

# MONITORING OF HASHTGERD LAND SUBSIDENCE INDUCED BY OVEREXPLOITATION OF GROUNDWATER USING SAR INTERFEROMETRY

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## ABSTRACT:

It was recognized that a large area in Hashtgerd plain, in the vicinity of Tehran, is subject to the land subsidence. GPS continuous measurements and precise leveling surveys carried out by National Cartographic Center of Iran (NCC) recognized the land subsidence occurrence in Hashtgerd. To map the extent and pattern of the subsidence in southwest of Tehran, the Interferometric SAR (InSAR) method was used. The subsidence contains one main lobe which agrees very well with the cultivated lands. Two interferograms were processed using 4 ENVISAT ASAR raw images obtained from track 149. One interferogram spanning the summer season in which the groundwater is over-extracted contains the subsidence signal up to 7 cm within 35 days. The other interferogram due to the winter recovery season contains strong uplift effects. It was recognized that the piezometers information is not in agreements with pumping wells depths. It was assumed that another aquifer system may exist in Hashtgerd area. InSAR-derived subsidence pattern significantly fits the aquifer system hypothetical boundary. Therefore, the InSAR data proves the existence of a confined aquifer system from which the groundwater is pumped out.

## 1. INTRODUCTION

Land subsidence is mostly occurred in urban and suburban areas due to various reasons including excess exploitation of groundwater and mining. High subsidence rate in urban areas increases the risk of flooding and damages of their infrastructures due to the induced surface fracturing by subsidence. Therefore, in order to be able to better risk assessment and resource management, temporal and spatial monitoring of subsidence is required. GPS stations give precise continuous measurements at a few sparse points of the deformed area [Lanari *et al.*, 2004]. Therefore, they are not able to map the extent and pattern of the ground surface deformation caused by subsidence.

Among various Geodetic and space-based techniques available, Interferometric SAR (InSAR) technique has shown its ability for measuring spatially continuous land subsidence (Amelung *et al.*, 1999; Crosetto *et al.*, 2002; Fruneau & Sarti, 2000; Tesauro *et al.*, 2000). InSAR technique provides very precise measurements using highly correlated RADAR images. This method is used for identification of land subsidence phenomenon in an area.

In this study, InSAR method was used in order to extract the surface deformation due to subsidence in Hashtgerd area. Hashtgerd area is located in Tehran province (Figure. 1). The area is mainly covered by cultivated lands. The most amount of water required for agricultures is provided from pumping wells. The decline in water level in recent years shows that the excessive groundwater is pumped out.



Figure 1. Hashtgerd area located in the north of Iran. © Google Earth

In the next section, InSAR results including the pattern and extent of the subsidence are presented. InSAR results and their combinations with other data types used to study Hashtgerd subsidence will be discussed in section 3. Finally, some concluding remarks will be presented in section 4.

## 2. SAR INTERFEROMETRY METHOD

RADAR interferometry technique is based on the comparison of the phases of two SAR acquisitions [Daniel *et al.*, 2003]. In this study 4 raw ENVISAT ASAR images obtained from descending track 149 and spanning from 2003 to 2004 was used. The data was selected such that they covered different seasons. The data was obtained from the European Space

Agencies (ESA) and converted to SLC format using ESA orbital parameters as well as GAMMA software.

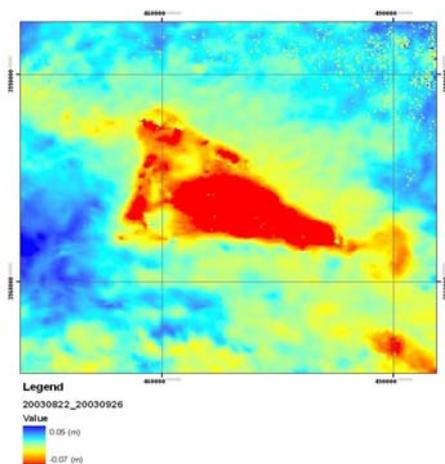
The study area is covered by cultivated lands. Hence, the time decorrelation increases significantly by the increase of the temporal baseline. Therefore, in order to mitigate the temporal and base line decorrelation effects the processed interferograms were characterized by small temporal and spatial baselines. 2 interferograms were processed by GAMMA software. In order to remove the topographic effect, SRTM DEM with the spatial resolution of 90 m was then applied. The details of the interferograms constructed for this study are demonstrated in table 1.

