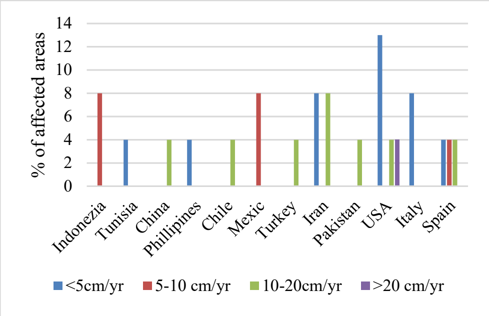

Figure 5. Percentages of urban areas affected by land subsidence due to groundwater withdrawal for agricultural activities, considering different intervals of displacements

Climatic, hydrogeological, geological aspects of the studied areas

Most urban areas affected by land subsidence due to groundwater withdrawal for agricultural purposes are located in arid and semi-arid regions worldwide, from Western U.S.A., Mexico, Middle East, Southern Asia, North Africa, or Mediterranean basin. As rivers and surface water sources are poor or unavailable in some periods of the year in the arid and semi-arid regions, groundwater is the main water source (Pirouzi & Eslami, 2017; Espiritu et al., 2022; Cigna et al., 2022; Ustun et al., 2010; Baniani et al., 2021; Dehghani et al., 2009; Haghighi & Motagh, 2021), or the only water source (Ahmad et al., 2022).

In many cases, severe droughts (Ruiz-Constan et al., 2016; Tessitore et al., 2016; Boni et al., 2015) and climatic changes (Ahmad et al., 2022) contributed to the groundwater overexploitation, unless the anthropic factors are the most pregnant.

The presence of the alluvial compressible deposits with variable thicknesses (Galloway & Hoffmann, 2006; Ahmad et al., 2022; Baniani et al., 2021; Ghorbani et al., 2022; Calo et al., 2017; Chen et al., 2016; Chaussard et al., 2013) and of aquifer systems with highly compressible fine-grained interbeds (Fabris et al., 2022; Dehghani et al., 2009; Chaussard et al., 2014; Chaabani & Deffontaines, 2020) are also part of the factors that favour the occurrence of land subsidence when important quantities of groundwater are pumped.

Demographic indicator assessment for Murcia and Madrid regions

Spain is between the most arid countries in Europe having a massive hydrogeological potential, groundwater usage development contributing significantly to Spanish agricultural and regional development. Spain's current total water use is distributed between irrigation (67%), urban needs and industry (14%) and independent industrial use and cooling (19%) (Llmas & Garrido, 2007). As a consequence on the difficulties in the planning and control of groundwater use, ecological and socio-economic impacts arisen.

The Regulation for the Public Water Domain says that "an aquifer is overexploited when the continuation of existing uses is in immediate threat as a consequence of abstraction being greater or very close to the mean annual volume of renewable resources, or when it may produce a serious water quality deterioration". This is due to the dramatic increase usage of groundwater by thousands of individual farmers, industries in different regions with very limited public involvement.

Comprehensive research on groundwater use and resources in Spain are introduced in the Groundwater White Book (MIE & MOPTM, 1995), the Water White Book (MMA, 2000) and the book by Llamas et al. (2001).

Based on other related research (Richey et al., 2015) which employ satellite measurement of Earth's gravity, it is proved that a third of big groundwater basins are in distress endangering water security and resilience at regional level. In densely populated areas from arid and semi-arid regions, this problem is intensified by climate change and rapid increase of population (Bejar-Pizarro et al., 2017).

With regard to the social analysis of the groundwater monitoring, focusing on the evolution of demographic indicators, two regions in Spain are laid out, adjoining Urban Atlas (Copernicus, 2018) statistical figures.

Murcia is located in the southeast of the Iberian peninsula, at the very centre of the peninsular Mediterranean arc with a semiarid climate, which determines a high rate of erosion, has a total surface of 11,314 km^2 (2.2% of the Spanish surface). The region has an increasingly population number in the period from 2006 to 2018 (Figure 6), having decreasing features in

2013, continued by a rise to 2018. The rural area takes up to 83% of the regional territory with 36% of Murcia's population living there (RDP, 2010).

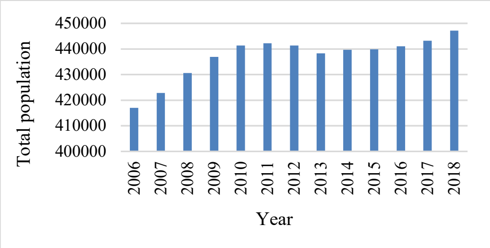

Figure 6. Total population number in Murcia region, Data source: Spanish Institute of Statistics (INE, 2023)

The economic crisis occurred in Spain since 2008, led to unemployment, which causes changes in the demographic trend (Moya Ortega & Garcia Marin, 2015). The highest percentage of the natural increase rate is registered in 2008 (Figure 7), determined by highest birth rate in the analysed time series (2006-2018). The natural increase rate and birth rate values of the data series are decreasing from 2008, while the death rate was continually increasing (Figure 7). The population employed in agriculture has increased from 1999 to 2006. The region presents great agricultural potential, one of the most intensive in Europe, with crops such as almond tree and cereals in dry lands, and vegetables as potatoes, cabbage and pepper, irrigated fruit trees such as the lemon tree, orange tree, peach and plum tree (Andrade-Limas et al., 2007), due to the favourable environmental conditions in the area, such as high temperatures all over the year, and fertile soils. Lately, Murcia has become one of the main producers of fruits and vegetables in Spain. As the region covers 4.3% of the Spanish population, having the power of the country's export for between 20 and 30%, in this segment, it consequently incur a considerable part of its economic productivity to the agricultural sector (Murcia Today, 2017).

