

**MINISTRY OF EDUCATION
TECHNICAL UNIVERSITY OF CIVIL ENGINEERING BUCHAREST**

PhD Thesis Summary

**USE OF REMOTE SENSING TECHNIQUES FOR URBAN
GROUNDWATER DYNAMICS MONITORING**

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ABSTRACT

Groundwater is one of the main resources needed for anthropogenic activities in urban areas, as it satisfies the needs of the population and an improved quality of life. Consequently, it reaches a high importance in the urban planning process. However, there are situations when due to the exploitation of large groundwater quantities or due to the association of its exploitation with other underground and above-ground urban activities, land degradation phenomena generating vertical displacements appear. These can lead to buildings or infrastructure elements deterioration. By monitoring the vertical ground displacements, it is possible to indirectly estimate the phenomena that generated them, one of the most important such phenomenon being related to the dynamics of urban groundwater. The recent method for monitoring urban subsidence is the satellite remote sensing technique that uses PSI (Persistent Scatterer Interferometry), the vertical ground displacements being determined to a millimeter order.

Globally, scientific studies cite groundwater exploitation as one of the main causes of subsidence phenomena. The 53 case studies from the first chapter document the spread of this phenomenon worldwide. **A comparison is presented between countries with a long history of groundwater pumping and where subsidence areas are beginning to have decreasing values (eg., Tokyo, Japan) and countries with a recent history of groundwater pumping.** Negative vertical displacements of land occur more rapidly in areas with a more recent history of subsidence, due to the very large quantities of groundwater that are pumped to meet water needs for the population and industry (eg., Indonesia).

In the second section of the thesis a case study on the Municipality of Bucharest is carried out, considering the particularities of the subsidence phenomena at city level, at local level, and at regional level. Two time periods for which data sets from two European satellite radar missions were available were taken into consideration. Thus, for the period 2004-2010 data from the ENVISAT ASAR mission were used and processed using the PSI technique, and for the period 2014-2018 data from the current European radar mission, Sentinel-1 were used. Maps of the vertical displacements of the terrain at the level of the entire urban area were generated using these data sets, for the two abovementioned time intervals. Following the two generated maps of the terrain displacements, the consistency of the results for the two-time intervals was observed. Numerous areas of instability identified on the land displacements map for the period 2004-2010 show the same trends for the 2014-2018 interval as well. **As a novelty, the use of a new cartographic product obtained through combining the map of the vertical land displacements with the surface terrain change detection map is proposed. Therefore, the potential areas that locate the source of vertical displacements can be established more accurately. For both time intervals there was a general trend of stability in the city. However, a particular trend of occurrence and maintenance of negative vertical displacements for certain areas, located especially along the corridors of the two rivers that cross Bucharest: Dâmbovița River and Colentina River, has been identified.**

At local level, the Barbu Văcărescu area (Bucharest) was studied, which has a history of subsidence since the '90s, when from the SAR time series analyzed since 1992, this area was identified as an instability area. The land displacements, lithological, geological, and hydrogeological data available for this area were analyzed. **Analyzing the vertical**

displacements of the terrain in the PSI maps generated for time intervals between 1992 and 2018, it can be observed that the trend of instability is not marked by its spatial expansion and the predominance of PS points indicating subsidence, but by changes in the location of the PS points. The analysis focuses on the relationship between land displacements and the dynamics of the urban aquifer system in the Barbu Văcărescu area, and presents a particular case study of a building in the study area. **The results of PSI processing highlight a pattern of dynamic instability related to the presence of the upper layer of anthropogenic materials.** For future work, when urban planning and design procedures take into account construction operations that change the dynamics of the aquifer system, it is necessary to carefully analyze the layer of anthropogenic materials and its hydraulic behavior as part of the urban aquifer system.

As the regional urban study, the chosen area is located along the Colentina River corridor. A methodology for characterizing the area for the period 2014-2018 was proposed, taking into account specific elements of the studied area, such as: the presence of subsidence, the presence of land changes, hydrogeological, geological, hydrological characteristics, history of the study area (considering the location and extension of old quarries of building materials), changes in the topography of the lakes of the Colentina River in the last 100 years, and climatic aspects. **The obtained results showed a major concordance between the water level in the lakes and the vertical movements of the surrounding areas, both with decreasing tendencies, in the context of a strong hydraulic connection between the Colentina riverbed and the first aquifer strata.** The presence of anthropogenic deposits associated with groundwater fluctuations can have an even stronger effect in terms of ground vertical displacements, compared to cases where the surface layer consists of natural deposits. Another association that can produce land movements is given by the existence of marshy soils as a basis for a heterogeneous anthropogenic deposit.

The phenomenon of subsidence in urban areas, such as Bucharest, can have multiple causes. Changes in the hydraulic head of the aquifer due to losses in water distribution networks, the behavior of anthropogenic strata, or the decrease of water infiltrations into aquifers due to the urban fabric surface play an important role. These phenomena contribute directly to the dynamics of urban groundwater and consequently lead to ground weakening problems. A better understanding of the complex connections between the ground displacements with the geological and hydrogeological processes, as part of the urban water cycle, increase the quality of the subsurface urban planning and improve the urban development process. Given the developments in the European Sentinel-1 satellite mission, which provides free of charge SAR data, InSAR techniques may need fewer financial resources than other methods. However, the best results can be achieved only by combining various monitoring methods.

INTRODUCTION

Urban environment is characterized by permanent changes, development and expansion due to urban population growth. This aspect brings challenges in meeting the needs of the population, which often materialize in anthropogenic activities that can substantially change the natural environment. One of the most important needs is related to the access to freshwater resources. In addition to surface waters, much of the water needs are covered by groundwater resources. Groundwater exploitation activities are associated with other anthropogenic activities that require the groundwater pumping for various purposes, such as building constructions or infrastructures, or to keep them in working order. Anthropogenic activities can generate various phenomena of degradation of the earth's surface, such as landslides, erosion, vertical and horizontal displacements.

Some of the most activities important activities from the urban environment leading to ground vertical displacements are related to the hydrogeological aspects, considering massive groundwater pumping for industrial purposes, or to the construction and working order of urban infrastructures. Hydrogeological aspects are accompanied by other phenomena and processes specific to the urban underground environment, related to the geology or geotechnics, which are often associated with the construction of residential, office or commercial buildings, underground or above-ground infrastructure. Vertical ground displacements can have the effect of degradation of the existing buildings or infrastructure elements.

The dynamics between urban above-ground environment and underground environment, including groundwater, need monitoring tools. Monitoring is very difficult to carry out in most cases, especially since for some areas it is possible that the problems related to the dynamics of the two environments are not visible in the initial stage. In this paper, radar remote sensing techniques are proposed as monitoring tools. Remote sensing techniques through quantitative and qualitative observations repeatedly acquired and with a wide spatial coverage, can provide the opportunity for early detection of the subsidence problems that may occur in urban areas. Satellite Synthetic Aperture Radar data offer special operational utility and detection capabilities which can be used for the update of the vertical displacements maps and monitor the dynamics of subsidence processes over time.

Considering the dynamics of the urban environment, subsidence monitoring by in-situ methods (such as precise leveling networks) would require important human, material and time resources. InSAR techniques allow easy mapping of subsidence areas and can be also used to estimate certain parameters after correlations between InSAR and hydraulic head time series.

The main purpose of this thesis is to propose the remote sensing techniques that can be used for the most accurate recognition of areas of instability caused by subsidence phenomena, as well as for the most accurate quantification of displacement values, in correlation with highlighting the cause of the ground vertical displacements.

This thesis consists of four chapters and a last section of general conclusions. First chapter presents the state of the art of the use of remote sensing techniques for monitoring the urban underground environment. In the first part of this chapter the remote sensing data sources which can be used for the groundwater management are presented, considering the water cycle. The second part of the first chapter presents a synthesis of international research on urban vertical

ground displacements monitoring, taking into account several parameters, such as: the causes of the subsidence, remote sensing techniques used for subsidence monitoring, SAR data used, hydrogeological or geotechnical modelling of the phenomena, the specifics of the geographical area, the affected area, the maximum displacement value recorded. A history of the subsidence monitoring techniques starting with the early twentieth century is also presented, along with the advantages and limitations of each of these methods. The third part of the first chapter presents the state of the art of the research on urban subsidence monitoring at national level. This chapter discusses also the different definitions of subsidence phenomena, considering the specific domain in which it is used, and other relevant aspects.

The second chapter of this work presents the chosen urban study area, namely Bucharest city, together with the remote sensing techniques which were used for land surface monitoring, considering the working methodology, the radar satellite data used, the results obtained at city level, as well as the conclusions related to the obtained results. Both remote sensing techniques for subsidence monitoring and ground change detection are presented, as well as the cartographic product obtained by combining the two types of remote sensing techniques and its use. The radar images used for the determination of vertical displacements come from the current European radar mission Sentinel-1 (for the 2014-2018 time interval) and from the previous European mission, ENVISAT ASAR (for the time interval 2004-2010). More processing software were used: the ENVI SARscape software produced by L3Harris Geospatial, the ESA SNAP platform, and an in-house software used in the frame of the Norwegian National Ground Motion Service, INSAR Norway. The Sentinel-1 images were processed in the frame of the INXCES (www.inxc.es.eu) project. The cartographic product obtained by the combination of vertical displacements map with the ground change detection map is proposed to be used for establishing more accurately the potential areas where the source of the vertical displacements is situated.

If the second chapter presents the results at the city level, the third chapter presents a local study case for a specific area from Bucharest city, named Barbu Vacarescu. In this area, the more phenomena and processes from the urban underground conducted to the vertical displacements phenomena, considering hydrogeological, geotechnical, geological and hydrological aspects. The relationship between ground displacements and the dynamics of the urban aquifer system from Barbu Vacarescu area is taken into account and a particular study case of a building in the study area is also presented. The chapter ends with discussions and conclusions on the phenomena and in the studied area. In this chapter, the PSI processing results highlight a pattern of dynamic instability related to the presence of the upper anthropogenic material layer. The anthropogenic layer together with its connections to the urban aquifer system, needs to be carefully analyzed for future work, in the frame of the urban planning and design activities, when construction operations that change the dynamics of the aquifer system are considered.

Chapter four presents an analysis of the subsidence phenomena at the urban regional level. The chapter begins with the presentation of the motivation and the working methodology, continuing with the presentation of the selected regional study area, and with the analysis of the specifics of the various areas included in the regional study area. Thus, the regional study area was chosen along the corridor of the Colentina River, taking into account the high number of subsiding areas included. There are several factors that are considered for understanding the phenomena in the area, including the history of each area, the combined use of the displacement identification map

with the change detection map, as well as other hydrological, hydrogeological, geological and geotechnical aspects.

The last chapter of this thesis presents the general conclusions regarding the studies carried out, the personal contributions and the research directions proposed for future activities considering the results of this study. The general conclusions take into account the observation and monitoring techniques of subsidence phenomenon, the way in which the InSAR techniques highlight the subsidence phenomena generated by the anthropogenic change of groundwater dynamics, the subsidence at local urban level, the subsidence phenomenon at regional urban level, as well as the hydrogeological aspects characteristic of the urban environment and their influence in the ground vertical displacements processes.

1. STATE OF THE ART ON THE USE OF REMOTE SENSING TECHNIQUES FOR URBAN UNDERGROUND ENVIRONMENT MONITORING

1.1. USE OF REMOTE SENSING DATA FOR THE MANAGEMENT OF GROUNDWATERS

The processes of the water cycle are complex and difficult to monitor, making the groundwater management a complex process (NOAA, 2018).

The main factors responsible for aquifer recharge are the climatic factors, which are complemented by hydrological and geological factors (Scrădeanu & Alexandru, 2007). Thus, temperature, atmospheric precipitation, evapotranspiration, air humidity, influence the recharge of the aquifers (Zhao, et al., 2019; Scrădeanu & Alexandru, 2007), as well as the vegetation and the soil (Scrădeanu & Alexandru, 2007).

The quantitative evaluation of the water cycle can be done with the help of the water balance equation (Scrădeanu & Alexandru, 2007), in which the mentioned components, factors and elements intervene directly or indirectly. In a simplified form, this equation can be written as:

$$S = P - Q - E \quad (1.1)$$

where

S is the water storage, P represents precipitations, Q is the runoff, and E is the evapotranspiration.

Earth Observation, by satellite sensors, can help improving groundwater management, providing data and analysis of different phenomena and processes included in the water cycle, as well as of factors influencing the groundwaters and environmental elements involved in all these phenomena and processes.

A series of specific and general remote sensing missions that play directly or indirectly, an important role in the characterization of groundwaters are presented:

- **Precipitations** estimations using the following missions:
 - TRMM- Tropical Rainfall Measuring Mission satellite- the first mission launched for weather and climate research, to study rainfall in the tropical and subtropical regions of the Earth, by means of active radar
 - GPM- Global Precipitation Measurement- measures global precipitations, including both rainfall and snowfall (NASA GPM, 2017; Rodell, 2015)
- **Evapotranspiration**- The evapotranspiration global data set is **MODIS Evapotranspiration Data Set (MOD16)**.
- **Snow cover characterization** - beside MODIS, snow cover and ice products can be obtained using data from active sensors, such as the European missions ERS-1, ERS-2, ENVISAT ASAR, Sentinel 1.
- **Soil moisture**
 - Soil Moisture and Ocean Salinity- SMOS
 - Soil Moisture Active Passive (SMAP)
- **Global Reservoirs/Lakes level monitoring (G-REALM)**- regularly monitor lake and reservoir height variations for many large lakes around the world.

- **Global groundwater depletion-** Satellite gravimetry can be used for reaching the depletion of groundwater at regional or global level, considering the variations of the Earth gravity field.
 - Gravity Recovery and Climate Experiment (GRACE)
 - Gravity Field and Steady-State Ocean Circulation Explorer- GOCE (GOCE, 2015).

- **Vegetation index**

One of the most used vegetation indices is the Normalized Difference Vegetation Index (NDVI) (Meijerink, 2007) which takes values in the interval [-1,1]:

$$NDVI = (NIR - Red) / (NIR + Red) \quad (1.1)$$

where NIR is the Near Infrared spectral band and Red is the red spectral band.

- **Land Surface Temperature-** it can be obtained from the combination of different spectral bands, the thermal one being very important. (Dupigny-Giroux & Lewis, 1999).
- **Multispectral remote sensing data for assessing parameters associated with the hydrological cycle**

From the 1970s a series of passive satellite missions were launched, such as: the longest and still active mission, Landsat ((USGS, 2021), the SPOT satellites series (CNES, 2021), PLEIADES mission (Airbus, 2021). In the frame of Copernicus, the actual European Programme for Earth Observation, Sentinel-2 mission was launched. This mission comes with new capabilities related to the spectral and temporal resolution, allowing a good monitorization of the environment (ESA, 2018).

- **Synthetic Aperture Radar (SAR) Satellite Missions**

Using their own source of energy, the main advantages of these types of satellites are: the possibility to acquire imagery both day and night, regardless weather conditions, they can penetrate clouds, fog or precipitations. These properties allow the use of radar satellite data for flood extension monitoring, snow cover mapping, but also for monitoring many of the parameters mentioned in the previous sections of this work. Thus, by combining radar data with optical data it can be obtained an estimation of the vegetation cover and biomass, estimation of soil moisture, global groundwater resources monitoring.

By using SAR data time series acquired approximately from the same point in orbit and for the same land surface, it is possible to determine the vertical displacements of the land surface that occur as a result of water pumping of fluid injection activities (Galloway & Burbey, 2011). At the same time, the spatial extension of this deformation surface can be estimated (Galloway, et al., 1998).

1.2. STATE OF THE ART ON VERTICAL GROUND DISPLACEMENTS MONITORING ON URBAN ENVIRONMENT, AT INTERNATIONAL LEVEL

1.2.1. Vertical ground displacements characterisation in the urban environment

Land subsidence represents one of the degradation forms affecting land surface (Bawden, et al., 2003; Burkett, et al., 2003; Sneed, et al., 2014; Bitelli, et al., 2015). Generated by natural or anthropogenic causes, this phenomenon is characterized by sinking or settling of the land surface (Allaby, 2013) and can affect either local or large areas (USGS, 2017).

According to the Oxford Dictionary of Environment and Conservation, in geology, subsidence is “a settling of the ground surface as a result of the collapse of porous formations from which large amounts of groundwater were removed” (Park & Allaby, 2017).

The Geological Society specify that subsidence “can be regarded as ground movement that takes place due to the removal of mineral resources from within the ground, whether they be solid, liquid or gas” (The Geological Society, 2018).

Besides the definition where subsidence is associated with the removing of different materials from the underground, in the Dictionary of Geology and Earth Sciences other definitions are given:

- “A progressive depression of the Earth's crust, which allows sediment to accumulate and be preserved. Subsidence is caused by mantle convection and by sediment loading. The subsidence rate will control the proportion of deposited sediment which will be preserved in the subsiding area”.
- “Sinking or settling of the ground surface due to natural or anthropogenic causes. Surface material with no free side is displaced vertically downwards with little or no horizontal movement” (Allaby, 2013).

There are several characteristics of the subsidence, related to the causes of occurrence, affected surface, how the phenomenon is produced. Thus, at the ground surface displacements can occur, produced by different natural or anthropogenic factors from the underground or overground. Most often the ground displacements are caused by a combination of natural and anthropogenic factors (Aditiya, et al., 2017), such as: natural settlement of sediments, groundwater pumping, the use of geothermal fluids, removal of mineral resources, oil and gas extraction, earthquakes, volcanic activity, underground and overground constructions (Aditiya, et al., 2017; Galloway & Burbey, 2011). California Water Science Center of US Geological Survey states that subsidence is one of the most varied phenomena of ground failure, covering either small or local collapses to extensive regional areas (USGS, 2017).

Also, most of the times when the monitoring of ground displacements is done by InSAR remote sensing techniques, the used term for these displacements is subsidence. We can talk about a generalization on the use of this term, subsidence, for naming the vertical displacements, no matter it is a compaction or a settlement.

