5th Joint International Symposium on Deformation Monitoring (JISDM), 20-22 June 2022, Valencia, Spain
DOI: http://doi.org/10.4995/JISDM2022.2022.13899

Monitoring of land subsidence in the city of Recife/Brazil using Sentinel-1 SAR interferometry

Wendson de Oliveira Souza[1], Antonio Miguel Ruiz-Armenteros[2], Jaime J. da Silva Pereira Cabral[3, 4]

[1] Department of Transports, Federal University of Piauí (UFPI), 64049-550 Teresina, Brazil, (wendsonsouza@ufpi.edu.br)
[2] Department of Cartographic, Geodetic and Photogrammetry Engineering, Microgeodesia Jaén Research Group (PAIDI RNM-282), Center for Advanced Studies on Earth Sciences, Energy and Environment CEACTEMA, University of Jaén, 23071 Jaén, Spain, (amruiz@ujaen.es)
[3] Department of Civil and Environmental Engineering, Federal University of Pernambuco (UFPE), 50670-901 Recife, Brazil, (jaime.cabral@ufpe.br)
[4] Department of Civil Engineering, Polytechnic School University of Pernambuco (UPE), 50720-001 Recife, Brazil

Key words: *land subsidence; Sentinel-1; PSInSAR; Recife*

ABSTRACT

One of the main causes of land subsidence in the world is the exploitation of groundwater above the regeneration capacity of the aquifer systems. However, the rapid urban growth in estuarine areas can also contribute to the development of this phenomenon. An example of this occurs in the city of Recife, northeastern Brazil. The municipality is built on an estuarine plain composed of several rivers (Capibaribe, Beberibe, Tejipió), which formation results from the occupation of humid areas and mangroves. In recent decades, the excessive removal of water resources from the subsoil has caused the reduction of more than 100 meters of the deep aquifer piezometric level in some places. The presence of these factors in Recife may contribute to land subsidence. To detect this phenomenon, the Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) technique was used. The dataset consisted of 135 Sentinel-1A Interferometric Wide (IW) Single Look Complex (SLC) images from September 2016 to April 2021. The images were acquired in descending orbits and VV polarization. The results of the PSInSAR analysis reveal that in Recife there are several areas of land subsidence with a rate close to -15 mm/year. The main occurrence of soil settlement is observed in large recently built areas in the west zone, and small areas in the north zone. Minor cases occur in the southern zone due to the exploitation of groundwater. The identification of these land subsidence areas can help in the study of urban drainage to avoid flooding sites and in the adoption of mitigating measures for the suitable use of underground water resources.

I. INTRODUCTION

Land subsidence is present in several locations around the world. Surface movement can occur in native and/or built-up areas. In general, the displacement is slow and gradual. However, over the years its effects can accumulate and reach significant values. This can cause irreversible damage to the population and the environment.

Land subsidence is related to natural and human factors (Prokopovich, 1979). The main cause of this phenomenon comes, above all, from the anthropic influence on natural resources. That is, in the capture of groundwater, ores, oil, and natural gas. Among these, the excessive exploitation of groundwater represents the main cause of land subsidence on the world stage. The surface changes motivated by the use of aquifer systems account for almost 80% of the occurrences on the planet (Wang, 2017).

In that regard, urban development is a complex challenge. It is present, mainly, in large cities and metropolises. It involves social, economic, and housing issues. Urban sprawl can impact the environment and infrastructure. Sometimes, the damage is significant in emerging countries due to the disorderly occupation of urban spaces and the pressure that it exerts on the water supply system.

The description of this reality can be seen in several Brazilian cities. An example of this occurs in Recife, the capital of Pernambuco state, located in the northeast Brazil. The municipality is built on an estuarine plain made up of several rivers (Capibaribe, Beberibe, Tejipió), precisely in an area of the delta and lower valley of the Capibaribe River that establishes a kind of archipelago city in its layout (Melo, 1978).

In the last 40 years, the urbanization of Recife has presented high growth in the sectors of industry, commerce, transport, and real estate. The rapid urban expansion, however, reveals several environmental problems, such as suffocation of drainage with the emergence of flooding areas, insufficient recharge of aquifers due to surface impermeabilization, reduction of the aquifer level due to the accentuated exploitation of groundwater, landfill of flooded areas with surface instability (Gusmão Filho, 1998).