CHS is the Segura River Basin Authority in the Region of Murcia, in charge of the general management of water resources, including the aquifers in the Basin (Mamais et al., 2020). As Murcia Region is one of the most water-stressed regions in the Mediterranean basin with frequent extreme meteorological events, such as multi-annual droughts (Calatrava & Martinez-Granados, 2017), the structural water deficit is the biggest challenge faced by CHS in the area. As a consequence, the various water users in the basin through a long history, gained a strong expertise in water culture, aiming at balancing groundwater use for both drinking and irrigation purposes (Mamais et al., 2020).

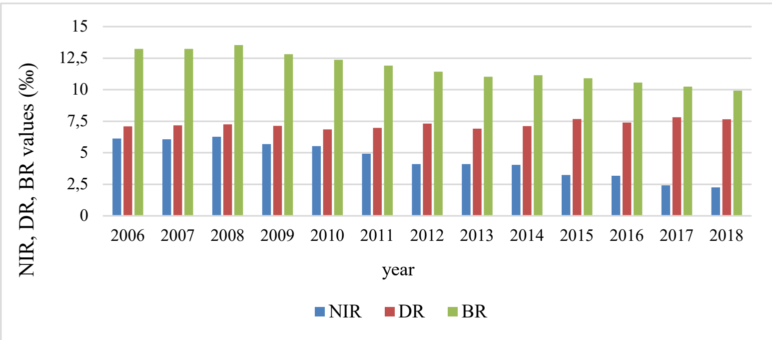

Figure 7. NIR, DR, BR evolution in Murcia region during 2006 and 2018
Data source: Spanish Institute of Statistics (INE, 2023)

Construction of illegal wells and of canals, followed by illegal groundwater use, have become an increasing phenomenon in the region, due to the implementation of a restrictive policy in terms of access to groundwater and an increasing agricultural cultivation. The high rate of illegal groundwater abstraction is explained by the huge profits that encourage farmers to expand their farmland despite ineffective controls by public authorities. As a consequence, river basin authorities are continuously under both, political and economic pressure, which involve restrictions on their efforts to deal with illegal water use and aquifer exploitation (WWF, 2006).

Another Spanish urban area to be mentioned, is Madrid, as one of the best documented Spanish example (De Stefano et al., 2015), where groundwater is a critical resource to prevent failures in the urban supply system, especially during droughts.

Madrid, the most populated region in Spain, generates 17% of the country's gross domestic product and is the second most important industrial centre of the country, currently ranking second among the cities of the European Union behind Berlin, and the third place among the largest urban agglomeration in Europe, behind Île-de-France, and Greater London.

Madrid's population has experienced growth since 2008 due to significant number of foreign immigrants settling in the city (Observatorio Economico, 2010) due to the strength of Madrid's economy, the main economic hub and decision making centre in Spain.

During the demographic data series assessment (Figure 8), the highest number of the population in 2010 starts to decrease, recording the lowest people number in 2015, followed by an increased trend in the number of populations till 2018.

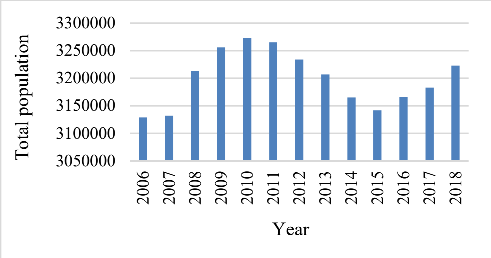

Figure 8. Total population number in Madrid during 2006 and 2018. Data source: Spanish Institute of Statistics (INE, 2023)

The natural increase rate has positive values during the analysed period, given the highest birth rate than the death rate. The birth rate is slightly decreasing since 2006, while the death rate has an annually increasing rate until 2018. Based on this, the natural increase rate register decreasing values frequency, the lowest value being recorded in 2018 (Figure 9).

Concerning the monitoring availability of several European urban regions which can increase groundwater development and management solutions, the Copernicus Land Monitoring Service step into action (Copernicus, 2023). It provides geographical information on land cover/land use and on variables related to vegetation state and the water cycle.

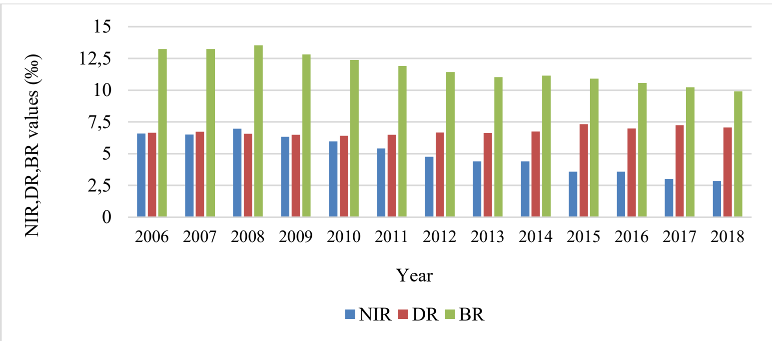

Figure 9. NIR, DR, BR evolution in Madrid region during 2006 and 2018
Data source: Spanish Institute of Statistics (INE, 2023)

It supports applications in a variety of domains, such as spatial planning, forest management, water management and agriculture.