One of the anthropogenic sources of land subsidence in urban areas is the intensive groundwater withdrawal to assure different urban needs and functionalities, by causing the compaction of the liable aquifer systems (Galloway & Burbey, 2011). This comes in the context of rapid population growth and industrial development (Poland, 1984). Hence, the pumped groundwater is used for industrial purposes, for irrigating the agricultural areas of the cities and of the green areas, for water supply, and for maintaining the functionality of different underground infrastructures. As

usually this land surface degradation occurs at a slow rate, the problem is not too often caught in the field until a visible effect arise (UNESCO, 2015). However, Galloway (2011) underlines that land subsidence can also occur as a sudden sinking of different ground sections. The effects can affect manmade infrastructures (roads, railways, bridges, pipelines, buildings) or natural systems (wetlands, surface drainage patterns, river course changing, and erosion) (USGS, 2017; UNESCO, 2015).

1.2.2. Monitoring of urban areas affected by land subsidence due to groundwater pumping

The most recent techniques for land displacement monitoring are the InSAR techniques which became popular since the 1990s, the time period when enough SAR data became available for using SAR interferometry to determine ground displacements (Bamler & Hartl, 1998). A summary of several studies related to land subsidence in urban areas using InSAR techniques, mainly due to groundwater pumping was made. Figure 1-1 show that studied areas are spread all over the world.

1.2.3. Geographical distribution analyses and historical occurrence of urban subsidence

Studies from more than 20 countries and over 50 urban areas were consulted in this work, as currently facing land subsidence. U.S.A is one of the countries with many subsiding areas in different states, from both eastern and western coast. It is also known for having a long **history of land subsidence**, starting from the beginning of 20th century. Considering the endurance of land subsidence, another area with long subsidence history is Mexico City and the surrounding areas.

When looking at the **location of the subsiding areas**, it can be observed that many of them are placed on

- coastal areas (e.g., Coachella Valley, Los Angeles, New Orleans, Houston-Galveston, Oporto City, Lisbon, Barcelona, Venice, Naples, Istanbul, Thyborøn, Medan, Jakarta, Surabaya, Tokyo),
- deltaic areas (e.g., Kolkata, Tianjin, Delta Municipality region Greece, Po delta (Emilia-Romagna region), Vancouver), or
- coastal with reclaimed land areas (e.g., Incheon, Busan, Shenzhen, Hong Kong).

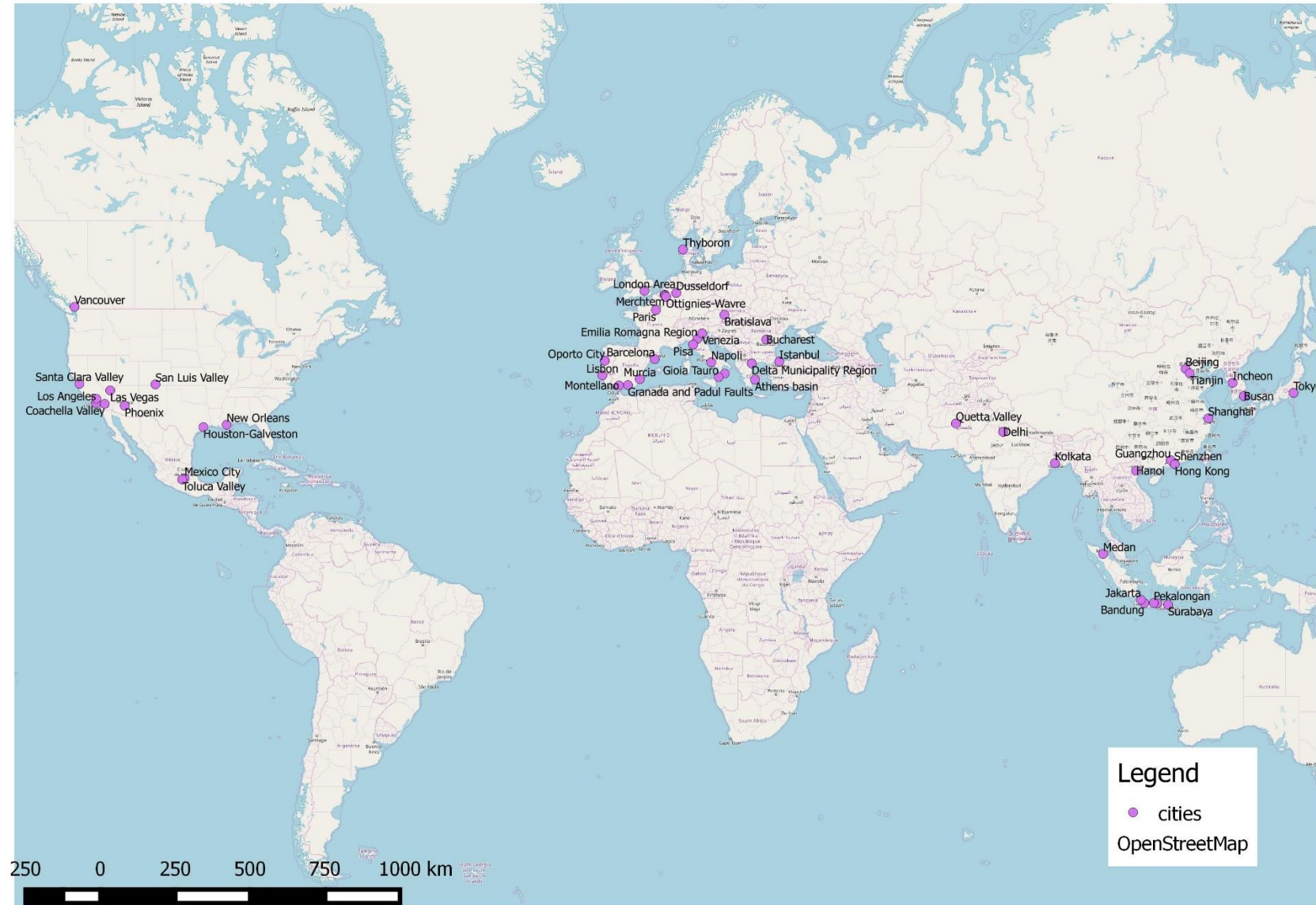


Figure 1-1 Overview of urban areas affected by land subsidence

1.2.4. Clasification of urban subsidence areas taking into account their main characteristics

Considering the study of Chaussard, et al. (2013), subsidence locations can be classified using the following criteria: deformation rate, spatial extent and land use. Starting from these parameters, Table 1-1 presents the distribution of the studied areas.

Table 1-1 Subsidence locations classification criteria (modified after (Chaussard, et al., 2013))

Parameter	Description	Criteria	Cities
Deformation rates	Slow	<5cm/yr	e.g., Lisbon, Montellano, Athens, Murcia, Barcelona, Bratislava, London, Venice, Brussels, Merchtem, Thyborøn, Paris, Istanbul, Kolkata, Busan, Shenzhen, Surabaya, Las Vegas, Los Angeles, New Orleans, Vancouver
	Rapid	≥ 5cm/yr	e.g., Napoli, Delhi, Mexico City, Hanoi City, Hong Kong, Beijing, Medan, Jakarta, Bandung, Pekalongan, Semarang,
Spatial extent	Large scale	≥100 km ²	e.g., London Area, Venice, Gioi Tauro, Mexico City, Beijing, Jakarta, Bandung, Las Vegas, Los Angeles
	Local Scale	10-100 km ²	e.g., Murcia, Athens, Istanbul, Delhi, Kolkata, Toluca Valley, Incheon, Hanoi, Medan, Semarang, San Luis Valley
	Patchy	1- 10km ²	e.g., Oporto, Montellano, Barcelona, Pisa, Napoli, Brussels, Düsseldorf, Thyborøn, Busan, Hong Kong, New Orleans
	Punctual	< 1 km ²	Bratislava, Paris,
Land use		Agricultural	e.g., Montellano, Delta Municipality Greece, Gioi Tauro, Pekalongan, Santa Clara Valley, Coachella Valley
		Urban	e.g., Mexico City, Tokyo, Pisa, Istanbul, Quetta Valley, Hanoi, Shanghai, Santa Clara Valley, Lisbon, Oporto
		Industrial	e.g., Oporto, Brussels, Toluca Valley, Shenzhen, Surabaya, Medan, Jakarta, Bandung, Semarang, Antelope Valley

• Geological and geotechnical particularities of the urban areas affected by subsidence

Vertical ground displacements appear as a result of pumping great amounts of groundwater, the geological and geotechnical characteristics of the underground from the subsidence area being implicitly changed. Thus, the presence of certain types of soil as surface layers or as component layers of the aquifer or aquitards, favor the appearance of subsidence phenomena, or can lead to an increase in the velocity of displacement:

- Presence of clay intercalation between other layers (eg, Lisbon, Montellano, Delta Thessaloniki, Pisa
- Presence of heterogeneous sediments layers – in many cases these are associated with the presence of the clay intercalations, leading to the associated influence of the two types of layers on subsidence (eg., Montellano, Gioia Tauro Plain.
- Presence of organic deposits- vertical displacements in these areas have a natural component and an anthropogenic component (ex. Hanoi, Blanakan, Pekalongan, New Orleans.
- Presence of anthropogenic material layers- there are several types of areas in which such deposits can be found, such as:
 - Land reclamation areas (eg., Singapore, Shenzhen, Hong Kong, Busan), deltaic areas (eg., New Orleans);
 - Areas where natural disasters took place (earthquakes- eg., Ciudad Guzman, Mexic) or

- Areas with anthropogenic material layers used for filling old quarries (eg., Bucharest).
- **Land subsidence associated to ground and underground infrastructures constructions**

Beside the land use, in many areas, it can be observed the presence of some specific works for ground or underground infrastructures construction, such as:

- underground railway: Lisbon, London, Napoli, Shanghai,
- Railway station: Barcelona,
- Metro line tunneling: Athens, London, Düsseldorf, Vancouver, Shanghai,
- Dam infrastructure: Bratislava,
- Underground constructions: Paris, Busan, Beijing, Surabaya.

All these works are also influencing the water pumping regime and the occurrence of land subsidence.

1.2.5. Subsidence monitoring methods

Several methods were used over time for monitoring land subsidence worldwide. Starting with the classical levelling technique, continuing with extensometer wells, GNSS (GPS as being developed the first), and finally with SAR interferometry, each method presents advantages and disadvantages considering more criteria (Bitelli, et al., 2015). Some of them are: the sensed order of magnitude, the financial effort, the covered area, and the human resources.

Precise levelling by spirit levelling

The most precise method of measuring elevation changes at land surface is the precise levelling. This method consists in determining the elevation of a bench mark network at land surface. By repeated surveys of the network of bench marks at different time intervals, it can be revealed whether vertical movements appeared compared to the control bench marks (Poland, 1984).

Borehole extensometry

Vertical borehole extensometers are used to measure the movement or change of the vertical distance between the bottom of the borehole and the ground surface, considering the thickness of sediments or rocks.

Global Navigation Satellite Systems (GNSS) acquisitions

GNSS techniques lie in the use of at least four navigation satellites for determining absolute (X, Y, Z) coordinates with respect to a global well-defined geocentric reference system (Zerbini, et al., 2007).

1.2.6. Synthetic Aperture Radar (SAR) Interferometry techniques and SAR data used for land subsidence monitoring

In the last decades, remote sensing by its qualitative and quantitative acquisitions made repetitively and with a large spatial coverage, offered the opportunity for early detection of land subsidence in urban areas. Time-series SAR Interferometry data started to be used for revealing different parameters characterizing the dynamics of groundwater (e.g. seasonal and long-term aquifer-system response, flow properties, groundwater barriers identification) (Chen, et al., 2016).

InSAR technique

Interferometric SAR (InSAR), is a measuring technique dating back to the 1970s, but which became popular in the 1990s, when European Space Agency (ESA) launched the ERS-1 mission (Bamler & Hartl, 1998). SAR interferometry is exploiting the phase difference of two acquisitions made on the same area at different time moments, from almost the same look angle, generating an interferogram (Bamler & Hartl, 1998). Their phase difference represents the interferometric fringes which can be used for generating, by multiple processing steps, Digital Elevation Models (DEM) (Rocca, et al., 1997).

DInSAR technique

If multiple SAR scenes acquired with the same geometry and at different time moments are available for a studied area, the effects of the topographic component and of other factors can be removed and the terrain motion component can be measured. This is also available if an external DEM is used for subtracting the topographic component from the interferometric phase (Ferretti, 2007). This technique represents the Differential SAR Interferometry (DInSAR).

Multi-temporal techniques or A-DInSAR techniques

In order to estimate and correct residual atmospheric phase, DEM errors, sub-pixel target position related phase offsets, and the loss of coherence (CCIAS, 2015; Wasowski & Bovenga, 2014), new InSAR techniques were developed, considering long temporal series of SAR data (Wasowski & Bovenga, 2014). These are the multi-temporal InSAR (MTI). The two primary categories of MTI are:

- the **Persistent Scatterers Interferometry (PSI)** (Ferretti, et al., 2001) and other similar approaches. This is an MTI method considering long temporal SAR data acquisitions (over 20 images) for vertical displacements detection (Ferretti, et al., 2001). These interferograms are used for the identification and usage of stable natural highly reflective ground features, characterized by reliable amplitude and coherent signal phase over all SAR scenes (Ferretti, et al., 2001; Wasowski & Bovenga, 2014). These are the permanent or persistent scatterers (PSs). Permanent scatterers are revealing the displacements in the time series studied area, relatively to a reference point (Ferretti, et al., 2007).
- the **Small Baseline Subset (SBAS)** and related methods. SBAS methods are focusing on pairs of interferograms characterized by small spatial baselines (Berardino, et al., 2002) for using more spatially dispensed information. The SBAS concentrates on distributed scatterer, as they are more sensible to temporal and volume decorrelation than PSs (Wasowski & Bovenga, 2014).

In most of the consulted studies PSI and SBAS techniques are used, and in some cases combinations between the two methods are used. The different techniques used in the studied are: Stacked Interferometric Technique, Wavelet Based InSAR (WabInSAR) technique, Stable Point Network (SPN) technique, Coherent Pixels Technique (CPT), Coherent Pixel Technique-Temporal Sublook Coherence, Persistent Scatterer Pairs Differential InSAR (PSP-DIFSAR) technique, Intermittent SBAS technique (ISBAS), PSIG technique, Stanford Method for

Persistent Scatterers (STAMPS) technique, Stanford Method for Persistent Scatterers- Multi-Temporal InSAR (STAMPS/MTI) technique, SqueeSAR technique

1.2.7. Subsidence modelling

According to (Galloway & Burbey, 2011), the analysis and simulation of land subsidence following the aquifer system deformation due to groundwater pumping, concerns mainly the unconsolidated alluvial or basin-fill aquifer systems composed by aquifers and aquitards. Modeling is based on the relations between head, stress, compressibility, and groundwater flow. Several approaches were revealed over the time, the core model for most of them being Terzaghi's model. This approach assumes that changes in the effective stress can result from changes in the total stress or changes in the pore-water pressure (Galloway & Burbey, 2011; Roy & Robinson, 2009). Starting from this theory, two approaches were proposed: the conventional groundwater flow theory and the linear poroelasticity theory (Biot, 1941). The first one is the most used as it considers only the vertical deformation of the skeletal aquifer matrix and it is easier to implement. Biot theory describes the 3D deformation of the matrix (Biot, 1941; Galloway & Burbey, 2011).

The following models were used in the analyzed studies:

- The finite element model
- Mohr-Coulomb elastic-perfectly plastic model
- The finite element code TRANSIN-IV
- The hydro-mechanical finite element code GEHOMADRID
- The mathematical model of crustal behavior, glacio-isostatic adjustment (GIA)

1.2.8. Comparisons and correlations between different land subsidence monitoring methods

When not too many parameters concerning the hydrological, hydrogeological, geological, or geotechnical aspects are available for modelling, simpler correlations between land subsidence and one or two parameters can be made.

Hence, for Brussels area a comparison concerning the evolution of the water table and the time series of averaged velocities around the selected piezometers was made. Another study from the urban Ottignies-Wavre area, investigated the correlation between the water catchments and the subsidence trends. (Declercq, et al., 2006). For San Luis Valley, Colorado, by the use of InSAR, considering the analyses for 24 wells, it could be revealed a temporal and a spatial correlation between the land deformation and the hydraulic head (Chen, et al., 2016). A comparison between the extensometer values, the InSAR deformation data, and a geodetic survey was made in Antelope Valley, Mojave Desert, California (Galloway, et al., 1998). In Delta Municipality region, Greece, a comparison between the vertical velocity of PSs and the leveling data at some benchmarks was made, unveiling millimetric differences, for yearly velocities in the order of 4 cm (Raspini, et al., 2014). Liu & Niemeier (2014) presents the analysis of a site where underground construction and water pumping during works were monitored using InSAR and leveling techniques, during a tunneling process. The comparison between the vertical velocities of PS points and the leveling benchmarks, revealed a good consistency of the two methods. In Venice region, the GPS time series for vertical velocities were compared with the computed Satellite LOS, evidencing the annual and semi-annual seasonal deformations, and also the long

term vertical velocity (Bock, et al., 2012). In Pisa, a correlation was made between the buildings age and the subsidence level and process (Solari, et al., 2017). Perissin, et al., (2012), made a correlation between the time openings of different metro lines from Shanghai, and the subsiding processes. Chaussard, et al. (2013) considers a correlation between subsidence and surface geology highlighting that, generally, subsidence is occurring in compressible deposits, such as surface deposits and swamp deposits.

1.2.9. European initiatives for urban subsidence monitoring: Terrafirma, PanGEO and EGMS

Some of the SAR data used in the different studies presented in the previous sections, represents the results of two European initiatives for providing ground motion hazard information services for relevant cities around Europe, namely PanGEO and Terrafirma. Ground motion was estimated using PSInSAR techniques, for both initiatives. (ESA & Terrafirma Partners, 2010; PANGEO, 2013).

