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GEOHAZARD PHENOMENON INDUCED BY SALT EXPLOITATION AND APPLIED NEW METHODS FOR MONITORING GROUND SURFACE MOVEMENTS

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A b s t r a c t: The subsidence occurring in the city of Tuzla in Bosnia and Herzegovina (B&H) is an important issue which has caused several damages in the past decades. This phenomenon is related to the massive extraction of salt and the presence of salt caverns below the city. The salt mine was closed between 2006 and 2007 by means of filling the salt mine rooms with water, but the subsidence still continues over some parts of the city. This paper presents geohazard phenomenon caused by the exploitation of the salt mine in Tuzla, as well as the interpretation of the monitoring results of subsidence measured by new satellite technology together with the previous results, i.e., 2004 – 2007 by GPS, 2013 – 2024 by GPS, 2014 – 2019 by DInSAR technology, and 2019 – 2024 by DInSAR from authors. The time transition for the subsidence obtained by DInSAR shows a good agreement with the monitoring results by GPS. It is found that the subsidence in Tuzla is still on-going at a rate of 1 – 2 cm/year in the measured points of salt deposit, while point number 16 and its surroundings currently have greater subsidence compared to the remaining part of the Tuzla salt deposit. This paper concludes that DInSAR technology has proven to be an excellent method for monitoring the subsidence of the terrain at the city of Tuzla and would represent an accurate and reliable approach for monitoring similary affected areas.

Key words: geohazard phenomenon; salt mine; subsidence; monitoring; GPS; SBAS-DInSAR

INTRODUCTION

The city of Tuzla in Bosnia and Herzegovina is facing serious issues related to subsidence, a phenomenon that has been ongoing for several decades and is caused by intensive and unregulated salt mining. The area beneath the city has undergone extensive salt exploitation, which involved injecting water into salt layers and subsequently pumping it out. This process led to the formation of numerous cavities within the salt layers, causing significant damage to urban structures such as buildings, roads, and other infrastructure. Although several studies have been conducted over the years to monitor the dynamics of this phenomenon, the most recent method for monitoring subsidence uses advanced DInSAR technology.

The subsidence in Tuzla represents a geohazard, resulting from a complex combination of geological processes and specific soil conditions, exacerbated by human activity, which can have severe consequences for infrastructure and the environment [1]. The salt mine in Tuzla was closed between 2006 and 2007, when all mining shafts were filled with water. Although mining activities have ceased, subsidence continues in certain parts of the city. Since 1956, numerous measurements and studies have been carried out to monitor and analyze the subsidence, including topographical measurements from 1956 to 2003, GPS measurements from 2004 to 2007, and geodetic and GPS analyses from 2007 to 2012. The latest research utilizes satellite technologies, such as Differential Interferometric Synthetic Aperture Radar (DInSAR), using the Small Baseline Subset (SBAS) algorithm to monitor surface displacement from 2019 to 2024.

The results show that SBAS-DInSAR provides highly accurate and efficient information on subsidence.

The aim of this research is to analyze the changes in the spatial distribution of subsidence from 1956 to 2024 and to compare the results obtained using SBAS-DInSAR technology with GPS measurements from 2019 to 2024. Additionally, the subsidence results obtained through GPS measurements from 2004 to 2007 will be presented.

GEOLOGY AND STRATIGRAPHY CONDITIONS OF SALT DEPOSITS IN TUZLA

The stratigraphy of the rocks beneath the city consists of layers of marl and clayey sandstones, banded marl, anhydrite rocks, and salt layers, as shown in Figure 1. The salt layers are primarily located within the banded marl layers at depths ranging from 300 m to 600 m below the surface [2] [3] [4]. Salt extraction in the southeastern part of the salt field (Hukalo–Trnovac) was carried out using a drilling method known as the "uncontrolled leaching method," which involves injecting brine and pumping it out. In the northwestern part (Tušanj), underground mining was performed using the classical "room-pillar" method, as well as extracting dissolved salt via pipelines. These two areas are separated by a safety pillar that has been left undisturbed during the salt extraction. The following Figure 2 shows a vertical cross-section of the various rock layers with the locations of the mining sites indicated.

In the past, salt exploitation in the Tuzla area was carried out by collecting natural brine springs, while modern techniques involve around 150 boreholes with pumps connected to underground brine flows, at an average depth of 400–500 meters [1]. Mining activities have altered the hydrogeological conditions, allowing the downward infiltration of fresh water, which has caused additional salt dissolution. Over the past 65 years, this process has led to significant surface ground movements, with land subsidence reaching up to 12 m in the most affected areas. Stress and deformation of the overlying rocks have resulted in the formation of numerous fractures over a large area (around 3 km²). As a consequence, serious damage has occurred to buildings and infrastructure, including water supply and sewage systems, and important buildings such as the Music School as a Church.