The participation of these last three problems contributes to the development of land subsidence in several places of Recife (Luna *et al*., 2017; Bedini, 2020). This geological phenomenon implies a lowering of the surface and causes greater concern in urban areas. Land deformation can cause significant impacts on infrastructure and the environment, cause economic and social damage, and jeopardize people's quality of life (Abidin *et al*., 2015).

In Recife, over the last four decades, the population growth has caused extensive intervention in the physical environment with changes in the physiognomy and structure of the city. This may have resulted from the absence or fragility of measures adopted in territorial planning. This finding can be seen in the sharp use of groundwater resources and in urban expansion over unstable plains (estuarine zones, reclaimed areas).

The use of groundwater has occurred in large part in the plain, effectively, since the 1970s. The use intensified between 1993 and 1998 when the population of the Metropolitan Region of Recife (RMR) goes through a long period of water rationing due to drought in the region. However, the excessive withdrawal of aquifer systems during this period causes the lowering of the piezometric surface, which reaches 100 m in the south of the city (Cabral *et al*., 2008; Montenegro *et al*., 2009).

The city of Recife has one of the highest densities of wells in the country with almost 13,000 captures, most of which are illegal and of unknown existence by Organs public administration agencies (Alisson, 2013). The southern zone of Recife is responsible for the largest number of wells in the city. The region concentrates a large portion of the high-income population which leads to the concentration and verticalization of buildings.

In order to avoid the excessive exploitation of groundwater in Recife, at the end of the last century, a zoning scheme for exploitable areas was created. By means of this model, the drilling of new wells for pumping groundwater in the neighborhood of Boa Viagem (zone A) is prohibited due to the water decrease in the Cabo aquifer, located in the southern region (Costa *et al*., 1998).

The risk of lowering the land in this region is a matter of attention on the part of the technical-scientific community, management bodies, and inhabitants. The excessive exploitation of groundwater decreases the potentiometric surface of the aquifer and reduces the pressure of the pores that support the overlying layers of the soil. In addition, as a result, it can lead to reduced water supply and compromised water security.

The study of land subsidence due to the reduction of groundwater using a geodetic technique originates from the application of terrestrial measurement methods, such as GNSS (Romão *et al*., 2003; Santos *et al*., 2010; Santos *et al*., 2012; Luna *et al*., 2021) and precision geometric leveling (Luna *et al*., 2017). Among these techniques, so far, the slow sinking of soils in the southern zone is capable of being detected by geometric leveling.

The investigation using this method reveals a drop of -3.86 cm in altitude value for one of the levels analyzed between 1958 and 2015. The vertical displacement speed is estimated at -0.68 mm/year for the area of restriction of the zone “A” of the zoning of exploitable sites, in the neighborhood of Boa Viagem (Luna *et al*., 2017). The slow lowering of the terrain in this region may indicate that the phenomenon is at an early stage of development (Santos *et al*., 2012).

According to Scott (1978), the time interval required to complete soil consolidation varies from a few years to tens of years (compaction, large-scale water exploitation, surface loading, hydrocompaction). In this sense, the process of land subsidence can be difficult to predict. It demands specific studies for each case.

In addition to the exploitation of groundwater, the subsidence of Recife's soils is also the result of rapid urban growth in estuarine areas. The municipality is built on the estuary of the Capibaribe River and other small rivers that share the same river mouth. Over the last five centuries, Recife has developed with the recovery of large areas of land in stretches of streams, swamps, and mangroves (Cabral *et al*., 2008).

Historically, the urban expansion of Recife began in the 17th century with port activity in the city center. From that time until the 19th century, changes took place from the center of Recife towards the areas drained by the Capibaribe River due to the presence of existing rural activity in its vicinity. This involves using this river to transport sugarcane production to its mouth in the Atlantic Ocean, where the port of Recife is located.

From the 20th century to the present time, the urban evolution of Recife remains active with changes in the contour and stability of the city due to the incorporation of new spaces and geographic features. During this period, Recife grows at an accelerated rate through the creation of landfills in flooded areas. The urban growth over these sites represents 19 km^2. This is equivalent to 17.5% of the plain geological unit and 9.1% of the total area of the city (Gusmão Filho, 1998).

The use of PSInSAR technology in the determination of areas of surface instability due to recent urbanization in Recife occurs in a pioneering way in the work of Bedini (2020). That study uses Sentinel-1 images (from April 2017 to September 2019) to detect drawdown values of up to -15 mm/year in several neighborhoods in the west zone. In some cases, the rate is up to -25 mm/year in small areas due to the construction of buildings in the last decade.