Urban Atlas is focused on FUAs (Functional Urban Area), which include core cities and their commuting zones, providing reliable, inter-comparable, high-resolution land use maps for 2006, 2012, and 2018 (Copernicus, 2023). In total, the Urban Atlas includes 27 land cover classes, of which 17 are urban classes and 10 are rural classes.

The agriculture segment of Murcia and Madrid regions (Figure 10), determined from Urban Atlas classes (within the three available databases, in 2006, 2012 and 2018) cover nearly 76% of the total functional urban area, including arable land, herbaceous vegetation associations, pastures, permanent crops (vineyards, fruit trees, olive groves), open space with little vegetation, wetlands. No major changes are registered between the different time periods. Looking only at the surface occupied by arable, pastures and permanent crops, the percent is around 40% for Murcia and 44% for Madrid, with a higher percent of permanent crops for Murcia (24%) and of arable land for Madrid (33%).

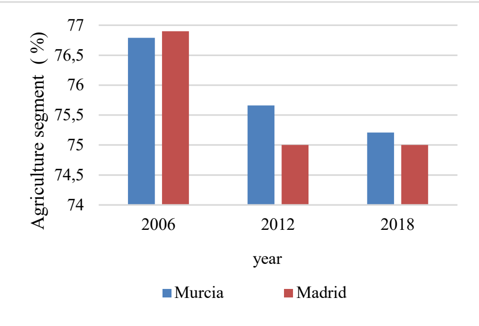

Figure 10. The evolution of Urban Atlas agriculture land class in 2006, 2012 and 2018 for Murcia and Madrid, including arable land, herbaceous vegetation, pastures, permanent crops, open space with little vegetation, wetlands. Data source: Urban Atlas (Copernicus, 2018)

CONCLUSIONS

Land subsidence is mainly caused by human activities, as highlighted in the present review, mainly due to groundwater pumping for anthropogenic activities.

Groundwater withdrawal for agricultural purposes in urban areas, is encountered mainly in arid and semiarid regions, where surface waters are very limited. Considering also the presence of the alluvial compressible deposits and of aquifer systems with highly compressible fine-grained interbeds, these areas are prone to the occurrence of land subsidence. The major impacts of land subsidence include direct damages with the loss of functionality and/or integrity of the structures such as buildings, roads, subways and underground utility networks (infrastructures). The most usual indirect effects are related to changes in relative surface and groundwater levels. In this context, a method of continuous monitoring of subsidence is of great importance. InSAR techniques represent a feasible subsidence monitoring method for urban areas with agricultural activities. From the consulted scientific literature, it could be noticed that the techniques from SBAS family are the most suitable for subsidence monitoring in urban areas with agricultural activities, as some InSAR limitations related to vegetation are mitigated. For the still remaining limitations, a combination between an InSAR technique and an in-situ technique is the most feasible monitoring approach.

In order to manage land subsidence's both consequences and exposed elements, there is a need to have human component assessment, through demographic indicators evaluation.

Following a statistical data evaluation, during 2006 – 2018, Murcia and Madrid regions present a positive natural increase rate due to a balanced population change (the birth rate higher than the death rate).

Both land subsidence monitoring and demographic indicators evaluation represent valuable instruments for decision making for urban planning, in the context of sustainable development.

REFERENCES

Abidin, H., Andreas, H., Gumilar, I., Wangsaatmaja, S., Fukuda, Y., & Deguchi, T. (2009). *Land subsidence and groundwater extraction in Bandung Basin, Indonesia*. In Trends and Sustainability of Groundwater in Highly Stressed Aquifers, IAHS Publ. 329, IAHS Press 2009, UK.

Ahmad, A., Wang, C., Tang, Y., Sultan, M., Falak, A., Duan, W., & Wang, J. (2022). Subsidence Monitoring and Assessment of the Factors Involved in the Occurrence of Subsidence, Lahore City. *Journal of Resources and Ecology*, *13*(5), 826-841. doi: 10.5814/j.issn.1674-764x.2022.05.007

Ahmad, A., Sultan, M., & Falak, A. (2021). *Urban subsidence monitoring by PSInSAR and its causes in Lahore, Pakistan*. SAR in Big Data Era (BIGSARDATA), Nanjing, China, 2021, pp. 1-4, doi: 10.1109/BIGSARDATA53212.2021.9574414.

Allaby, M. (2013). *A Dictionary of Geology and Earth Sciences* (4th ed.). Oxford University Press. 10.1093/acref/9780199653065.001.0001

Andrade-Limas, E., Faz-Cano, A., García-Fernández, G., & Arnaldos-Lozano, R. (2007). *Farmer classification. An approach to soil quality in Murcia, SE of Spain* (Research report no.7). European Soil Bureau. Retrieved from url: https://esdac.jrc.ec.europa.eu/ESDB_Archive/eusoils _docs/esb_rr/n07_ESBResRep07/407Andrade.pdf on 14.03.2023

Bai, Z., Wang, Y., & Balz, T. (2022). Beijing Land Subsidence Revealed Using PS-InSAR with Long Time Series TerraSAR-X SAR Data. *Remote Sens. 14*(11), 2529. https://doi.org/10.3390/rs14112529

Bamler, R., & Hartl, P. (1998). Synthetic aperture radar interferometry. *Inverse Problems, 14*, R1–R54.