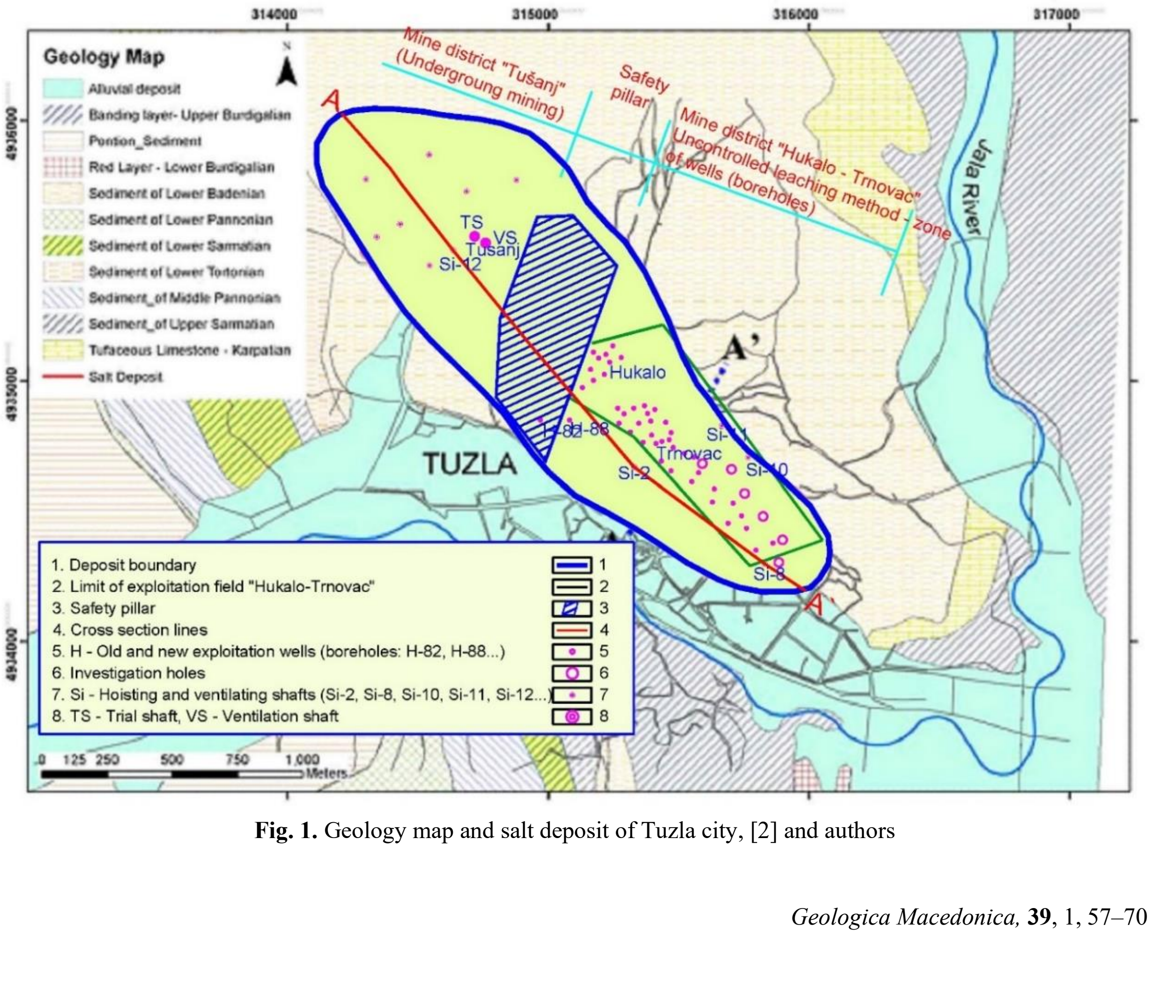


Fig. 1. Geology map and salt deposit of Tuzla city, [2] and authors

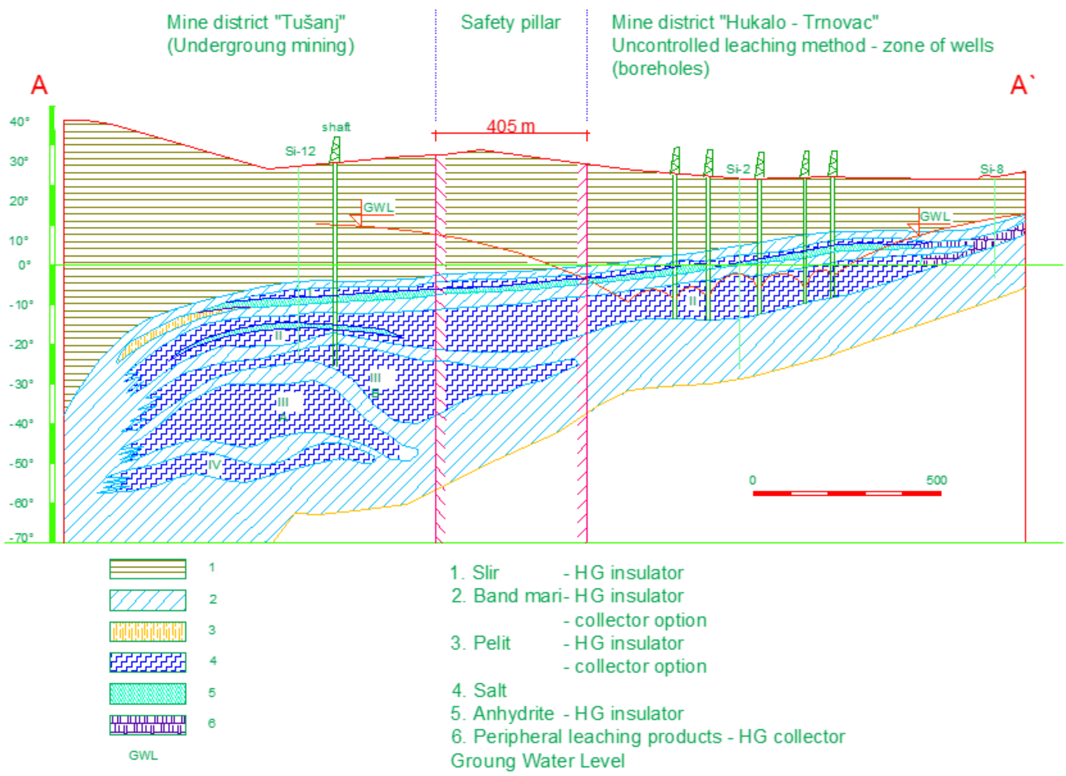


Fig. 2. Vertical cross section of the geological conditions in Tuzla, [2] and authors

Salt extraction activities in the city of Tuzla have been suspended, but the consequences of subsidence are still being felt. Over the past 65 years, the local authorities have developed a geohazard monitoring system, collecting a wide range of data based on geodetic measurements, measurements of pumped brine quantities, the extent of the salt body, and geotechnical parameters. The ground subsidence phenomenon in Tuzla can be defined as a geohazard, which resulted from an unfavorable combination of geological processes and ground conditions caused by human activity, specifically the extraction of brine from the ground.

The Tuzla salt mine was closed during the period from 2006 to 2007 by filling the mine chambers with water. However, ground subsidence continues in certain parts of the city. Since 1956, numerous studies and geodetic surveys have been conducted to measure subsidence in Tuzla, including: traditional topographic surveys from 1956 to 2003, GPS surveys from 2004 to 2007, and combined GPS and geodetic surveys from 2007 to 2012. The most recent measurements were conducted using satellite technology – Differential Interferometric Synthetic Aperture Radar (DInSAR), applying the Small Baseline Subset (SBAS) time-series algorithm to monitor ground surface movements during the period from 2019 to 2024. These studies confirm the effectiveness of this method in the investigated area of Tuzla. It has been determined that SBAS-DInSAR can be a useful and effective tool for monitoring the geohazard phenomenon in Tuzla and for addressing similar problems related to ground subsidence.

Salt exploitation history

The Tuzla salt deposit has the shape of an irregular, elongated ellipse, with a length of 2500 m and a width ranging from 600 to 900 m. The depth of overlying sediments above the deposit varies from 150 m in the southeastern part to 500 m in the northwestern part of the salt deposit (Figure 2). The salt body consists of five series (Figure 2), labeled as I, II, IIIB, IIIA, and IV, extending from the surface to the depth of the deposit. The composition of the salt, as a product of chemical sedimentation, includes deposits of halite – $NaCl$, anhydrite – $CaSO_4$, and thenardite – Na_2SO_4, forming monomineralic layers of mirabilite – $Na_2SO_4 \cdot 10H_2O$, northupite – $Na_3NaCl(CO_3)_2$, and nahcolite – $NaHCO_3$, along with some other minerals [1] [5].

The production of brine through uncontrolled salt dissolution in the Tuzla deposit lasted for a very long time and can be divided into three distinct periods:

- Period of natural salt dissolution (saline springs) – until 1480.
- Period of primitive production – until 1906 (shallow wells).
- Period of industrial exploitation (1906–2005):
  - uncontrolled salt extraction from the eastern hill of Hukalo–Trnovac (1906–2005),
  - room-and-pillar excavation in the western part from the Tušanj salt cavern (1967–2002),
  - controlled leaching west of the Tušanj cavern (1983–1992).

It is estimated that in periods 1480 til 1906, around 2,000,000 m³ of brine was produced, with an average salt concentration of 300 kg/m³, amounting to 600,000 tons of salt. During the industrial production period (1906–2005), approximately 91,000,000 m³ of brine was extracted from the deposit. With an average salt concentration of 310 kg/m³, the dissolved salt totaled 28,210,000 tons.

An additional amount of brine was produced through an uncontrolled procedure during 1982–1992 by exploiting part of the deposit located below the lowest mining horizon of the Tušanj cavern, using a controlled leaching process through individual wells. A total of 62 wells were formed, with chamber diameters of 24, 30, and 35 meters (Figure 3).

This process produced approximately 11,000,000 m³ of brine, with an average salt concentration of about 300 kg/m³. Overall, uncontrolled salt exploitation from the Tuzla mine has resulted in the production of over 100,000,000 m³ of brine, causing a salt mass deficit of approximately 12,000,000 m³ beneath the immediate urban area of the city of Tuzla. The area affected by the wells is about 25 hectares, the salt deposit covers about 160 hectares, and the area of land subsidence exceeds 500 hectares [3] [4] [8].