In this context, it is observed that the extensive human intervention in the physical environment of Recife contributes to surface instability. The city lives with the risk of land subsidence due to two factors: the exploitation of underground water resources and recent urbanization. In view of this, the objective of the research is to detect surface displacement. For that, it uses the PSInSAR technique in this study.

The use of this technology employs a SAR dataset consisting of 135 Sentinel-1A images, Single Look Complex (SLC), and Interferometric Wide (IW) mode for the period from September 2016 to April 2021. The images are acquired in orbits descending and VV polarization. The PSInSAR results reveal that land subsidence in Recife remains active. There are several drawdown areas with a rate close to -15 mm/year.

The main occurrence of land subsidence is observed in large newly built areas in the west zone, and small areas in the north zone. There are indications of smaller cases in the southern zone resulting from the exploitation of groundwater. The identification of cases of land subsidence can help in the urban planning of the city, such as: improving urban drainage and promoting the sustainable use of groundwater resources.

II. Study Area

Recife has an area close to 218 km^2 and it is delimited by latitudes (8°9'S and 7°55'S) and longitudes (35°1'W and 34°50'W). It is the capital of the State of Pernambuco, located in northeastern Brazil (Figure 1). It is a commercial and tourist city, formed by a coastal plain. The formation of the plain results from fluviomarine sediments, produced by marine transgressions and regressions.

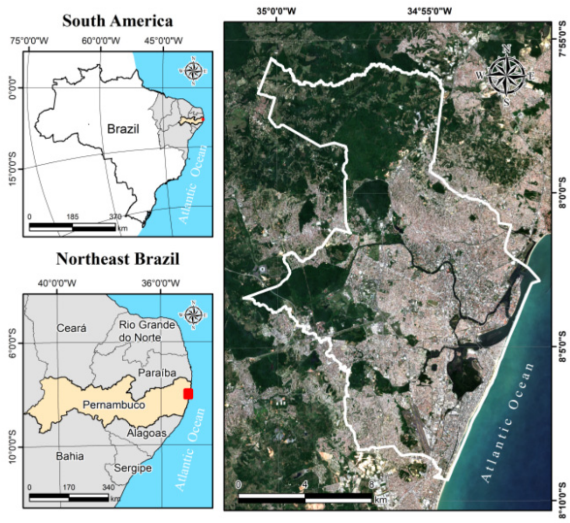

Figure 1. Location of Recife in Sentinel-2 image.

Recife is surrounded by hills, the Atlantic Ocean and several rivers (Capibaribe, Beberibe, Tejipió) that cross its domains. The composition of its area is distributed in: 67.43% of hills, 23.26% of plains, and 9.31% of aquatic. Much of the urbanization of the city is inserted in a relief surface of the plain. It has an altitude a little above sea level (Figure 2).

The urban expansion of Recife occurs in the areas of plains towards the hills. It has a high rate of urbanization due to the presence of buildings and paved road systems. It has large vertical buildings in the most coastal locations of the city, that is, in real estate areas with great monetary value. Currently, the human occupation of Recife represents more than three-quarters of natural spaces in the municipality.

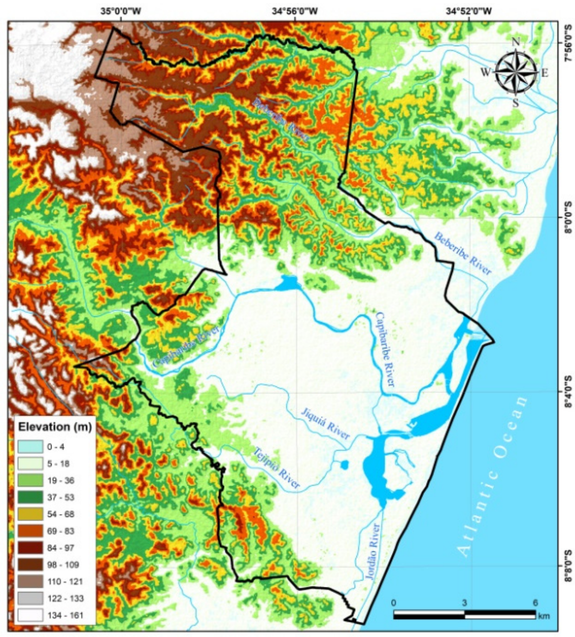

Figure 2. Elevation of Recife in SRTM image.

