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Quantifying Geotechnical Changes in the Rafsanjan Plain in Time Series and Finding Out Their Causes Using Radar Remote Sensing Techniques

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Abstract

Subsidence is the earth's surface movement towards down relative to a datum such as sea level. The main reason of subsidence in Iran is groundwater overuse which if not managed correctly, it causes irreparable damages. Therefore, the first step in solving this problem is identification of subsidence areas and estimating the rate which will have a significant role in controlling this phenomenon. One of the most suitable methods of identification of subsidence is using Interferometric Synthetic Aperture Radar (InSAR)technique. This method is superior to other detection T in terms of cost, precision, extent of the study area and time and it can provide an accurate estimate of the area. In this research, zone of the Rafsanjan plain has been investigated between 2006 and 2010. In order to calculate subsidence rate, SAR data related to the ASAR sensor in C-band and ALOS PALSAR in L-band were used. Generalized linear models in C-band and L-band with values of 0.91 and 0.89 and RMSE coefficient of 0.37 and 0.61 represented a strong linear relationship. Also the relationship between subsidence and the changes inpiezometric levels (groundwater extraction) in the study area showed that for each 4.7 centimeters groundwater level decrease, there has been 1 centimeter subsidence.

Keywords: Geotechnic, Radar interferometry, Subsidence, Rafsanjan

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1. Introduction

According to the United States institute of geology, land subsidence is sinking or downward settling of ground's surface which can be with a small horizontal displacement vector (USGS, 2011). Land subsidence is sudden or gradual sinking of the ground's surface due to changes in shape and displacement of particles (Rahnama et al., 2006) caused by natural factors (volcanoes, sinkholes in soluble rocks, wrinkles) and human factors (mining, construction, extraction of groundwater, oil and gas) (Roy et al., 2005). Although this phenomenon occurs in many sequences and frequencies, usually its understanding and measuring are not possible. For this reason, in most areas, this event is just known when it affects surface morphology as well as facilities and equipment. Sometimes this phenomenon has a wide range because of exacerbation and stimulation of its trigger factors such as increased pressure in exploitation or operation beyond the capacity of groundwater resources of the plains. In addition to creating many morphological outcrops in earth's surface, subsidence becomes a threat to human life. Creating sinkholes, foundation movement, tilting tall buildings etc. are the most common damages caused by the intensified subsidence. Sometimes these risky situations can be catastrophic because of special conditions of locations and proximity and having a hazardous infrastructure as a result of other natural hazards like earthquake. In other words subsidence and natural hazards in a place together can turn small disasters to great catastrophes (Sharifikia, 2012). There has been land subsidence in Iran since many years ago and some studies have been conducted in some areas. Among these areas, Rafsanjan was one of the first areas in which this phenomenon was identified (Geology institute, 1998). The closest research in terms of geographic location to the studied area is a research by Sharifikia titled "Determination of the rate and extent of land subsidence in the Noogh-Bahreman plain using radar data in C- and L- band between 2005 and 2010". In this research, subsidence has been calculated with an average annual of about 30 centimeters in an area of 281 square kilometers in the middle part of the plain. Also by comparing the rate of subsidence with changes in level of exploited water in peizometric wells, it was concluded that in this plain every 3.2 centimeters ground water lowering can cause a subsidence of 1 centimeter. Haghighatmehr et al., (2013) in a survey named "Time series analysis of Hashtgerd subsidence using radar interferometry and global positioning system", used SAR interferometry (InSAR) and global position system (GPS) in order to study the subsidence in Hashtgerd plain that has been affected by subsidence due to excessive groundwater extraction. Additionally, in order to analyze the deformation time series, they used small baseline subset (SBAS) algorithm and they performed time series analysis using 6 interfrograms calculated from 4 ENVISAT ASAR data spanning 4 months in 2008. Time series results showed the area is subsiding continuously. moreover mean LOS deformation velocity map obtained from time series analysis revealed a considerable subsidence rate of 48 mm per month. To assess the time series analysis results, a dense GPS network consisting of 18 measuring stations was established. The GPS stations were collecting the data simultaneously with radar data acquisitions. Then horizontal and vertical components of the subsidence were extracted from GPS measurements. The comparison of InSAR and GPS time series showed the high compatibility of the results demonstrating the high performance of InSAR technique. Heshmati and Almodaresi (2014) in another paper named "Modeling subsidence of the Neishabour plain using time series and DINSAR technique" studied Neishabour plain between 2003 and 2010. In order to calculate subsidence rate, SAR data related to ASAR sensor prepared in C-band was used. The amount of displacement using GPS data in Neishbour statin was compared with the amount of displacement using ASAR data. They did not have a significant difference. Also the relation between subsidence and changes in peizometric surface (groundwater extraction) showed for every 3 centimeters lowering of peizometric surface there has been 0.816 centimeter subsidence.