Bawden, G., Sneed, M., Stork, S., & Galloway, D. (2003). *Measuring Human-Induced Land Subsidence from Space.* Reston, VA: U.S. Geological Survey. doi:https://doi.org/10.3133/fs06903.

Bejar-Pizarro, M., Ezquerro, P., Herrera, G., Tomas, R., Guardiola-Albert, C., Ruiz Hernandez, J., Fernandez Merodo, J., Marchamalo, M. & Martinez, R. (2017). Mapping groundwater level and aquifer storage variations from InSAR measurements in the Madrid aquifer, Central Spain. *Journal of Hydrology*, *547*, pp. 678-689, doi: 10.1016/j.jhydrol.2017.02.011

Berardino, P., Fornaro, G., & Lanari, R. (2002). A New Algorithm for Surface Deformation Monitoring Based on Small Baseline Differential SAR Interferograms. *IEEE Transactions on geoscience and remote sensing, 40*(11), 2375-2383. doi:10.1109/TGRS.2002.803792

Bitelli, G., Bonsignore, F., Pellegrino, I., & Vittuari, L. (2015). Evolution of the techniques for subsidence monitoring at regional scale: the case of Emilia-Romagna region (Italy). *Proc. IAHS, 372*, 315-321. doi:10.5194/piahs-372-315-2015

Boberg, J. (2005). *Liquid Assests: How Demographic Changes and Water Management Policies Affect Freshwater Resources*. Santa Monica, CA: RAND Corporation. Retrived from URL: https://www.rand.org/content/dam/rand/pubs/monographs/2005/RAND_MG358.pdf, on 14.03.2023

Boni, R., Herrera, G., Meisina, C., Notti, D., Béjar-Pizarro, M., Zucca, F., Gonzales, P., Palano, M., Tomas, R., Fernandez, J., Fernández-Merodo, J.A., Mulas, J., Aragon, R., Guardiola-Albert, C., & Mora, O. (2015). Twenty-year advanced DInSAR analysis of severe land subsidence: The Alto Guadalentín Basin (Spain) case study. *Engineeering Geology, 198,* 40-52. https://doi.org/10.1016/j.enggeo.2015.08.014

Braadbaart, O., & Braadbart, F. (1997). Policing the Urban Pumping Race: Industrial Groundwater Overexploitation in Indonesia. *World Development*, *25*(2), 199-210. doi:10.1016/S0305-750X(96)00102-7

Burkett, V. R., Zilkoski, D. B., & Hart, D. A. (2003). Sea-Level Rise and Subsidence: Implications for Flooding in New Orleans, Louisiana. In *U.S. Geological Survey Subsidence Interest Group Conference: Proceedings of the Technical Meeting, Galveston, Texas, November 27-29, 2001* (pp. 63-70). U.S. Geological Survey.

Calatrava, J., & Martínez-Granados, D. (2018). The limited success of formal water markets in the Segura River basin, Spain. *International Journal of Water Resources Development*, *34*(6), 961-981, doi: 10.1080/07900627.2017.1378628.

Calo, F., Notti, D., Galve, J.P., Abdikan, S., Gorum, T., Pepe, A., & Sanli, F.B. (2017). DInSAR-Based Detection of Land Subsidence and Correlation with Groundwater Depletion in Konya Plain, Turkey, *Remote Sens., 9*, 83, doi:10.3390/rs9010083

Ceccatelli, M., Del Soldato, M., Solari, L., Fanti, R., Mannori, G., & Castelli, F. (2020). Numerical modelling of land subsidence related to groundwater withdrawal in the Firenze-Prato-Pistoia basin (central Italy), *Hydrogeology Journal, 29*, 629-649, https://doi.org/10.1007/s10040-020-02255-2.

Chaabani, A. & Deffontaines, B. (2020). Application of the SBAS-DInSAR technique for deformation monitoring in Tunis City and Mornag plain, *Geomatics, Natural Hazards and Risk, 11*(1), 1346-1377, doi: 10.1080/19475705.2020.1788654

Charef, A., Ayed, L., & Azzouzi, R. (2012). Impact of natural and human processes on the hydrochemical evolution of overexploited coastal groundwater: Case study of the Mornag aquifer refill (South-East Tunis, Tunisia). *Chemie der Erde*, *72*, 61-69. doi:10.1016/j.chemer.2011.11.005

Chaussard, E., Amelung, F., Abidin, H., & Hong, S-H. (2013). Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. *Remote Sensing of Environment, 128*, 150-161. https://doi.org/10.1016/j.rse.2012.10.015

Chaussard, E., Wdowinski, S., Cabral-Cano, E., & Amelung, F. (2014). Land subsidence in central Mexico detected by ALOS InSAR time-series. *Remote Sensing of Environment, 140*, 94-106. http://dx.doi.org/10.1016/j.rse.2013.08.038