III. InSAR Data and Methods

From the Copernicus Open Access Hub platform (https://scihub.copernicus.eu/dhus) of the European Space Agency (ESA) and the European Commission (EC), 135 Sentinel-1A VV-polarization images were obtained for the period from 25 September 2016 to 8 April 2021 from the descending Track 9. The selected sub-swath was IW1 with a mean incidence angle of 32.9° and a spatial resolution of 3.4 x 22.5 m (range x azimuth).

The deformation determination resulted from the exploration of the interferometric phase calculated from the phase difference between two SAR images acquired at different times (Figure 3), in almost the same satellite position (Hanssen, 2001).

The displacement information derives from the interferometric phase which is influenced by several factors, according to Equation 1 (Crosetto *et al.*, 2016):

$$\varphi_{Int} = \varphi_{Displ} + \varphi_{Topo} + \varphi_{Atm} + \varphi_{Orb} + \varphi_{Noise} + 2k\pi \qquad (1)$$

where φ_{Int} = interferometric phase
φ_{Displ} = displacement phase
φ_{Topo} = topographic phase
φ_{Atm} = atmospheric phase
φ_{Orb} = orbital phase
φ_{Noise} = noise phase
k = noise phase

The PSInSAR technique (Ferretti *et al.*, 2001) was used to monitor the deformation of the urban area of Recife.

The method selects a number of points (or targets) known as Persistent Scatterers (PS).

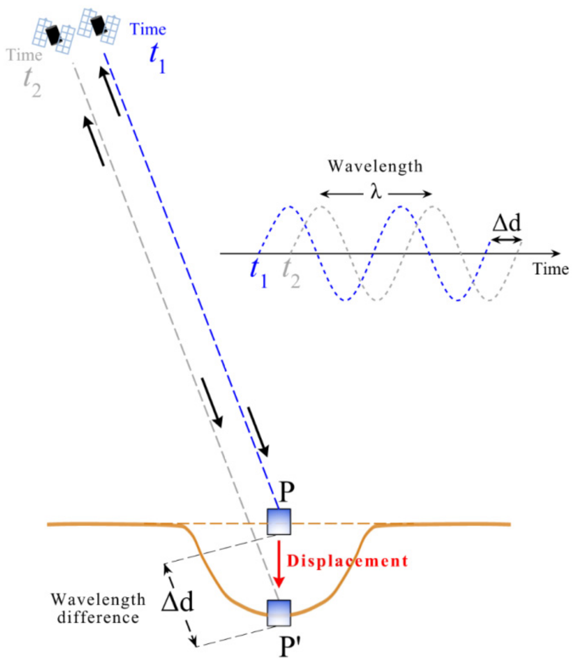

Figure 3. Deformation measurement scheme.

According to Crosetto *et al.* (2016), the PSs represent a specific class of DInSAR techniques, which exploits multiple SAR images acquired over the same area, and appropriate data processing and analysis procedures to separate φ_{Displ} from the other phase components represented in Equation 1.

The conduction of PSInSAR analysis in this work took place using SARPROZ (Perissin, 2020). The technique was used in the classical multitemporal InSAR (MT-InSAR) processing, in which the linear deformation estimate was adopted in time to generate deformation time series.

The set formed by N-1 differential interferograms was made from the choice of a single N master SAR image, chosen on October 21, 2018 (Figure 4). The software selected the master image automatically to minimize spatial and temporal decorrelations.

The co-registration of the SAR images was related to the master image using Precise Orbit Ephemerides (POE), then the initial differential phase was extracted. Topographic phase removal was performed with a Digital Elevation Model (DEM) SRTM 30 m. The selection of PSs candidates (PSC) was based on different parameters, such as Amplitude Stability Index (ASI), spatial coherence, and reflectivity.

The Atmospheric Phase Screen (APS) estimate resulted from PSC over stable locations in the area of interest (Figure 5). The removal of APS occurred using PS points with a value equal to 0.8 for the ASI. For the final processing step, PS pixels with temporal coherence greater than 0.7 were selected. The main products of the PS procedure resulted in the Line-Of-Sight (LOS) velocity and deformation time series.