Fig. 3. Illustration of a salt well and the salt extraction principle in the Tuzla area

Brine exploitation activities

Data on brine pumping activity from wells began to be officially collected in the first half of the twentieth century. However, since surface subsidence above the city of Tuzla has been systematically monitored since 1956, salt production in this study is considered for the period from 1957 to 2003.

The volume of pumped brine is recorded as the annual amount in m³ per well. During 2006 and 2007, salt exploitation was halted, but brine pumping activities have continued in order to prevent the rise of the ground water level.

Salt exploitation reached its peak in 1982, with more than 2 million m³ of brine pumped (Figure 4).

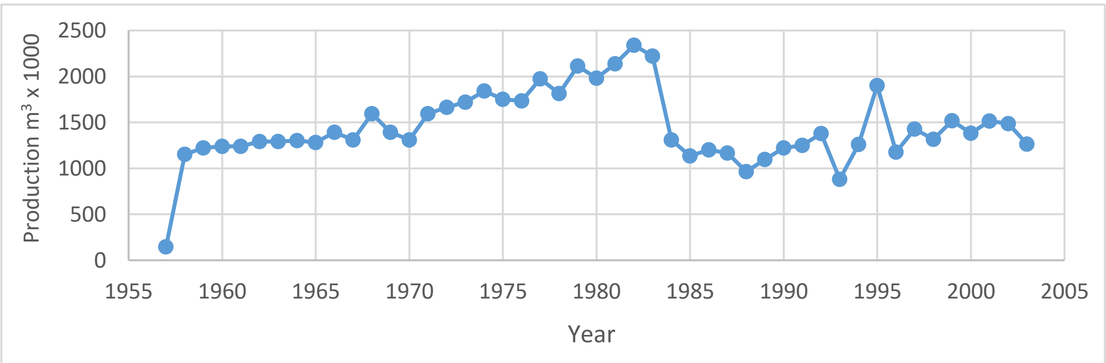


Fig. 4 Annual salt production

METHODOLOGY OF MULTI-TEMPORAL DInSAR TECHNOLOGY

SAR (Synthetic Aperture Radar) is a remote sensing technology that enables the acquisition of high-resolution images regardless of weather conditions or time of day. The device is mounted on a satellite and emits side-looking microwave signals toward the Earth's surface (Figure 5) [6], using a specific wavelength (λ, or frequency band). The reflected signals are then recorded, and information on their amplitude and phase is stored in a single data file known as SAR data.

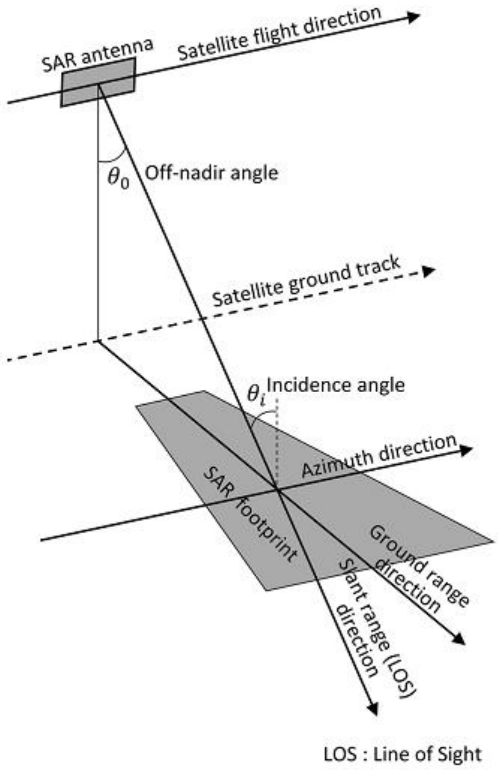


Fig. 5 Geometric configuration of the SAR (Synthetic Aperture Radar) system [6]

DInSAR (Differential Interferometric Synthetic Aperture Radar) is an advanced method for detecting ground surface displacements using SAR data [3, 6, 7]. This technique uses two images of the same area, captured at different times and from slightly different satellite positions. The difference in distance between the satellite and the observed point on the Earth's surface, identified through changes in the phase of the reflected waves, is interpreted as ground displacement in the direction of the wave propagation, known as the line-of-sight (LOS). This method was chosen as suitable for Tuzla due to the rather large area of the Tuzla salt basin. Otherwise, this satellite method is suitable for larger areas of measuring ground subsidence, while it has not proven to be good on extremely small areas (e.g., ground subsidence after an earthquake in the area of Hrvatska Kostanica). Also, this method is extremely good because it does not require personnel or frequent field trips. Therefore, the first author tries to show through a large number of examples that this satellite method agrees with GPS GNNS measurements, so that the satellite method becomes a standard method. The authors agree that there is a certain error, especially in spring, but these errors can be eliminated by mathematical procedures.

SAR data collection

In this study, SAR data collected using the TOPSAR technology (Zan and Guarnieri, 2006) from the Sentinel-1A and Sentinel-1B satellites, operated by the European Space Agency (ESA), were used. Since the data from these satellites are free of charge, an economical and efficient method for terrain monitoring is enabled.

The period covered includes subsidence measurements from May 28, 2019, to January 2, 2024, collected in the descending orbit direction. As the Sentinel-1A and Sentinel-1B satellites are in continuous operation, the amount of available SAR data can be updated every 6 to 12 days, allowing continuous and precise monitoring of changes on the Earth's surface [6].

SBAS-DInSAR analysis

In this study, the SARscape software was used to perform the SBAS-DInSAR analysis. The initial step involved selecting SAR data pairs based on defined thresholds for the temporal and spatial baselines. The maximum temporal baseline was set to 48 days, while the maximum spatial baseline was limited to 150 meters. Using these parameters, a total of 498 data pairs (interferograms) were generated for further processing. Each of these pairs was analyzed using the standard DInSAR method. Following the SBAS procedure, both spatial and temporal series of surface displacements in the line-of-sight (LOS) direction were obtained for all acquisition dates. The spatial resolution of the displacement data in this analysis is 25 × 25 meters [6, 7, 11].

Estimation of subsidence based on measured displacements along the los

The displacements detected using the SBAS-DInSAR method are expressed along the line of sight (LOS), allowing for the analysis of vertical ground deformations in this single dimension, as illustrated in Figure 6 [6].