Chen, M., Tomás, R., Li, Z., Motagh, M., Li, T., Hu, L., Gong, H., Li, X., Yu, J., & Gong, X. (2016). Imaging Land Subsidence Induced by Groundwater Extraction in Beijing (China) Using Satellite Radar Interferometry. *Remote Sensing, 8*, 468. https://doi.org/10.3390/rs8060468

Cianflone, G., Vespasiano, G., De Rosa, R, Rocco, D., Apollaro, C., Vaselli, O., Pizzino, L., Tolomei, C., Capecchiacci, F., & Polemio, M. (2021). Hydrostratigraphic Framework and Physicochemical Status of Groundwater in the Gioia Tauro Coastal Plain (Calabria - Southern Italy). *Water, 13*, 3279. doi.org/10.3390/w13223279

Cianflone, G., Vespasiano, G., Tolomei, C., De Rosa, R., Dominici, R., Apollaro, C., Walraevens, K., & Polemio, M. (2022). Different Ground Subsidence Contributions Revealed by Integrated Discussion of Sentinel-1 Datasets,Well Discharge, Stratigraphical and Geomorphological Data: The Case of the Gioia Tauro Coastal Plain (Southern Italy). *Sustainability, 14*, 2926. https://doi.org/10.3390/su14052926

Cigna, F. & Tapete, D. (2022). Urban growth and land subsidence: Multi-decadal investigation using human settlement data and satellite InSAR in Morelia, Mexico. *Science of the Total Environment 811,* 152211. http://dx.doi.org/10.1016/j.scitotenv.2021.152211

Colesanti C & Wasowski J. (2006). Investigated landslide with space-borne Synthetic Aperture Radar (SAR) interferometry. *Eng Geol. 88*(3-4), 173–199.

Copernicus (2018). Urban Atlas. Retrieved from URL: https://land.copernicus.eu/local/urban-atlas/urban-atlas-2018, on 27.02.2023.

Copernicus (2023). Copernicus Land Monitoring Service at a glance. Retrieved from URL: https://land.copernicus.eu/, on 14.03.2023

Corbau, C., Simeoni, U., Zoccarato, C., Mantovani, G., & Teatini, P. (2019). Coupling land use evolution and subsidence in the Po Delta, Italy: Revising the past occurrence and prospecting the future management challenges. *Science of the Total Environment. 654*, 1196–1208. https://doi.org/10.1016/j.scitotenv.2018.11.104

Crossetto, M., Monserrat, O., Cuevas-Gonzalez, M., Devanthery, N., & Crippa B. (2016). Persistent Scatterer Interferometry: a review. *ISPRS J Photogramm Remote Sens. 115*, 78–89.

De Stefano, L., Fornés, J.M., López-Geta, J.A. & Villarroya, F. (2015). Groundwater use in Spain: an overview in light of the EU Water Framework Directive. *International Journal of Water Resources Development, 31*(4), 640-656. doi: 10.1080/07900627.2014.938260.

Del Soldato, M., Farolfi, G., Rosi, A., Raspini, F., & Casagli, N. (2018). Subsidence Evolution of the Firenze–Prato–Pistoia Plain (Central Italy) Combining PSI and GNSS Data. *Remote Sens. 10*, 1146. doi:10.3390/rs10071146

Dehghani, M., Zoej, M.J.V., Entezam, I., Mansourian, A., & Saatchi, S. (2009). InSAR monitoring of progressive land subsidence in Neyshabour, northeast Iran. *Geophys. J. Int. 178*, 47-56. doi: 10.1111/j.1365-246X.2009.04135.x

Dumitrache, L., Erdeli, G. (2009). *Geografia populatiei mondiale*. Bucharest, RO: Editura Universitara.

ESA (2023). *ERS Overview*. Retrieved from URL: https://earth.esa.int/eogateway/missions/ers/description, on 27.02.2023.

Espiritu, K.W., Reyes, C.J., Benitez, T.M., Tokita, R.C., Galvez, L.J., & Ramirez, R. (2022). Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) reveals continued ground deformation in and around Metro Manila, Philippines, associated with groundwater exploitation. *Natural Hazards, 114*, 3139-3161. https://doi.org/10.1007/s11069-022-05509-2

Ezquerro, P., Del Soldato, M., Solari, L., Tomás, R., Raspini, F., Ceccatelli, M., Fernández-Merodo, J.A., Casagli, N., & Herrera, G. (2020). Vulnerability Assessment of Buildings due to Land Subsidence Using InSAR Data in the Ancient Historical City of Pistoia (Italy). *Sensors, 20,* 2749. https://doi.org/10.3390/s20102749

Ezquerro, P., Guardiola-Albert, C., Herrera, G., Fernández-Merodo, J.A., Béjar-Pizarro, M., & Boni, R. (2017). Groundwater and Subsidence Modeling Combining Geological and Multi-Satellite SAR Data over the Alto Guadalentín Aquifer (SE Spain). *Geofluids, 2017,* 1359325. https://doi.org/10.1155/2017/1359325

Ezquerro, P., Herrera, G., Marchamalo, M., Tomas, R., Béjar-Pizarro, M., & Martinez, R. (2014). A quasi-elastic aquifer deformational behavior: Madrid aquifer case study. *Journal of Hydrology, 519,* 1192-1204. http://dx.doi.org/10.1016/j.jhydrol.2014.08.040

