Determination and Analysis of Land Deformation in Nairobi City County Based ALOS/Palsar and Sentinel-1 InSAR Processing

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Determination and analysis of land deformation in Nairobi City County based ALOS/Palsar and Sentinel-1 InSAR Processing

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Abstract Nairobi city is one of the fastest-growing cities in Africa. The rapid development has put pressure on the existing resources such as water resulting in overexploitation of groundwater. Nairobi had been reported to be susceptible to environmental hazards such as subsidence associated with the overexploitation of groundwater due to depletion of its aquifer. However, the subsidence has not been empirically quantified because Kenya lacks a functioning deformation monitoring framework. Through the use of InSAR, land subsidence in Nairobi was spatially quantified for the first time that confirms fears of subsidence as suggested by previous hydrogeological studies. We observed an increase in the spatial extends and the rates of subsidence, the highest rate of subsidence being approx. 62mm/yr located in the largest deforming area West of Nairobi. The deformation can majorly be linked to overexploitation of groundwater as it matches with regions with the highest rate of decline of groundwater levels. However, there exist also subsidence linked to rapid development. Given the significance of Nairobi to the Kenyan economy, the ripple effects of subsidence could be devastating and measures need to be taken to mitigate them. The deformation map provides an important tool for planning mitigation measures to prevent further deformation such as regulating the drilling of boreholes, planning of construction of buildings and transport networks, and locations for the observation wells for monitoring groundwater levels. It also reinforces the need for updating the geodetic network that has been rendered unreliable due to land subsidence.

Keywords Nairobi land subsidence · Nairobi Groundwater · InSAR · Depletion of Nairobi aquifer

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1 Introduction

Nairobi City, the capital city of Kenya is one of the fastest-growing cities in Africa (Ren et al., 2020). The current population of Nairobi city stands at 4.3 million as per the 2019 census (KNBS, 2019) which represents a growth of approximately 250% during the last three decades. The city serves as a host to various land use such as residential, industrial, transport, and commercial. The rapid population growth in the recent past has put pressure on the existing resources resulting in environmental problems such as pollution, flooding, and shortage of amenities such as housing and water. This is exemplified more in the increased demand for housing which has led to rapid urbanization Otiso and Owusu (2008), the development of high-rise buildings, shopping malls, and other infrastructural projects. Similarly, an exponential increase in the waste with no alternative sites for water disposal has put pressure on the existing landfill, Dandora landfill, with tones of waste being disposed of daily (Hudson Hill, 2020; Haregu et al., 2017). Aside from the obvious environmental hazards, the addition of 5000 tonnes of waste daily is a recipe for land subsidence to the adjacent properties mechanical and biochemical processes at the landfill is a recipe for land subsidence for the adjacent properties (Gasparini et al., 2014; Baek et al., 2019). Additionally, unplanned development in fragile environmental locations such as flood plains characterized by high population density could also induce subsidence (Rateb and Abotalib, 2020). The interplay of these factors together with the depletion of the aquifer could act as a catalyst to subsidence. Land subsidence has been associated with over-exploitation of groundwater but urbanization due to the rapid development of buildings can also contribute to land subsidence due to the consolidation process (Chen et al., 2015). The land subsidence due to the construction of new buildings has been reported for example in Ezquerro et al. (2020); Pratesi et al. (2016); Xu et al. (2012); Yang et al. (2018). Similarly, Nairobi city has witnessed rapid construction of high rise buildings even in regions that were not zoned for such buildings to meet the increasing housing demand (Makunda, 2018) which can lead to subsidence. The water exploitation induced subsidence is due to the increased distribution of effective stress in the strata and the compression of the aquifers (Guo et al., 2015). Land subsidence due to overexploitation of groundwater has been witnessed in other cities such as Mexico (Chaussard et al., 2014), China (Chen et al., 2003) Italy (Ezquerro et al., 2020), Nepal (Bhattarai et al., 2017), Taiwan (Hung et al., 2012), Indonesia (Abidin et al., 2011) and Brazil (de Luna et al., 2017). Nairobi's daily demand for water is 790,000 m³ against the supply of 525,000 m³ by Nairobi water Sewerage Company, the authority in charge of water supply in Nairobi. Due to unreliable piped water supply, the residential houses and other establishments depend on groundwater to ensure a consistent supply of water. The shortage in water supply has increased the overexploitation of the aquifer to meet the demand for residential, commercial and industrial activities (Chakava et al., 2014; Mumma et al., 2011). The rate of groundwater extraction has increased in proportional to the population growth leading to a depletion of the aquifer (Oiro et al., 2020). The depletion of the aquifer is characterized by the decrease water table, which has been reported to decrease at the rate of 3-7m per year within Nairobi city. The decrease in the water table may consequently lead to land subsidence. For Nairobi, previous hydrogeological studies have acknowledged the possibility of subsidence associated with groundwater exploration. For instance, Foster and Tuinhof (2005), Nairobi City Council (2007) and Onyancha et al. (2012) reported on the fear of subsidence in Nairobi due to groundwater overexploitation. A similar observation was noted by Onyancha et al. (2011) who opined on the possibility of land subsidence in Nairobi due to overexploitation and its geology which was once a swamp. The first attempt to model the possible subsidence in Nairobi was by Mathu et al.