In this study, to convert displacements along the line-of-sight (LOS) into subsidence, it is assumed that the displacements are mainly caused by vertical movements, while horizontal displacements are neglected. Based on this assumption, the relationship between LOS displacement D_{LOS} and subsidence D_{sub} is shown in Figure 6, and the subsidence can be calculated using Equation 1 [6]:

$$D_{\mathrm{sub}} = -\frac{D_{LOS}}{\cos\theta_i} \tag{1}$$

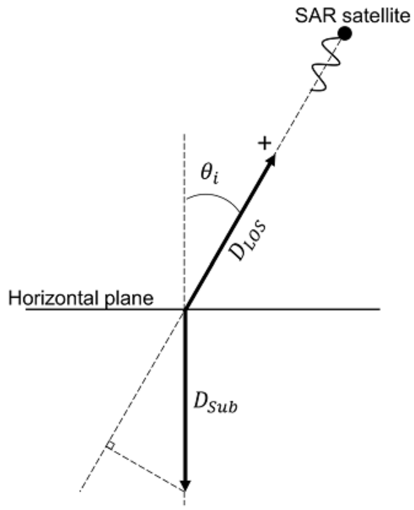


Fig. 6. Correlation between LOS displacements and subsidence [6]

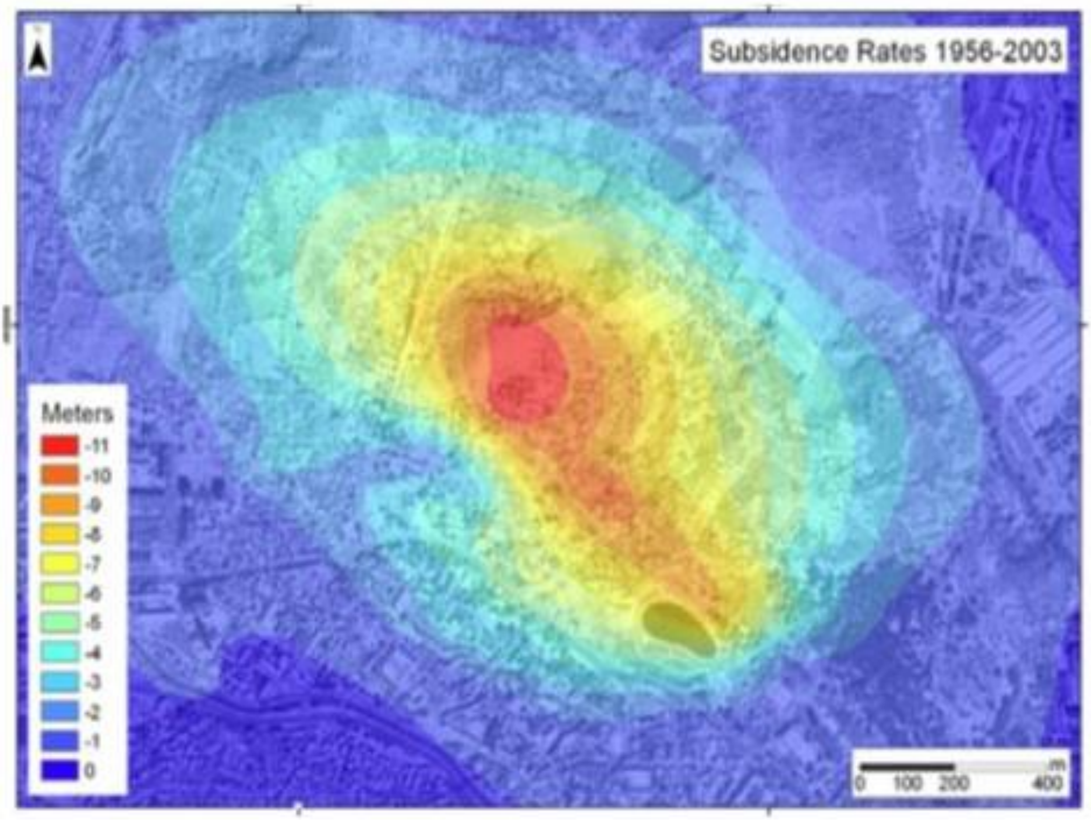
RESULTS OF GROUND SUBSIDENCE MONITORING

Spatial patterns of ground subsidence from 1956 to 2024

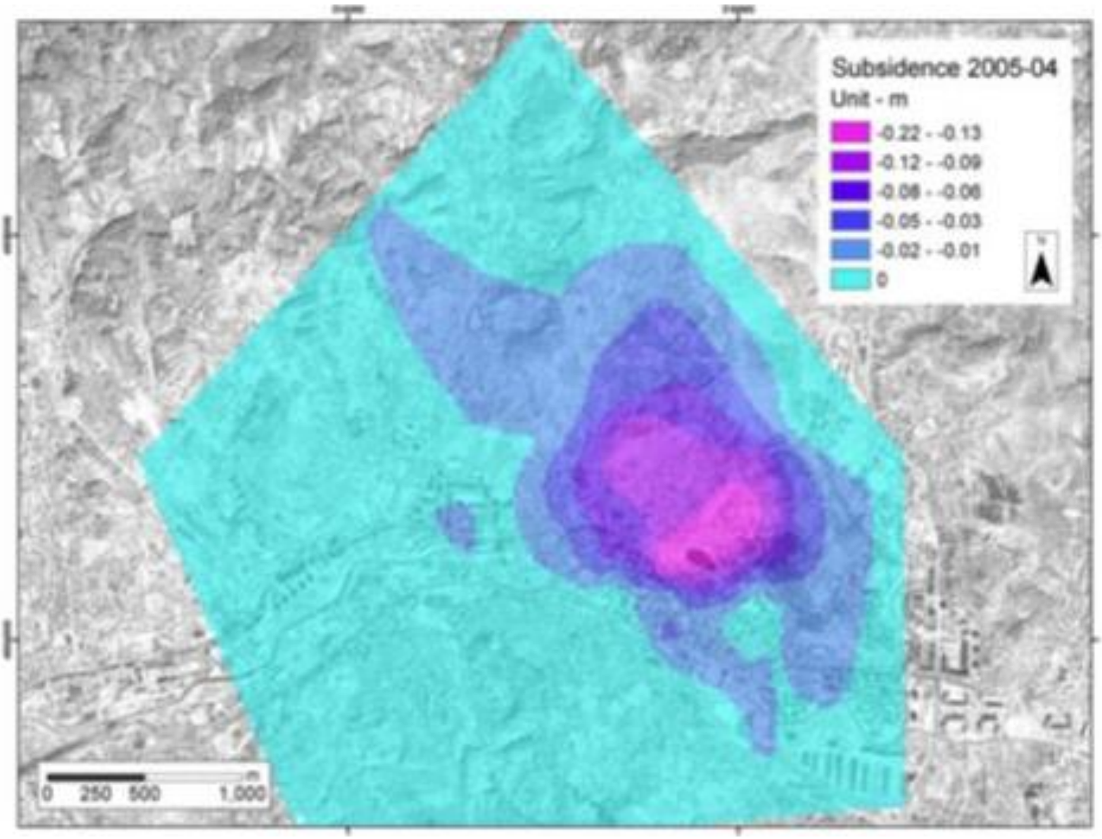
Geodetic surveys of the terrain in the city of Tuzla continued even after the closure of the salt mines. Analysis of the collected data and significant ground subsidence indicated the need for regular and systematic monitoring.

The first geodetic survey in Tuzla was conducted in 1914, while systematic surveys of the subsidence zone in the city began in 1956. To monitor the progression of subsidence and define the boundaries of the affected area, a network of fixed geodetic points was established in 1955. Between 1956 and 1991, annual surveys were conducted to track vertical displacements and changes in the positions of these points. The number of measurement points varied over time. During the period from 1956 to 1991, there were over 300 points with known vertical displacements and about 40 points with known horizontal displacements.

In his work, Francesco Stecchi (2008) [1] presented the spatial distribution of ground subsidence in Tuzla for the period from 1956 to 2003. It was found that the maximum subsidence exceeded 14 meters, which caused serious problems in maintaining urban structures and infrastructure in the area. Figures 7b [1], 7c [1], and 7d [1] show the cumulative subsidence in Tuzla until 2007 [1]. Figure 8 displays GPS subsidence measurement data for Tuzla. Figure 8a shows cumulative data for the period 2008–2012, while Figure 8b presents DInSAR measurement results for the period 2014–2019. Figure 8c provides the latest DInSAR data obtained over the last five years from 2019 to 2024. Comparison of the DInSAR and GPS results confirmed that DInSAR is an accurate and reliable method for monitoring and quantifying ground subsidence in the Tuzla salt deposit, as well as in similar areas affected by subsidence issues.