Fabris, M., Battaglia, M., Chen, X., Menin, A., Monego, M., & Floris, M. (2022). An Integrated InSAR and GNSS Approach to Monitor Land Subsidence in the Po River Delta (Italy). *Remote Sens., 14*, 5578. https://doi.org/10.3390/rs14215578

Farhat, K., Waseem, L., Khan, A., & Baig, S. (2018). Spatiotemporal Demographic Trends and Land Use Dynamics of Metropolitan Lahore. *Journal of History Culture and Art Research*, *7*(5), 92-102. doi:http://dx.doi.org/10.7596/taksad.v7i5.1774

Farr, T., & Liu, Z. (2015). *Monitoring Subsidence Associated with Groundwater Dynamics in the Central Valley of California Using Interferometric Radar*. In Remote Sensing of the Terrestrial Water Cycle, (eds V. Lakshmi, D. Alsdorf, M. Anderson, S. Biancamaria, M. Cosh, J. Entin, G. Huffman, W. Kustas, P. van Oevelen, T. Painter, J. Parajka, M. Rodell and C. Rüdiger). https://doi.org/10.1002/9781118872086.ch24

Ferretti, A., Monti-Guarnieri, A., Prati, C., Rocca, F., & Massonnet, D. (2007). *InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation (TM-19, February 2007).* ESA Publications

Ferretti, A., Prati, C., & Rocca, F. (2001). Permanent Scatterers in SAR Interferometry. *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, 39*(1), 8-20.

Galloway, D. L., & Burbey, T. L. (2011). Review: Regional land subsidence accompanying groundwater extraction. *Hydrogeology Journal, 19*, 1459-1486. doi:10.1007/s10040-011-0775-5.

Galloway, D. L., & Hoffmann, J. (2006). The application of satellite differential SAR interferometry-derived ground displacements in hydrogeology. *Hydrogeology Journal, 15*(1), 133–154. doi: 10.1007/s10040-006-0121-5.

Galloway, D. & Riley, F.S. (1999). *San Joaquin Valley: California Largest Human Alteration of the Earth's Surface. Land Subsidence in the United States*, U.S. Geological Survey Circular, 1182, 23-34.

Ghorbani, Z., Khosravi, A., Maghsoudi, Y., Mojtahedi, F. F., Javadnia, E. & Nazari, A. (2022). Use of InSAR data for measuring land subsidence induced by groundwater withdrawal and climate change in Ardabil Plain, Iran. *Sci Rep, 12,* 13998. https://doi.org/10.1038/s41598-022-17438-y

Gonzales, P., & Fernandez, J. (2011). Drought-driven transient aquifer compaction imaged using multitemporal satellite radar interferometry. *Geology 39*(6), 551-554. https://doi.org/10.1130/G31900.1

Haghshenas Haghighi, M. & Motagh, M. (2021). Land subsidence hazard in iran revealed by country-scale analysis OF Sentinel-1 INSAR. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLIII-B3-2021,* 155–161. https://doi.org/10.5194/isprs-archives-XLIII-B3-2021-155-2021

Hu, L., Dai, K., Xing, C., Li, Z., Tomas, R., Clark, B., Shi, X., Chen, M., Zhang, R., Qiu, Q., & Lu, Y. (2019). Land subsidence in Beijing and its relationship with geological faults revealed by Sentinel-1 InSAR observations. *International Journal of Applied Earth Observation and Geoinformation 82,* 101886. https://doi.org/10.1016/j.jag.2019.05.019

Hussain, M.A., Chen, Z., Zheng, Y., Shoaib, M., Ma, J., Ahmad, I., Asghar, A., & Khan, J. (2022). PS-InSAR Based Monitoring of Land Subsidence by

Groundwater Extraction for Lahore Metropolitan City, Pakistan. *Remote Sens.*, *14*, 3950. https://doi.org/10.3390/rs14163950

INE (Instituto Nacional de Estadistica). 2023. Retrieved from URL: https://www.ine.es, on 14.03.2023.

Karila, K., Karjalainen, M., Hyyppä, J., Koskinen, J., Saaranen, V., & Rouhiainen, P. (2013). A Comparison of Precise Leveling and Persistent Scatterer SAR Interferometry for Building Subsidence Rate Measurement. *ISPRS Int. J. Geo-Inf., 2*, 797-816. doi:10.3390/ijgi2030797

Khodapanah, L., Sulaiman, W.N.A., Hyyppä, J., & Nassery, H.R. (2011). Hydrogeological Framework and Groundwater Balance of a Semi-Arid Aquifer, a Case Study from Iran. *Journal of Water Resource and Protection, 3*, 513-521. doi:10.4236/jwarp.2011.37061

Liu, Z., Liu, P-W., Masooud, E., Farr, T., Lundgren, P., & Famiglietti, J. (2019). Monitoring Groundwater Change in California's Central Valley Using Sentinel-1 and GRACE Observations. *Geosciences, 9*, 436. doi:10.3390/geosciences9100436

Llmas, R., Fornes, J., Hernandez-Mora, N. & Martinez Cortina, L. (2001). Aguas subterráneas: retos y oportunidades [Groundwater: Challenges and opportunities]. Madrid, USpain: Mundi-Prensa, ISBN 92-9220-016-X.

Llmas, R. & Garrido, A. (2007). Lessons from Intensive Groundwater Use in Spain: economic and social benefits and conflicts. In Giordano M. & Villholth (Eds.). *The agricultural groundwater revolution: opportunities and threats to development*. pp 266-295. Wallingford, UK: CABI.