The Research objectives:

Increasing population and fulfilling the needs of today's human societies have led to more attention to exploitation of water resources especially in warm and dry areas such as Iran. Due to the climatic conditions of Iran, it is necessary that development plans and exploitation of water resources for various uses (drinking, industrial and agriculture) in different regions of the country to be identified to achieve optimal and sustainable exploitation of water resources. Subsidence affects a vast area but it is not easy to recognize and generally in cases where the facility and buildings are damaged, it will be identifiable. Subsidence event is preventable and at the time of occurrence, we are able to reduce its trend or even stop it. In this research, it is tried to identify and manage the areas involved in subsidence before the subsidence destroys the main infrastructures and causes casualties and financial losses. Finding a significant relationship between groundwater reduction and subsidence rate is the next step.

In this research, a significant relationship between groundwater level changes and surface deformation has been found using Interferometric synthetic aperture radar. The main question of this research is:

1- Can the relationship between ground water reduction and subsidence rate using Interferometric synthetic aperture radar and C- and L- band images be modeled?

To answer this question, two hypotheses are proposed:

1- Satellite radar images in the range of microwave with wavelengths of C- and L- band are appropriate for calculating of subsidence rate.

2- There is a significant linear relationship between groundwater reduction and subsidence rate.

Since the Rafsanjan plain is one of the most critical plains in the country in terms of overuse of groundwater, the phenomenon of subsidence is quite tangible, but no research has been done in the central part of the Rafsanjan plain using this method and C- and L-band data so far. Also the proof of the relationship between the subsidence in the Rafsanjan plain and groundwater extraction is one of the aspects of innovation of this research.

2. Materials and Methods

2.1. Used data

Used data in this paper is divided into two categories, terrestrial and satellite data. Terrestrial data was obtained from the Kerman Regional Water Studies Office and satellite data was prepared from the European Space Agency.

Table 1. Details of the used ASAR sensor images in the Rafsanjan plain

Space headway (meter)	Time headway (day)	Date	Image mode
188/958	419	2006	ASA_IMS
		2008	ASA_IMS
50/933	144	2008	ASA_IMS
		2010	ASA_IMS

Table 2. Details of the used ALOS PALSAR sensor images in the Rafsanjan plain

Space headway (meter)	Time headway (day)	Date	Image mode
375.36	695	2007	JAXA-FBS
		2009	JAXA-FBS
698.74	1050	2007	JAXA-FBS
		2010	JAXA-FBS

According to statistical obtained from Kerman Regional Water Studies Office between 1384 and 1389 in the area of study, there has been 31 piezometric wells. In this statistic, the number which is related to the piezometric surface shows water surface elevation from earth's surface and its unit is in meters.

2.2. Area of the study

Rafsanjan city is located in the northwest of Kerman province. Its geographical coordinates are 54° 56′ to 43° 56′ eastern longitude of Greenwich meridian and 29° 55′ to 31° 17 ′northern latitude. Its area is about 7678 square kilometers and it is accounted for 4.19 percent of the province's total area. It is limited to Bafgh in Yazd province from the north, to Sirjan and Bardsir from the south, to Anar and Shahr-e- Babak from the west and to Zarand from the northeast. The city center is located at 1469 meters above sea level. The lowest point is in the output of the Rafsanjan plain, in Noogh region with 1260 meters and the maximum height of the city is in Raviz Mountains and Sarcheshmeh, 2900 meters above sea level. Rafsanjan has different names which are related to its underground resources. For example, Rafsankan or Rafsank consists of two words, Rafsank means copper and Kan means mine and Rafsanjan is Arabic. Sarcheshme copper mine known Chashmefiroozehei (turquois eye) is the largest open pit mine in the world. Also Rafsanjan is the largest pistachio producer in the world and because of its high quality pistachios, it is a well-known city in the world. In this city there are 80000 hectares of pistachio gardens which are irrigated by 1300 agricultural wells. Also the world's largest adobe house is located in Rafsanjan, one of the most beautiful ancient monuments with 110 rooms. This historical city has the richest copper mines and Sarcheshmeh copper complex is the third largest copper processing plant in the world. The area of study in this paper is central part of the Rafsanjan plain with an area of 2680 square kilometers.