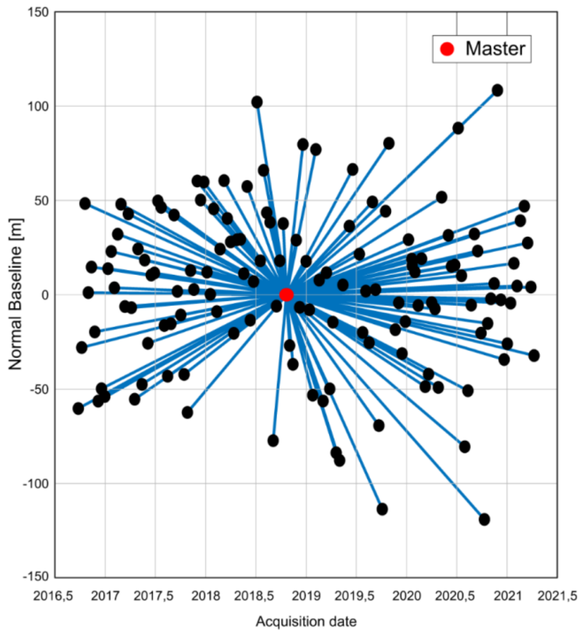

Figure 4. Each point represents an image in the normal baseline/temporal baseline space and each link is an interferogram.

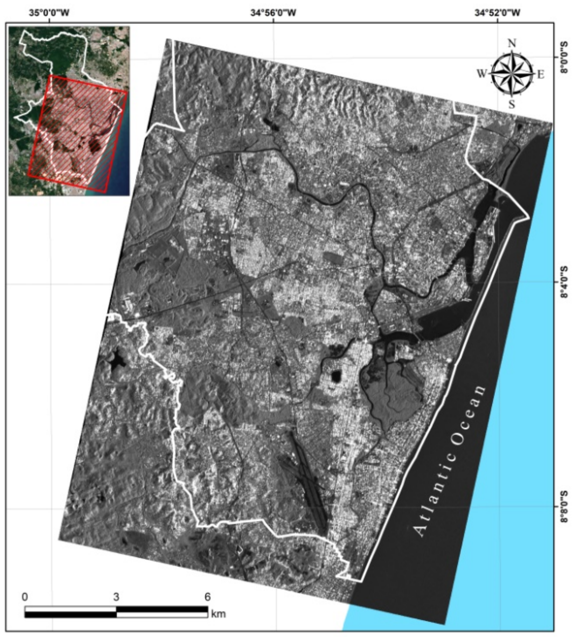

Figure 5. Sentinel-1 image of the Recife study area.

IV. Result and discussion

The investigation of land subsidence in the city of Recife covered a time interval of 4.5 years of InSAR interferometric monitoring, from September 25, 2016 to April 8, 2021. Over this period, the average revisit time of Sentinel-1 images was of 12.2 days, with a maximum variation of 24 days and a minimum of 12 days.

The PSInSAR monitoring study involved 44,588 measurement points, most with a temporal coherence value equal to 0.75. The points covered an area of 153,037 km^2 of Recife. Analysis of these data revealed several sites of land subsidence in the city (Figures 6 and 7). The main occurrences were in the west zone.