Interferogram	Master Date	Slave Date	Spatial Baseline (m)
1	2003.08.22	2003.09.26	64
2	2004.11.19	2004.12.24	43

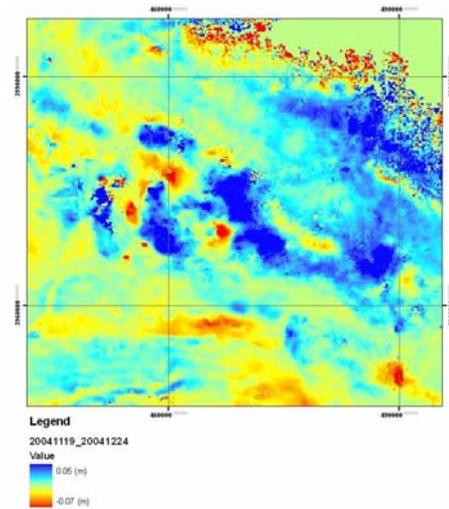
Table 1. Details of the constructed interferograms

As a final step, the processed interferograms were geocoded based on a Look-Up-Table generated from SRTM DEM. The computed interferograms are illustrated in Figure. 2. The interferograms are mainly influenced by several error types including atmospheric artifacts about which will be discussed later, decorrelation noise, topographic artifacts and unwrapping errors. Except the atmospheric effects, the mentioned error sources can be neglected. Other error sources existing in the interferograms are related to the orbital tilts and offsets which appear as a phase ramp in the interferograms. The orbital errors can be removed by subtracting a plane fitted to the data in the far field, away from the deformation signal. It should be noted that the interferograms shown in Figure. 2 have been flattened. Although the area is covered by the cultivated lands, temporal decorrelation effect is minimized by selecting the ENVISAT images spanning the shortest period of time (35 days for ENVISAT). The processed interferograms span different seasons.

In Iran, the summer drawdown season typically occurs during May to October and the rest of the year belongs to the recovery season. The first interferogram shown in Figure. 2(a) is covering summer season in which the most amount of groundwater is extracted from the pumping wells.



(a)



(b)

Figure 2. Constructed interferograms spanning different time intervals: (a) 2003.08.22 to 2003.09.26, (b) 2004.11.19 to 2004.12.24.29

The subsidence signal can be clearly observed in this interferogram. The signals due to the subsidence deformation include a fix geolocation. In spite, the atmospheric artifacts do not appear in a constant position in all interferograms. Therefore, they can be easily recognized in the interferograms. The large signal in the middle of the first interferogram (Figure. 2(a)) is due to the subsidence deformation. This signal was observed in other interferograms of different track (track 421). Interferogram 1 also includes some atmospheric effects in the margins of the area specifically southwest of the frame. The maximum subsidence detected within the central subsidence bowl was 7 cm during 35 days which is critical.

The second interferogram depicted in Figure. 2(b) is spanning winter which is a recovery season for aquifer system. Since the aquifer is recharged in this period of time, the interferogram was influenced by uplift phenomenon and the subsidence seems to decrease over the entire area. Moreover, this interferograms is strongly affected by atmospheric artifacts. During November to December the atmosphere is somehow unstable due to various atmospheric events. As a result, master and slave images might contain different amount of water vapor and the processed interferogram is strongly suffered from the atmospheric effects. In this case, the processed interferograms spanning this period of time is not much reliable. Hence, the uplift effect observed in the second interferogram can be referred to atmospheric artifacts as well. In addition to the uplift effects, some localized subsidence can be observed in the area.