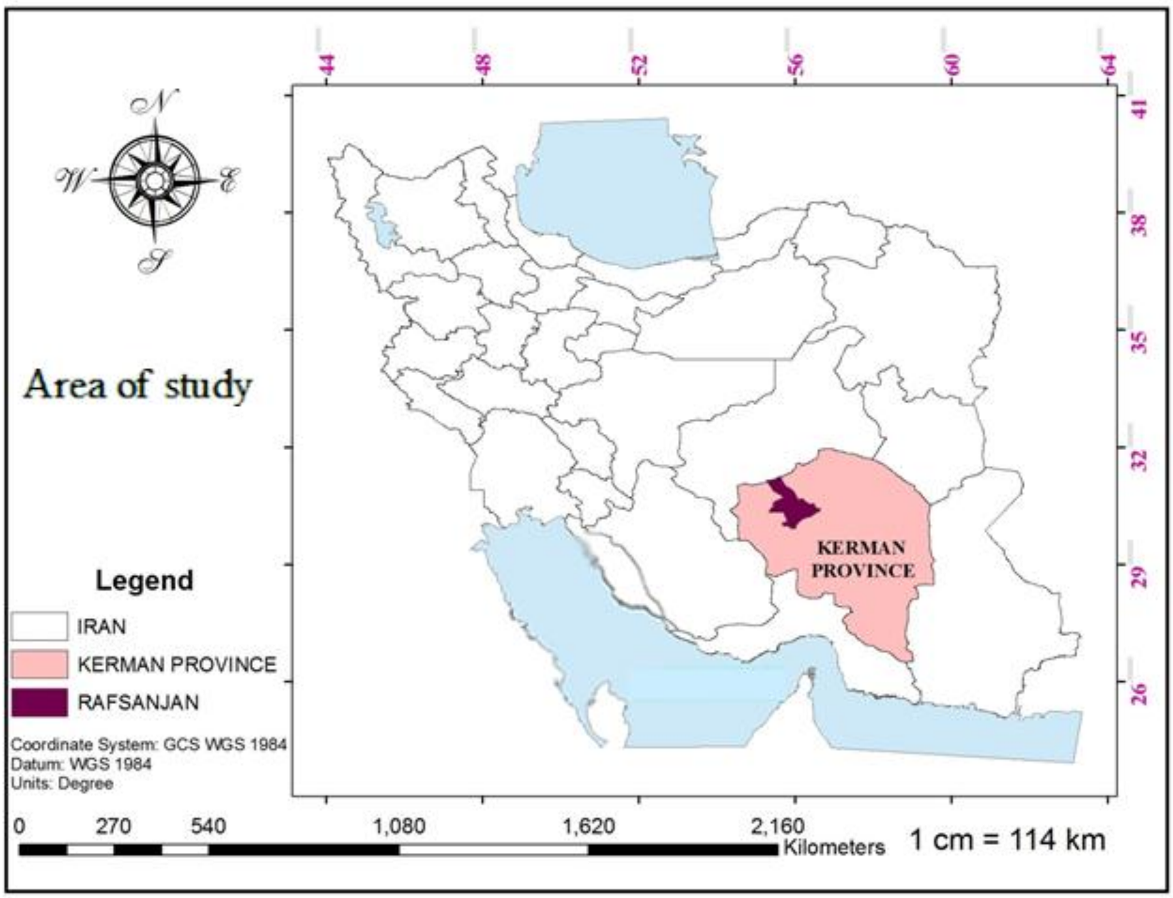

Figure 1. Area of the study

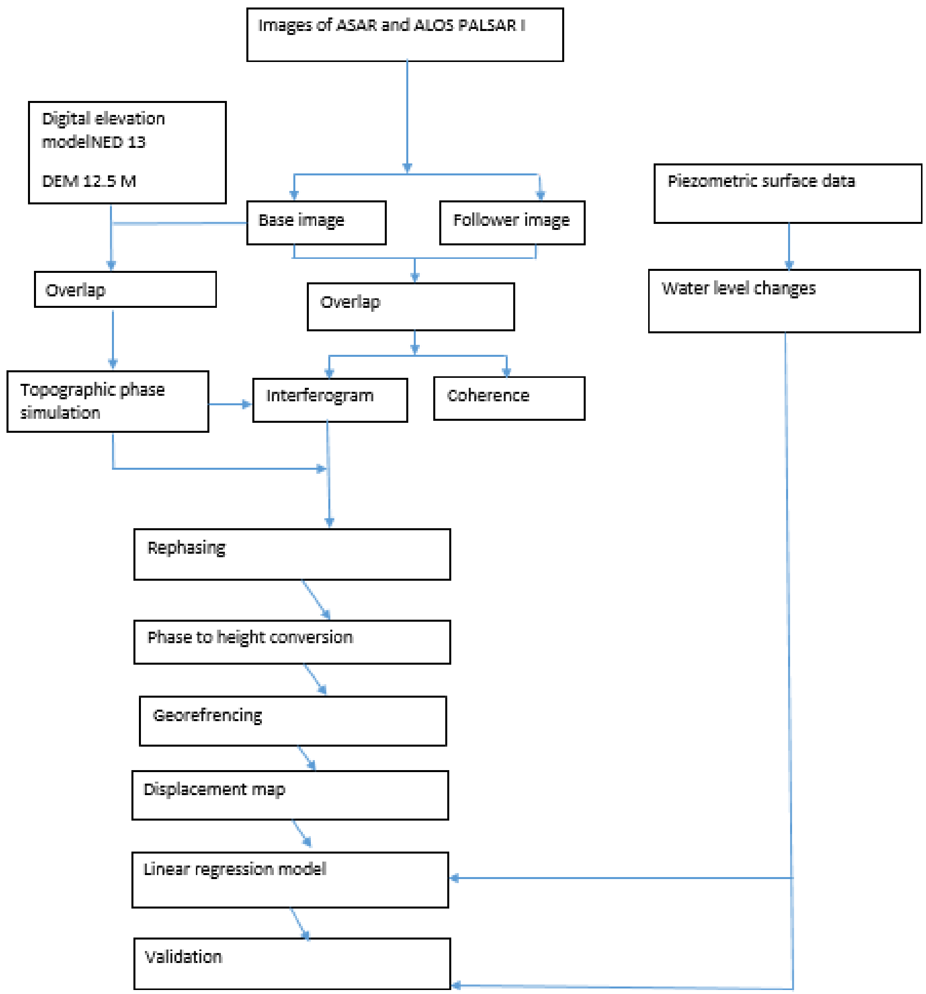

Figure 2. Work flowchart

2.3. Differential Synthetic Aperture Radar Interferometry technique

Differential interferometry (DinSAR) gives an estimate of surface variation (both flat and altitude) by interferometry. The basis of this is similar to ground surveying for data collection in preparing a contour map based on raster which was prepared 5 years ago and a contour map based on raster that was made a week ago (a raster map is made up of pixels, each containing a value that indicates elevation). If two maps are exactly the same, an array of zero will be obtained from minus pixels of two images. If some values in obtained image (difference of two images) are not zero, it means there has been a change. The rate of changes is proportional to the pixel brightness value in the obtained image. In fact, here the first (previous) contour map based on raster has been used to remove topographic effects of the new map. The same can be done for two DEM$_s$ obtained from SAR images which are prepared before and after an important event such as an earthquake. The difference between two images obtained from interferometry represents changes in the surface caused by the earthquake. Four SAR images in SLC format are needed to create two DEM$_{s.}$ Since the first DEM obtained from inter ferometry should indicate a good approximation of ground level altitude; it should be created by a pair of radar images with long wavelength. As the second DEM obtained from interferometry should show most of the details of the surface, it should be created by a radar image with short wavelength. In places where a target (for example: an iceberg) is moving, wavelength should be short for the second pair of SAR images with SLC format. The wavelength should be 300 meters, 20 meters and 5 meters respectively for production DEM, study of land displacement and movement analysis (Paul, 2011).