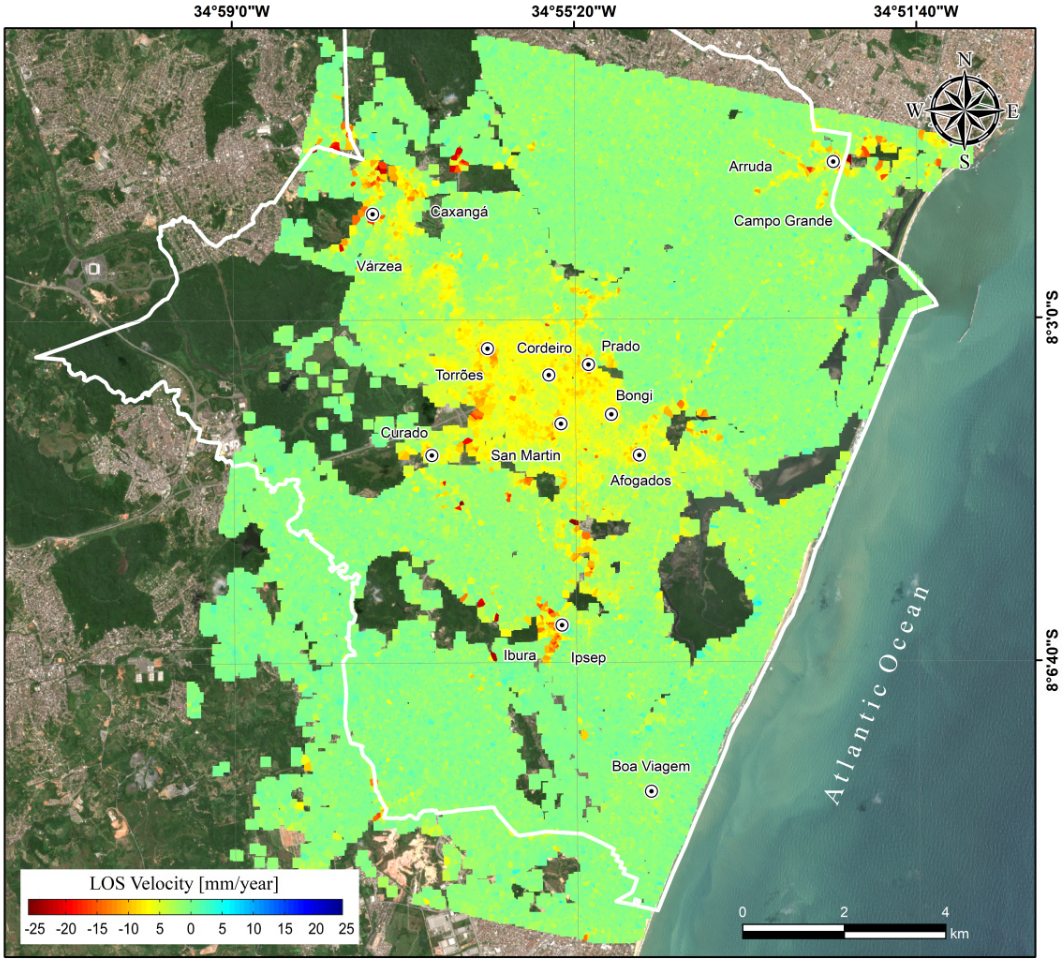

Figure 6. Deformation LOS velocity map.

In this region, large areas of drawdown with a rate of up to -15 mm/year were observed in the neighborhoods of Curado, Cordeiro, Torrões, San Martin, Afogados, Bongi, Prado, Várzea and Caxangá. Similar cases, but with a smaller area, occurred between the neighborhoods of Ibura and Ipsep, responsible for the largest sinking rate in the city, with a rate close to -18 mm/year. The situation in the west may be due to the compaction of soils in newly built areas.

In this regard, similar case, but with a smaller area, also occurs in the northern zone of city between the neighborhoods of Arruda and Campo Grande with a velocity equal to -16.8 mm/year.

In addition to these locations, there were signs of lowering in the south due to the exploitation of groundwater. The velocity was -2.5 mm/year in areas affected by the piezometric reduction in Boa Viagem neighborhood.

V. Conclusions

The use of the PSInSAR technique reveals several cases of land subsidence of Recife. The widespread human intervention is responsible for surface instability. This is due to the recent urbanization process with the recovery of flooded areas and the exploitation of groundwater with piezometric level reduction.

The main occurrences occur in the west of Recife. The region has large areas of drawdown with a LOS rate of up to -15 mm/year in the neighborhoods of Curado, Cordeiro, Torrões, San Martin, Afogados, Bongi, Prado, Várzea and Caxangá. There are cases of smaller area with a value close to -18 mm/year in the neighborhoods of Ibura and Ipsep, responsible for the biggest sinking in the city. The causes may be due to soil compaction in newly built areas. The process can take several years for settlement.

The recent urbanization also caused smaller areas of land subsidence in the northern zone, with a velocity close to -17 mm/year between the neighborhoods of Arruda and Campo Grande.

In addition to these regions, there are signs of lowering in the south related to the exploitation of groundwater. The LOS velocity is around -2.5 mm/year in areas affected by the piezometric reduction in the neighborhood of Boa Viagem.

Thus, the development of Recife requires care in several aspects. The identification of land subsidence areas can help in the study of urban drainage to avoid flooding sites and in the adoption of mitigating measures for the suitable use of groundwater resources.