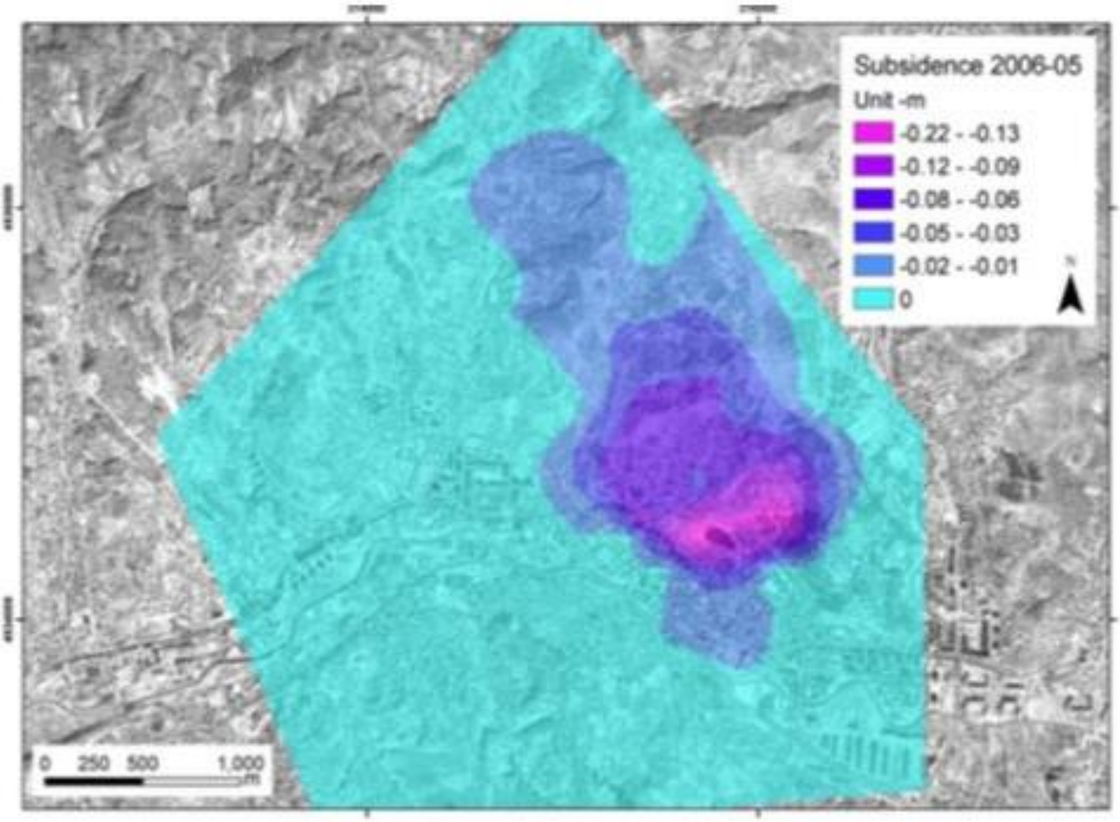


a) Overal substance occurred in the area of Tuzla along the period 1956–2003 (Stechhi, 2008)

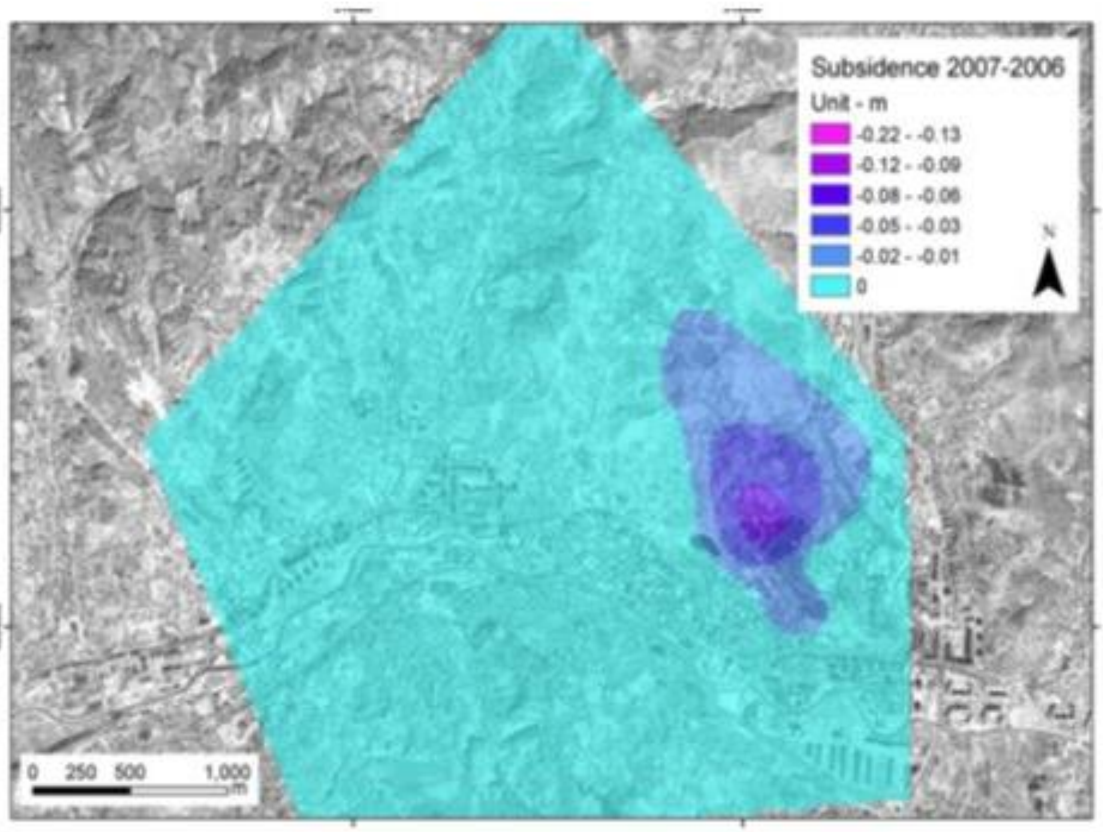


b) Substance rates 2004–2005 obtained by the comparison of the first two champaigns