In order to succeed in DinSAR method, low correlation between two interferogram should be as small as possible. In water areas and forest areas, low correlation occurs quickly so that separating of effects of deformation of the earth, land subsidence and ice mass movement from the effects of low correlation is impossible. Long wavelengths have less low correlation than short wavelengths, so that they penetrate more in canopy of plants and they are less influenced by the geometry of plant canopies (Paul, 2011).

2.4. Linear regression method

Statistical models such as regression run better for small sample sizes when theory or experiment shows a systematic relationship between dependent and independent variables. Linear regression has been used by many researchers to estimate various parameters. In this paper, linear regression method has been used in MATLAB software environment. Linear regression may be simple or multiple. Simple linear regression consists of a dependent variable and an independent variable. A regression equation is an equation which shows the relationship between dependent and independent variables and the value of the dependent variable can be estimated using the independent variable.

3. Results and Discussion

In this part results and output from ASAR and ALOS PALSARI images processing have been used. At first, displacement rate was obtained using differential synthetic aperture radar interferometry technique and then its linear equation was calculated using correlation between displacement rate produced by two sensors and terrestrial data of piezometric levels. At each step, produced maps were validated.

3.1. Values of ASAR sensor displacement

Interferograms were generated using DinSAR method. Then they were converted to vertical displacement values in meters after final processing in SARCAPE software. Displacement maps obtained from ASAR sensor images in C-band have been showed in figures 3 and 4.