Mamais, L., Oligschläger, C., & Khabarov, N. (2020). *A case study: Aquifer Management in Spain* (Sentinels Benefits Study SeBS-CR-009). European Association of Remote Sensing Companies (EARSC), Funded by the EU and ESA – ESA Contract Number: 4000119743/17/I-SBo. Retrieved from URL: https://earsc.org/sebs/wp-content/uploads/2020/10/Aquifer-Management-in-Spain_vf.pdf on 14 March 2023.

Matano, F., Sacchi, M., Vigliotti, M., & Ruberti, D. (2018). Subsidence Trends of Volturno River Coastal Plain (Northern Campania, Southern Italy) Inferred by SAR Interferometry Data. *Geosciences, 8*, 8. doi:10.3390/geosciences8010008

Meza-Gastelum, M.A., Campos-Gaytán, J.R., Ramírez-Hernández, J., Herrera-Oliva, C.S., Villegas-León, J.J., & Figueroa-Núñez, A. (2022). Review of Groundwater Withdrawal Estimation Methods. *Water, 14*, 2762. https://doi.org/10.3390/w14172762

MIE (Ministerio de Industria y Energia) & MOPTM (Ministerio de Obras Publicas, Transportes y Medio Ambiente) (1995). *Libro Blanco de las Aguas Subterráneas [Groundwater White Book]*. Retrieved online from URL: https://hispagua.cedex.es/en/node/66985 on 14.03.2023

Miller, M. M., & Shirzaei, M., (2015). Spatiotemporal characterization of land subsidence and uplift in Phoenix using InSAR time series and wavelet transforms, J. *Geophys. Res. Solid Earth, 120*, 5822–5842, doi:10.1002/2015JB012017.

Mokadem, N., Redhaounia, B., Besser, H., Ayadi, Y., Khelifi, F., Hamad, A., Hamed, Y., & Bouri, S. (2018). Impact of climate change on groundwater and the extinction of ancient "Foggara" and springs systems in arid lands in North Africa: a case study in Gafsa basin (Central of Tunisia), *Euro-Mediterranean Journal for Environmental Integration, 3*, 28, https://doi.org/10.1007/s41207-018-0070-0.

Moya Ortega, C. & Garcia Marin, R. (2015). Population aging in Murcia Region: causes and consequences. *Geography papers*, *61*. doi: http://dx.doi.org/10.6018/geografia/2015/213901

MMA (Ministerio de Medio Ambiente) (2000). *Libro Blanco del Agua en España [White Book of Water in Spain]*. Retrieved online from URL: https://faolex.fao.org/docs/pdf/spa192539.pdf, on 14.03.2023

Murcia Today (2017). Understanding water and the drought in Murcia and the Segura basin. Retrieved from URL: https://murciatoday.com/understanding-water-and-the-drought-in-murcia-and-the-segura-basin_171862-a.html on 14.03.2023.

NASA. (2017). *NASA Data Show California's San Joaquin Valley Still Sinking*. Retrieved from URL: https://www.nasa.gov/feature/jpl/nasa-data-show-californias-san-joaquin-valley-still-sinking, on 27.02.2023.

Observatorio Economico. (2010). *Madrid Economy 2010*. Area de Gobierno de Economia, Madrid. Retrieved from URL: https://www.madrid.es/UnidadesDescentralizadas/UDCObservEconomico/MadridEconomia/Ficheros/MadridEconomia2010Ingles.pdf

Orellana, F., Moreno, M., & Yáñez, G. (2022). High-Resolution Deformation Monitoring from DInSAR: Implications for Geohazards and Ground Stability in the Metropolitan Area of Santiago, Chile. *Remote Sens.*, *14*, 6115.https://doi.org/10.3390/rs14236115

Pirouzi, A. & Eslami, A. (2017). Ground subsidence in plains around Tehran: site survey, records compilation and analysis, *Geo-Engineering, 8*, 30. https://doi.org/10.1186/s40703-017-0069-4

Poland, J. S. (1984). *Guidebook to studies of land subsidence due to ground-water withdrawal.* UNESCO.

Radutu, A. &Gogu, R.C. (2018). *Chronological reflection on monitoring urban areas subsidence due to groundwater extraction*. In E3S Web of Conferences, Volume 85, Proceedings of the EENVIRO 2018 Conference: Sustainable Solutions for Energy and Environment, Cluj Napoca, Romania, 9–13 October 2018; Balan, M.C., Bode, F., Croitoru, C., Dogeanu, A., Georgescu, A., Georgescu, C., Nastase, I., Sandu, M., Eds.; EDP Sciences: Paris, France, 2019; pp. 07015.

Rafiei, F., Gharechelou, S., Golian, S., & Johnson, B.A. (2022). Aquifer and Land Subsidence Interaction Assessment Using Sentinel-1 Data and DInSAR Technique. *ISPRS Int. J. Geo-Inf.*, *11*, 495. https://doi.org/10.3390/ijgi11090495

Rajabi Baniani, S., Chang, L., & Maghsoudi, Y. (2021). *Mapping and analyzing land subsidence for Tehran using Sentinel-1 SAR and GPS and geological data*. EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-295, https://doi.org/10.5194/egusphere-egu21-295, 2020.