Fig. 7

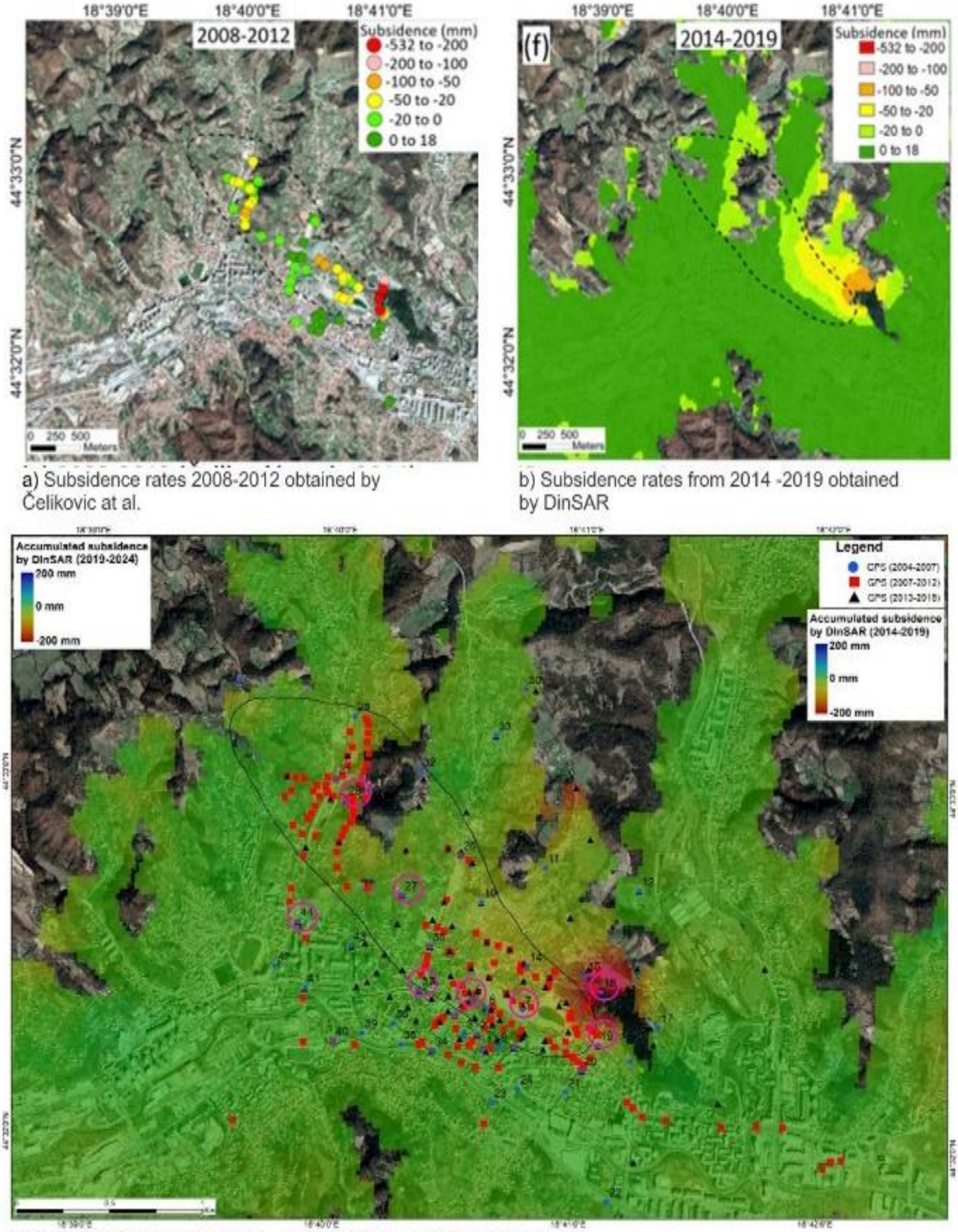


c) Substance rates 2005–2006 obtained by the comparison of the second and third champaign



d) Substance rates 2006–2007 obtained by the comparison of the last two champaigns

Fig. 7 Time transition of spatial distribution of subsidence in Tuzla [1, 4]: a) cumulative subsidence obtained by traditional topographic surveys from 1956 to 2003, b) subsidence in Tuzla obtained by GPS surveys from 2004 to 2005, c) subsidence in Tuzla



a) Subsidence rates 2008-2012 obtained by Čelikovic at al.

b) Subsidence rates from 2014 -2019 obtained by DinSAR

c) Subsidence rates from 2019 – 2024 obtained by DInSAR by authors

Fig. 8 Subsidence in Tuzla: a) Subsidence from 2008 to 2012 obtained by GPS and geodetic methods [1, 3, 4, 8, 9, 10], b) Subsidence from 2014 to 2019 obtained by SBAS-DInSAR [6, 13], c) Subsidence from 2019 to 2024 obtained by DInSAR by authors

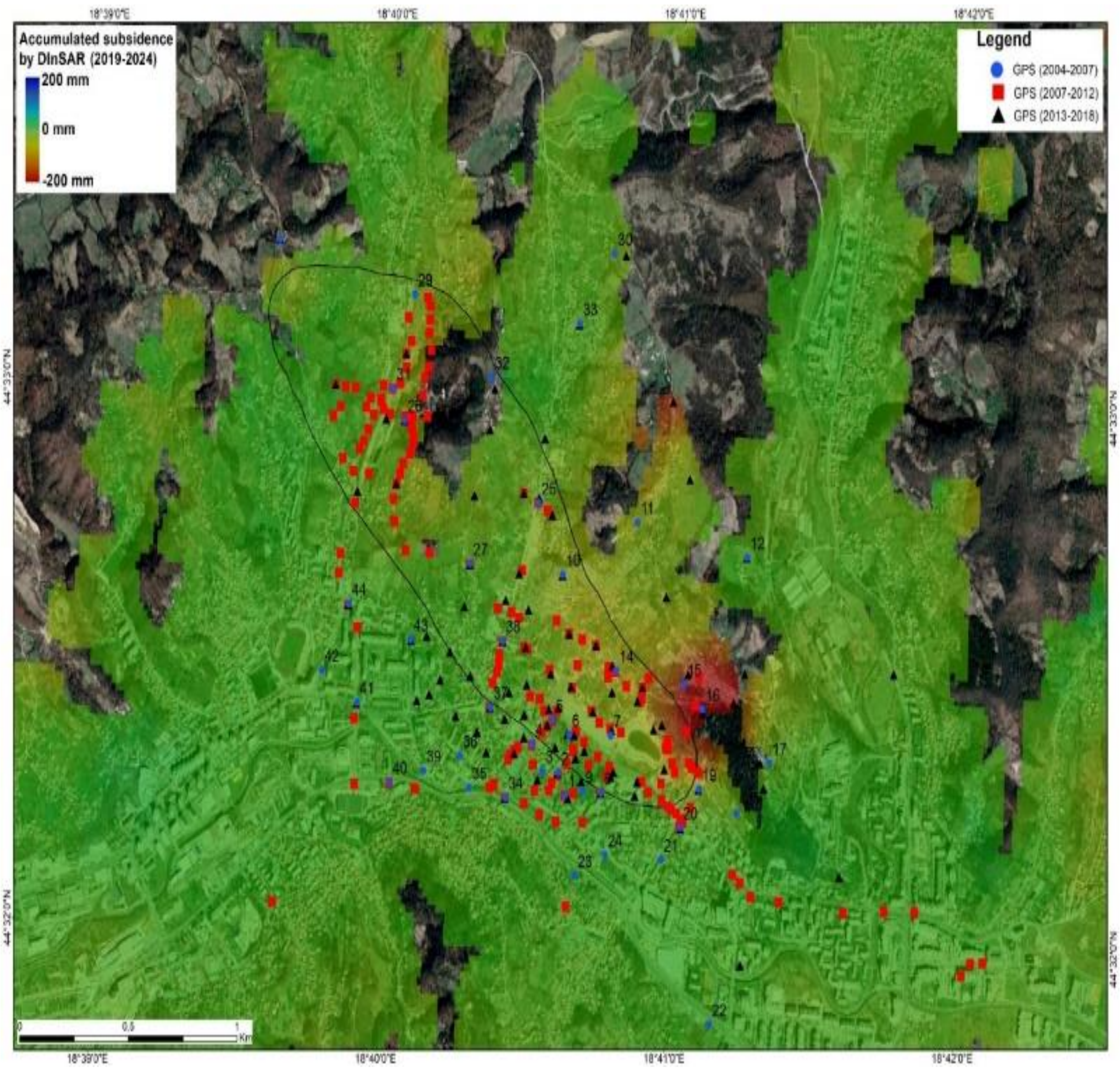


Fig. 9 Geographic distribution of GPS monitoring points and cumulative ground subsidence derived from DInSAR measurements (2019–2024)

TEMPORAL EVOLUTION OF GROUND SUBSIDENCE (2004–2024)

Changes in ground subsidence over the past two decades were analyzed based on data obtained from GPS measurements in the periods 2004–2007, 2007–2012, and 2013–2018, as well as from DInSAR data covering the periods 2014–2019 [12] and 2019–2024. Figure 9ows the locations of all GPS survey points, while seven representative points were selected for a detailed discussion of subsidence trends: P5, P7, P16, P19, P26, P27, and P37.

