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Estimation of groundwater abstraction induced land subsidence by SBAS technique

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The groundwater over pumping induced land subsidence is one of the major geological hazards in the alluvial aquifers. The objective of this study is to assess the rate of land subsidence in Kolkata metropolitan area, India. Land subsidence can be estimated with high precision by Small Baseline Subset (SBAS) analysis. The advantages of this method are generation of a mean deformation map. The ENVISAT ASAR data acquired at six different periods over the study site were processed by SBAS technique. The decline in the piezometric head from the year 2003 to 2010 was about 6 m. Land subsidence velocity was ∼8 mm/year at Salt Lake City and Science City (near the eastern metropolitan bypass). The major cause for land subsidence is over pumping of groundwater from the confined aquifers in these areas. There is a reasonable comparison between the maximum region of land subsidence and low value piezometric head contours confirming that the over extraction of the confined aquifer of this region is responsible for land subsidence. It is necessary to control the groundwater pumping so as to arrest the declining trend of piezometric head of study area for managing the problem of land subsidence. Hence, the possible remedial measures that can be taken are reducing groundwater pumping in the study region.

Keywords. Kolkata; SBAS; confined aquifer; land subsidence; remedial measures.

1. Introduction

Land subsidence induced by groundwater extraction is a man-induced geological hazard affecting many cities in the world (Hung *et al.* 2012; Modoni *et al.* 2013; Pacheco-Martínez *et al.* 2015). Over pumping of groundwater from the confined aquifers results in compaction of confining layer which leads to land subsidence. Precise monitoring of ground elevation is necessary to improve the understanding of this hazard and to provide guidance for sustainable withdrawal of groundwater. Microwave remote sensing data was used to investigate land subsidence over the last two decades. The slow process of land subsidence can be estimated with high precision by multi-temporal Interferometric Synthetic Aperture Radar (InSAR) obtained with the Small Baseline Subset (SBAS) analysis. The Differential Interferometric Synthetic Aperture Radar (D-InSAR) technique has been recognized as a most important tool for monitoring and measuring the land subsidence deformation (Chaussard *et al.* 2014; Castellazzi *et al.* 2016; Pepe and Calo 2017). This D-InSAR technique has become popular as it offers effective and efficient alternative to estimate land subsidence with high precision. The D-InSAR methodology has been applied first to investigate single deformation events (Massonnet *et al.* 1993; Peltzer and Rosen 1995; Rignot 1998). It has also been

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used to monitor the land subsidence due to over pumping of groundwater from confined aquifer systems by many researchers (Galloway *et al.* 1998; Mora *et al.* 2003; Chang *et al.* 2004; Calderhead *et al.* 2009). However, in these studies atmospheric corrections were not included, and there are many papers using multi-temporal InSAR for subsidence monitoring that include atmospheric correction (Lanari *et al.* 2007; Chaussard *et al.* 2014). Berardino *et al.* (2002) proposed a Small Baseline Subset (SBAS) approach to detect and investigate deformation phenomena based on exploiting time series of European Remote Sensing (ERS) SAR data. The D-InSAR technique exploits the phase difference, often referred to as interferogram. The SBAS approach permits the use of multilook D-InSAR interferograms to detect and follow the temporal evolution of surface deformation with a high degree of temporal and spatial coverage (Lanari *et al.* 2007). SBAS approach has been successfully used to study the land deformation caused by depletion of groundwater (Stramondo *et al.* 2007; Guzzetti *et al.* 2009).

The recent Gravity Recovery And Climate Experiment (GRACE) data have highlighted the extent of groundwater depletion in the Indo-Gangetic Basin (Aeschbach-Hertig and Gleeson 2012) and land subsidence due to exploitation of groundwater has been reported in Kolkata which is a part of Indo-Gangetic Plain by Chatterjee *et al.* (2006), Bhattacharya (2011), and Sahu and Sikdar (2011). Sikdar *et al.* (1996) and Sahu and Sikdar (2011) have used one dimensional consolidation theory for land subsidence study. The understanding of the characteristics and behaviour of the confining layer due to the decrease of the piezometric level is important to effectively analyse the mechanism of land subsidence. The decrease in confining pressure due to the withdrawal of water from confined aquifers results in the loss of pore-pressure or neutral stress and consequent increase in effective stress. The distribution of stress at the interface of a confining bed and confined aquifer is as follows:

$$\sigma_t = \sigma_e + P,$$

where, σ_t is the total vertical stress, σ_e is the effective stress, and P is the pore-pressure or neutral stress. The increase in effective stress is accommodated by a solid matrix of aquifers by elastic compression during the decline of confining pressure. This can be calculated by the equation for one-dimensional consolidation theory given by Dominico (1972). Chatterjee *et al.* (2006) used ERS SAR data for the period from 1992 to1998 to assess the land subsidence by D-InSAR technique. Suganthi *et al.* (2017) has also carried out an assessment of land subsidence in this region by D-InSAR method for the period 2003–2010. However, this method does not bring out the mean spatial deformation map. Hence, the present study was carried out with the objective of assessing the rate of land subsidence using SBAS technique and to delineate the regions of land subsidence in Kolkata region.

2. Description of hydrogeo-morphological setting of the study area

Kolkata is located in the lower part of the Gangetic alluvial plain in the eastern part of India, which contains a thick pile of quaternary sediments. It is a typical deltaic flat land with surface elevation ranging between 3.5 and 6 m above mean sea level. The hydro-geomorphological features of the study area were mapped using LISS III satellite data and Kolkata Municipal Corporation 2007 report. The major geomorphologic features such as alluvial plain in the centre of the study area, eastern side of Kolkata contains marshy land and in some places levee deposit is present along the Hooghly River (figure 1). The study region mostly comprises alluvial plains which are potential zone for groundwater storage. The six borehole logs were collected from State Water Investigation Directorate (SWID), Kolkata. Geological cross-section of the study area is shown in (figure 2). Geologically, the study area is underlined by formations ranging in age from quaternary to recent. The study area is dominated by clay, sand and sand with pebble which are of fluvial deltaic origin. From the top 3 m from the ground surface contains a mixture of sand and silty clay, followed by a thick layer of clay at a depth ranging from 15 to 60 m occurs above the entire alluvium sequence from the ground surface in the study area. The average thickness of clay layer is 40 m from the top of the earth surface in the study area. Both top and bottom clays are dark grey in colour and sticky and of plastic nature and the upper clay bed often contains decomposed woods. Sands of various grades with occasional gravel occur between the clay beds form the main aquifer system in study area. A large-scale withdrawal of groundwater for municipal and industrial uses from the confined