In 2016 started the process of defining the EGMS, as part of the Copernicus Land Monitoring Service's product portfolio. The EGMS purpose is to provide consistent, regular, standardized, harmonized and reliable information regarding natural and anthropogenic ground motion phenomena over Europe and across national borders, with millimeter accuracy (Copernicus, 2021).

1.3. STATE OF THE ART ON THE USE OF INSAR TECHNIQUES FOR LAND SUBSIDENCE MONITORING IN URBAN AREAS, AT NATIONAL LEVEL

1.3.1. Research on land subsidence monitoring due to anthropogenic dynamics

At national level, most studies on land subsidence were performed considering Bucharest city. The studies begin with research activities for interferometric generation of digital elevation model for Bucharest city, using TerraSAR-X (Poncos & Dana, 2008).

Poncos et. al. (2010) presents a map of ground displacements generated from a series of 43 ERS 1/2 images acquired in the time span 1992-1999, using DInSAR technique. Same ERS temporal data series covering 7 years is processed (Poncos, et al., 2012) by using two A-DInSAR techniques: Stacking Interferometry and PSI. Stacking Interferometry Technique and PSI are used also for the processing of a time series of 32 SLC TerraSAR-X images, acquired in the StripMap mode for the July 2011- December 2012 period (Poncos, et al., 2013).

As part of the European PanGEO initiative, the Geological Survey of Romania made an interpretation of the PSI displacements maps generated for Bucharest city. The radar satellite data sets used are ERS 1/2 for time span 1992-2000 and ENVISAT ASAR for time span 2002-2009 (Vîjdea & Bindea, 2013).

Poncos et al. (2014) complete the studies related to the instability of the Bucharest city by generating PSI displacements maps using satellite data from ERS1/2, ENVISAT and TerraSAR-X satellite missions, covering the time intervals 1992-1999, 2003-2009 and 2011-2012 (Poncos, et al., 2014). The authors extend the study on the instability areas identified in the PanGEO project, for the time period 2011-2012. In the same study, Poncos et. al. (2014) presents the displacements 'evolution of the urban area where a new metro line is being built, considering the

three time periods mentioned previously. Using a multidisciplinary approach with the inclusion of interferometric, hydrogeological and geotechnical investigations, Boukhemacha, et al. (2021) continue the investigations on the construction area of the new metro line in Bucharest, during the excavations for the metro galleries, during 2014 and the beginning and 2015. SAR data from TerraSAR-X mission are used. Using the Delft Persistent Scatterer Interferometry (DePSI) technique, (Gheorghe, et al., 2020) present the results of the metro line M5 monitoring for the time span 2014-2018, using Sentinel-1 data and capturing one of the incidents that occurred at the end of 2015, during the depletion works at a subway station.

In the context of the geomorphological peculiarities of each urban area, Gheorghe and Armas (2015) apply InSAR techniques for the analysis of Bucharest city, highlighting the importance of these techniques for environmental studies and, in particular, for geomorphology studies.

Using multidimensional dynamic analyses together with multi-temporal InSAR analyses (SBAS and PSI), Armaş et al. (2017) identify the land displacements mechanisms that include long-term natural trends overlapping short-term patterns, caused mainly by the recent dynamics of the city. The results of the TSX data processing are validated by GNSS observations, coming from a GNSS control network built at the level of Bucharest city (Armas, et al., 2016).

Having as test site a part of the Bucharest city, Dănişor et al. (2020) proposes to evaluate the use SqueeSAR principles for the SAR Tomography multi-temporal processing technique (Danisor, et al., 2020).

Research on ground displacements is also carried out for Constanta city, located on the coastal area of the Black Sea, using PSI technique for Sentinel-1 data (Toma, et al., 2018).

1.3.2. Research on land subsidence monitoring as an effect of mining works

For the study of Ocnele Mari area, affected by land uplift, with values between 2-4 mm/year, caused by the exploitation of existing salt deposits in the area, Poenaru et al. (2011) uses 9 TSX images acquired in the time span August-November 2010, applying the DInSAR processing technique. The research continues with the use of a set of RADARSAT-2 images, acquired in the time period July-December 2014, processed by classical InSAR and DInSAR techniques.

1.3.3. Research on land subsidence monitoring in seismic areas

Using a series of 30 SAR complex images acquired by the ERS-1 and ERS-2 satellites in the time period May 1995- June 2000, Dănişor et al. (2018) evaluates the linear deformations in the area of Focsani and Buzau cities, located in the Vrancea seismic area, using a PSI processing chain.

Bălan et al. (2016) monitors the displacements that occur in several areas of Bucharest city, where the superficial layer is constituted by anthropogenic materials, as well as at the Cernavoda nuclear power plant, using PSI technique, both situated in the seismic area.

1.3.4. Research on land subsidence monitoring for UNESCO cultural heritage

Using a series of 18 TerraSAR-X HS images acquired between March 2014 and October 2014, Dana Negula et al. (2015) generates a land displacements map of Sighisoara, using the PSI technique. Moise et al. (2021) presents a spatial and temporal evolution of Alba Iulia city, one of the Romanian cities with a rich historical past, using historical data and current remote sensing data. A PSI displacements map of the city is generated using Sentinel-1 images. Other two cities,

part of the UNESCO world cultural heritage where ground vertical displacements are monitored using PSI techniques and Sentinel-1 A/B data are Deva (Dana Negula, et al., 2019) and Hunedoara (Moise, et al., 2020).

2. CASE STUDIES IN BUCHAREST CITY, ON LAND SUBSIDENCE MONITORING AND URBAN UNDERGROUND ENVIRONMENT CHARACTERIZATION USING REMOTE SENSING TECHNIQUES

2.1. GENERAL PRESENTATION OF THE STUDY AREA: BUCHAREST CITY

Located in the southeastern part of Romania, with a surface area of about 240 km² and a growing population of over 2.1 million in 2019 (INS-DRS, 2019), Bucharest city is crossed by two rivers: Dambovitza River which was extensively channelized, and Colentina River which was remodeled at the beginning of the 20th century in a series of lakes connected with the shallow aquifer (Gaitanaru, et al., 2017).

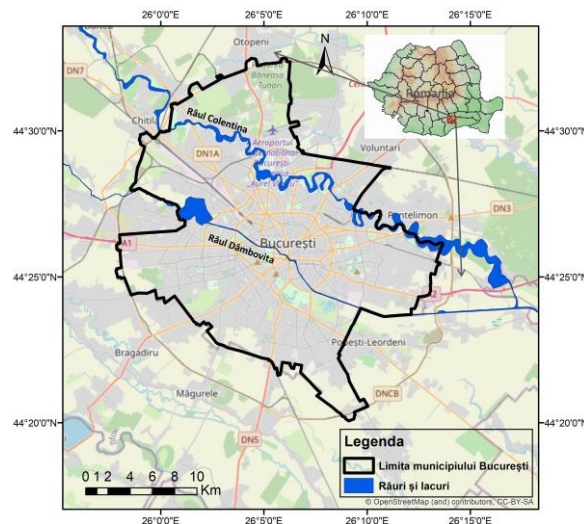


Figure 2-1 Bucharest Map. Map generated in Esri®ArcMap™ 10.3

From a geomorphological point of view, Bucharest is located in the Bucharest Plain, in the central part of the Romanian Plain, with the Snagov Plain to the north, the Călnăului Plain to the south, Lunca Argeș-Sabar to the west, and the Mostiștei Plain to the east (Lacatusu, et al., 2008). From the geological point of view, Bucharest city is located in the central part of the Moesian platform which lies on a rigid base made of metamorphites, and various igneous intrusions (granodiorite, granite) (Serpescu, et al., 2013). The sedimentary deposits covering this rigid base are made by different phases of erosion and sedimentary processes (marine, lacustrine, or continental) ending with Quaternary sediments (Mutihac, 1990). The Quaternary deposits have been organized in 6 structural units given from top to down as follows: (Serpescu, et al., 2013; Gaitanaru, 2017b; Lacatusu, et al., 2008):

- Superficial deposits represented by loess and anthropogenic materials;
- Colentina Formations made up of poorly sorted, cross-stratified sand and gravel with clayey lens;
- Intermediary deposits made mainly of clay and silty-clay with fine sand intercalation;

- Mostistea Formation made of sediments with a variety of grain size, from fine sand to coarse sand with small intercalations of gravels and scrap of woods;
- Marly Complex made by a succession of marls and clays with lenticular sandy intercalations indicating a fluvial-lacustrine environment;
- Fratesti Formation made of sand and gravel which includes A, B and C Fratesti levels.

From the hydrogeological point of view, the city of Bucharest lies on the Quaternary sedimentary aquifer system composed of three units, referred as Fratesti strata (deepest Quaternary aquifer), Mostistea (middle-confined aquifer) and Colentina (the shallow aquifer). (Boukhemacha, et al., 2015).

The climate of Bucharest is characteristic of the temperate continental climate (Lacatusu, et al., 2008), with a tendency of continentalization from west to east, considering the climatic transition influence in the west and the climatic excessive influence in the east (Grigorescu, 2010).

2.2. GENERATION OF THE PSI LAND DISPLACEMENT MAP FOR BUCHAREST CITY, FOR THE TIME INTERVAL 2004-2010

Based on the data from the radar European mission ENVISAT ASAR, a land displacement map was generated for the time interval 2004-2010, using PSI technique (see Figure 2-2). The ENVI SARscape software was used for data processing (<https://www.l3harrisgeospatial.com/Software-Technology/ENVI-SARscape>). The logical workflow for the generation of the land displacement map is characteristic for the SARscape PS module of ENVI software.

Main PSI processing steps include:

- ENVISAT ASAR images import in ENVI SARscape;
- Applying Orbit File – precise orbit files were downloaded from ESA archive when the SAR images were also downloaded;
- Connection Graph Generation – this functionality defines the SAR pair combination (Master and Slaves) and connection network, which is used for the generation of the multiple differential interferograms. For the used data set the Master image was acquired on the 24.02.2007;
- Area of Interest Definition, for the case when AOI is smaller than the whole frame coverage;
- Interferometric process, including Coregistration, Interferogram Generation, Flattening and Amplitude dispersion index. At this stage, the digital elevation model (DEM) to be used was specified. For this processing the STRM-3 v4 DEM was used;
- Inversion: First Step – this functionality estimates the first model inversion to derive the residual height and the displacement velocity. They are used to flatten the complex interferograms;
- Inversion: Second Step – estimation of the atmospheric phase components, considering the first linear model product coming from the previous step. The velocity and residual height values are refined.
- Geocoding – the PS products are geocoded and the displacements can be displayed.

Land displacements have values between -26.80 mm/year and 20,92 mm/year, with a mean value of -0.29 mm/yr, a standard deviation of ± 0.84 mm/yr and a point density of 283 PSs/km².

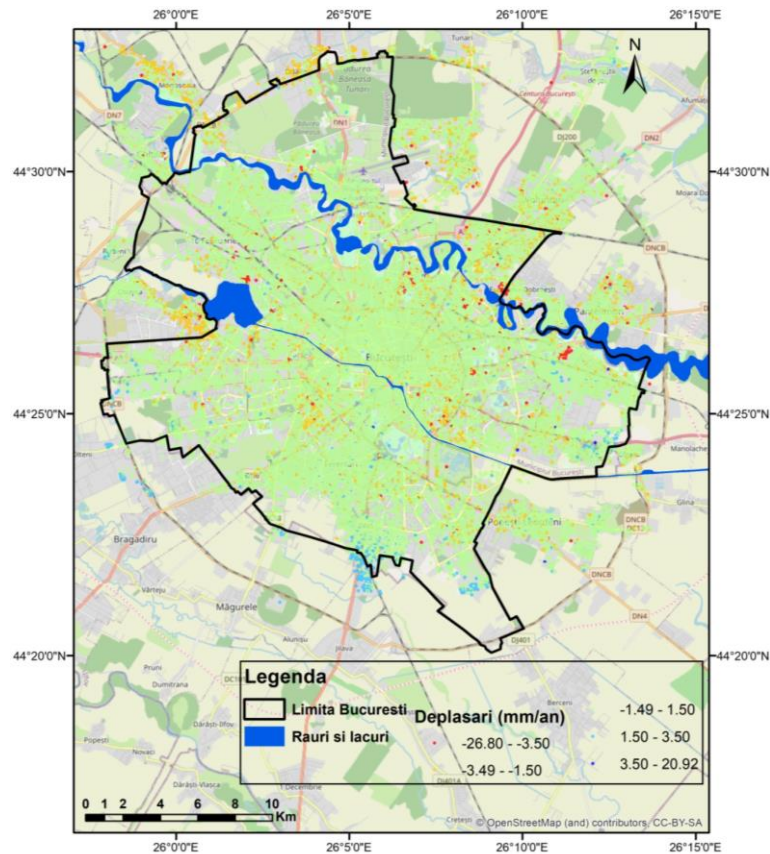


Figure 2-2 PSI ground displacement map for Bucharest city, obtained from ENVISAT ASAR 465D data, for time period 2004-2010

For the time interval 2004-2010, several trends of ground displacements were observed: general trend at city level is stability; there are several areas with subsidence tendency, located mainly along the corridors of the two rivers crossing the city; there are several areas in the south and east-southeast of the city with uplift trends.

2.3. GENERATION OF THE PSI LAND SUBSIDENCE MAP FOR BUCHAREST CITY, FOR THE TIME INTERVAL 2014-2018

PSI land subsidence map for time interval 2014-2018 was generated using SAR Sentinel-1 images. The data used covers the time period October 2014- April 2014 and take into consideration data acquisitions from the 109D- descending orbit, and 131A- ascending orbit. Table 2-1 offers the details related to the acquisition time period and the available number of acquisitions for each temporal series (both for the ascending and descending time series).

The PSI ground displacement maps were produced by the Geological Survey of Norway using the same processing chain and software that are used for the Public National Norwegian Ground Motion Service, INSAR Norway, www.insar.no. Sentinel-1 processing was realized as activity in the frame of INXCES- INnovations for eXtreme Climatic EventS project (www.inxc.es.eu), in which the Groundwater Engineering Research Center of UTCB was involved as partner.

Table 2-1 Sentinel-1 data used for the generation of the ground displacement maps

Sensor	Orbit	First Acquisition/Last Acquisition	No. of used images
Sentinel 1	131 Ascending	14.10.2014/ 26.04.2018	115

	109 Descending	13.10.2014/ 25.04.2018	153
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Based on the ascending and descending geometry of the two PS points data-sets and the LOS displacements values, the vertical and horizontal (only east–west direction) components of displacements were computed, considering the approach proposed by Dalla Via et al. (2012):

$$D_e = (D_d \cos \theta_a - D_a \cos \theta_d) / \sin(\theta_a + \theta_d)$$

$$D_v = (D_d \sin \theta_a + D_a \sin \theta_d) / \sin(\theta_a + \theta_d) \quad (2.1)$$

where D_e is the horizontal displacement, D_v is the vertical displacement, D_d is the descending LOS displacement, D_a is the ascending LOS displacement, and θ_a and θ_d are the look angles for both orbits modes.

For the combination of ascending and descending PS points, the nearest neighbor vector approach was used (Foumelis, 2016). For each PS point from the ascending orbit, the nearest spatial PS point from the descending orbit was assigned. After the join between the two data-sets, the horizontal and vertical displacements were computed using Equation (2.1). The approach was based on GIS softwares, using tools and functionalities of the ESRI's ArcMap software package and of the free and open source QGIS software.

The PSI vertical ground displacement map of Bucharest city generated for the time period October 2014- April 2018 is presented in Figure 2-3. The vertical displacements computed by using data from both ascending and descending orbits reach values between -13.05 mm/yr and $+17.24$ mm/yr, with a mean value of -0.27 mm/yr, a standard deviation of ± 0.91 mm/yr and a 1050 point density/km.

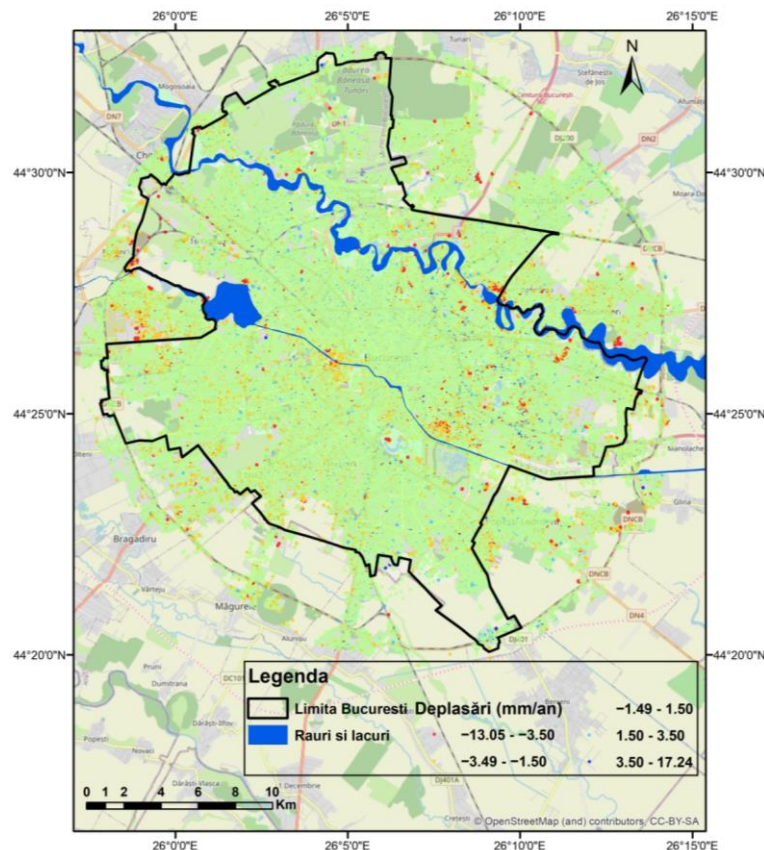


Figure 2-3 PSI vertical ground displacement map of Bucharest city, for the time interval 2014-2018, using Sentinel-1 data from the 131A ascending orbit and 109D descending orbit

As in the previous monitoring period (2004-2010), several ground displacement trends were identified in Bucharest city. General trend for 2014-2018 at city level is stability. Several areas with subsidence tendencies were identified along the corridors of the two rivers crossing the city, as in the previous monitoring period. Several areas with alternating trends for which an analysis on a longer period is necessary for establishing the correct trend were also identified.