The Line-Of-Sight (LOS) displacements measured at locations A to H in interferograms 1 and 2 (Figure. 1) are listed in Table 2. The measured displacements are averages over areas of 360,000 m<sup>2</sup> (9 pixels) at each location. The locations of points are shown in Figure. 6. Figure. 6 presents the average of two interferograms superimposed on the LANDSAT 7 ETM<sup>+</sup> image of the area.

It should be noticed that the InSAR technique gives the deformation along the Line-Of-Site (LOS) of the RADAR satellite. However, the incidence angle of RADAR is almost small (23 deg.). Furthermore, the major part of deformation due to the land subsidence can be assumed as vertical displacement.

Therefore, the main amount of surface deformation caused by subsidence can be measured in the computed interferograms.

Point	Summer (Interferogram 1) Displacement (m)	Winter (Interferogram 2) Displacement (m)
A	-0.0169	-0.0120
B	-0.0334	+0.0183
C	-0.0018	+0.0112
D	-0.0340	+0.0024
E	-0.0226	+0.0148
F	-0.0100	+0.0028
G	-0.0565	+0.0058
H	-0.0308	-0.0121

Table 2. LOS measured displacement magnitudes for the locations depicted in Figure. 6

The points have been selected evenly over the entire study area. In Table 2 the negative numbers are referred to subsidence while the positive ones represent the uplift phenomenon. All locations except A and H show the subsidence and uplift in the interferogram 1 and 2, respectively. Points A and H show localized displacements patterns that may be related to local pumpage.

In order to study the subsidence pattern of the area, several profiles mapped on Figure. 6, were constructed using interferogram 1. The generated profiles indicate that the subsidence has a "V"-shape pattern. This means that the margins of the subsidence bowl has gradual changes. The constructed profiles are illustrated in Figure. 2.

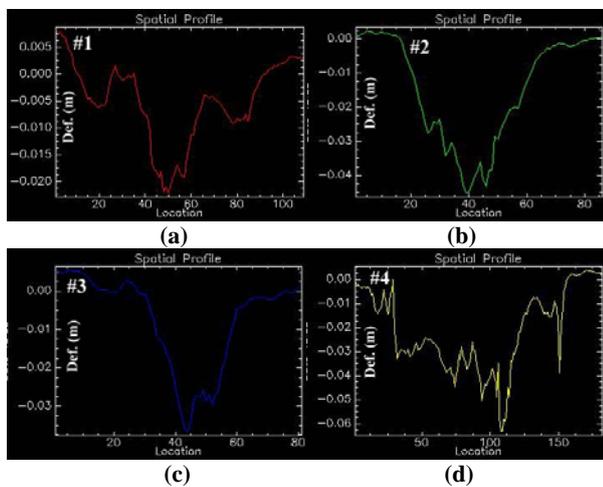


Figure 3. Constructed Profiles using interferogram 1. (a) profile #1, (b) profile #2, (c) profile #3 and (d) profile #4

### 3. DISCUSSION

The amount of subsidence is directly related to the amount of water pumping (Dehghani *et al.*, 2007). In summer, more groundwater would be extracted from the pumping wells. The interesting feature in this area was that in spite of the short time intervals of the interferograms, the subsidence signals can be still observed. This fact shows that the excessive groundwater withdrawal would be occurred.

When the groundwater is pumped out, the intergranular stress within the aquifer system increases (Terzaghi, 1925). The changes in the effective stress result in the compaction of fine-grained compressible sediments layers within the aquifer system. This fact leads to the ground surface deformation.

A significant number of piezometers is distributed in the study area (Figure. 4) in order to measure the water table of the aquifer system. Polygon in Figure. 4 covers almost the subsidence area in Hashtgerd. The contours in Figure. 4 present the water table declines during 32 years (1971 to 2003). The amount of water table decline reaches to 100 meters during this period of time.