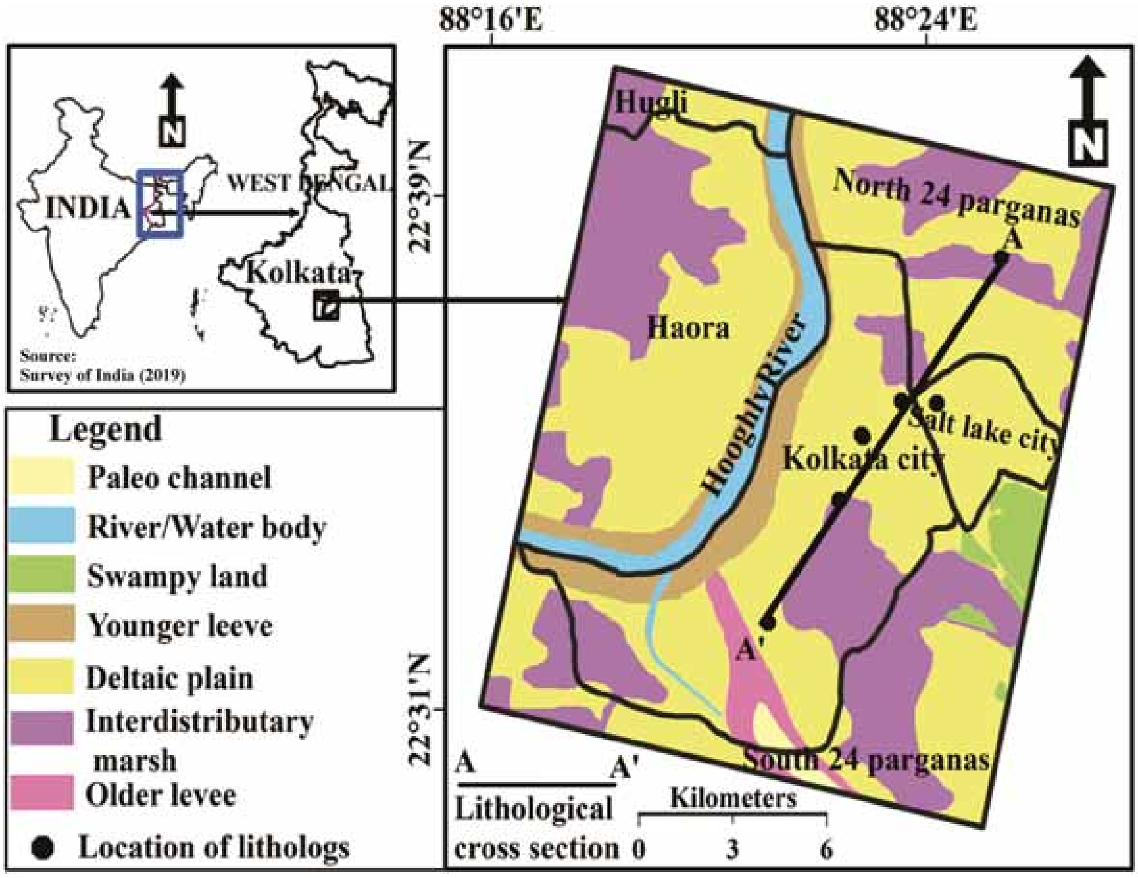

Figure 1. Location of the study area over the geomorphological features.

aquifers has resulted in the sharp decline of piezometric level, which poses a hazard of land subsidence (Sikdar *et al.* 1996).

3. SBAS methodology

The description of SBAS approach followed in the present study is available in Lanari *et al.* (2007). The key point of the SBAS technique, in addition to the use of multilook interferograms is that the data pairs involved in the generation of the interferograms are properly selected in order to minimize the spatial and temporal separation (baseline) between the acquisition orbits, thus mitigating the decorrelation phenomena (Lanari *et al.* 2007). For the present study, the data of the ENVISAT Advanced Synthetic Aperture Radar (ASAR) C-band Single look Complex (SLC) image was acquired from European Space Agency (ESA). A data pair with small baseline is necessary to avoid residual topographic effects and geometric decorrelation. Several images are available for the period from 2002 to 2012. Only six images were with baseline less than 300 m (table 1). Stramondo *et al.* (2007) has used pairs with 200 m. Lanari *et al.* (2007), Guzzetti *et al.* (2009), and Lee *et al.* (2012) have used pairs with 300 baseline for land subsidence studies. The selected SAR images for the present study are of the months of August and December 2003, November 2006, May and June 2007, and February 2010. The baseline and temporal baseline of interferometric master and slave ASAR images are listed in table 1.

The flow chart showing methodology followed in this study is shown in figure 3. The SARscape software in ENVI was used to process the six data sets by SBAS method as carried out by Lanari *et al.* (2007). All possible image combinations were made, generating 15 interferograms for the SAR data acquired during 6 times between years 2003 and 2010. Phase unwrapping is the process that resolves this 2π ambiguity using minimum cost flow algorithm. The orbital refinement and re-flattening is a correct transformation of the unwrapped phase information into displacement values (Baek *et al.* 2008). Further, the phase noise