2.4. GROUND CHANGE DETECTION MAP GENERATION USING SENTINEL-1 GRD DATA

Two Sentinel-1 GRD images, first from 5.10.2014 and the second from 25.10.2018 were used for change detection. The steps for the change detection processing using Sentinel-1 GRD data (uni-goettingen, 2021) were performed using the SNAP software platform developed by ESA:

1. Sentinel-1 GRD data import
2. Subsetting- the area of interest is chosen and a spatial subset is generated for images. Amplitude information and VV polarization are selected for each image.
3. Applying Orbit File
4. Radiometric Calibration
5. Single Product Speckle Filter
6. Range-Doppler- Terrain Correction using SRTM 1 sec HGT DEM
7. Create Stack

The product obtained by coregistration is converted from the standard format SNAP (.dim) in GeoTiff format for easy display in GIS software, for change detection analysis.

Figure 2-4 presents the ground change detection map for Bucharest city. City border is symbolized using a red dotted line, and the detected changed areas between 2014 and 2018 are marked in red on the map. The areas where no changes are detected are marked in gray.

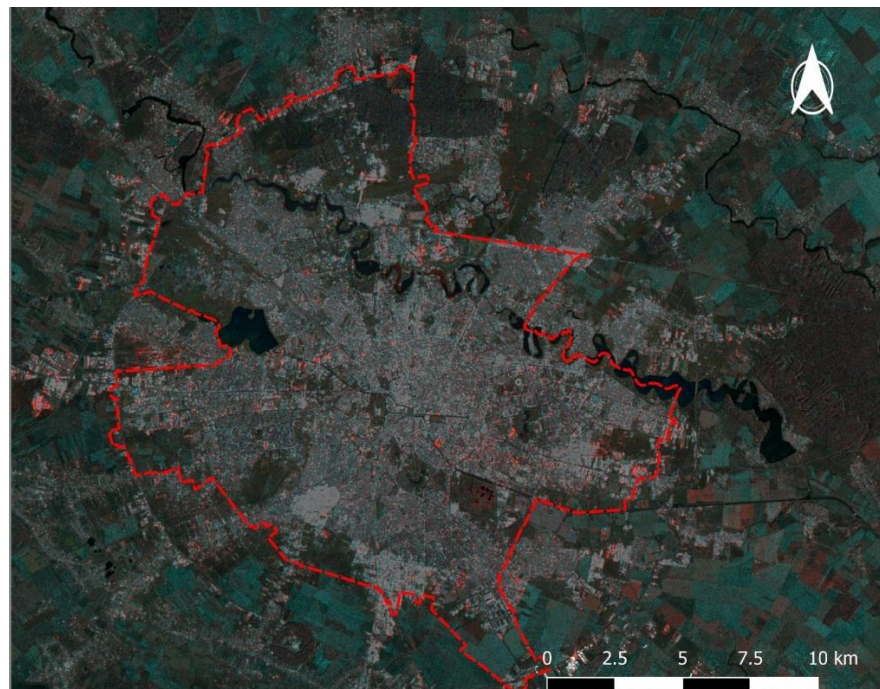


Figure 2-4 Ground change detection map for Bucharest city (2014-2018), generated from Sentinel-1 GRD images

The main changes that are highlighted are related to the expansion of residential neighborhoods (eg., Military Residential Area from the western border of the city), the emergence of commercial warehouses on the outskirts of the urban area, the emergence of shopping centers in urban area (eg., IKEA Pallady in the eastern part of the city, close to the city border), office buildings close to the city center.

2.5. INSTABILITY AREAS IDENTIFIED IN THE 2014-2018 TIME INTERVAL BASED ON THE SENTINEL-1 PSI GROUND DISPLACEMENT MAP

The vertical ground instability areas were identified and marked on the ground displacements map generated for 2014-2018. In Figure 2-5, these areas are delimited in red. Instability areas have been identified and analyzed. These areas can be classified according to several criteria. Depending on the major cause of displacement, these identified subsidence areas can be classified as follow:

- Areas where surface anthropogenic deposits are present (eg., A1, A12, A8, A9 areas);
- Areas affected by underground construction works (eg., A2 area);
- Areas where surface constructions are executed (eg., residential buildings, office buildings, commercial spaces, above-ground infrastructures), but for which there may be connections with the underground environment (eg., A7, A13, A11, A3, A4, A6 areas);
- Areas with very old buildings (eg., A10, A5 areas).

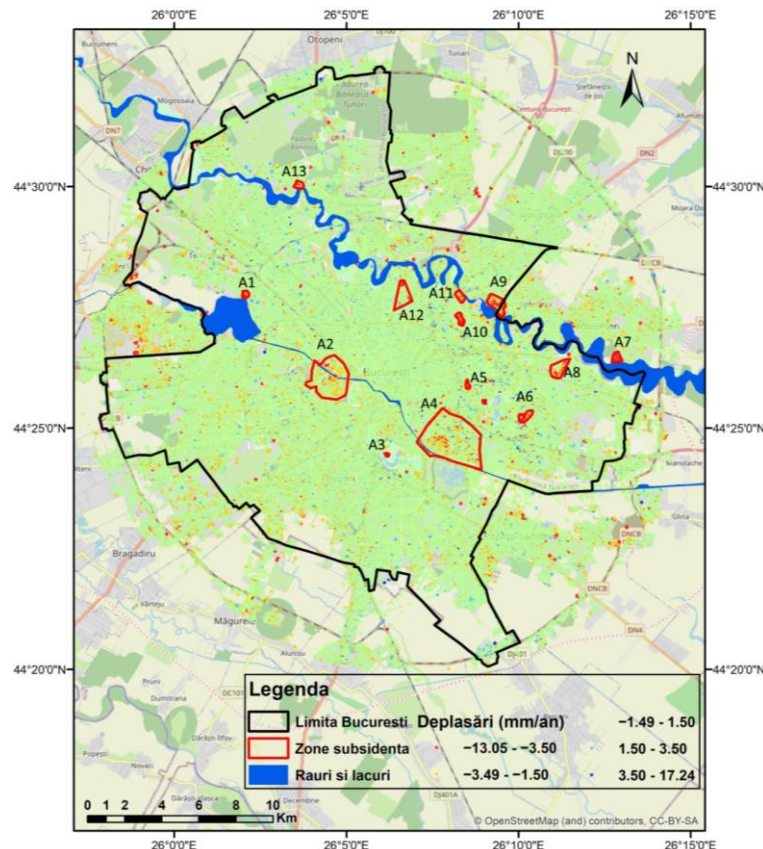


Figure 2-5 Sentinel-1 PSI vertical ground displacement map of Bucharest city and the identified subsidence areas

Considering the land use category, the identified instability areas can be classified into:

- Areas with above-ground constructions of smaller dimensions and smaller number of levels, in which demolition works took place and new residential, office and commercial spaces were built- eg., A4, A12, A10 areas;
- Urban areas in which green spaces were transformed in residential areas in the last 10-15 years- eg., A6, A9, A13 areas;
- Out-of-town areas in which woods or pastures were transformed in residential areas in the last 10-15 years- eg., A7;
- Green areas were replaced by sport infrastructures (eg., bicycle tracks, tennis courts, skateboard infrastructure) – eg., A3, A5 areas.
- Areas where land use didn't change but specific factors causing subsidence are present inside these areas (eg., presence of surface anthropogenic deposits)- eg., A1, A8 areas.

2.6. COMBINATE USE OF PSI TECHNIQUES AND CHANGE DETECTION TECHNIQUES FOR THE IDENTIFICATION OF THE POTENTIAL INSTABILITY AREAS

One of the most important limitations is related to the fact that only PS points (persistent scatterers) with sufficiently high coherence, for the entire monitoring time frame are taken into account. Consistency is an indicator of the stability of the persistence point phase on the earth's surface (Wickramanayake, et al., 2016). In areas with rich vegetation or forests, decorrelation occurs, which makes a very small number of PS points to be available in these areas. The same applies if construction work takes place during the monitoring time, or other factors occur and change the surface of the land. If work takes place in a certain area at a certain time after the start of the monitoring, the points in the area that were initially consistent are lost once the work starts. These construction works can cause land subsidence both in the area where they are being carried out and in the neighboring areas. If the neighboring areas are affected, the effect of the works can be translated by the appearance of PS points that indicate land displacements. From the way the PS points are arranged on the velocity map, it will not be possible to take into account that the identified displacements could be caused by changes in the neighboring area, due to the lack of information about that area. By combining PS techniques with techniques for detecting changes in the earth's surface, it is possible to determine more precisely the source of certain instability problems.

2.6.1. Joint analyses based on the PSI ground displacements map and the change detection map for Bucharest city, in the period 2014-2018

Considering the two types of maps that have been presented in the previous sections, a joint analysis of displacement information and land change detection can be carried out. If on the map of the detection of changes for Bucharest city, presented in Figure 2-4, the information from the PSI displacements map is also added, a new cartographic product is obtained, presented in Figure 2-6. Based on the change detection map, several areas where changes to the land surface have been identified near Pipera Metro Station. Figure 2-7 presents these areas.

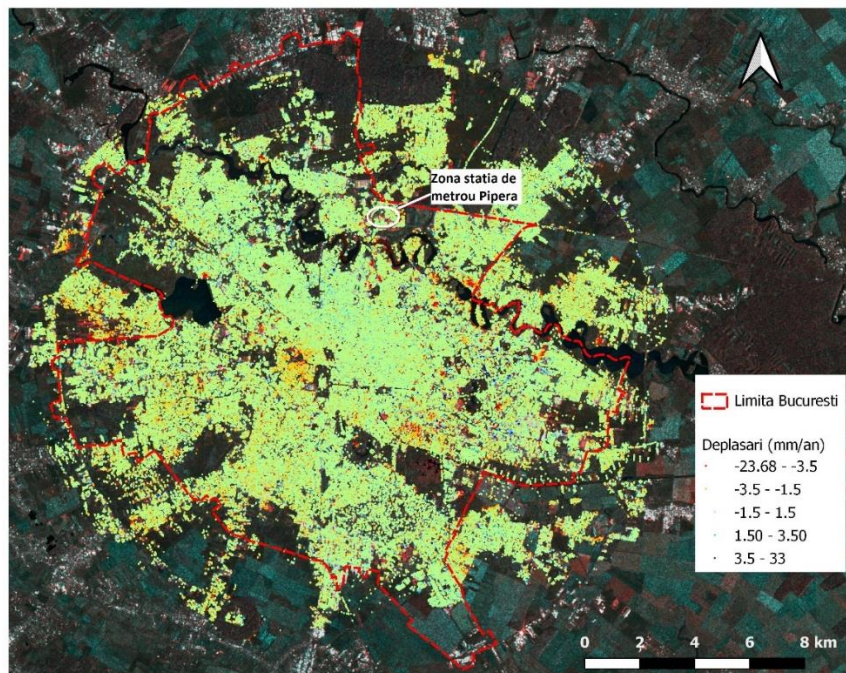


Figure 2-6 Ground displacement map and change detection map for Bucharest city, in the time period 2014-2018

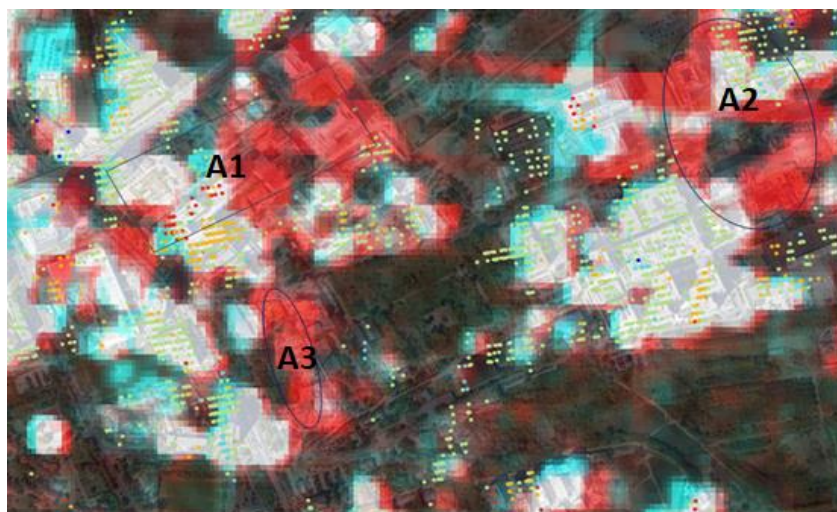


Figure 2-7 Change detection map and PSI displacements map for Pipera area

These changes have been documented with optical remote sensing images. In the case of A1 and A2 zones, buildings were built on site between the two time points and in A3 zone, the urban landscape changed by demolishing a building. If only the PSI vertical displacements map had been taken into account, the search area for the source of the movements would have been restricted only to the existing building, for lack of other information. By using land surface detection information, the process of identifying the source of the movements may be extended for situations where the building or infrastructure itself is not identified as the cause.

3. PHENOMENA AND PROCESSES IN THE URBAN UNDERGROUND ENVIRONMENT ASSOCIATED WITH LAND SUBSIDENCE, DETERMINED BY PSI TECHNIQUES. STUDY CASE: BARBU VACARESCU AREA, BUCHAREST CITY

3.1. GENERAL CONTEXT

As in many other urban areas, the hydrogeological problems of Bucharest city are produced by the interaction between the aquifer system and the underground infrastructures (Gogu, et al., 2017).

Based on the PSI ground displacements map generated from the Sentinel-1 data processing, Figure 2-5 from the previous chapter presents the identified instability areas in Bucharest city. One of these areas is A12 area (Figure 2-5), delineated by Lacul Tei Boulevard, Barbu Vacarescu Street, and Opanez Street, represents the focus of this study, a comprehensive analysis on the behavior of the anthropogenic thick layer of debris from urban constructions, situated in Barbu Vacarescu area being highlighted (Figure 3-1).

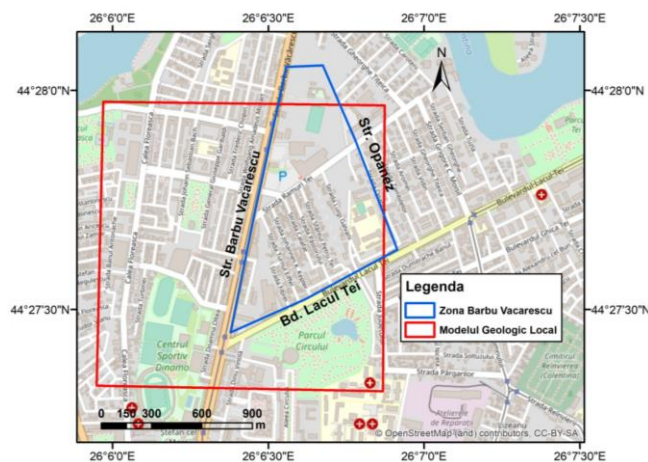


Figure 3-1 Barbu Văcărescu area

3.2. DEVELOPMENT OF THE URBAN LOCAL GEOLOGICAL MODEL FOR THE BARBU VACARESCU AREA

A better understanding of the local geology in relationship to the urban infrastructure (anthropogenic layers, deep foundations, tunnels, excavations, and others) could have been achieved only by generating an accurate local geological model of 1200 x 1200m, for the study zone (Figure 3-1).

The operational steps were the following:

- Collection of data consisting of lithological information from 16 boreholes with depths from 15 m up to 170 m; the 3D position of the boreholes was precisely measured;
- After analyzing the lithological and stratigraphical information of the boreholes, six geological cross-sections were generated, based on a digital elevation model (DEM) of the area;
- From the geological cross-sections, supplementary interpolation points were used to generate the geological model;

- The structural units of the Quaternary deposits have been identified to generate the geological model.

The generated local model, developed by litho-stratigraphic correlation using in-house software (Gogu, et al., 2011), outlines the following lithological units, from top to down:

- Urban soil (anthropogenic material) layer, with depths up to approximately 12 m;
- Clay, sandy clay, and sandy silty clay layer with thicknesses up to 10 m;
- Sand and gravel layer with thicknesses up to 14 m;
- Discontinuous clay layer with thicknesses up to 5.3 m;
- Discontinuous sand and gravel layer with thicknesses up to 6 m;
- Sand layer with thicknesses up to 12 m;
- Clay layer with thicknesses up to 11.6 m.

3.3. HYDROGEOLOGICAL DATA ASSEMBLAGE

Hydraulic head time series were available mainly for the Circului Park green area. Table 3-1 mentions the boreholes and the corresponding monitored aquifer strata. Figure 3-2 illustrates the location of the monitoring boreholes in the study area. The hydraulic-head measurements cover the time period February 2013 to July 2019.