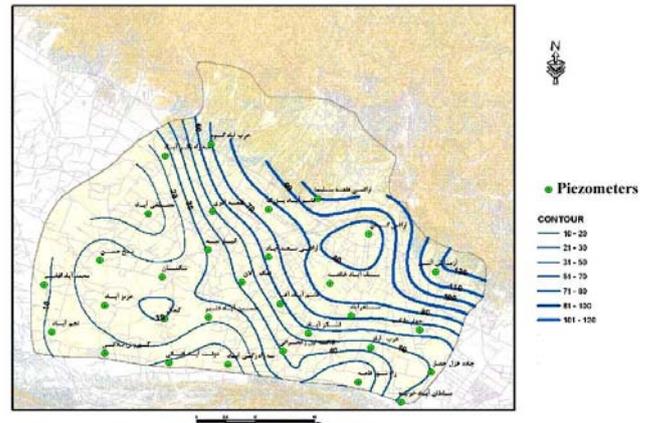


Figure 4. Water table decline contours and the locations of piezometers

In addition, unit hydrograph generated from the piezometric information shows different declines in water table of the aquifer system from 1989 to 2004. Hashtgerd unit hydrograph is shown in Figure. 5. The most amount of water table decrease has been occurred from 1996 to 2001. However, before 1996 and after 2004, the water table has been nearly constant.

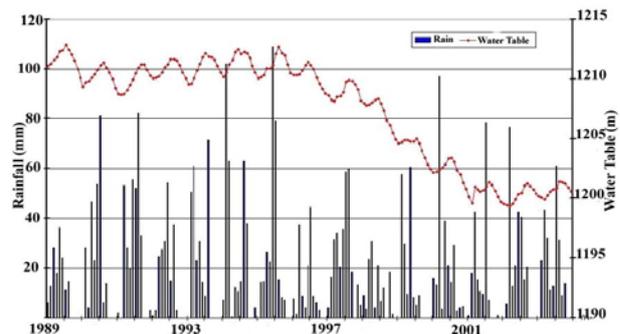


Figure 5. Unit hydrograph of Hashtgerd

It should be considered that there is not necessarily a linear relation between land subsidence and water head changes. Because of the characteristically low vertical hydraulic conductivity of compressible sediments that constitute the interbeds of the aquifer system, there is a time delay between the water table decline and subsidence. Therefore, the subsidence in interferogram 1 may be caused due to water withdrawal in before. However, better assessments can be carried out by determination of vertical diffusivity and the thickness of the fine-grained interbeds (Hoffmann *et al.*, 2003).

It should be noted that the pumping wells in the area include bigger depths in comparison to the piezometers. Water level in these wells has decreased significantly during the recent years. This fact does not agree with the shallower piezometers information. Therefore, we found that a confined aquifer system may exist below the first aquifer system. The water is pumped out from this aquifer to the wells. The boundary of the confined aquifer system is roughly estimated which is depicted in Figure. 6. As can be observed the boundary of aquifer system is in great agreement with the subsidence extent extracted from InSAR data. Therefore, the hypothesis of confined aquifer existence is verified by InSAR data. However, the precise boundary should be corrected with respect to InSAR-derived subsidence pattern.

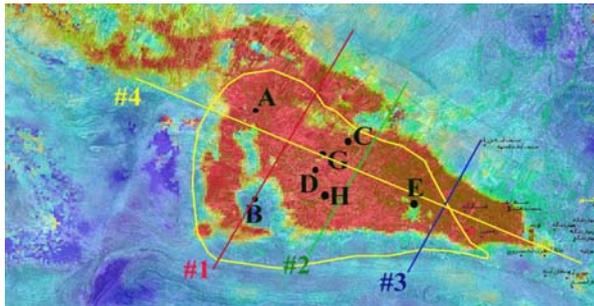


Figure 6. Hypothetical confined aquifer system boundary superimposed on the averaged interferogram.

Great agreements between the deformation pattern and the confined aquifer system indicate that the subsidence occurrence is due to the water withdrawal of the mentioned aquifer system. In order to monitor the water table of confined aquifer system it would be recommended to use piezometers in the confined aquifer depth.