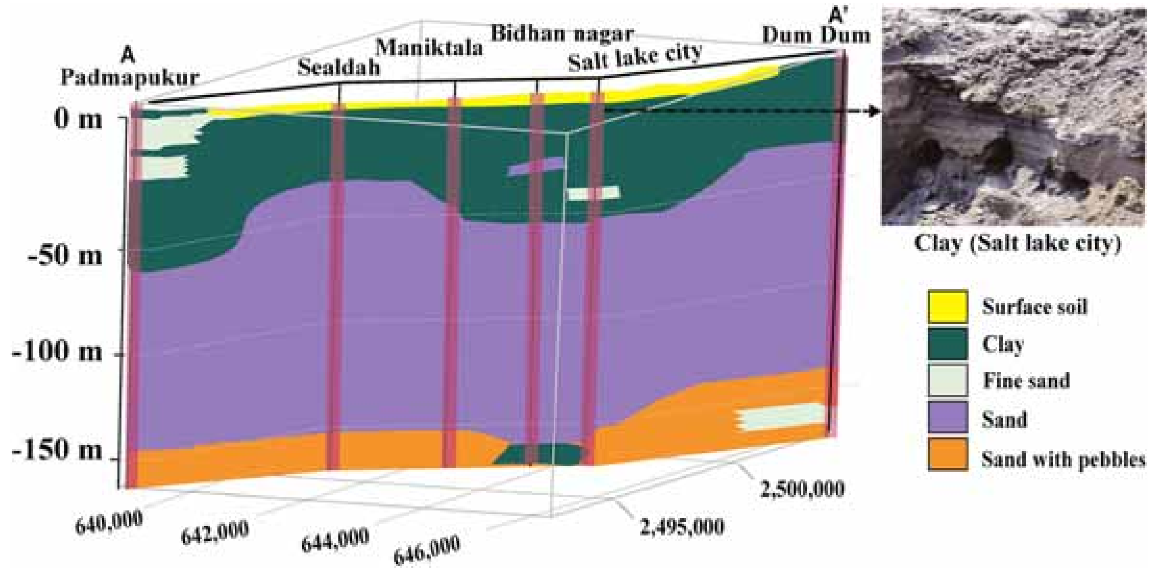

Figure 2. Geological cross-section along A to A′ shown in (figure 1).

Table 1. *Details of six ENVISAT ASAR master and slave images and their perpendicular and temporal baseline used for SBAS study.*

ENVISAT master orbital number/acquisition date)	ENVISAT slave orbital number/acquisition date)	Perpendicular baseline (m)	Temporal baseline in days
(7745/2003-08-24)	(9248/2003-12-07)	–229	105
(7745/2003-08-24)	(24779/2006-11-26)	–165	1190
(7745/2003-08-24)	(27284/2007-05-20)	–62	1365
(7745/2003-08-24)	(27785/2007-06-24)	45	1400
(7745/2003-08-24)	(41813/2010-02-28)	–177	2380
(9248/2003-12-07)	(24779/2006-11-26)	72	1085
(9248/2003-12-07)	(27284/2007-05-20)	179	1260
(9248/2003-12-07)	(27785/2007-06-24)	262	1295
(9248/2003-12-07)	(41813/2010-02-28)	52	2275
(24779/2006-11-26)	(27284/2007-05-20)	111	175
(24779/2006-11-26)	(27785/2007-06-24)	195	210
(24779/2006-11-26)	(41813/2010-02-28)	31	1190
(27284/2007-05-20)	(27785/2007-06-24)	85	35
(27284/2007-05-20)	(41813/2010-02-28)	–126	1015
(27785/2007-06-24)	(41813/2010-02-28)	–210	980

in the interferogram due to radar signal was removed by the Goldstein filtering technique to reduce phase noise and enhance the fringe visibility in the interferograms and to produce coherence image (Calderhead *et al.* 2011). The re-flattened interferograms, together with the phase-height pair-by-pair proportionality factors were used to estimate the residual height and the displacement corresponding to the displacement velocity (in mm/year). The interferograms generated will have errors due to topographic variation, spatial and temporal decorrelation and atmospheric variation, signal noise during data acquisition. Digital Elevation Model (DEM) of the study area derived from SRTM data was used to remove the residual topographic effects. In order to mitigate the effect of possible atmospheric artefacts, a space–time filtering operation, described by Berardino *et al.* (2002) was used. The 15 interferograms were analysed by SBAS algorithm and map of subsidence per year was generated for regions having coherence values greater than 0.2.

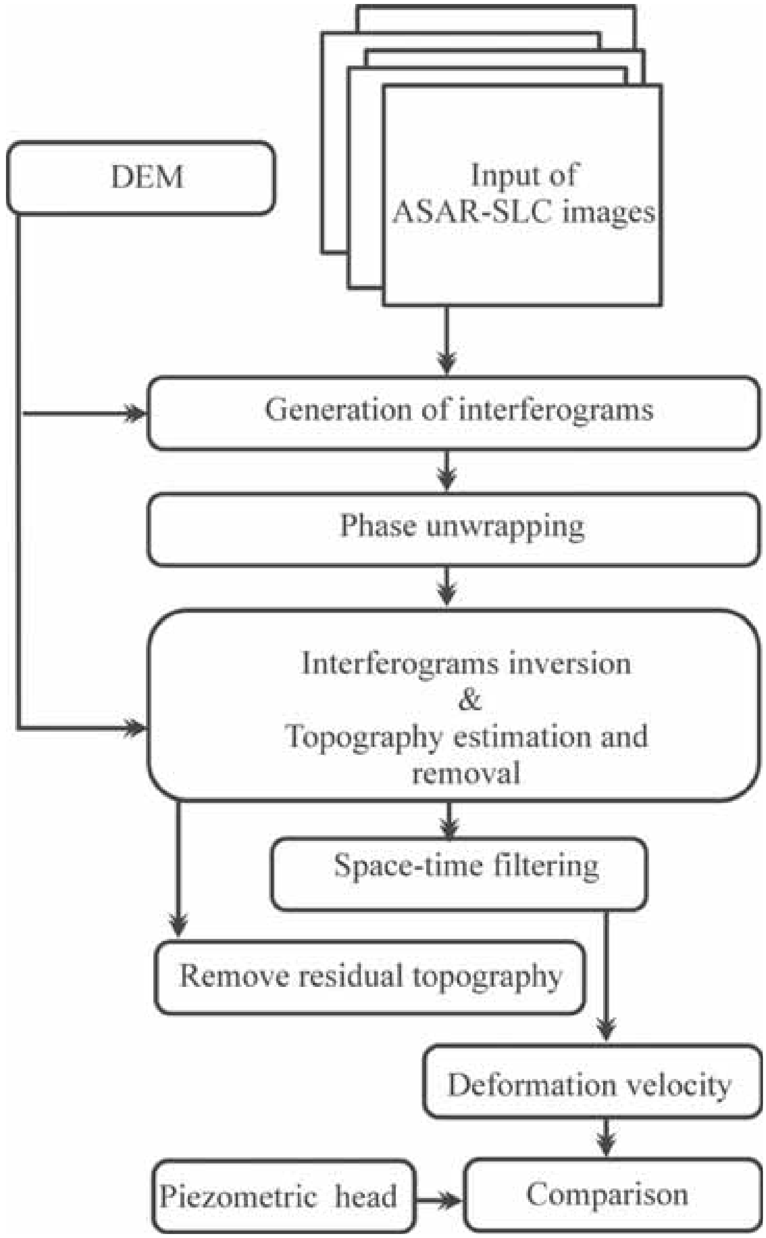

Figure 3. Flow chart showing methodology adopted for SBAS.