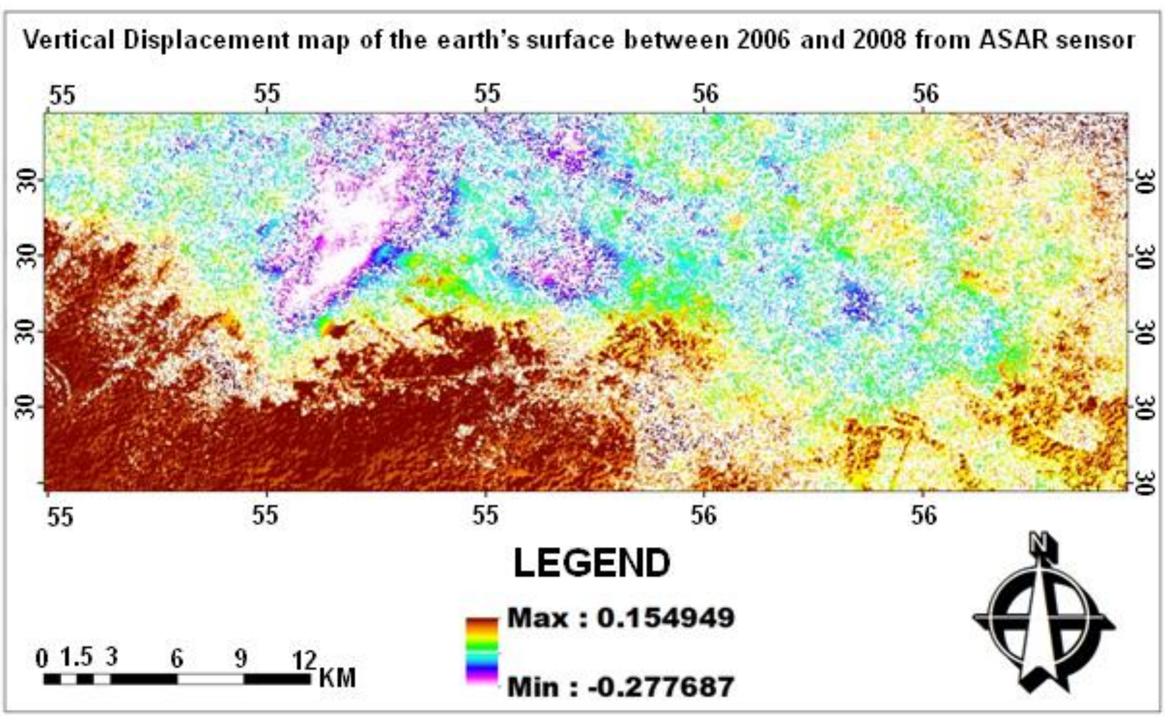

Figure 3. Displacement map

Map of the vertical displacement of the earth's surface between 2006 and 2008 from the ASAR sensor

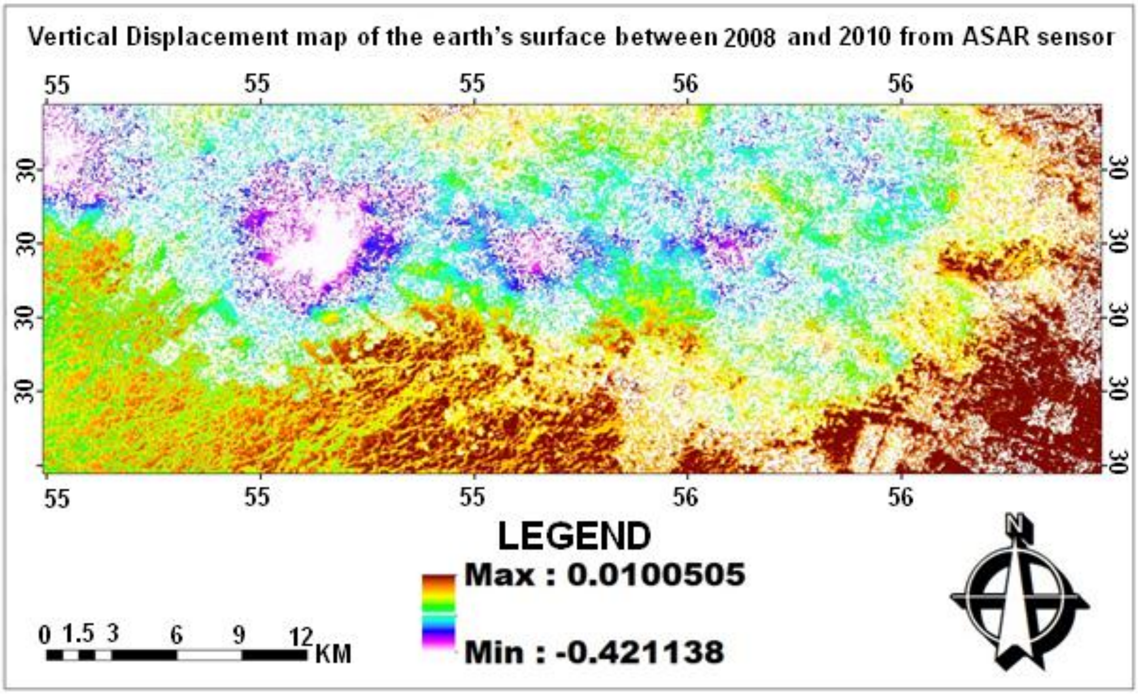

Figure 4. Displacement map

Map of the vertical displacement of the earth's surface between 2008 and 2010 from the ASAR sensor

3.2. Values of ALOS PALSARI sensor displacement

After performing the interferometric method on ALOS PALSAR images and creating interferograms and after final processing in SARCAPE software, interferograms were converted to vertical displacement values in meters. Displacement maps obtained from ALOS PALSAR in L-band have been shown in figures 5 and 6.

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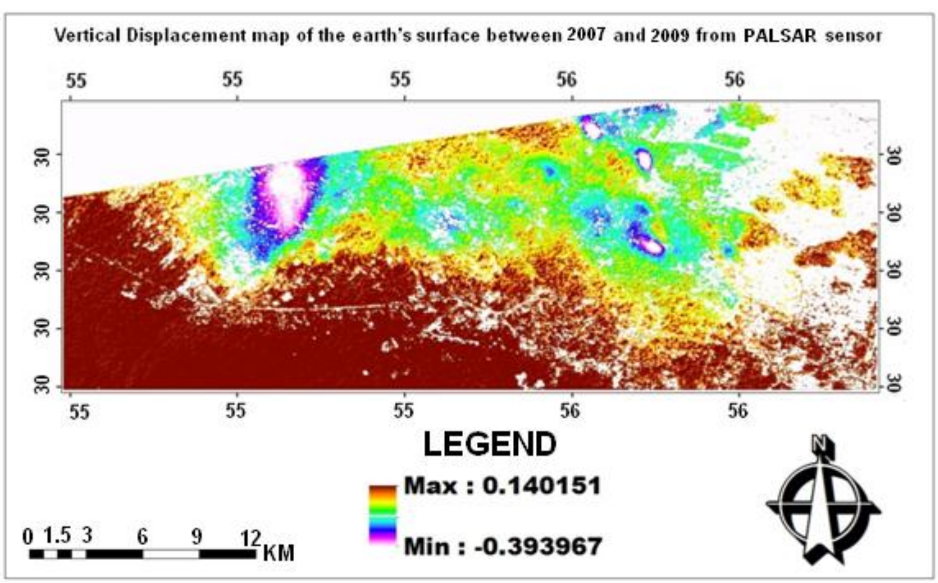