Table 3-1 Monitoring boreholes in the Circului Park, Figure 6 shows location

No.	Borehole Code	Aquifer Stratum
1	F15C	Shallow
2	PC1LC	Shallow
3	FC1LC	Shallow
4	FM2LC	Shallow
5	FM1LC	Middle
6	F14M	Middle

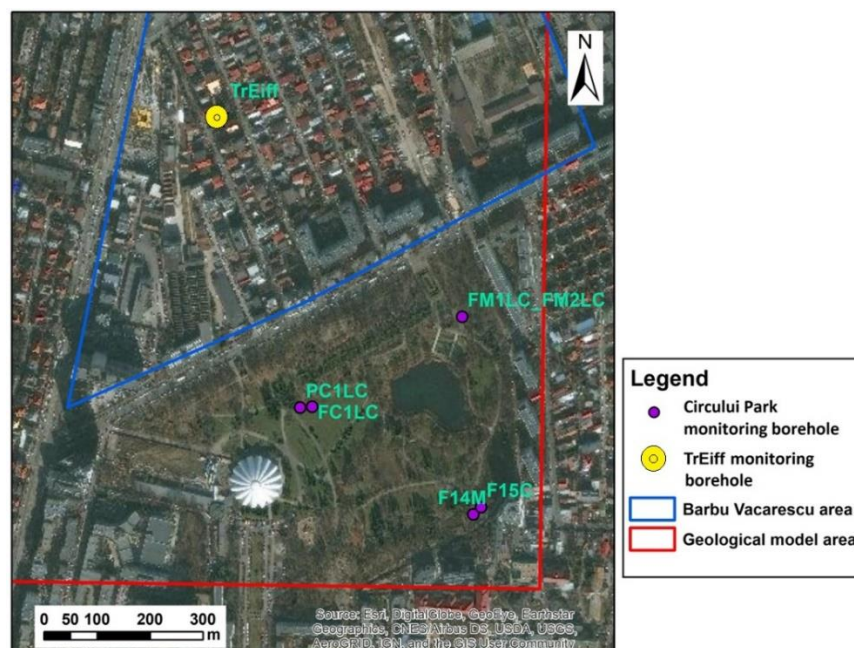


Figure 3-2 Monitoring boreholes in the Circului Park area (purple circles), located in the southeastern corner of the study area (Figure 3-1) and the monitoring borehole inside Barbu Vacarescu area (yellow)

3.4. GROUND DISPLACEMENTS IN BARBU VACARESCU AREA AND THE CONEXIONS WITH THE UNDERGROUND ENVIRONMENT

Barbu Vacarescu is one of the areas where subsidence has been revealed by all the existing SAR time series, since 1992 (Vîjdea & Bindea, 2013; Poncos, et al., 2013). The distribution of the PS points can be seen in Figure 3-3. Velocity values for the selected area with the generated geological model are between -10.72 mm/yr (red points) and $+3.88$ mm/yr (blue points) with a standard deviation of ± 1.11 mm/yr.

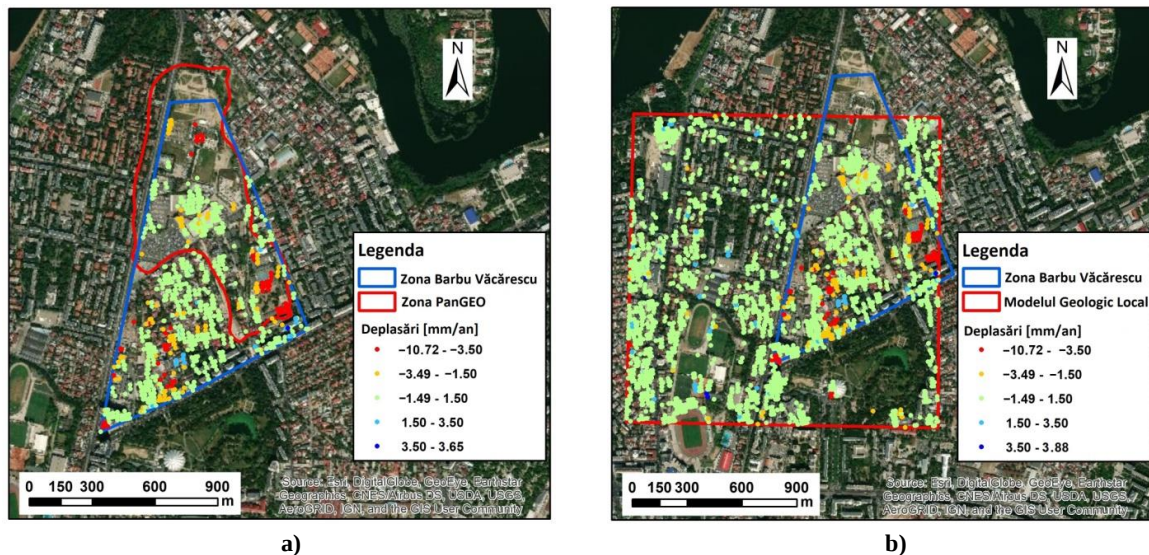
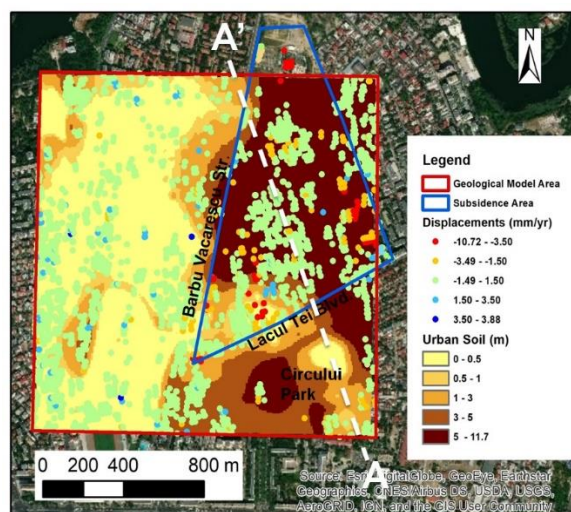


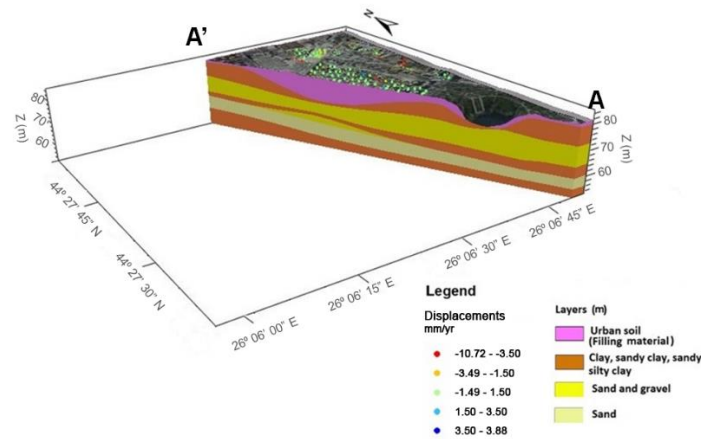
Figure 3-3 PSI in Barbu Vacarescu area (a) Red limit represents the identified subsidence area in the PANGEO project; blue limit represents the subsidence area identified in this study. (b) Red limit represents the geological model area; blue limit represents the subsidence area identified in this study.

3.4.1. Subsidence Analysis of the Anthropogenic and Geological Deposits in the Barbu Vacarescu Area

The studied area is extensively covered by a deep anthropogenic stratum as it is illustrated in Figure 3-4.



(a)



(b)

Figure 3-4 Barbu Văcărescu area: a) The thickness of the anthropogenic layer and the corresponding PS points. The geological cross-section is indicated along profile AA' crossing the Barbu Vacarescu area and Circului Park from SE to NW; b) geological model following geological cross-section AA' giving the lithological strata of the subsurface.

This urban soil layer is largely composed by urban waste due to the presence of a former quarry exploitation for aggregate construction material that has been later filled by other types of anthropogenic materials (Vîjdea & Bindea, 2013).

The trend of several PS points displacements of the analyzed area is shown by Figure 3-5. Both locations indicate an approximately linear tendency of subsidence with a mean annual value of $-5.2 \text{ mm} \pm 1.4 \text{ mm}$ and cumulative values of about -35 mm for the time span October 2014–April 2018.

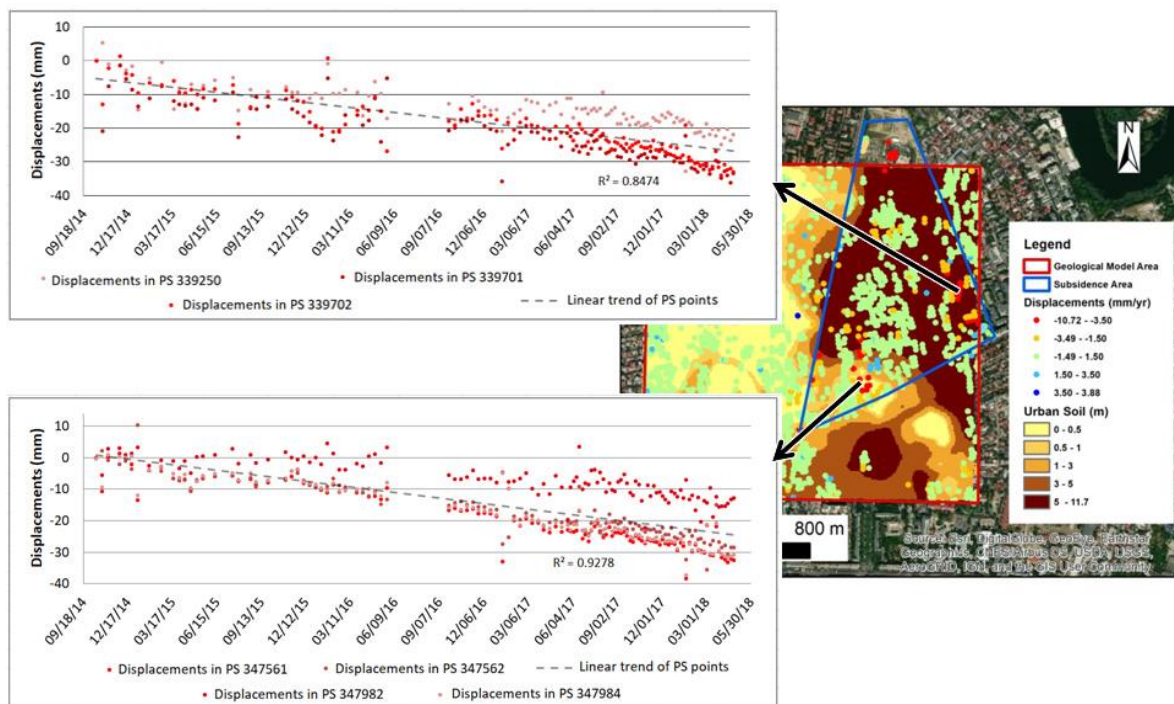


Figure 3-5 PSI displacement trends in Barbu Vacarescu area

3.4.2. Relationship between Ground Surface Displacements and the Urban Aquifer System Dynamics in the Barbu Vacarescu Area

Hydraulic-head measurements corresponding to Circului Park have been used in this study in conjunction with the vertical displacements to identify the possible connection between the

urban aquifer system dynamics and the terrain surface movements. The main steps to analyse the hydraulic head data against the vertical displacements of the Circului Park are further described. A 100 m buffer zone for the PS data was generated around each existing borehole, and a spatial query operation has been applied to identify the corresponding PS points. If PS points were found inside this buffer zone, the specific borehole and the corresponding PS points were included in the analysis. As for example for the boreholes PC1LC and FC1LC no PS points closer than 100 m could be found, due to fact that the area is covered with vegetation and therefore no PS points were obtained. Consequently, these boreholes were not included in the analysis. After verifying the available hydraulic head temporal series of F15C, data from this monitoring borehole could not be considered due to existing inconsistencies.

A further spatial analysis was based on the data from the boreholes FM1LC, FM2LC, and F14M. FM1LC and FM2LC are placed in the same location, respectively monitoring the confined middle aquifer and the shallow aquifer. These two points are part of the Bucharest city groundwater monitoring system as reported by Gaitanaru et al. (2017). Only two PS points are situated at a distance less than 100 m for FM1LC and FM2LC. Figure 3-6 illustrates them, their PS codes being 333 807 and 333 808 respectively. For the F14M monitoring borehole, the analysis was made for the middle-confined aquifer strata, as more than 60 PS points are within the 100 m buffer zone.

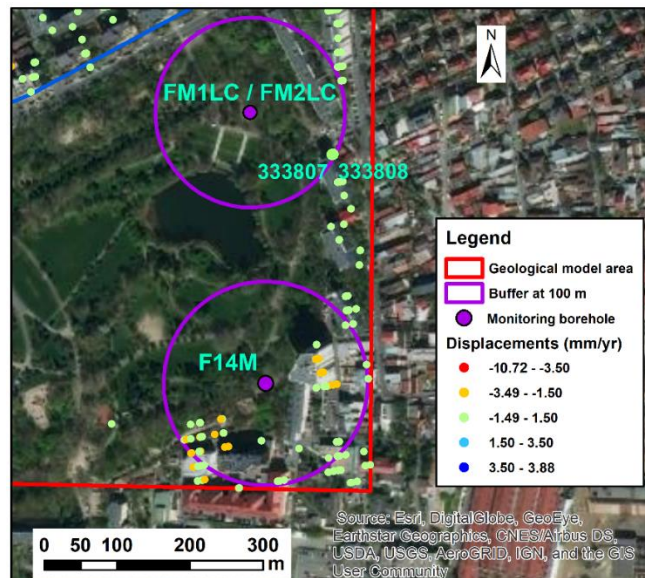


Figure 3-6 PS points situated within the 100 m buffer zone from FM1LC/FM2LC and F14M monitoring boreholes. Close-related to FM1LC/FM2LC borehole PS points codes: 333807 and 333808.

In Figure 3-7, the blue line illustrates the groundwater hydraulic head variation for the FM1LC (middle confined aquifer strata) and FM2LC boreholes (shallow unconfined strata) and a correlation with the vertical ground movement of PS data points (green lines).

For both boreholes penetrating respectively the shallow aquifer (FM2LC) and the confined middle aquifer (FM1LC), the hydraulic head has a descending trend while the area neighbouring the PS points show a slightly ascending trend. However, as the annual value of the vertical displacements for the same time period is less than -1.5 mm, for these two mentioned PS points the area can be interpreted as stable. Consequently, Figure 3-7 does not show a correlation between vertical displacements and the hydraulic head variation.

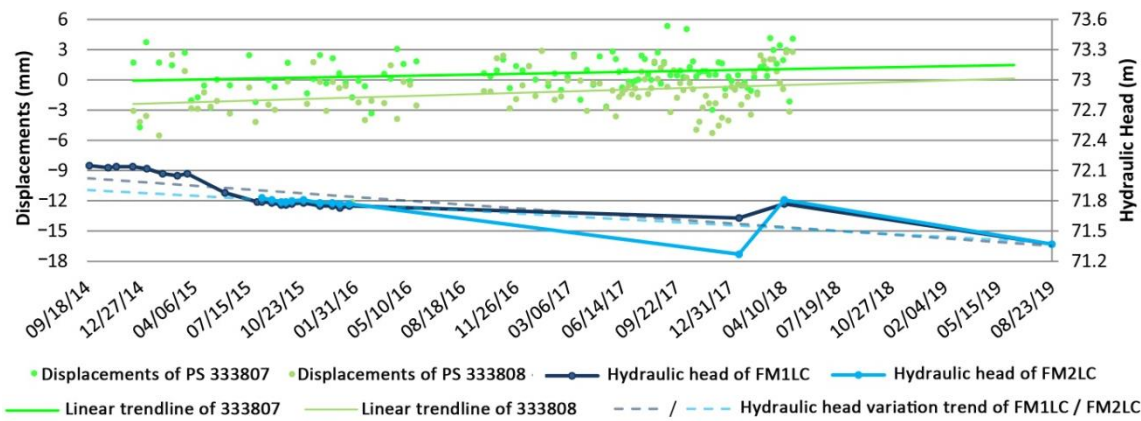


Figure 3-7 Correlation between displacements of PS points and hydraulic head of boreholes FM1LC and FM2LC.

On the contrary, for F14M borehole penetrating the middle confined aquifer, Figure 3-8 shows the correspondence of the two types of data. Here, a decrease in hydraulic head corresponds to vertical negative ground displacements (subsidence). This strengthens the hypothesis that the Circului Park area, or parts of it, has the same behavior as the study area situated in the north side of the park. Red circles represent the variation of the displacements considering the mean of the PS points inside the 100 m buffer.

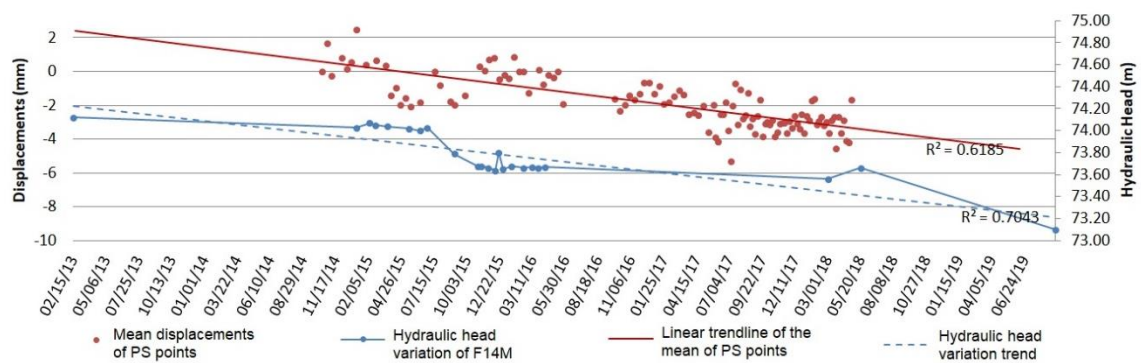


Figure 3-8 Correlation between displacements of PS points and hydraulic head. Left y-axis indicates displacements, right y-axis indicates hydraulic head variation, and the x-axis indicates the time scale.

A good correspondence is registered between the hydraulic head variation of FM2LC borehole in the shallow aquifer and the water level in Circului Lake which has a direct connection with the shallow aquifer and is representative for the area aquifer hydraulic head trend since 2006.

3.4.3. Study case of a Building situated in the Barbu Vacarescu Area

In 2011, a stability-geotechnical expertise has been made for a building situated inside the study area Barbu Vacarescu (Manea, 2016), triggered by signs of instability. Degradations occurred after the beginning of construction works in a neighboring property located in the north eastern area. The construction works involved modifications of an existing building (Figure 3-9). The geological stratification mapped in the construction site is in accordance with the geological model (Figure 3-4) and a monitoring borehole -TrEiff-, was drilled close to the boundary between the two properties, near the new building.