4. Results and discussion

The SBAS technique was used to understand the surface deformations in and around Kolkata City from the year 2003 to 2010. The SAR data for six different time periods of the study site was processed by SBAS technique by inclusion of topographic and atmospheric correction. The processing of datasets resulted in a map of velocity of surface deformation of the study area. This map of spatial variation in the velocity of deformation over the period from the year 2003 to 2010 is shown in (figure 4). This shows the mean rate of subsidence velocity in the line of sight direction. The red and pink areas in figure 5 represent subsidence and uplift relative to the surface information of master data. The negative values indicates the region of land subsidence (figure 4). The maximum land subsidence in the region was about 8 mm/year, in the northeastern part of the area. The localities including Baguiati, Ultadanga-Nazrul Islam Sarani, Salt Lake, Salt Lake Karunamoyee, Salt Lake Sector-III, Beleghata, Tangra, Science City near the Eastern Metropolitan bypass, Nayabad, Machhua bazar, Rajabazar and Calcutta University (table 2 and figure 4) have undergone land subsidence and

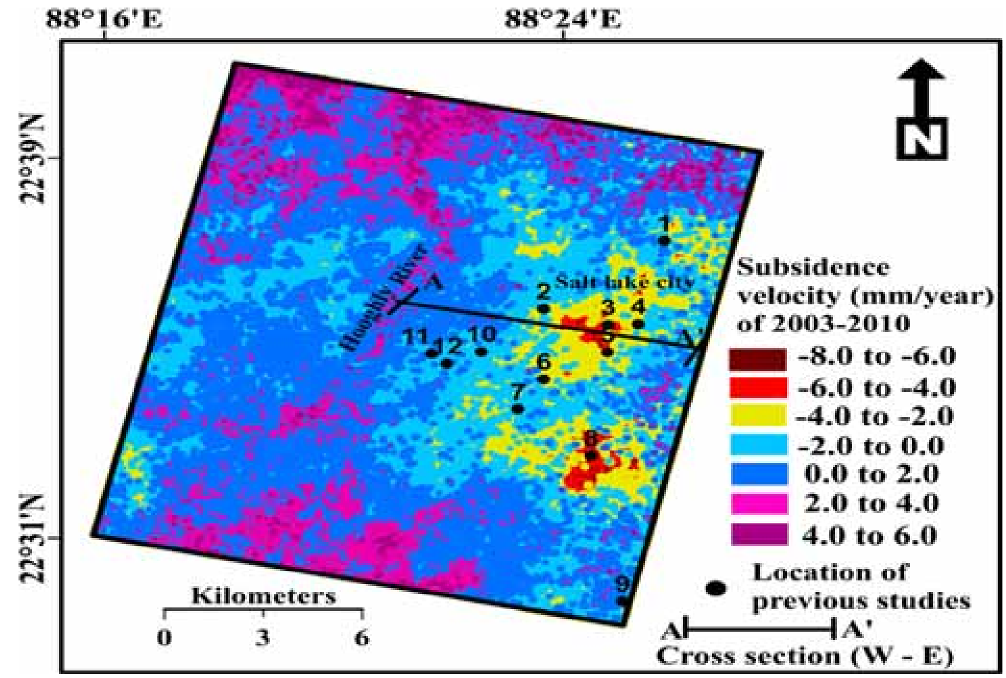

Figure 4. Velocity of subsidence rates measured over the period from the year 2003 to 2010 (negative values stand for relative subsidence).

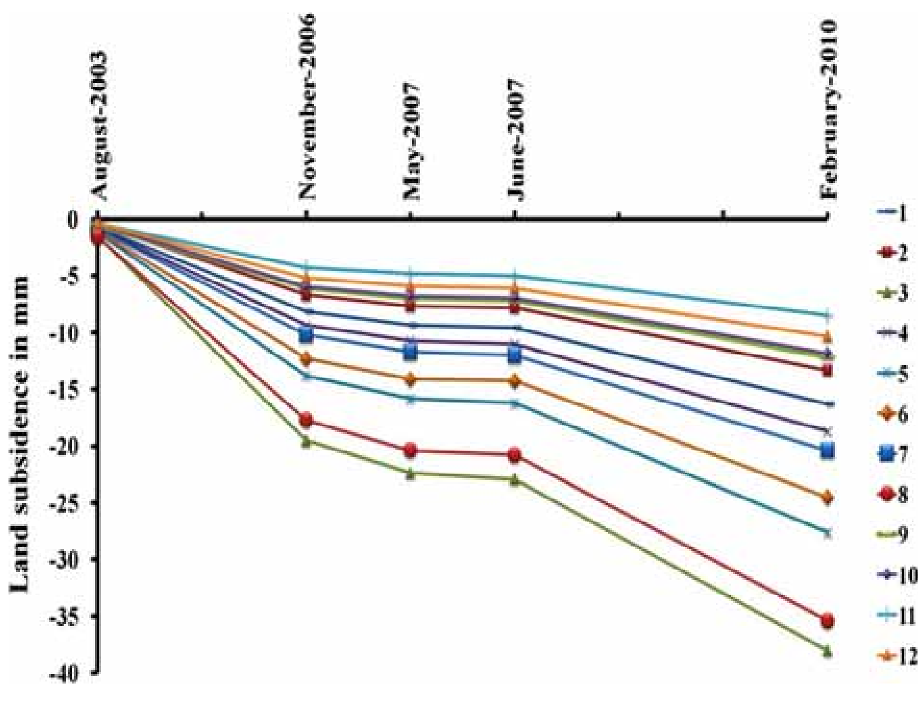

Figure 5. Temporal variations in land subsidence.

the total amount of subsidence ranges from 39 to 52 mm from the year 2003 to 2010. The maximum land subsidence has occurred in Salt Lake City and Science City.