- Point P5 is located in the southern part of the salt deposit, near the Panonnica Lakes. In 2006, it experienced a subsidence of 8 cm, which gradually decreased over time. The current subsidence is approximately 2 cm. Diagrams indicate a complete match between GPS and DInSAR measurements.
- Point P7, also within the deposit, previously recorded a maximum subsidence of about 40 cm. Today, the rate has slowed to around 2 cm per year. The high correlation between GPS and DInSAR data confirms the accuracy and reliability of the DInSAR method.
- Point P16 is located outside the main salt bed, but it represents the area with the most significant current subsidence. Interestingly, the zone of maximum subsidence no longer coincides with the most heavily exploited areas but has shifted southeast. Current subsidence at this point is 17.5 cm, with excellent agreement between the two methods.
- Point P19 lies on the southern edge of the salt deposit. Subsidence is minimal (0.3 cm), and

measurement accuracy between GPS and DInSAR methods is nearly identical.

- Point P26, located in the northern part of the deposit in the Tušanj district, where controlled underground salt extraction took place, currently shows 2.5 cm of subsidence. The results from GPS and DInSAR methods show a high level of consistency.
- Point P27 represents the central area of the Tuzla salt deposit. It currently records a subsidence of 0.7 cm, with excellent agreement between the GPS and DInSAR results.
- Point P37 is located on the western edge of the deposit and currently exhibits the lowest levels of subsidence. Over the last five years, virtually no movement has been recorded, as confirmed by both GPS and DInSAR data.

Based on the analysis of these results, it can be confidently concluded that there is a strong correlation between GPS and DInSAR measurements. This consistency confirms that DInSAR is a powerful and effective tool for accurately monitoring ground subsidence, not only in the Tuzla region but also in other areas affected by similar geotechnical challenges. When combined with GPS and GNSS technologies, the DInSAR method provides a comprehensive solution for geohazard monitoring, enabling timely responses and effective planning for infrastructure protection and land management.