Figure 5. Displacement map

Map of the vertical displacement of the earth’s surface between 2007and 2009 from the ASAR sensor

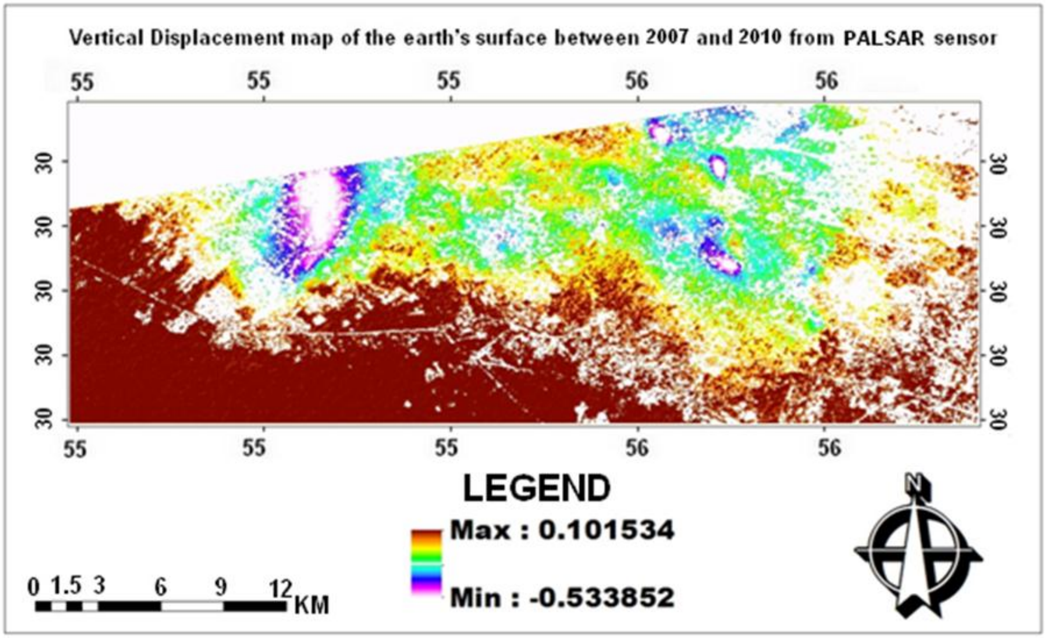


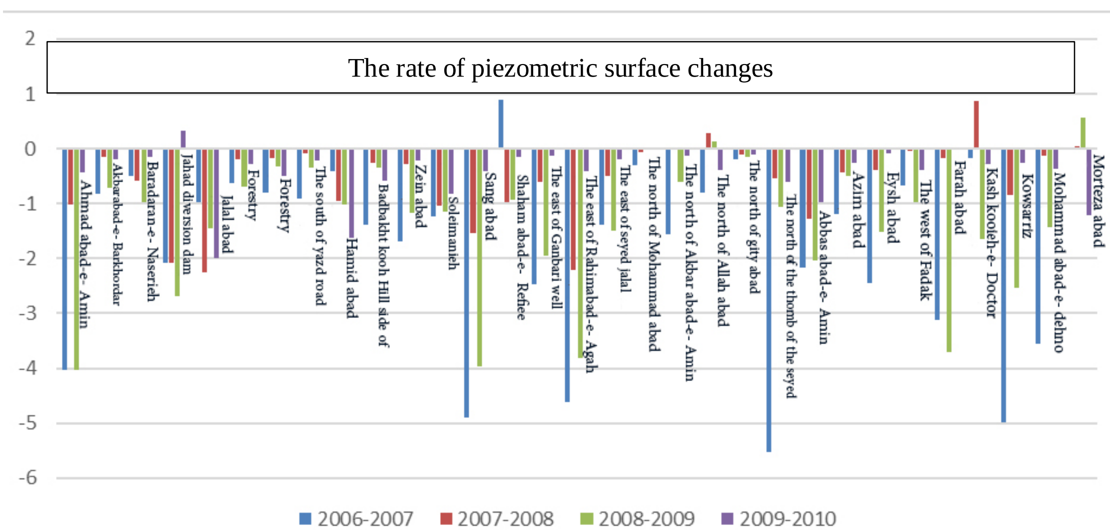
Figure 6. Displacement map

Map of the vertical displacement of the earth’s surface between 2007and 2010 from the ASAR sensor