Figure 5 indicates that the land subsidence was very rapid during the period from May 2007 to February 2010. During this period, the land subsidence was about 15 mm in Salt Lake City whereas it was about 5 mm in Machhua Bazar. During the period from August 2003 to November 2006 the amount of land subsidence was ranging from about 5 to 20 mm. Temporal evolution of land subsidence from 2003 to 2010 is shown in figure 5. The temporal variation determined at all the 12

Table 2. *Estimated land subsidence in some locations by SBAS technique.*

Previous study						Present study	
Location no.	Location	References	Year	Land subsidence (mm/ year)	Year	Land subsidence velocity (mm/year)	Amount of land subsidence velocity in mm (2003–2010)
1	Baguiati	Bhattacharya and Kumar (2012)	1956–2000	7.52	2003–2010	2–4	13–26
2	Ultadanga-Nazrul Islam Sarani	Bhattacharya (2008)	1958–2000	18.23	2003–2010	2–4	13–26
3	Salt Lake	Sahu and Sikdar (2011)	2001–2004	16.40	2003–2010	6–8	39–52
4	Salt Lake Karunamoyee	Bhattacharya (2008)	1956–2000	10.56	2003–2010	2–4	13–26
5	Salt Lake Sector-III	Bhattacharya (2008)	1956–2005	20.46	2003–2010	6–8	39–52
		Sahu and Sikdar (2011)	1981–2004	2.69			
6	Beleghata	Sahu and Sikdar (2011)	1956–2005	5.94	2003–2010	4–6	26–39
7	Tangra	Bhattacharya and Kumar (2012)	1956–2000	7.47	2003–2010	4–6	26–39
		Sahu and Sikdar (2011)	2001–2005	7.80	2003–2010		
8	Science city	Bhattacharya (2011)	1956–2000	13.00	2003–2010	6–8	39–52
9	Nayabad	Sahu and Sikdar (2011)	2001–2005	23.60	2003–2010	2–4	13–26
10	Rajabazar	Chatterjee *et al.* (2006)	1992–1998	5–6.5	2003–2010	2–4	13–26
11	Machhua Bazar			5–6.5	2003–2010	0–2	0–13
12	Calcutta University			5–6.5	2003–2010	2–4	13–26

locations by this study is also given in table 2. Several other researchers have used one dimensional consolidation theory and D-InSAR methods to estimate land subsidence in this region for different period during 1956 to 2005. The estimated land subsidence rates determined by these researchers are also compared with the present study and are given in table 2. As land subsidence is a very slow process, validation of SBAS technique derived land subsidence is very difficult due to the lack of accurate historical elevation information. The rate of land subsidence estimated by a few researchers estimated by consolidation and linear theory for a few locations are much higher than the values estimated in the present study (table 2). This may be due to the limitations in the application of one dimensional consolidation method where effective stress per meter fall in piezometric head is considered. Whereas in the present study SBAS technique was used which depend on multilook D-InSAR interferograms prepared for the time variant dataset. Hence, in this approach, estimation of temporal variation in land subsidence was carried out with better accuracy.

4.1 *Over extraction of groundwater*

A part of the study region was mostly marshy and having shallow salt water lakes which were developed as an auxiliary township of Kolkata in the year 1962 and this region was named as Salt Lake City. During the development of this township, the lakes and marshy land were filled with sediments dredged from the River bed of Hooghly (Sahu and Sikdar 2011). Hence the upper layers of soil are

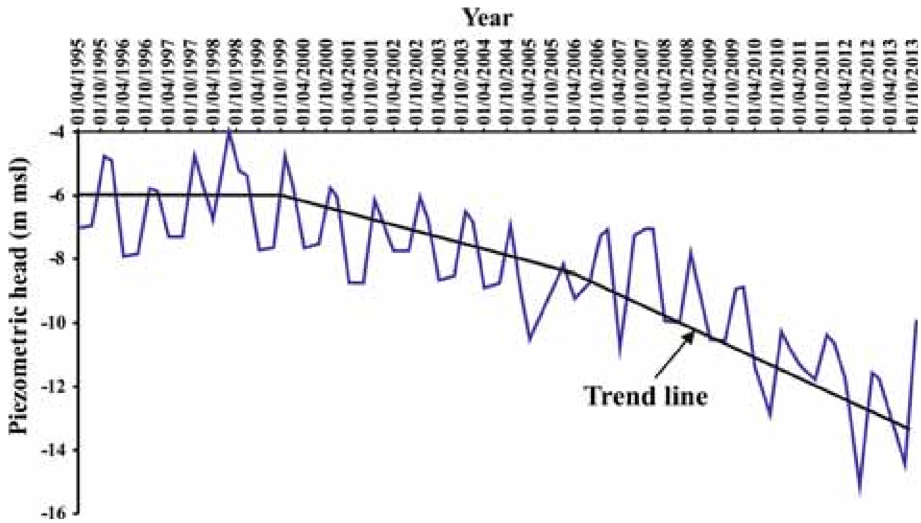

Figure 6. Changes of the groundwater level in the Salt Lake City (CGWB 2014).