Raspini, F., Cigna, F., & Moretti, S. (2012). Multitemporal mapping of land subsidence at basin scale exploiting Persistent Scatterer Interferometry: case study of Gioia Tauro plain (Italy), *Journal of Maps, 8*(4), 514–524. 10.1080/17445647.2012.743440

Raucoules, D., Colesanti, C., & Carnec, C. (2007). Use of SAR interferometry for detecting and assessing ground subsidence, *C. R. Geoscience, 339*, 289–302. https://doi.org/10.1016/j.crte.2007.02.002

Rickey, S., Thomas, B., Lo, M-H., Famiglietti, J., Swenson, S., Rodell, M. (2015). Uncertainty in Global Groundwater storage estimates in a total groundwater stress framework. *Water Resources Research*. *51*(7), 5189-5216. DOI: 10.1002/2015WR017351

Rigo, A., Bejar-Pizzaro, M., & Martinez-Diac, J. (2013). Monitoring of Guadalentín valley (southern Spain) through a fast SAR Interferometry method, *Journal of Applied Geophysics, 91*, 39-48. http://dx.doi.org/10.1016/j.jappgeo.2013.02.001

RDP, 2010, *Rural Development Programme of Murcia – Spain, European Network for Rural Development*. Retrieved from URL: https://enrd.ec.europa.eu/sites/default/files/fms/documents/RDP/RDP_Murcia%20_Spain.pdf, on 14.03.2023

Rodolfo, K., & Siringan, F. (2006). Global sea-level rise is recognised, but flooding from anthropogenic land subsidence is ignored around northern Manila Bay, Philippines, *Disasters, 30*(1), 118-139. https://doi.org/10.1111/j.1467-9523.2006.00310.x

Ruiz-Constan, A., Ruiz-Armenteros, A., Lamas-Fernandez, F., Martos-Rosillo, S., Delgado, J., Bekaert, D., Sousa, J., Gil, A., Cuenca, M., Hanssen, R., Galindo-Zaldivar, J., & de Galdeano, C. (2016). Multi-temporal InSAR evidence of ground subsidence induced by groundwater withdrawal: the Montellano aquifer (SW Spain). *Environ Earth Sci, 75*(242), 1-16. doi:10.1007/s12665-015-5051-x

Schmidt, D. A., & Burgmann, R. (2003). Time-dependent land uplift and subsidence in the Santa Clara valley, California, from a large interferometric synthetic aperture radar data set. *Journal of geophysical research, 108*(B9). doi:10.1029/2002JB002267

Sidiq, T.P., Gumilar, I., Abidin, H.Z., & Gamal, M. (2019). Land subsidence induced by agriculture activity in Bandung, West Java Indonesia. *IOP Conf. Ser.: Earth Environ. Sci., 389*(012024). doi: 10.1088/1755-1315/389/1/012024

Sneed, M., Brandt, J. T., & Solt, M. (2014). *Land Subsidence, Groundwater Levels, and Geology in the Coachella Valley, California, 1993–2010: US Geological Survey.* Scientific Investigations Report 2014–5075. http://dx.doi.org/10.3133/sir20145075

Solari, L., Del Soldato, M., Bianchini, S., Ciampalini, A., Ezquerro, P., Montalti, R., Raspini, F., & Moretti, S. (2018). From ERS 1/2 to Sentinel-1: Subsidence Monitoring in Italy in the Last Two Decades. *Front. Earth Sci. 6*, 149. doi: 10.3389/feart.2018.00149

Suarez, G., Jaramillo, S., López-Quiroz, P., & Sánchez-Zamora, O. (2018). Estimation of ground subsidence in the city of Morelia, Mexico using Satellite Interferometry (INSAR)s. *Geofísica Internacional 57*(1), 41-60.

Tessitore, S., Fernández-Merodo, J.A., Herrera, G., Tomas, R., Ramondini, R., Sanabria, M., Duro, J., Mulas, J., & Calcaterra, D. (2016). Comparison of water-level, extensometric, DInSAR and simulation data for quantification of subsidence in Murcia City (SE Spain). *Hydrogeol J, 24*, 727-747. doi 10.1007/s10040-015-1349-8

Toufigh, M., Tabatabaei Aghda, S.T., Fahmi, A. & Mortazavi, S.M. (2004). *Land subsidence and its consequences of large groundwater withdrawal in Rafsanjan, Iran*. Conference: Management of Aquifer Recharge and Water Harvesting in Arid and Semi-arid Regions of Asia. At: International Center of Qanat, Yazd, Iran.

USGS. (2017). *California Water Science Center*. Retrieved from URL: https://ca.water.usgs.gov/land_subsidence/california-subsidence-cause-effect.html on 27.02.2023.

Ustun, A., Tusat, E., & Yalvac, S. (2010). Preliminary results of land subsidence monitoring project in Konya Closed Basin between 2006–2009 by means of GNSS observations. *Nat. Hazards Earth Syst. Sci.,10*, 1151-1157. doi:10.5194/nhess-10-1151-2010

WWF (2006). *Illegal water use in Spain. Causes, effects and solutions*. Madrid, Spain: WWF/Adena. Retrieved from URL: https://wwfeu.awsassets.panda.org/downloads/illegal_water_use_in_spain_may06.pdf on 14.03.2023