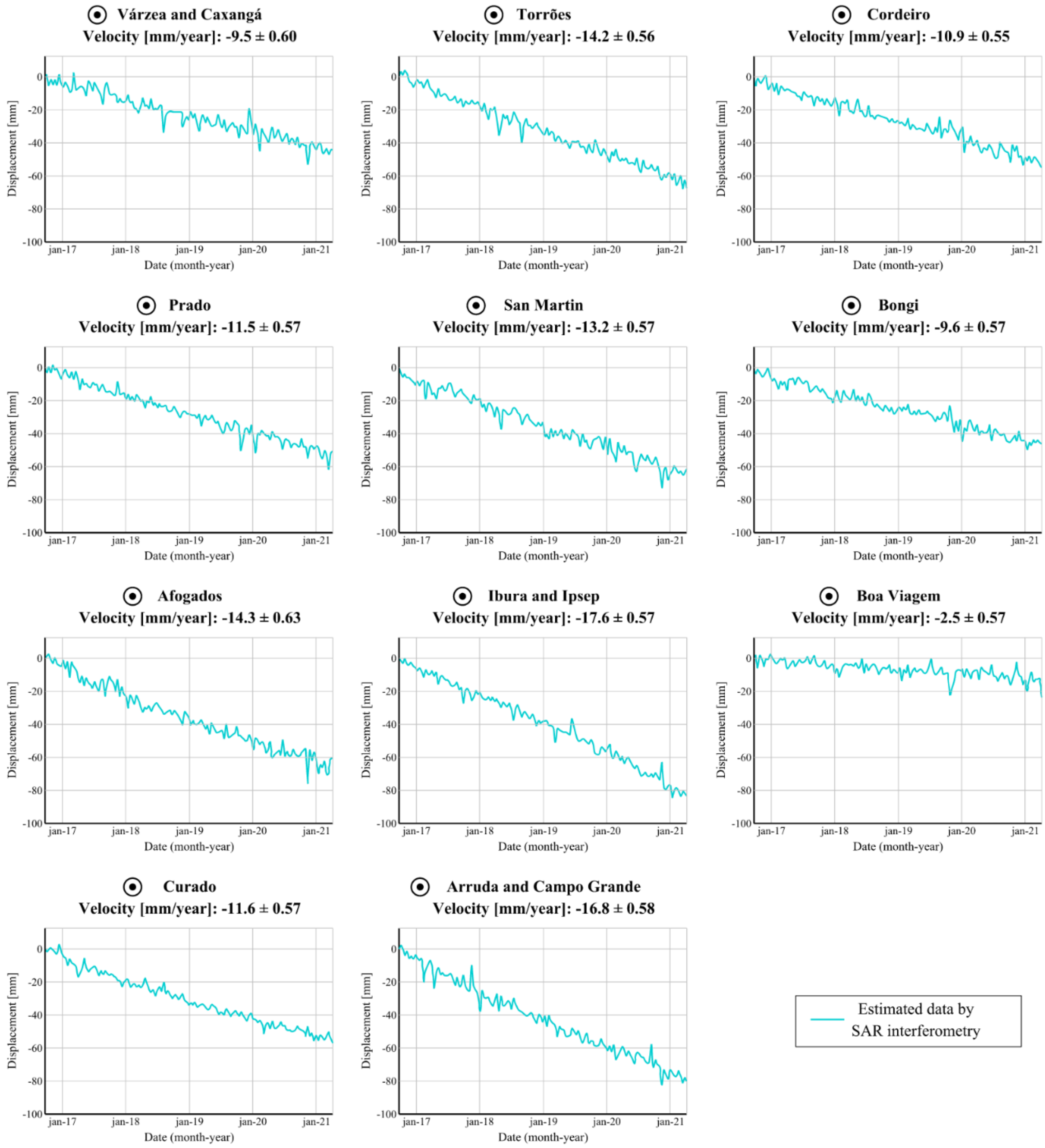

Figure 7. Estimated deformation time series.

VI. Acknowledgements

Sentinel-1 data were freely provided by ESA through Copernicus Programme. Data have been processed by SARPROZ (Copyright (c) 2009-2022 Daniele Perissin). Research was supported by POIUJA-2021/2022 and CEACTEMA from University of Jaén (Spain), and RNM-282 research group from the Junta de Andalucía (Spain).

References

Abidin, H.Z., H. Andreas, I. Gumilar, T.P. Sidiq, and M. Gamal, (2015). Environmental Impacts of Land Subsidence in Urban Areas of Indonesia. In: *FIG Working Week 2015*, Sofia, Bulgaria, pp. 1-12.