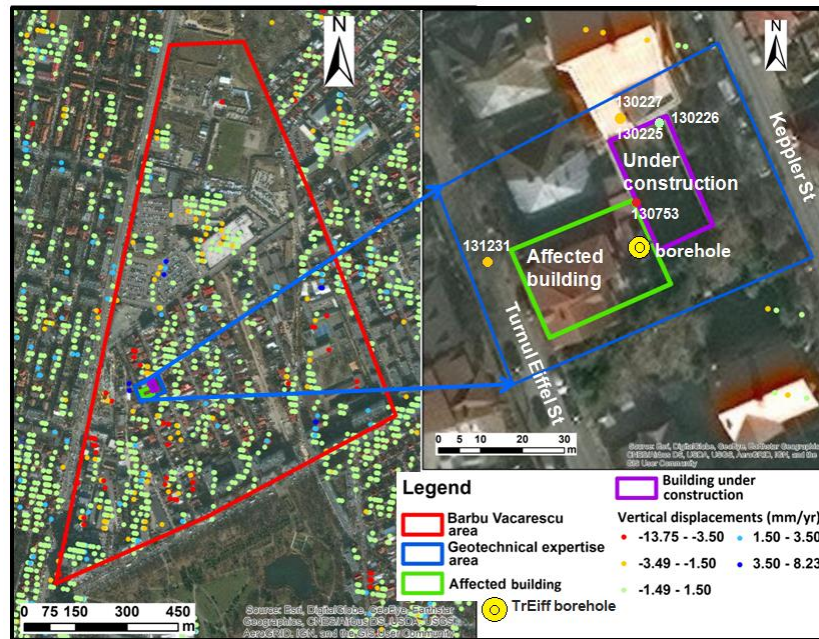


Figure 3-9 Study case on a building situated in the Barbu Vacarescu area. PSI velocity map is generated from Sentinel-1 109 Descending orbit data. Codes of PS points situated inside the studied area are marked on the map.

The main difference between the two buildings, the one showing instability and the one under-construction, is related to the foundation system. The affected building from the Turnul Eiffel Street has a slab type foundation located in the anthropogenic material stratum and the building from the neighbouring property (under construction) has a pile type foundation. The beginning of the construction works in August 2010, started on the second mentioned building (located on Kepler Street), induced ground deformations causing subsequently an instability effect on the neighbouring buildings.

The shallow aquifer, located at depths of about 9–10 m, shows continuous variations in hydraulic head with an increase from 2011 to mid of 2012 and then a decrease until June 2016. This was intercepted by the borehole drilled close to the boundary between the two properties (Figure 3-9). The alternation in hydraulic head is clearly affecting the ground stability as indicated by PS data in Figure 3-10.

The graph of Figure 3-10 shows the ground surface subsidence trend that occurs in the same period of time when the hydraulic head decreasing trend is detected.

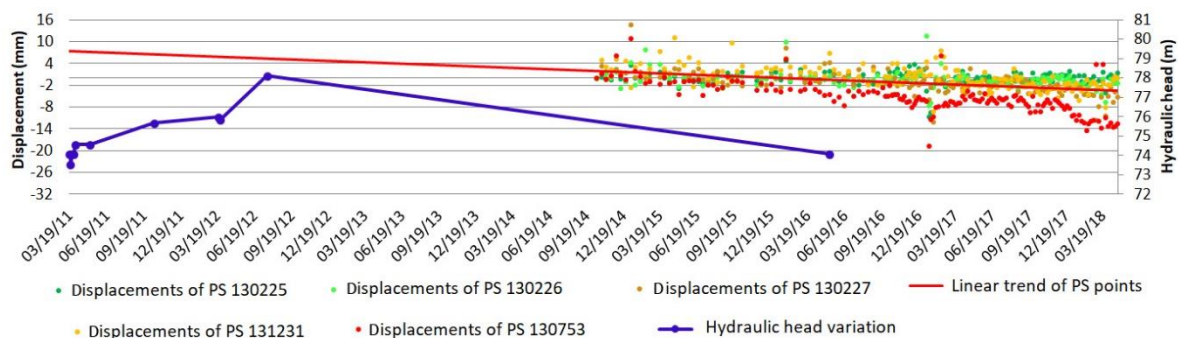


Figure 3-10 Comparison between the evolution of hydraulic head data for TrEiff borehole and displacements (left y-axis indicates displacements, right y-axis indicates hydraulic head variation, x-axis indicates time): PS points from 109 Descending orbit.

Hydraulic head measurements were available for 2011-2016, while displacements time series are available for 2014–2018 time period. Although there is an overlapping period of two years of common measurements, there is only one measurement for hydraulic head in the period August 2012–May 2016.

3.5. DISCUSSIONS AND CONCLUSIONS

One of the main advantages of the SAR techniques consists in detecting ground displacements and so improving considerably large area monitoring capability. This allows identifying specific areas affected by vertical displacements which were unknown before applying SAR monitoring and shows the evolution of areas where subsidence or uplift could occur. This is the case for the Barbu Vacarescu area, which was identified as having a subsidence trend in the SAR time series analyzed since 1992. When analyzing the PSI vertical displacements maps between 1992 and 2018, it can be clearly observed that the instability trend of this area is mainly shown by the changes of the location of the PS points indicating ground displacements and not by the predominance of the subsidence affected areas in the bounded area.

The ground movement recorded by radar satellites and the InSAR techniques does not display the cause but allows highlighting different geological, hydrogeological, or geotechnical problems that influence the ground surface and subsurface Displacement's dissimilarity trend observed for the PS points correlated to boreholes FM1LC/FM2LC and F14M might be due to the differences of the land use in vicinities of the Circului Park.

Ground weakening that occurred for the buildings analyzed in the Barbu Vacarescu area, has a combination of sources. The solutions related to foundation techniques, the presence of the urban anthropogenic material stratum, the construction activity, the seepage from the losses of the water supply system which existed before the start of construction works, the variations of the aquifer hydraulic head, have led to ground displacements and consequently to the degradation of the building described in the second study case (Turnul Eiffel Street).

Subsidence in cities, such as in Bucharest, may have multiple causes. A better understanding of the linked complex geological and hydrogeological processes relating to the urban water cycle and ground subsidence will provide improvements on urban subsurface planning and urban development.

4. ANALYSIS OF THE SUBSIDENCE PHENOMENON AT URBAN REGIONAL LEVEL: CHARACTERIZATION OF THE CRITICAL SUBSIDENCE AREA IN BUCHAREST, HIGHLIGHTED BY REMOTE SENSING TECHNIQUES

4.1. THE PURPOSE, AND THE METHODOLOGY OF THE STUDY. REGIONAL STUDY AREA

In the previous chapter of this work, characteristics at local level concerning the behaviour of areas affected by vertical land displacements have been identified, taking into account the sources producing these movements, as well as the phenomena and processes accompanying land displacements. In an attempt to identify as accurately as possible and quantify the sources that produce the vertical land displacements phenomena for wider areas, based on the

The following steps are identified for the characterization of the regional urban area:

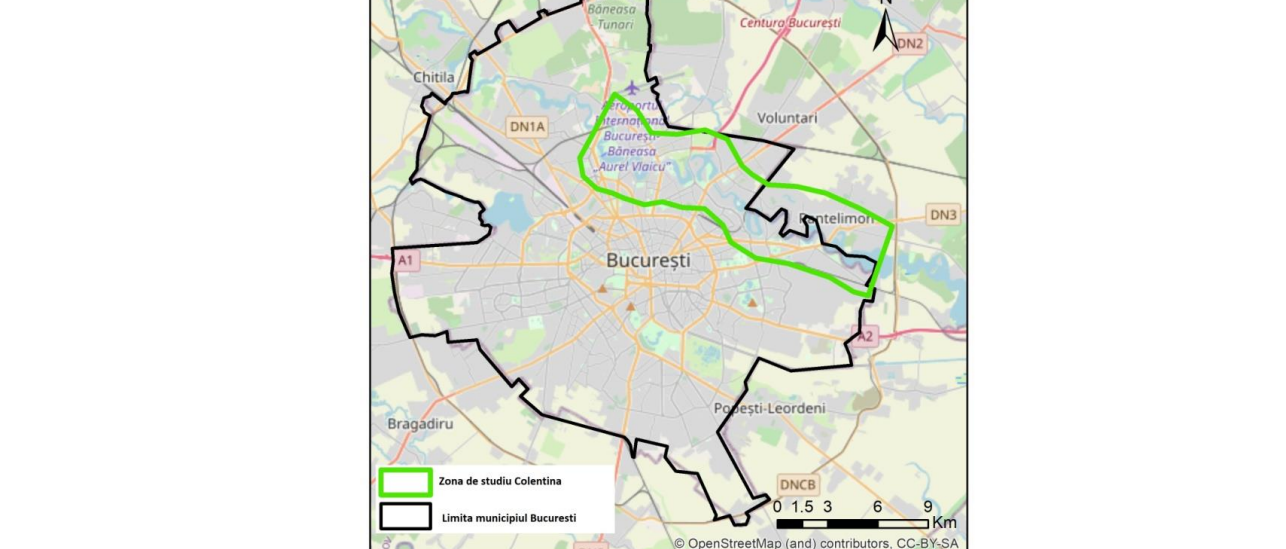
- Defining the regional urban study area

- For the characterisation of the subsidence areas within the regional area of study, complementary

Area with Displacements Geological/lithol



Figure 4-2 shows the extension of the regional study area along Colentina River corridor



4.2. DATA SOURCES USED FOR THE CHARACTERIZATION OF THE STUDY AREA

For a more detailed analysis of the area, to help understand the phenomena and processes that take place along the Colentina River corridor, several types of data sources were used, starting from data that describe the natural environment, the general conditions, up to specific data of hydrogeology, hydrology or geotechnics. The analyzed time period is 2014-2018, the same period for which the Sentinel-1 PSI land subsidence map is generated.

- Remote sensing data
 - ENVISAT ASAR- subsidence areas in 2004-2010;
 - Sentinel-1 SLC- subsidence areas in 2014-2018;
 - Sentinel-1 GRD- change detection areas in 2014-2018.
- Historical maps
 - Austrian Maps (1: 200 000) – 1910;
 - „Lambert-Cholesky” Maps (1: 20 000)- 1918;
 - Plan of the Colentina ponds before sanitation – 1936;
 - Sovietic Maps (1: 100 000) – 1970;
 - Military Topographic Maps (1: 25 000)- 1982;
 - Sovietic maps (1: 50 000) – 1985- 1990.
- Hydrological data
 - Water level in the lakes of Colentina River between 2014-2017;
- Geographical characteristics
 - Map of relief units;
 - Morphological map of Bucharest city;
 - Hypsometrics map of Bucharest city;
 - Digital Surface Model (DSM);
 - Digital terrain Model (DTM);
- Geological data
 - Geological Map (IGR);
 - Map of the thickness of Loess formation;
 - Geological cross-sections;
- Hydrogeological data
 - Hydrogeological Map of Bucharest city (1: 50 000)
 - Hydraulic-head measurements;
- Geotechnical data
 - Areas with anthropogenic deposits;
 - Geotechnical boreholes;
 - Site map of former construction materials quarries
 - Geotechnical zoning map of Bucharest
- Climatic data
 - Precipitations
 - Temperature.

4.3. EVOLUTION OF LAND INSTABILITY AREAS FOR THE REGIONAL STUDY AREA AND THE ANALYSIS OF LAND CHANGE DETECTION

Based on the PSI vertical displacement of the land surface maps, for the intervals of 2004-2010 and 2014-2018, it is possible to follow the evolution of vertical displacements in the Colentina study area (Figure 4-3). In red are highlighted the land subsidence areas in the time interval 2004-2010, and in purple are highlighted the land subsidence areas in the 2014-2018 time interval.

From the change detection map generated for the Colentina study area from Sentinel-1 GRD data, there were identified the areas where land use changes occurred in the period 2014-2018. All areas where changes occurred are marked in brown.

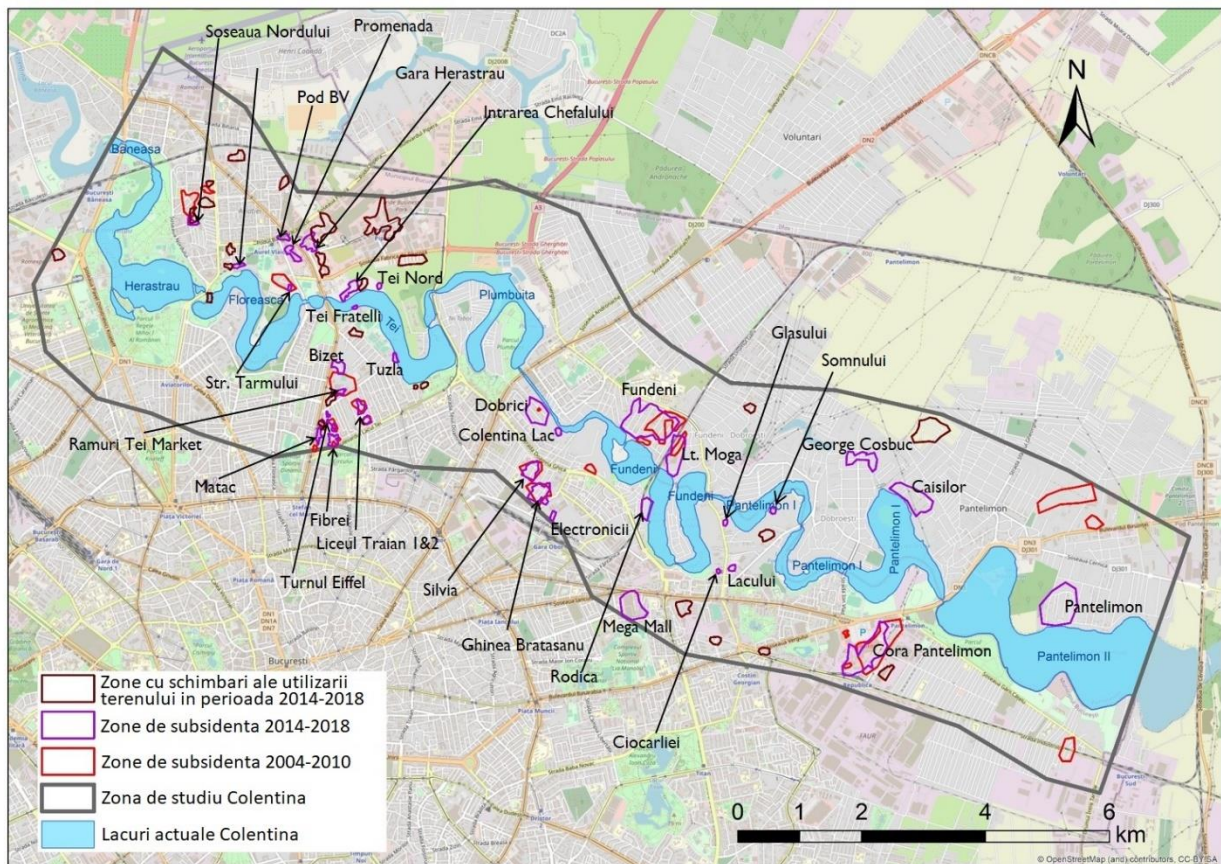


Figure 4-3 Land displacements areas inside Colentina regional study area, for periods 2004-2010 and 2014-2018, and change detected areas for period 2014-2018

4.4. TOPOGRAPHY ANALYSIS TO IDENTIFY AREAS WITH INSTABILITY POTENTIAL

A first step in order to characterize the study area is to observe the evolution of that area over a as long as possible period of time. Thus, sources of historical topographic data were searched, the oldest source being represented by the Austrian Maps (1: 200 000), which were made in 1910 (geo-spatial.org, 2021). Section 4.2 shows the historical maps consulted for the analysis of the temporal evolution from the topographical point of view of the study area. Swampy or water-covered areas in the past that now have another use may be areas with some degree of instability. Considering the areas identified in each of the historical maps, it is possible to generate a map on

which all these areas are represented. Figure 4-4 shows all these urban areas that in the past were covered with water or swamp, highlighted in red shades.

From the Geotechnical Zoning Map there were highlighted the boreholes in whose lithological description the anthropogenic deposits appear as a surface layer. In addition to the information obtained based on historical maps, from the lithological information associated with the existing monitoring boreholes in the SIMPA database of CCIAS (CCIAS, 2013), there were delimited the areas that have as surface layer anthropogenic deposits with thicknesses greater than 1 m. Figure 4-4 illustrates these delimitations and highlights in pink-purple shades.

Figure 4-4 also brings together both areas with potential instability and areas with negative vertical displacements determined from PSI maps generated from Sentinel-1 data, for the period 2014-2018 and from ENVISAT ASAR data for the period 2004-2010, as well as areas with land detected changes.