3.3. Statistical description

3.3.1. Variable of piezometric surface changes

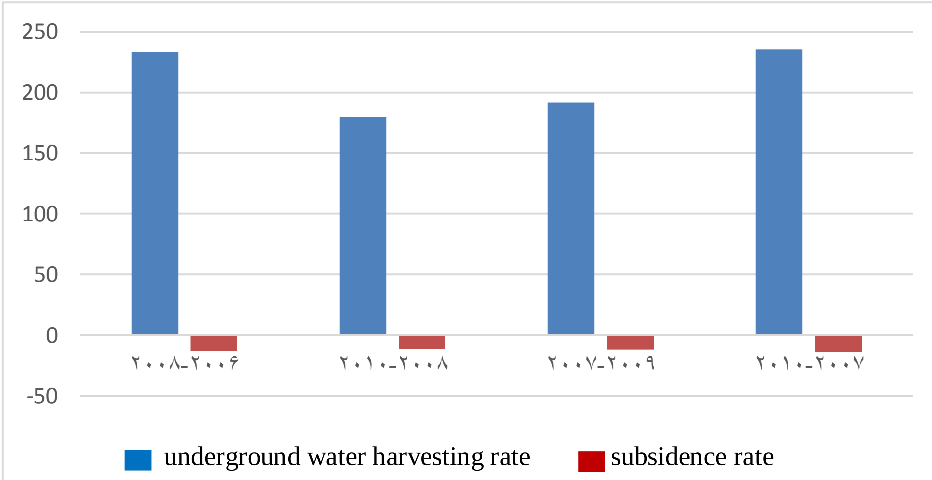
The frequency diagram of variable of piezometric surface changes, generally and without considering the year of measurement is given below. According to diagram 2, the largest amount of groundwater extraction (piezometric surface changes) is from 2006 to 2008 with an average of 233 centimeters and its lowest amount is from 2008 t0 2010 with an average of 179 centimeters.



Graph 1. Variable frequency of changes in water levels in piezometric wells

Table 3. Description of the variation of changes in piezometric surface

Number	Maximum	Minimum	Standard deviation	Average	
124	5.53	0.089	0.11224	1.0388	Underground excavation

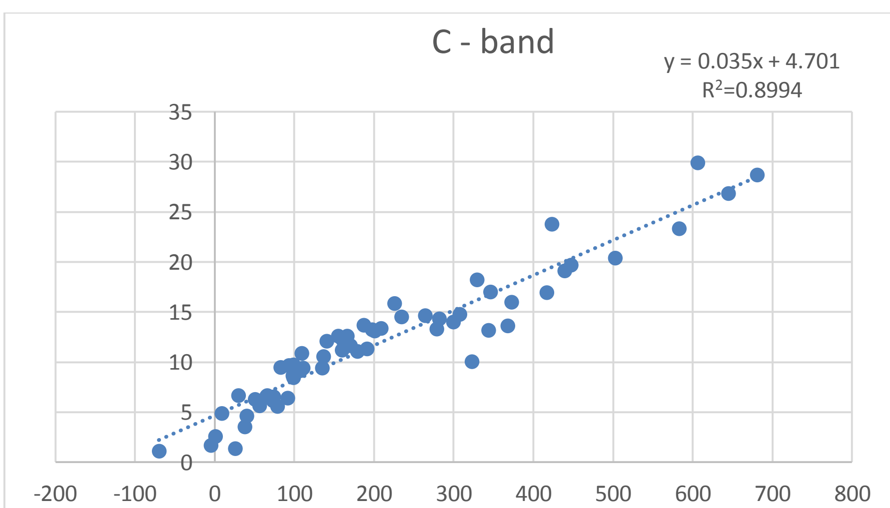


Graph 2. The mean of underground water harvesting and land subsidence variables in different years

3.4. Linear regression modeling

3.4.1. Modeling for c-band data

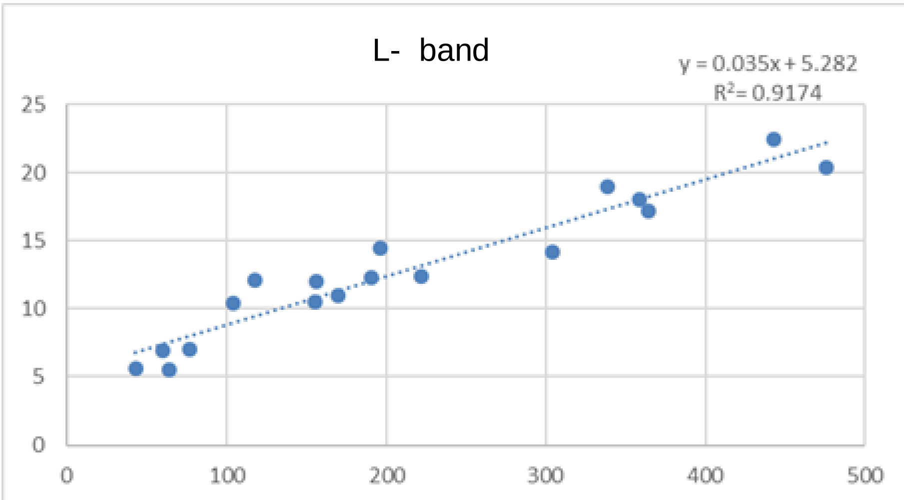
At first using data of the rate of well levels changes and subsidence rate obtained from synthetic radar interfrometric technique for ASAR sensor in c-band, a linear regression was created by MATLAB software. Subsidence rate was considered as a dependent variable and the amount of groundwater withdrawal (piezometric surface changes) from earth's surface was defined as an independent variable. This linear regression model was originally defined for the years 2006 to 2008, then for 2008 to 2010 and finally for 2006 t0 2010. Obtained results are shown in diagram 3. It shows a linear relationship with coefficient r^2 equal to 0.89 and RMSE equal to 0.62 which they have strong and positive correlation and this linear relationship is obtained : Y=0.035X + 4.701. In this equation X is the rate of groundwater extraction and Y is subsidence rate. The confidence level is 99 percent.