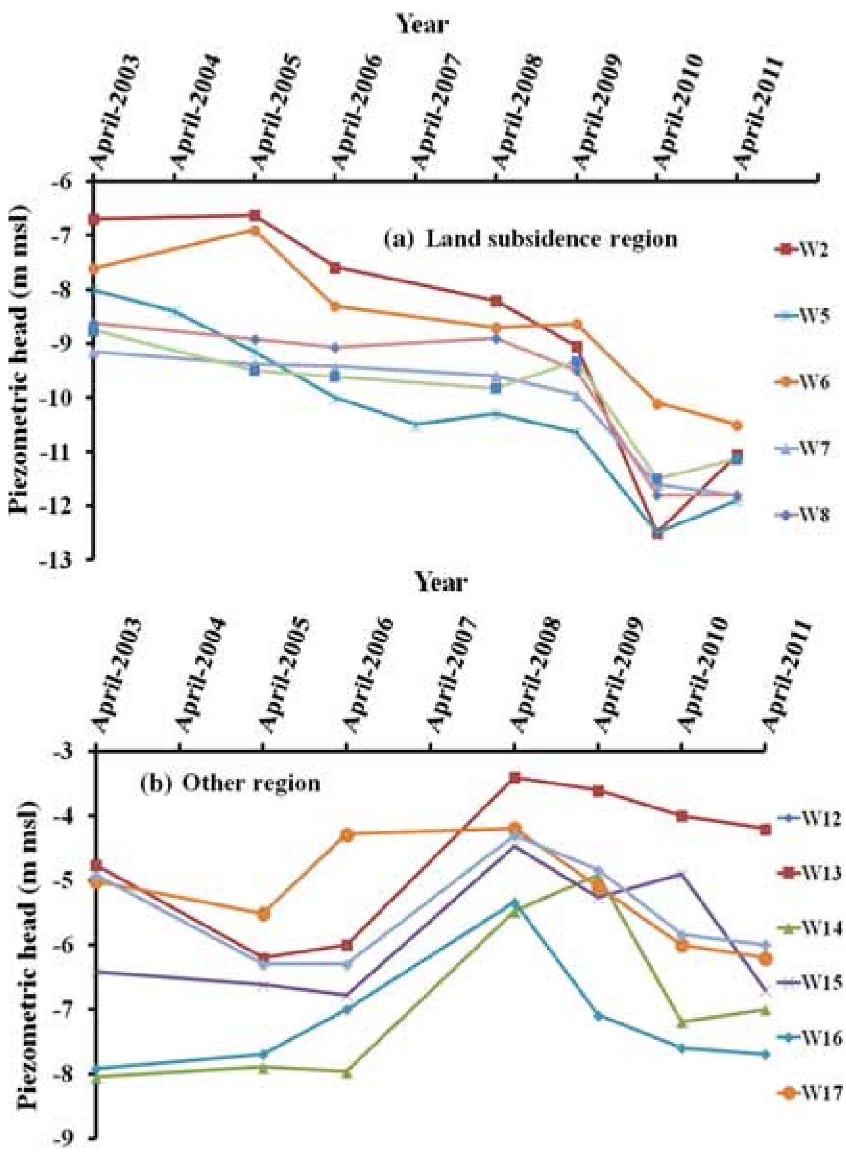

Figure 7. Year wise changes in the piezometric head in piezometers during the month of April in (**a**) land subsidence region and (**b**) other regions.

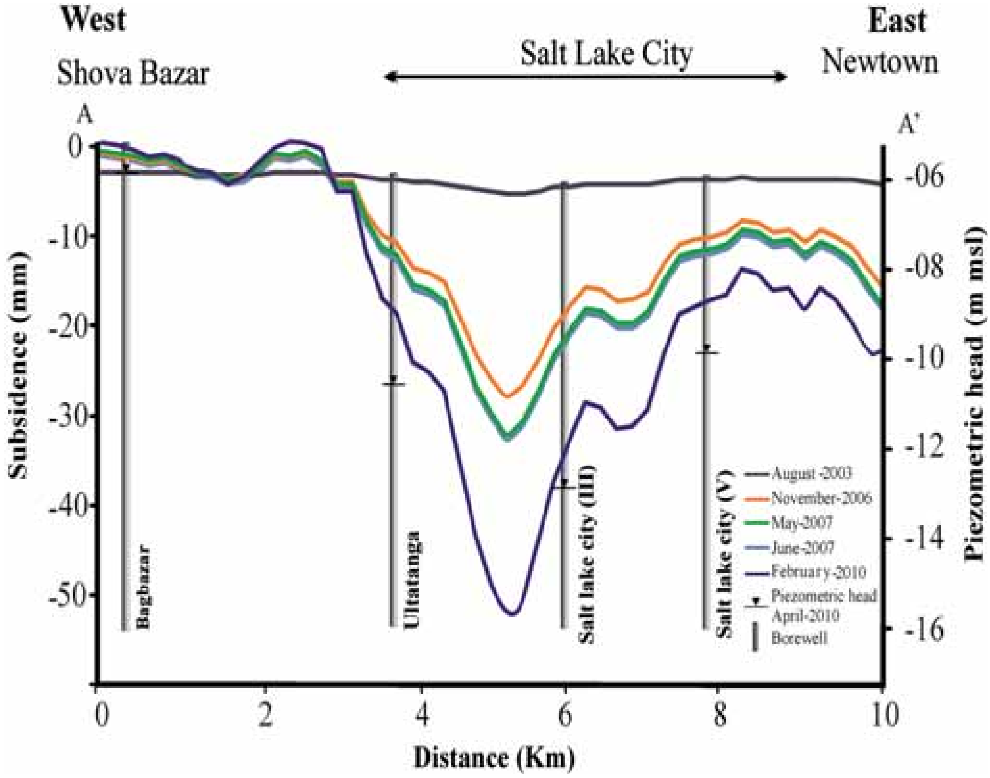

Figure 8. Estimated land subsidence along west to east section at different periods.