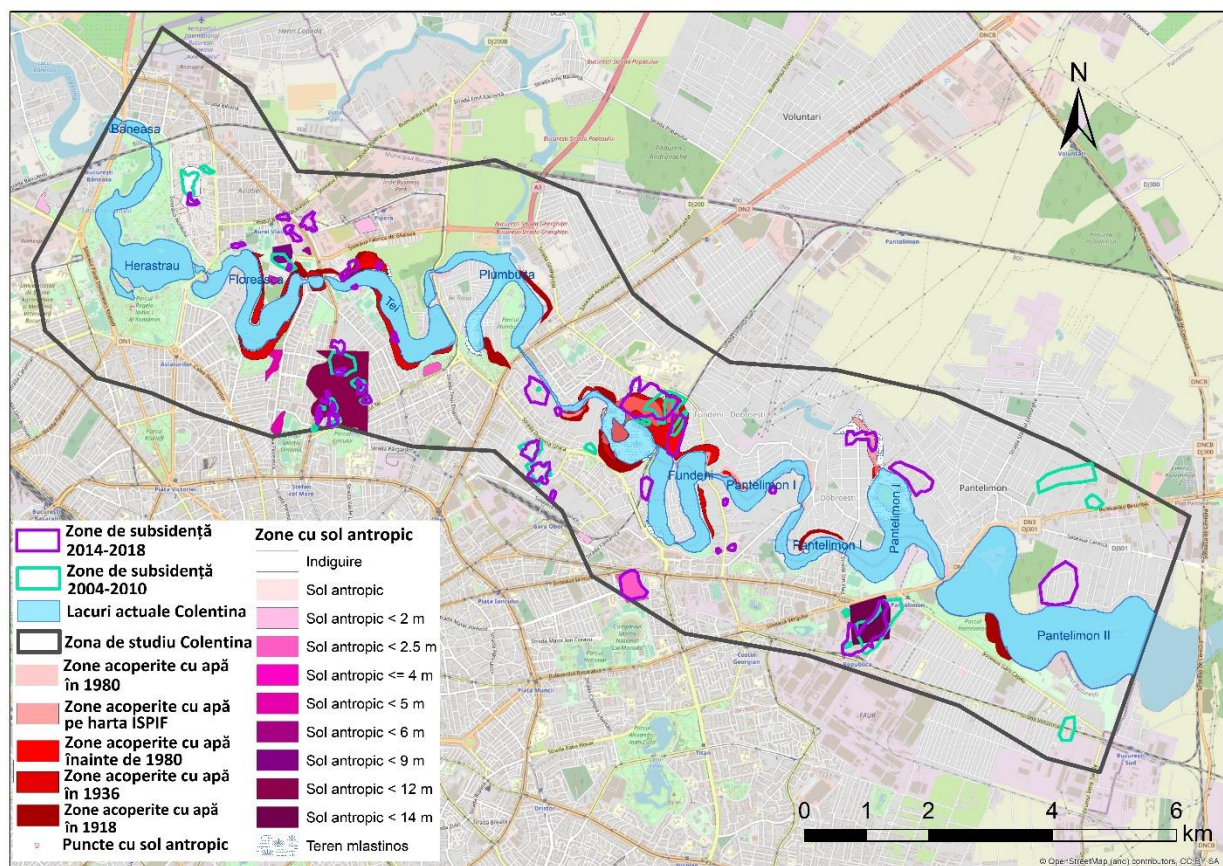


Figure 4-4 Potential instability areas and subsidence areas

For a better hydrogeological characterization of the studied area, from the CCIAS database the monitoring boreholes available for the study area were extracted. Figure 4-5 shows the location of these boreholes. In blue are marked the boreholes for which there is available only one measurement, and in dark blue there are the boreholes with more than nine measurements for the 2014-2018 time interval.

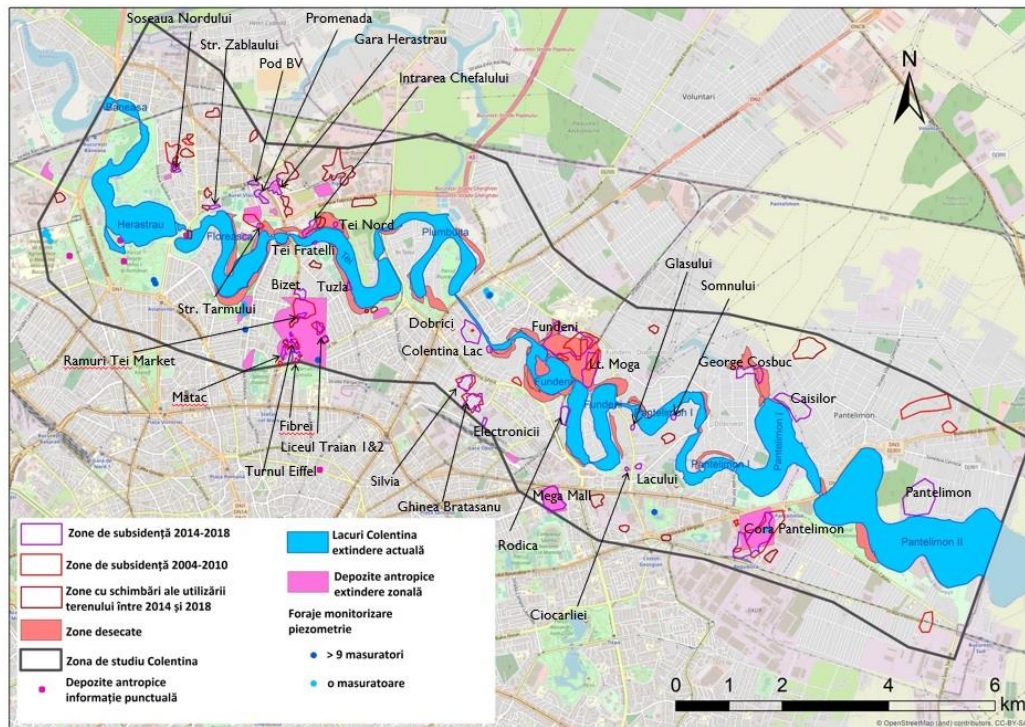


Figure 4-5 Subsidence areas, anthropogenic deposits, dried areas and monitoring boreholes (pizometry)

4.5. STUDY OF THE SUBSIDENCE AREAS

Based on the information extracted from the maps of various types that were presented in the previous subchapters, a centralization was performed for each subsidence area identified between 2014-2018, based on Sentinel-1 data from orbits 131A or 109D. Table 4-1 summarizes this centralization. There are 37 areas of instability identified from Sentinel-1 data. The columns contain the following information: 1) Area number; 2) The name of the area; 3) Sentinel-1 orbit used to generate the PSI map; 3) The situation of the area in the period 2004-2010; 4) mean annual velocity along the line of sight (LOS); 5) The distance between the centroid of the area and the lakes; 6) The presence of anthropogenic soil and its thickness; 7) The thickness of the loess layer; 8) History of the area regarding water or swamp coverage in the historical maps (dried areas); 9) The presence of a quarry of construction materials in the past; 10) Geology of the area; 11) Monitoring boreholes close to the area; 12) Depth to the shallow aquifer; 13) Depth to the piezometric level of the first aquifer.

Considering the centralized data, a detailed analysis of each subsidence area was performed, including comparative analyzes between time series of land subsidence and variations in lake level (Table 4-2), variations of hydraulic-head (Table 4-4), with variations in precipitation and variations in temperature.

The difference in slope between the subsidence areas and the lake edge was also interpreted (Table 4-3).

Table 4-1 Centralization of information on the displacements areas identified in the PSI Sentinel-1 maps for the period 2014-2018

No.	Name of the areas	PSI S1	Subsidence in the 2004-2010 period	Mean velocity (LOS) [mm/yr]	Distance lake-area [m]	Anthropogenic deposits [m]	Loess [m]	Dried area	Former quarry	Geology	Depth to the Colentina gravels [m]	Depth to the shallow aquifer (Colentina)
1	Pantelimon	131A	No	-4,9	232	No	0 - 6	bend (DSM)	No	qp2/3- Dd	0 - 5	8,7
2	Cora Pantelimon	131A	Yes	-2,4	576	2,8 – 13,8	No	No	Yes	qp2/3- Dd	0 -10	14,5
3	Caisilor	131A	No	-1,5	104	No	2,5 -9	Partly	No	qp2/3- Dd	5 -10	14,9
4	Str. George Cosbuc	131A	No	-1,1	408	No	2,5 - 9	Partly	No	qp2/3- Dd	0- 10	12,1
5	Somnului	109D	No	-4,8	54	No	< 2,5	No	No	qh2	0 -5	9,2
6	Glasului	131A	No	-3,8	84	No	0 - 6	No	No	qh2	0 -5	14,5
7	Ciocarliei	131A	No	-3,0	126	No	2,5 -6	No	Proximity	qh2	5 -10	6,8
8	Fundeni-Lacului	131A	No	-2,7	256	No	2,5 -6	No	Proximity	qh2	5 -10	12,8
9	MegaMall	131A	No	-1,4	623	0,6 -2,4	2,5 - 6	No	No	qp2/3- Dd	5 - 10	10,6
10	Str.Rodica	131A	No	-1,9	36	No	0 - 6	No	No	qh2	0 - 5	3,9
11	Str. Lt. Moga	131A	Yes	-2,4	217	No	6 - 9	Yes	No	qh2	0 - 5	6
12	Fundeni	131A	Yes	-2,3	266	No	0 - 9	Yes	No	qh2	0 - 5	6,7
13	Electronicii-H Intre Vii	131A	No	-1,5	850	No	2,5 - 6	No	No	qp2/3- Dd	0 - 5	11
14	Ghinea Bratasanu	131A	Yes	-4,8	867	No	2,5 - 6	No	No	qp2/3- Dd	0 - 5	11,5
15	Silvia	131A	Yes	-3,5	588	No	2,5 - 6	No	No	qp2/3- Dd	0 - 5	11,5
16	Colentina Lac	109D	No	-2,1	42	No	< 2,5	Partly	No	qh2	0 - 5	7,3
17	Dobrici	131A	Yes	-2,7	131	No	0 - 6	Nu	No	qh2	0 - 5	2,7
18	Tei-Tuzla	131A	No	-2,8	12	No	< 2,5	Yes	No	qh2	0 - 5	0,9
19	Matac	131A	Yes	-2,7	1019	0,5 - 6	2,5 - 6	No	Yes	qp2/3- Dd	5 - 10	8,6
20	Fibrei	131A	Yes	-2,5	1076	0 – 1,2	2,5 - 6	No	Proximity	qp2/3- Dd	5 - 10	8,3
21	Lic. Traian 1	131A	Yes	-4,1	596	7,5 - 9	2,5 - 6	No	Yes	qp2/3- Dd	5 - 10	8,3
22	Lic. Traian 2	131A	Yes	-3,6	632	7 – 7,5	2,5 - 6	No	Yes	qp2/3- Dd	5 - 10	8
23	Tr. Eiff30	131A	Yes	-2,4	985	3,5 – 7, 5	2,5 - 6	No	Yes	qp2/3- Dd	5 - 10	7,8

No.	Name of the areas	PSI S1	Subsidence in the 2004-2010 period	Mean velocity (LOS) [mm/yr]	Distance lake-area [m]	Anthropogenic deposits [m]	Loess [m]	Dried area	Former quarry	Geology	Depth to the Colentina gravels [m]	Depth to the shallow aquifer (Colentina)
24	Tr. Eiff 31	131A	Yes	-3,0	937	8 - 10	2,5 - 6	No	Yes	qp2/3- Dd	5 - 10	7,9
25	Tr. Eiff 62	109D	No	-2,5	874	8,5 - 9,5	2,5 - 6	No	Yes	qp2/3- Dd	5 - 10	7,3
26	BV Rossini	109D	No	-3,0	897	8 - 10,5	2,5 - 6	No	Yes	qp2/3- Dd	5 - 10	8,7
27	Ramuri Tei Market	131A	Yes	-1,3	731	8 - 10,5	Partly 2,5 - 6	No	Yes	qp2/3- Dd	5 - 10	10,1
28	BV Bizet	131A	Partly	-4,9	665	7 - 8,3	No	No	Yes	qp2/3- Dd	5 - 10	10
29	Tei Fratelli	131A	No	-2,7	6.8	No	< 2,5	No	No	qh2	0 - 5	0,5
30	Intr. Chefalului	131A	No	-1,7	77	No	0 - 6	Yes	No	qh2	0 - 5	3,5
31	Tei Nord	109D	No	-7,4	66	No	2,5 - 6	Yes	No	qh2	0 - 5	2,4
32	Tarmului	131A	Yes	-4,1	89	No	<2,5	No	Proximity	qp2/3- Dd	0 - 5	7
33	Promenada	109D	No	-1,3	460	No	No	No	Yes	qp2/3- Dd	5 - 20	0,3
34	Gara Herastrau	109D	No	-2,1	611	< 2	15-17	No	No	qp2/3- Dd	10 - 20	15,8
35	Pod BV	109D	No	-1,1	547	No	2,5 - 6 partly	No	Partly	qp2/3- Dd	10- 20	8,3
36	Zablului	131A	No	-1,3	75	No	<2,5	No	No	qh2	0 - 5	2,3
37	Sos. Nordului	131A	Partly	-1,4	513	No	2,5 - 6	No	No	qp2/3- Dd	0 - 5	4,27

Table 4-2 Examples of comparisons between the variation of land displacements in the PSI points in the identified subsidence areas and the variation of the water level in the nearest lake

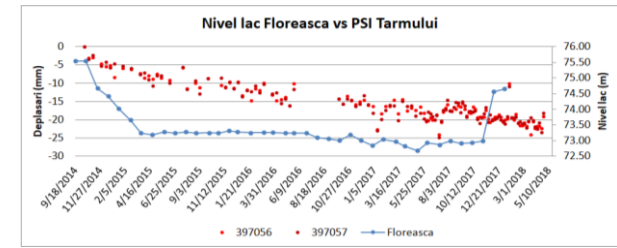
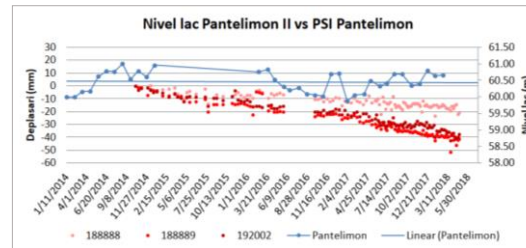
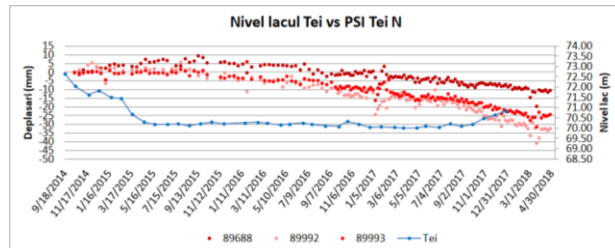
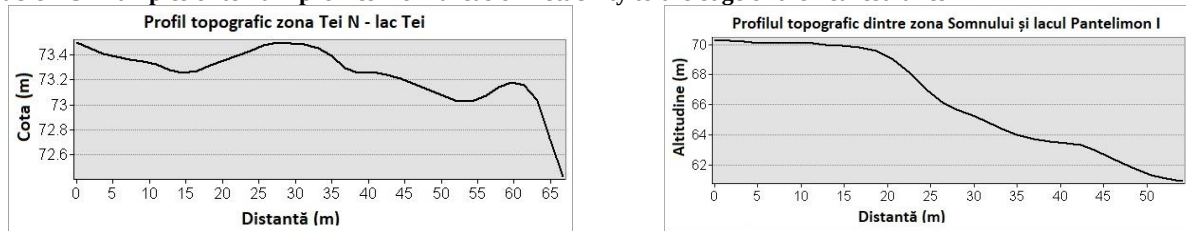
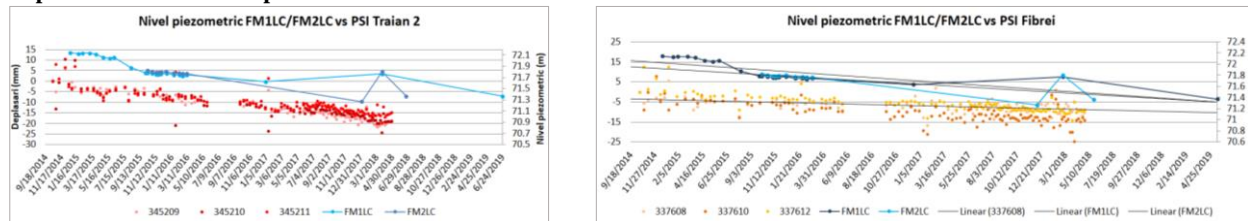


Table 4-3 Examples of terrain profiles from areas of instability to the edge of the nearest lakes

Table 4-4 Examples of comparisons between the variation of the hydraulic-head in boreholes and the variation of displacements in the PSI points


4.6. DISCUSSIONS AND CONCLUSIONS REGARDING THE ANALYSIS OF THE COLENTINA REGIONAL STUDY AREA

In all the analyzed cases along the Colentina river corridor, a major concordance between the variation of the water level in the lakes and the vertical movements of the neighboring areas it is very clear. In all cases, the decrease of the water level in the lakes is accompanied by the subsidence of the studied areas in their vicinity. The strong hydraulic connection between the lakes of Colentina River and the shalooow aquifer is well defined, being highlighted by numerous studies (CCIAS, 2015b) (Gogu, et al., 2015; Serpescu, et al., 2013) and hydraulic head data, although limited, validate this interaction. Consequently, this study highlights the clear link between the subsidence phenomena registered in the urban areas adjacent to the Colentina lakes and the decrease of the hydraulic head level in the shallow aquifer (Colentina gravels). The development of a monitoring system through observation wells, in order to ensure a sustainable management of the entire city is absolutely necessary. Hydrogeological data provide a coherent picture of the behavior of the underground environment of cities and document the development of underground and underground constructions.

Regarding the precipitation, in this study it was possible to establish only to a very small extent a correlation between their variation and the values of land movements. This analysis was introduced due to the fact that in the specialty literature are there are presented studies in which the very strong link between the variation of precipitations and the variation of land displacements was highlighted. It is especially specific to areas where the climate is characterized by a rainy season followed by a dry season, and the mineral matrix of the aquifer consists of clays (Chen, et al., 2016).

Another conclusion is related to the location of the study area, which includes the meadow and the terraces of the Colentina river. From the previous descriptions and analyzes it appears that the Colentina regional area is an area with strong urban dynamics, being subject to numerous works, with the aim of extending the residential areas to the edge of the lakes. The lakes themselves are landscaping works carried out to stop the negative effects of floods caused by the Colentina River, as well as to transform wetlands into urban or buildable recreational land.

Because there is a strong hydraulic connection between the shallow aquifer and the lakes along the Colentina River, landscaping and construction work in the areas adjacent to these lakes may affect the development of the phenomena and processes associated with the hydraulic connection.