Alisson, E. (2013). Aquíferos do Recife correm risco de salinização. Available in: https//agencia.fapesp.br/aquiferos-do-recife-correm-risco-de-salinizacao/183778.

Bedini, E. (2020). Persistent Scatterer Interferometry of Sentinel-1 Time Series to Detect Ground Subsidence in the City of Recife, Brazil. *Journal of Hyperspectral Remote Sensing*, Vol 10, No. 1, pp. 1-9.

Cabral, J.J.S.P., V.P. Farias, M.D.C. Sobral, A.L.R. De Paiva, and R.B. Santos, (2008). Groundwater management in Recife. *Water International*, Vol 33, No. 1, pp. 86-99.

Costa, W.D., J. ManoeL Filho, A. Santos, W.D. Costa Filho, A.B. Monteiro, F.J.A. Souza, A.V.G. Lopes, A.J.C. Santos, M.C. Silva Filho, and M.J. Silva, (1998). *Estudo Hidrogeológico da Região Metropolitana do Recife*. Convênio IDRC-UFPE-FADE. Recife, p. 128.

Crosetto, M., O. Monserrat, M. Cuevas-González, N. Devanthéry, and B. Crippa, (2016). Persistent Scatterer Interferometry: A Review. *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol 115, pp. 78-89.

Ferretti, A., C. Prati, and F. Rocca, (2001). Permanent Scatterers in SAR Interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, Vol 39, No. 1, pp. 8-20.

Gusmão Filho, J.A., (1998). *Fundações do Conhecimento Geológico à Prática da Engenharia*. Recife: Editora Universitária UFPE, p. 345.

Hanssen, R.F., (2001). *Radar Interferometry: Data Interpretation and Error Analysis*. Kluwer Academic Publishers, p. 308.

Luna, R.M.R., S.J.D.A. Garnés, J.J.S.P. Cabral, and S.M. Santos, (2017). Groundwater Overexploitation and Soil Subsidence Monitoring on Recife Plain (Brazil). *Natural Hazards*, Vol 86, No. 3, pp. 1363-1376.

Luna, R.M.R., S.J.D.A. Garnés, J.J.S.P. Cabral, and S.M. Santos, (2021). Suitability of GNSS for Analysis of Soil Subsidence in Recife in a Highly Urbanized Coastal Area. *Natural Hazards*, Vol 106, No. 3, pp. 1821-1837.

Melo, M.L., (1978). *Metropolitan Expansion and Underdevelopment: The Case of Recife*. Recife: UFPE, p. 257.

Montenegro, S.M.G.L., J.J.S.P. Cabral, A.L.R. Paiva, A.A.A. Montenegro, J.G.A. Demetrio, and G.L. Cavalcanti, (2009). Águas Subterrâneas na Zona Costeira da Planície do Recife (PE): Evolução da Salinização e Perspectivas de Gerenciamento. *Revista Brasileira de Recursos Hídricos*, Vol 14, No. 3, pp. 81-93.

Perissin, D., (2022). SARPROZ software. Official product web page: http://www.sarproz.com.

Prokopovich, N.P., (1979). Genetic Classification of Land Subsidence. In: *Evaluation and Prediction of Subsidence*, ASCE, pp. 389-399.

Romão, V.M.C., A.S. Silva, and S.M. Santos, (2003). Metodologia para Determinação de Subsidência de Solo na Região Metropolitana do Recife. In: *III Colóquio Brasileiro de Ciências Geodésicas*, Curitiba, pp. 1-12.

Santos, S.M., V.M.C. Romão, G.G. Seeber, and J.J.S.P. Cabral, (2010). Detecção de Deslocamentos Verticais Usando GPS em Áreas Costeiras. *Revista Brasileira de Cartografia*, Vol 62, No. 2, pp. 137-144.

Santos, S.M., J.J.S.P. Cabral, and I.D.D.S., Pontes Filho, (2012). Monitoring of Soil Subsidence in Urban and Coastal Areas Due to Groundwater Overexploitation Using GPS. *Natural Hazards*, Vol 64, No. 1, pp. 421-439.

Scott, R.F., (1978). Subsidence – A Review. In: *Evaluation and prediction of subsidence,* ASCE, pp. 1-25.

Wang, N., (2017). Estudio de Subsidencia por Extracción de Fluido. *Dissertation (Master)*, Escuela Técnica Superior, Universidad Politécnica de Madrid, pp. 33.