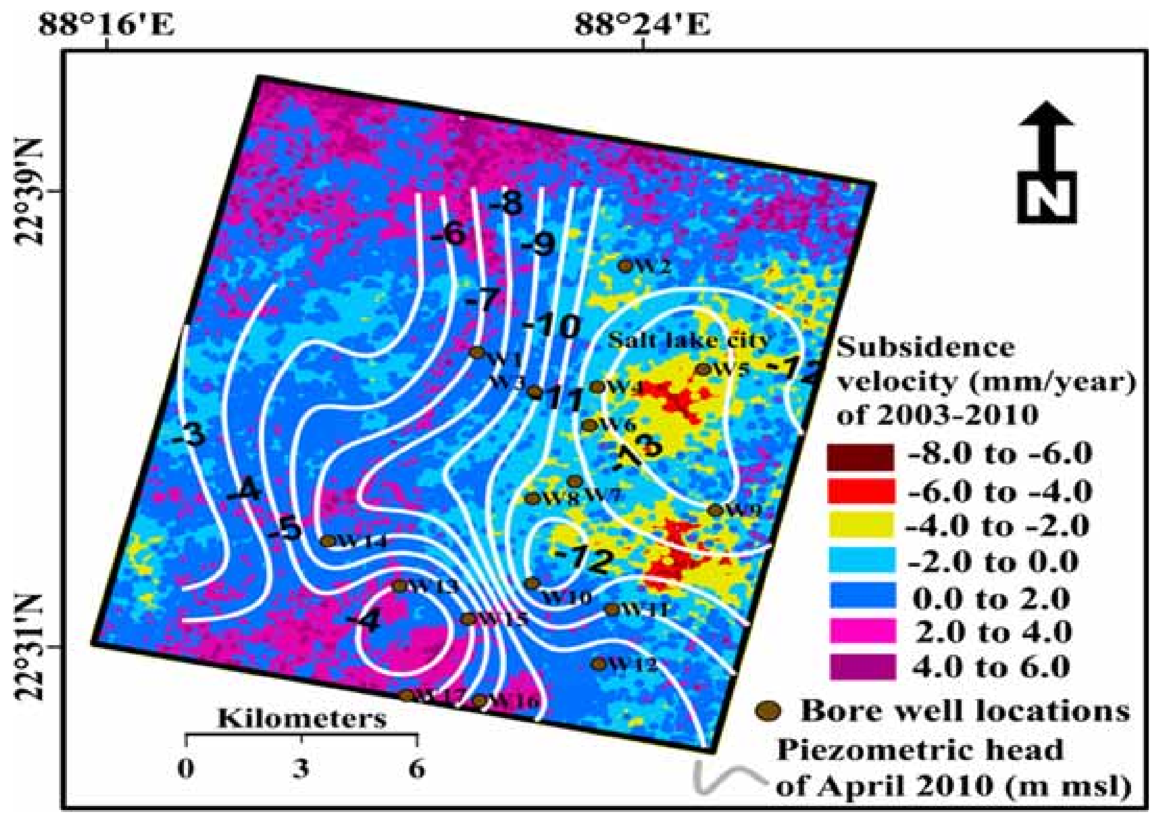

Figure 9. Variation in piezometric head overlaid on land subsidence velocity map.

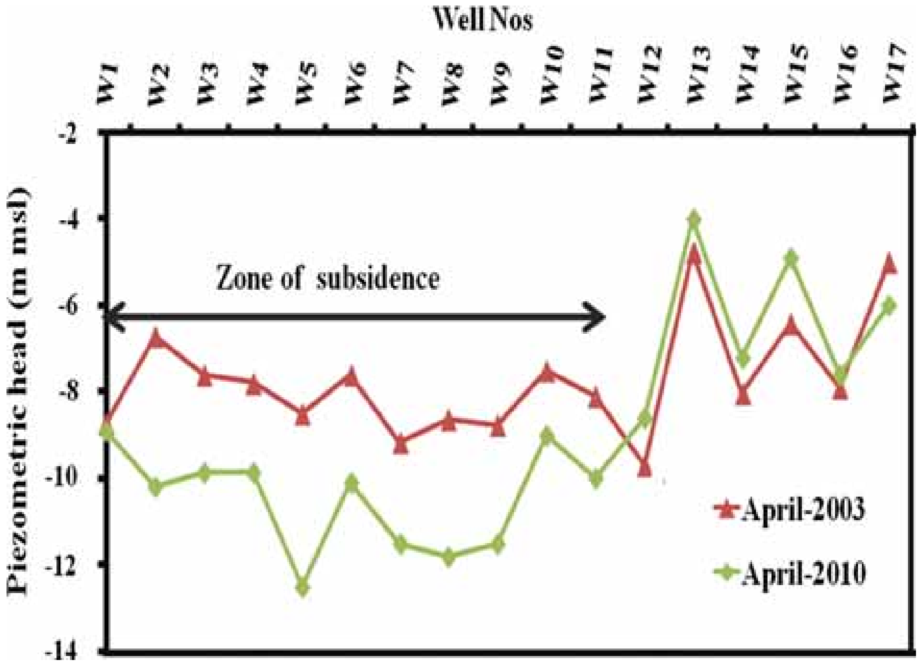

Figure 10. Variation in piezometric head in April 2003 and April 2010.

composed of filled up materials leading to slow processes of consolidation. In order to improve this area to facilitate construction of buildings, improvement of the ground was carried out by way of dumping sand (Bhattacharya 2008). However, beneath the layer of sand, clay of poor quality is present leading to compaction and land deformation. In addition to this, excessive groundwater withdrawal (figure 6) has taken place in this region from the year 1995 to 2013 (CGWB 2014).

Consolidation of filled material and over pumping of groundwater resulting in compaction of 50 m thick confining layer has also lead to development of cracks in some buildings located in Salt Lake City (Bhattacharya 2008). Consolidation of organic matter including peat present in the confining layer may also be leading to land subsidence (Chatterjee *et al.* 2006). The presence of very thick clayey confining layer from the ground surface and draining of water from this layer due to over extraction of groundwater from the confined aquifer beneath are also responsible for land subsidence (Suganthi *et al.* 2017).

The lowering of piezometric head in the regions undergoing land subsidence can be generally used to support the interference obtained from SBAS techniques. The amount of land subsidence between the years 2003 and 2010 was estimated by SBAS techniques. The lowering of piezometric head was estimated from the data obtained from 17 bore wells maintained by the SWID of Kolkata. The temporal variations in the piezometric head from April 2003 to April 2011 are shown in figure 7.

The increasing groundwater extraction from the confined aquifer in this region is evident from the piezometric head, which is declining from the year 2006. The decline in the piezometric head from the year 2003 to 2007 was about 2 m whereas from 2007 to 2010 the decline was about 4 m. Over abstraction of groundwater from the Salt Lake City as well as compaction of filled material has resulted in land subsidence in this region. To understand temporal evolution of land subsidence, the values of deformation in pixels at different years across west to east cross-section were obtained and it is shown in figure 8.

This indicates that the land subsidence was very high in the Salt Lake City and it was about 15 mm between the years 2007 and 2010, whereas in the region east of Salt Lake City, land subsidence was about 10 mm during this period. The variation in piezometric head with respect to space for the month of April 2010 was compared with the SBAS derived subsidence map (figure 9). This figure indicates that the region of the land subsidence derived from SBAS techniques compares well with the regions of lowering piezometric head. This region comprises of Salt Lake City which is predominantly made up of clay and refilled materials. That is, in general it is observed that the piezometric head is