The land vertical displacements generally have a combined cause, involving problems of geotechnics, hydrology, hydrogeology and geological aspects. The fact that in urban areas both the underground and the above-ground part are exposed to more factors than in the extra-urban area, makes it very difficult to accurately identify the causes and effects of certain phenomena that occur in this area. Here comes the historical component, related to the fact that in the past various works have been carried out without keeping coherent and concrete information on how these works were carried out. In the rare cases where this information exists, it is not sufficiently detailed.

Considering the combined cause of the subsidence, another component is noted for the Colentina area that has or may have an important role in the occurrence of vertical displacements. Thus, the construction of tall office or residential buildings, which are carried out in many locations in the Colentina study area, are provided with several underground levels to provide parking spaces, which makes the deep expansion of the building to exceed in many cases 10 m. It was observed that the depth to the Colentina gravels depending on the elevation of the land, in 26 areas out of the 37 studied, is less than 10 m. The design and then use of underground parking pumps to reduce the hydraulic head level of the upper aquifer (implementation of depletion systems), so as not to endanger the works during construction, and then to allow the optimal use of parking lots. Depending on the volume of water pumped, this operation can have effects on the flow of groundwater and can lead to the occurrence of displacements at the surface of the land. In the study area there are currently only a few monitoring boreholes, some of them being too far from the areas of instability, which makes it impossible to use them in the analyzes performed in the area. For those subsidence areas and for which there are groundwater monitoring boreholes in the area of incidence, the common trend of decreasing hydraulic head values and vertical displacement values was observed.

The location of the monitoring boreholes is a major problem in the urban space. The development of a network of hydraulic head monitoring stations in a correct and coherent way would demonstrate a link between groundwater pumping through drainage systems and vertical land displacements. The data could also be used to quantify land surface displacements generated by lowering the hydraulic head by pumping, taking into account other factors leading to vertical displacements. The presence of anthropogenic deposits associated with groundwater fluctuations can have an even stronger effect in terms of vertical displacement of the soil, compared to cases where the surface layer is natural terrain. Another association that can produce displacements of the land surface is given by the existence of swampy soils that can have as a top layer a heterogeneous anthropogenic deposit.

In the case of the analysis of the evolution of the water level in the lakes along the Colentina river, a decreasing trend was observed, as well as in the case of land displacements determined from the PS points, from the identified subsidence areas. An exception is Herastru Lake, where there is a slight increase in water levels for the period 2014-2017.

The time interval for which the analyzes were performed is relevant, being a period of four years. However, the use of a longer time series allows a broader analysis and identification of

processes with greater accuracy. This would make it possible to identify more accurately the causes of subsidence, namely predominantly geotechnical, geological or hydrogeological aspects.

An impediment in performing as coherent analyzes as possible is also related to the data acquisition interval and their heterogeneity. If there are daily measurements for climatic data, in the case of PS measurements the acquisition interval depends on the spatial resolution of the satellite. In recent years, this interval has decreased significantly with the launch of Sentinel satellites. The volume of data to be processed is another aspect for which various solutions are configured both in terms of storage capacity and processing capacity.

The presence in the Colentina Field of clays and ballast, used as construction material, led to the emergence of several quarries in this area of the city, favoring the subsequent emergence of heterogeneous anthropogenic deposits that are a major cause of vertical displacements in the study area.

5. CONCLUSIONS ON THE USE OF REMOTE SENSING TECHNIQUES FOR MONITORING THE DYNAMICS OF URBAN GROUNDWATER

5.1. GENERAL CONCLUSIONS

Techniques for observing and monitoring the subsidence phenomenon

From the research, it can be highlighted that in the last three decades, InSAR techniques have brought new elements in estimating and interpreting parameters specific to groundwater and groundwater dynamics, by investigating the effects on land surface of these parameters.

Currently, there are several methods for determining the vertical land displacements, which can be listed in chronological order: precise leveling, extensometry, GNSS observations, InSAR techniques (InSAR, DInSAR, MTI). These techniques can be used independently or can be combined or used for comparisons and validations, in order to better understand the phenomena of subsidence. Each of these methods has advantages and disadvantages, which can be highlighted according to several criteria:

- Considering the location of the instrument with which the observations are made in order to determine the vertical land displacements, a first classification of the various methods can be made. Thus, precision leveling and extensometry are methods that use field-based instruments (ground surface leveling, and extensometry in monitoring boreholes) that were developed before the era of space technologies. GNSS observations and InSAR techniques are space technologies, with monitoring tools on board the satellites.
- If we refer to accuracy, although it is the oldest method of monitoring, precise leveling is still the most accurate method of monitoring vertical movements. In the case of InSAR techniques, there is an evolution regarding the accuracy of the obtained results, so that from the centimeter order obtained with the help of InSAR classical technique, it was reached a magnitude of the measurements in the case of MTI techniques of millimeter order.
- Depending on the area covered, there are methods that use point networks (geometric leveling, extensometry, GNSS) and methods that have a surface coverage, which can

exceed 100 km² (InSAR, DInSAR, MTI techniques). This allows the identification of specific areas that are affected by landslides that were unknown before the use of SAR monitoring methods and shows the temporal evolution of land displacements for areas that are prone to subsidence or uplift phenomena.

- Depending on the temporal resolution, there are methods for which monthly or annual field campaigns can be established (geometric leveling, extensometry, GNSS observations) and methods for which the temporal resolution is given by the temporal resolution of the satellites with which the data are acquired (InSAR, DInSAR, MTI techniques)
- Depending on the human and financial resources required, the first three methods (precise leveling, extensometry, GNSS observations) make punctual acquisitions, which involve the use of more important human (field measurement campaigns) and financial resources, compared to InSAR techniques that they can cover very large areas with the involvement of a single person for data processing.

Regarding the SAR satellite data used to determine displacement and to detect terrain changes, there are several advantages, but also limitations related to temporal and spatial aspects. Thus, from a temporal point of view, we can talk about limiting the availability of SAR satellite data usable for determining land displacements, for the last decades. Before the 1990s there was not enough SAR data to generate interferograms needed later in time series processing. The advantage of using satellite data is that it offers the possibility to work in post-processing, the determination of land displacements can be determined at present for an area that in the 1990s was not of interest for monitoring. The global nature of satellite procurement allows the tracking of a current area of interest to be carried out from the moment satellite data is acquired. This is not possible with in-situ measurements. If it is an area with a history of subsidence older than 30 years, when SAR data were not available, the displacement values for that period can only be known if in-situ measurements were performed there. At the same time, with the evolution of satellite radar missions, the temporal resolution of the data has now increased for the Sentinel-1 mission, with data available every 6 days, considering data from both satellites, Sentinel-1A and Sentinel-1B, compared to 35 days in the case of ERS-1/2 and Envisat ASAR missions, in the 1990s, 2000. Analyzing the spatial aspects, there is an evolution of the pixel size of radar images of European missions, from 30 x 30 m in the case of ERS 1/2 and Envisat ASAR missions, up to 5 x 20 m in the case of the Sentinel-1 mission.

With regard to remote sensing techniques, there are limitations on their use in terms of land cover. Thus, for the areas covered with vegetation, the coherence is lost, which means that PS points are not generated in those areas to indicate the displacements. Another limitation is associated with processing capacity. Although a single person is sufficient as staff resources to perform the processing, the software and hardware requirements are quite high.

Analyzing this work from the point of view of the satellite sensors used and the results obtained, regarding the comparison of the two maps produced from ENVISAT data and Sentinel-1 data, we can see the improvements that have been made over time with radar sensor missions. Thus, from the spatial resolution of 30 x 30 m specific to the ENVISAT ASAR sensor, we moved to the spatial resolution of 5 x 20 m for Sentinel-1 sensors, which led to improved coherence and the generation of a higher number of PS points per surface unit.

Subsidence phenomena generated by anthropogenic modification of groundwater dynamics and highlighted by InSAR techniques

From the specialty literature it can be seen that, worldwide, studies mention groundwater pumping as one of the major causes of subsidence phenomena. The case studies in the first chapter document the spread of this phenomenon around the globe. A comparison can be made between countries with a long history of groundwater pumping and where subsidence areas are beginning to have very small values or even no more vertical displacements (eg Tokyo, Japan) and countries with a recent history of groundwater pumping. Negative vertical land displacements occur faster in areas with a more recent history of subsidence, due to the very large amounts of groundwater that are pumped to meet water needs for the population and industry (eg., Indonesia). For areas with a long history of subsidence, as many adverse effects have occurred over time as a result of subsidence (eg., flood risk, sewerage and water supply problems, sinking of certain buildings), measures have been taken to reduce negative vertical displacements.

Following the two maps of land movements that were generated, the consistency of the results of the two time intervals was observed, many of the areas of instability identified on the map of land displacements for 2004-2010 showing the same trends in 2014-2018.

The most precise results are obtained by combining the results from several methods of determining the land displacements, an important aspect being the validation of the results. Following the results obtained in previous works for monitoring land displacements in Bucharest (Gheorghe, et al., 2020; Armas, et al., 2017; Poncos, et al., 2014; Vîjdea & Bindea, 2013), it was found that the results obtained in this work are consistent with the conclusions of the other authors. These analyzes are also a way to validate the obtained results.

Acquisitions from satellite radar sensors provide several types of information that can be used for applications in various fields. In the case of land surface displacement analyzes, land surface change detection information can be used in the process of identifying the source of the displacements. By combining the PSI technique with the detection of changes in the land surface, the search area of the source of displacement is more correctly delimited and thus the identification of the cause of displacement can be determined more easily.

Considering the coverage of radar acquisitions, the common use of the two techniques can be achieved for large areas and can replace some of the limitations of the PSI technique.

To partially compensate the unavailability of hydrogeological data, in many analyzed areas, it was proposed to use a new cartographic product that consists of a combination of the PSI land displacement map and the terrain change detection map.

The phenomenon of subsidence at the local urban level

Regarding the case of the Barbu Văcărescu area, it was identified as an area of instability in the SAR time series analyzed since 1992. Following the vertical land displacements in the PSI maps generated for time intervals between 1992 and 2018, it can be seen that the trend of instability is not mainly due to spatial extension and the predominance of subsidence PS points, but to changes in the location of PS points indicating terrain displacement. In many cases the instability PS points of the various displacements maps of the terrain movements are not found exactly in

the places where they were located in the previous maps, but sometimes are in the immediate vicinity of those sites or partially comprise the former locations. Considering that the common attribute of the whole area is given by the presence of the anthropogenic layer of fillings containing waste and construction materials from demolition, the particularities being given by local geotechnical differences or local groundwater dynamics, it can be concluded that spatial displacement trends of the PS points highlight this type of urban layer. Highlighting the behavior of this type of urban stratum, existing in most large urban agglomerations, is pioneering and represents an important research direction that requires future investigations (Radutu, et al., 2020).

The high heterogeneity of urban anthropogenic material can seriously affect the ground stability in the urban environment.

The phenomenon of subsidence at the urban regional level

Considering the study at the urban regional level, in the cases analyzed along the Colentina river corridor, a major concordance is observed between the variation of the water level in the lakes and the vertical movements of the neighboring areas. In all cases, the decrease of the water level in the lakes is accompanied by the subsidence of the studied areas in their vicinity. The strong hydraulic connection between the Colentina lakes and the shallow aquifer is well defined, being highlighted by numerous studies (CCIAS, 2015b) (Gogu, et al., 2015; Serpescu, et al., 2013) and piezometric data, although limited, validate this interaction. Thus, this study highlights the clear link between the subsidence phenomena registered in the urban areas adjacent to the Colentina lakes and the decrease of the hydraulic head in the shallow aquifer (Colentina gravels).

The presence of anthropogenic deposits associated with groundwater fluctuations can have an even stronger effect in terms of vertical land displacement, compared to cases where the surface layer consists of natural deposits. Another association that can produce land displacements is given by the existence of swampy soils as a basis for a heterogeneous anthropogenic deposit.

The time interval for which the analyzes were performed is relevant, being a period of four years. However, the use of a longer time series allows a broader analysis and identification of processes with greater accuracy. This would make it possible to identify more accurately the causes of subsidence, namely predominantly geotechnical, hydrogeological or geological aspects.

Most of the time there is a main factor generating instability, however, there is an accumulation of phenomena and processes that trigger and maintain the land displacements, and may be involved geological, lithological, geotechnical, hydrological, hydrogeological factors. Thus, in most cases, there is a direct connection between the main cause of displacement and the processes that take place in the underground environment.

Hydrogeological aspects characteristic of the urban environment and their influence in the processes of vertical land displacement

Considering the urban hydrogeological time series available for the local study area and for the regional study area, for the subsidence areas located in the area of incidence of monitoring boreholes, the common tendency of decreasing hydraulic head values and vertical displacement

values was observed. An extremely important aspect that limits the obtaining of very precise results regarding the magnitude of the contribution of groundwater dynamics in the size of vertical land displacements, is the very low spatial and temporal availability of data from monitoring boreholes, such as hydraulic head measurements. This impediment was observed both in the local study area and in the Colentina regional area. For accurate results and well-founded analyzes, it would be necessary to implement a network with monitoring stations correctly located and managed coherently by the authorities. Also, a database with permanent and temporary depletions could help to form a correct picture of possible sources of displacement. The lack of long-term urban hydrogeological data and time series makes it difficult to obtain quantitative analyzes.

It was observed that in many cases, both in the studied instability areas and in the neighboring areas, there were residential or office buildings, with depths of more than 10 m. In those areas, from the set of hydrogeological data used, it is known the depth to shallow aquifer. In some cases, it reaches a depth of less than 3 m and consequently it is assumed that there may be situations where basement pumps are used periodically or continuously to reduce potential seepage into rooms built in the basement. Depending on the volume of water pumped, this operation may have effects on the flow of groundwater, as well as on the occurrence of displacements at the surface of the land. The presence of the network of monitoring stations for piezometric measurements would allow the validation of this hypothesis and could also be used to try to quantify the amount of displacement that is generated by this pumping phenomenon, taking into account the other factors that lead to vertical land displacements.

It is necessary that the hydrogeological data to be analyzed together with the existing geological and geotechnical data in the study area. In the subsidence areas of the Colentina area, the great influence of anthropogenic deposits in the occurrence of vertical land displacements was observed, taking into account the underground and above-ground infrastructures and constructions in the areas of interest.

5.2. PERSONAL CONTRIBUTIONS IN THE USE OF REMOTE SENSING TECHNIQUES FOR MONITORING THE DYNAMICS OF URBAN GROUNDWATER

The following personal contributions may be listed:

- Carrying out the documentary study on the current state of research on the use of remote sensing techniques in monitoring the urban underground environment;
- Obtaining the distribution map of land vertical displacements by combining the observations from the descending orbit with those from the ascending orbit Sentinel-1 for the interval 2014-2018. This is the first work at national level in which the value of vertical displacement is thus obtained;
- Processing of the the map corresponding to the detection of land surface changes for an interval of 4 years (2014-2018), for the Bucharest city;
- Development of a new cartographic product, obtained by combining the PSI map with the terrain change detection map that can be used to more accurately identify potential

factors involved in the occurrence of subsidence phenomena, as well as in the sustainable management of the urban environment;

- Carrying out the study on monitoring land displacements and characterizing the urban underground environment in Bucharest, using remote sensing techniques;
- Development of the analysis at local urban scale regarding the hydrogeological and geotechnical phenomena and processes in the urban underground environment associated with land displacements, determined by PSI techniques (Barbu Văcărescu area, Bucharest);
- Documenting the spatial evolution of the shape of lakes along the Colentina River from 1918 to the present.
- Extending the analysis of the subsidence phenomenon at urban regional level for the entire corridor of the Colentina river and identifying-characterizing the critical subsidence areas, highlighted by remote sensing techniques

5.3. POTENTIAL FUTURE RESEARCH DIRECTIONS

Following the experience gained in the development of this thesis, we have identified the following future research directions:

- Application and improvement of a new cartographic product, obtained by combining the PSI map with the terrain change detection map, which can be used to more accurately identify potential factors involved in the occurrence of subsidence phenomena and sustainable urban management.
- Development of analysis tools, based on remote sensing techniques, which can be taken over by urban area managers as well as by those responsible for implementing public policies in the field of territorial development.
- The development of a monitoring system based on a network of urban monitoring stations of hydraulic head measurements for the aquifer system consisting of the first two aquifers that have a major interaction with anthropogenic activities would allow an integrated management of the underground environment in Bucharest and demonstrate a link between the groundwater pumping through the depletion systems and the vertical land displacements. A useful tool for the urban environment would be the use of a complex urban monitoring station that would include an artificial reflective target, corner reflector, as well as surface sensors and components for the underground environment, including various sensors and equipment. This monitoring tool can improve procedures for determining land displacements in urban areas. Reflective artificial targets can provide consistent SAR data, thus obtaining information related to the land displacements and for areas covered with vegetation. For each station location, a wide range of other relevant parameters can be recorded by in-situ techniques. Grouped in the same urban monitoring station, centered around an inclinometric tube, these facilities have the ability to measure the vertical and horizontal displacements of the ground and the underground environment, piezometric levels, as well as other physical and chemical parameters (Gogu, et al., 2016). In this way, the influence of geotechnical and geological peculiarities in the occurrence of vertical landslides could be identified.

- Detailed study of existing anthropogenic deposits, in terms of hydraulic composition and characteristics, in order to analyze their behavior associated with groundwater level fluctuations will document and improve studies on vertical displacements of the urban surface and provide a solid documentary basis for geotechnical investigations of future above-ground and underground constructions and infrastructure elements.
- Swampy soils in urban areas, which may or may not have an upper layer of a heterogeneous anthropogenic deposit, must be correctly and thoroughly analyzed and documented, because they represent a real danger by generating accidents in case of development of regional urban infrastructure elements.
- To complete the geological and geotechnical studies, the inclusion of seismic microzoning information of the city of Bucharest may be of interest.
- Considering the temperature variations, it is possible to study the order of magnitude of the influence that the temperature has on the measurement value of the field displacements, taking into account the different materials that the persistent targets in the field have.

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