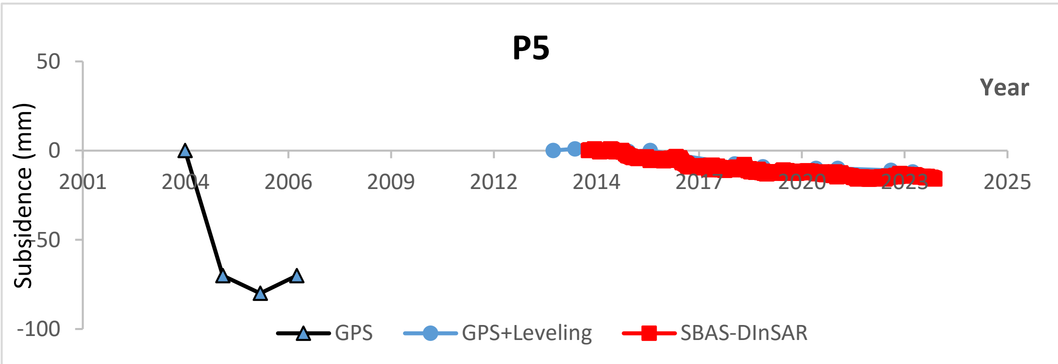


Fig.10a

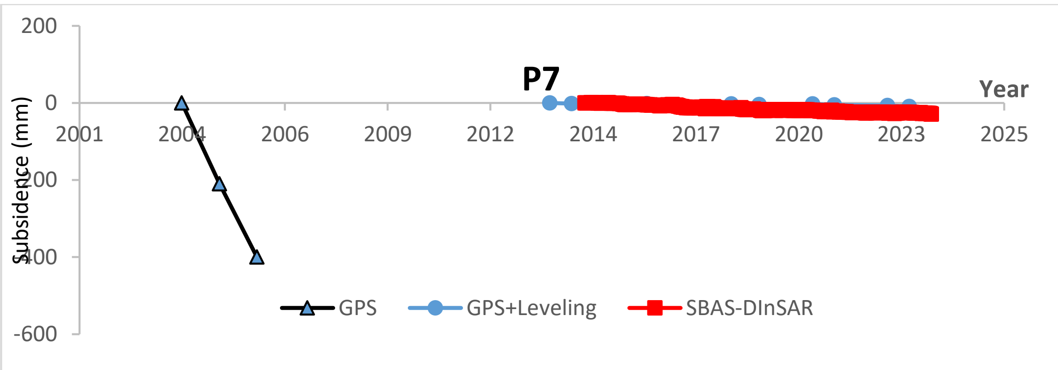


Fig.10b

Fig. 10

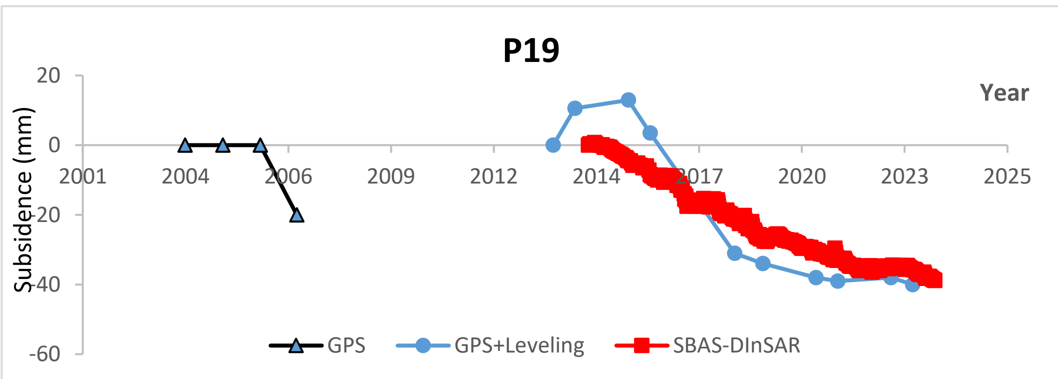


Fig.10c

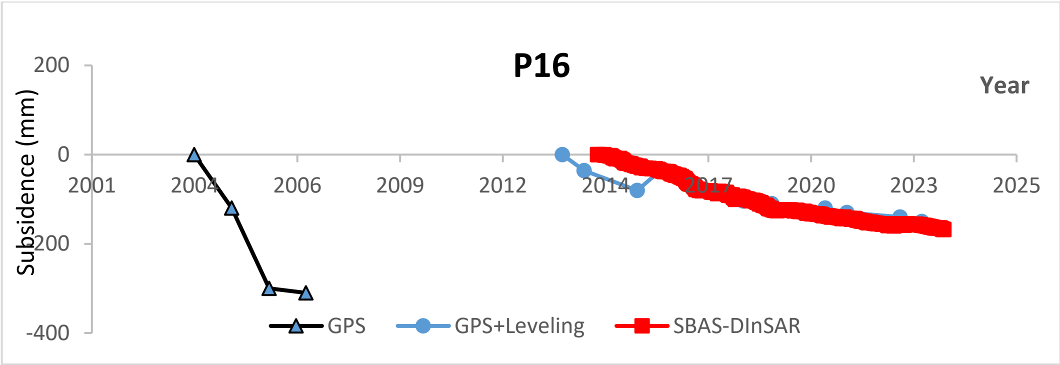


Fig.10d

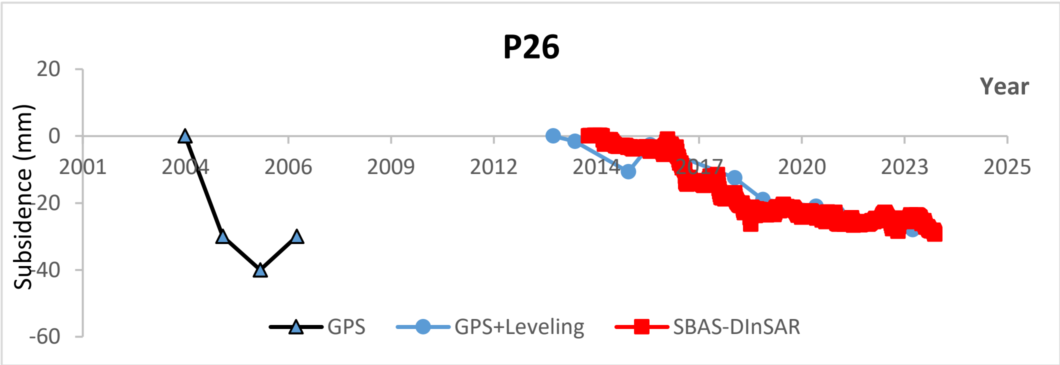


Fig.10e

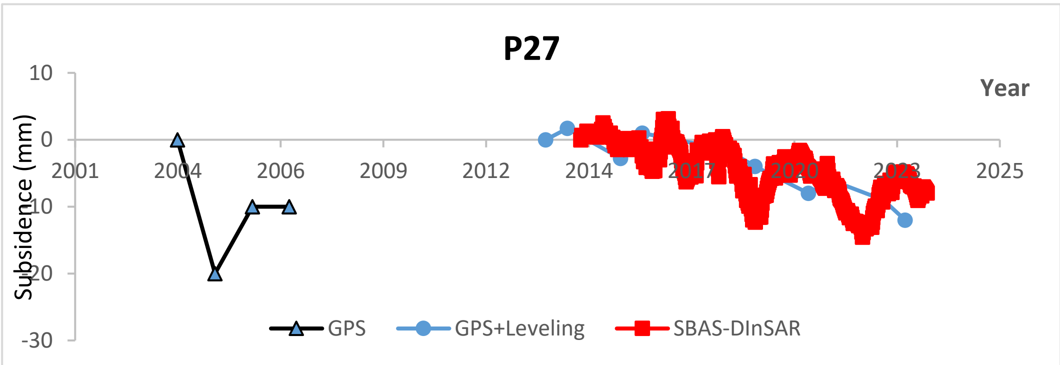


Fig.10f

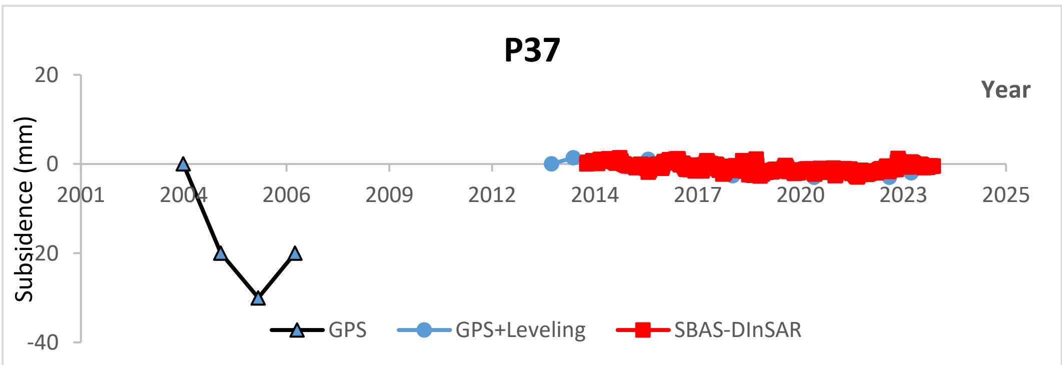


Fig.10g

Fig. 10. Temporal transitions of the subsidence at selected points observed by GPS and DInSAR from 2004 to 2024

CONCLUSION

The ground collapse phenomena in Tuzla are the result of uncontrolled brine extraction that has been ongoing for over a century. The leaching of saltwater beneath the city has significantly altered the natural regime of ground water, leading to the uncontrolled dissolution of Carpathian evaporite layers in the subsurface. As a consequence, serious damage has occurred to buildings and city infrastructure. This uncontrolled leaching process is manifested through ground subsidence, fluctuations in ground water levels, and the appearance of both shallow and deep surface fractures.

The subsidence process has been systematically monitored using modern geodetic techniques (GPS and GNSS), as well as the latest satellite-based SBAS-DInSAR technology, which enables detailed observation of surface ground movements in the salt exploitation zone of Tuzla. This study has confirmed the high accuracy of the DInSAR methodology in estimating annual subsidence rates, thus proving to be a valuable tool for sustainable urban planning in Tuzla and for making informed decisions based on reliable scientific analyses.

Since this study, which used the DInSAR method, considered only vertical ground displacements, future research should also include horizontal movements, which would lead to more accurate and comprehensive monitoring results.

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Р е з и м е

ФЕНОМЕНОТ ГЕОХАЗАРД ПРЕДИЗВИКАН СО ЕКСПЛОАТАЦИЈАТА НА СОЛ И ПРИМЕНА НА НОВИТЕ МЕТОДИ ЗА СЛЕДЕЊЕ НА ДВИЖЕЊЕТО НА ПОВРШИНАТА НА ЗЕМЈАТА

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Слегнувањето на теренот во градот Тузла во Босна и Херцеговина (БиХ) претставува значаен проблем кој предивикал сериозни оштетувања во изминатите децении. Овој феномен е поврзан со масовната експлоатација на сол и постоењето на солни пештери под самиот град. Рудникот за сол беше затворен во периодот 2006–2007 година со пополнување на просториите на рудникот со вода, но слегнувањето на теренот сѐ уште продолжува на одредени делови од градот. Овој труд го претставува геохазарниот феномен предизвикан од експлоатацијата на рудникот за сол во Тузла, како и интерпретацијата на резултатите од мониторингот на слегнувањето добиени со нова сателитска технологија, заедно со претходните податоци, добиени со технологиите: за 2004–2007 со GPS, за 2013–2024 со GPS, за 2014–2019 со DInSAR, како и податпоците за 2019–2024 добиени со DInSAR од авторите. Временската трансформација на слегнувањето добиена со DInSAR покажува добра усогласеност со резултатите од мониторингот преку GPS. Констатирано е дека слегнувањето во Тузла и понатаму се одвива со стапка од 1–2 cm/година во измерените точки на солниот слој, при што точката број 16 и нејзината околина моментално покажуваат поголемо слегнување во споредба со другиот дел од наоѓалиштето на сол во Тузла. Овој труд заклучува дека технологијата DInSAR се покажа како одличен метод за следење на слегнувањето на теренот кај градот Тузла и може да претставува прецизен и доверлив метод за следење на слични проблематични подрачја.