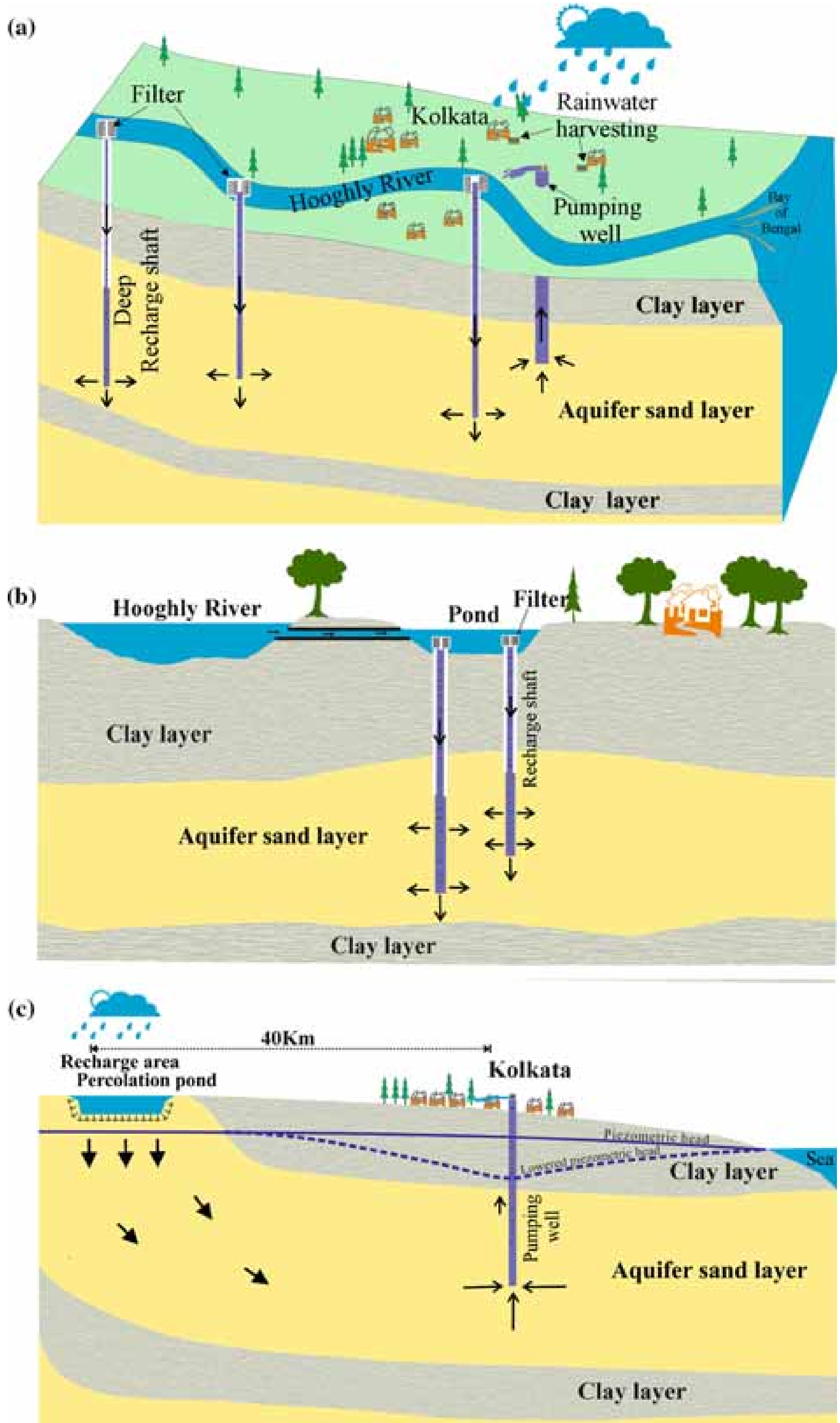

Figure 11. Conceptual diagrams showing remedial measures: (**a**) recharge shafts in the Hooghly river, (**b**) river water recharge through pond concept of UTFI (Pavelic *et al.* 2012), and (**c**) percolation pond in the recharge area.

very low in the regions of high land subsidence as observed by Suganthi *et al.* (2017). Land subsidence was very high in the northeastern part of the area where piezometric head was very low. The piezometric head of this region for the month of April 2003 and 2010 also indicates differences between the subsidence regions from the rest (figure 10).

5. Possible remedial measures

The land subsidence may be mitigated by reducing the quantum of withdrawal of groundwater to meet the domestic and other requirements. Hence, water supply to the city may be met by increasing the supply of surface water from the river after proper treatment (figure 11a). This will reduce the dependence on groundwater resulting in increase of piezometric surface over the years. The other measure for remediation for land subsidence is by increasing the groundwater recharge within the Kolkata City. This is possible by promoting rainwater harvesting and injecting the recharge water into the confined aquifer after proper filtering through the deep recharge wells. The problem of land subsidence can also be tackled by increasing the groundwater recharge in the outskirts of Kolkata City within the confined aquifer region. This can be carried out by the concept of Underground Taming of Floods for Irrigation (UTFI) (Pavelic *et al.* 2012). This involves diverting high water flows from rivers to the nearby existing or newly constructed ponds where a group of recharge wells can be constructed with a filters until the bottom of the pond (figure 11b). Further to increase the groundwater storage, measures have to be taken in the recharge area (40 km from North of Kolkata) by way of construction of large percolation ponds which can be filled by diverting water from Hooghly river (figure 11c).

6. Conclusion

In order to estimate the land subsidence more precisely in Kolkata City, SBAS techniques were used to extract information from The European Space Agency's ENVISAT spacecraft acquired ASAR data. In this technique, multilook D-InSAR interferograms were prepared for ASAR data acquired during six periods and the temporal evolution of land subsidence in this study area was determined. This study brought out the temporal evolution over the study area from the year 2003 to 2010. The maximum amount of land subsidence was varying from 39 to 52 mm. The rate of land subsidence is increasing from the year 2007. Land subsidence was maximum in Salt Lake City and Science City near the eastern metropolitan bypass. The region of land subsidence is elongated along north south direction. The major cause for land subsidence is the consolidation of sediments used to fill up the marshy land and lakes in the Salt Lake City area as well as due to over pumping of groundwater from the confined aquifers. The comparison between the region of land subsidence and low value of piezometric head contours conforms that the over extraction of the confined aquifer of this region is leading to land subsidence. The temporal variations in piezometric head of wells located in the land subsidence area are declining with respect to time from the year 2006 whereas, there is no significant trend in the piezometric head in the wells located away from the area of land subsidence. Further, the rate of subsidence also compares well with the rate of decline in piezometric head. The groundwater pumping from this region needs to be reduced and improvement of groundwater storage has to be carried out for mitigation of land subsidence. This needs to be ensured by continuous monitoring of piezometric head in the region of land subsidence. The remedial measures that can be taken are reducing the groundwater pumping, supply of river water, installation of recharge wells in the city and increasing infiltration in the recharge area north of the city.

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