#### 4. CONCLUSIONS

In this study, Interferometric SAR method was used to map the extent and pattern of the subsidence of Hashtgerd area. 4 ENVISAT ASAR images were used to generate 2 interferograms spanning different seasons. The interferogram spanning the summer season exhibited a subsidence signal with the maximum deformation of 7 cm. However, the interferogram spanning the winter recovery season demonstrated the uplift effects. Some localized subsidence areas were observed within the uplift effect. Another possibility for uplift was tropospheric delays caused by the water vapor in the atmosphere.

Subsidence occurrence in Hashtgerd is due to the excessive groundwater pumping from the aquifer system. Water levels in pumping wells decreased significantly in recent years. The depths of water level do not agree with the water information of piezometers. Hence, it was assumed that a confined aquifer system underlying the shallower aquifer system. The hypothesis of existence of a confined aquifer system is verified by InSAR results. The rough estimate of the confined aquifer system boundary is in well agreements with InSAR-derived subsidence pattern. The extent of the subsidence pattern extracted from InSAR technique allows us to map the exact boundary of confined aquifer system.

To control the subsidence evolution in the Hashtgerd plain, the ground water exploitation has been limited remarkably. As a future work, it has been planned to apply time series analysis

using a significant number of interferograms to obtain deformation rate. Using the deformation derived from the InSAR in addition to other datasets such as geo-technique studies would allow us to study the aquifer characteristics.

#### REFERENCES

- Daniel, R., C., Maisons, C., Carnec, S., Le Mouelic, C., King and S., Hosford, 2003. Monitoring of slow ground deformation by ERS radar interferometry on the Vauvert salt mine (France) Comparison with ground-based measurement, *Remote Sensing of Environment*, 88, 468-478.
- Dehghani, M., Valadan Zoej, M. J., Saatchi, S., and Entezam, I., 2007. 2007 Fringe Workshop, Frascati, Italy.
- Lanari, R., Lundgren, P., Manzo, M., & Casu, F., 2004. Satellite radar interferometry time series analysis of surface deformation for Los Angeles, California. *Geophysical Research Letters*, 31, doi:10.1029/2004GL021294.
- Schmidt, D. A. and Burgman, R. (2003), Time-dependent land uplift and subsidence in the Santa Clara valley, California, from a large interferometric, synthetic aperture radar dataset. *Journal of Geophysical Research*, 108, 8534-8543.
- Amelung, F., Galloway, D. L., Bell, J. W., Zebker, H. A., and Lacznik, R. J. (1999). Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer system deformation. *Geology*, 27(6): 483-486.
- Crosetto, M., Tscherning, C. C., Crippa, B., & Castillo, M. (2002). Subsidence monitoring using SAR interferometry: Reduction of the atmospheric effects using stochastic filtering. *Geophysical Research Letters*, 29(9): 26-1-26-4.
- Fruneau, B., and Sarti, F. (2000). Detection of ground subsidence in the city of Paris using radar interferometry: Isolation from atmospheric artefacts using correlation. *Geophysical Research Letters*, 27(24): 3981-3984.
- Hoffmann, J., Leake, S. A., Galloway, D. L. & Wilson, A. M. (2003). MODFLOW-2000 Ground-Water Model—User Guide to the Subsidence and Aquifer-System Compaction (SUB) Package. U.S. Geological Survey Open-File Report 03—233.
- Tesauro, M., Berardino, P., Lanari, R., Sansoti, E., Fornaro, G., and Franceschetti, G. (2000). Urban subsidence inside the City of Napoli (Italy) observed with synthetic aperture radar interferometry at Campi Flegrei caldera, *J. Geophys. Res.*, 106: 19,355– 19,366.
- Terzaghi, K. (1925). Principles of soil mechanics, IV, settlement and consolidation of clay, *Eng. News Rec.*, 95(3), 874–878.

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