Graph 3. The correlation between underground excavation and subsidence in C- band between 2006 and 2010

3.4.2. Modeling for L-band data

Like c-band data, for PALSAR sensor data in L-band, a linear regression model was created between subsidence rate as a dependent variable and the amount of groundwater extraction (piezometric surface changes) as an independent variable by MATLAB software. This linear regression model was created at first for the years between 2007 and 2009, then for 2009 to 2010. Results are observed in diagram 4 which represents a linear relationship with r^2equal to 0.91 and RMSE equal to 0.37 that the correlation between them is strong and positive. And this linear relationship is created: Y=0.035X+5.282 X is the amount of groundwater extraction and Y is subsidence rate. The confidence level is 99 percent.



Graph 4. The correlation between underground excavation and subsidence in L- band between 2007 and 2010

4. Conclusions

From the above context, it is apparent that synthetic radar inferometric technique is suitable for determining the rate and extent of subsidence in the studied area. Environmental dryness moderated the effect of phase shift caused by atmospheric compounds especially moisture and provided an accurate measure of the phase difference caused by surface displacement. Also, lack of vegetation minimized decoherence challenge in the phase of radar images and made it possible to measure phase changes for C- and L-band data at annual intervals. This finding emphasizes the effectiveness of this method in studying changes in earth's crust in most parts of the country. Findings using this method showed that changes in piezometric surface or the amount of groundwater extraction had a close relationship with subsidence. The most important reason of subsidence in sedimentary basins in arid and semi-arid regions is falling groundwater tables because of excessive extraction of these resources. According to the results obtained by differential synthetic aperture radar interferometry method in the Rafsanjan plain, between 2005 and 2010, there were 27 to 53 centimeters of subsidence and according to the results of linear regression model, for each 4.7 centimeters decreasing groundwater levels, there was 1 centimeter subsidence. This indicates that subsidence has a direct linear relationship with the rate of groundwater extraction by human factors like agriculture etc. In order to compare this paper with other researches, Sharifikia's research (2012) entitled "Determining the rate and extent of land subsidence in the Noogh- Bahreman plain using radar data in C- and L- band between 2005 and 2010" can be mentioned as the closet research in terms of geographical situation to the studied area. average annual subsidence of about 30 centimeters in an area of 281 square kilometers in the middle part of the plain was estimated. Moreover, comparison of the rate of subsidence with water level changes extracted from piezometric wells represents that every 3.2 centimeters ground water lowering is able to create a subsidence of 1 centimeter in this plain. In another research from Heshmati and Almodaresi (2014) entitled "Modeling subsidence of the Neishabour plain using time series and

DINSAR technique", the Neishabour plain has been studied between 2003 and 2010. It is proved that the relationship between subsidence and the amount of changes in piezometric surface (groundwater withdrawal). Also they determined that for each 3 centimeters decrease of piezometric surface, there was 0.816 centimeter subsidence. The results of these two studies are very close to the results of the present research.

As mentioned at the beginning of the article, in this research, a question is raised with two hypotheses and the answers are as follows:

The answer of hypothesis 1: Since microwave ranges with long wavelength of C- and L-band have more influence and they are less affected by the atmosphere, they are suitable for studying earth's surface changes. In fact, as the wavelength increases, the penetration power goes up. And longer wavelengths pass through the surface, so they have more control over the surface and show the changes better.

The answer of hypothesis 2: According to the results of this research, the precision of correlation coefficients between changes of piezometric surface and the rate of subsidence in C- and L-band is 91 and 89 percent and it is 0.37 and 0.61 for RMSE. These results are acceptable and have a fairly good accuracy.

In response to the main research question, according to the statements above and obtained results, it is possible to model the relationship between the amount of lowering groundwater level and the rate of subsidence using linear regression model. This model for C-band data in the area studied is a linear relationship that can be written in form of: $Y=0.35X+4.701$. And for L-band data, it is a linear relationship as: $Y=0.35X+5.282$ in which X is the amount of groundwater extraction and Y is the rate of subsidence. The confidence level is 99 percent.

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