(2014), who estimated a maximum of 5.9 m subsidence over the last 80 yrs, they noted that no subsidence had ever been reported in Nairobi associated with groundwater abstraction due to lack of deformation monitoring framework. Their estimates were based on the modelling of hydrogeological and piezometric data. Their estimates were cumulative and not spatially represented as is restricted to the location of observation wells with temporal data. Direct estimates of the rate of land subsidence that are spatially representative and have not been reported or quantified. Geodetic methods have been widely used to quantify the magnitude and spatial pattern of subsidence. These methods include leveling (Chrzanowski et al., 1989; Tosi et al., 2007), use of GNSS (Argyris et al., 2020; Ustun et al., 2010), and InSAR (Chaussard et al., 2014; Hirose et al., 2001). Levelling and GNSS show point deformation while InSAR has the capability of showing the areal subsidence. In Kenya, geodetic network maintenance and observation is the responsibility of the national mapping agency, the Survey of Kenya (SOK). Unfortunately, a modern and up to date geodetic network for mapping and other applications such as geophysical studies is lacking. The leveling geodetic network has not been updated or densified over the years, meaning that historical data needed for deformation monitoring are not available. Similarly, Kenya did not have a reliable GNSS network except for some three stations owned by International GNSS Service (IGS). Lately, however, there have been efforts by the private sector such as Measurement Systems Limited to establish their private geodetic network and deformation monitoring network such as Uganda-Kenya Eastern Branch GNSS Network (Stamps et al., 2019). However, the network is not large and dense enough to cover most of Nairobi City County, the study area, hence its applicability in deformation monitoring is still limited. The lack of accurate and sufficient geodetic data perhaps explains the lack of previous studies in deformation within the study area. Moreover, although InSAR has been used in other regions for monitoring subsidence, its application within Nairobi has not been reported. The use of InSAR as a geodetic tool for monitoring land subsidence due to groundwater extraction is well documented Guo et al. (2015); Neelmeijer et al. (2018). InSAR is based on observation of phase change; however, the conventional differential InSAR was faced with challenges of extracting deformation signal from other superimposed sources such as decorrelation and tropospheric modelling. Multi-temporal InSAR Berardino et al. (2002); Ferretti et al. (2000) was later introduced to address these challenges. The resulting velocity measurement is the line of sight (LOS); through the use of data acquired in descending and ascending orbits, the vertical and east-west components can be derived Eriksen et al. (2017); Hu et al. (2014). The aim of this study, therefore, was to determine the deformation within Nairobi City County through the use of InSAR, taking advantage of the large data sets of Sentinel 1 data. The nature of deformation was determined by decomposing the LOS velocity estimates into vertical and East-west movement and finally assigning the deformation to its causative agent.

2 Materials and Methods

2.1 Study area

The study is being undertaken in Nairobi City County, the capital city of Kenya. The geographical extends of Nairobi, the elevation the processing extends limited to the footprint of the ascending orbit, the geology and the land cover of Nairobi is shown in Fig. 1. The geological structures of Nairobi are mainly underlain by pyroclastic volcanic rocks interposed with sediments that were deposited in a series of lakes that extended from Doinyo Sabuk to Kajiado (Matheson, 1966; Oiro et al., 2020; Onyancha et al., 2011). The specific geological

formations are Nairobi phonolite, Kerichwa turfs, Nairobi trachytes, and Limuru trachyte, while other formations include Kabete trachytes and Mbagathi trachyte.

Fig. 1 Location of the study area its elevation ,related geology and Land cover clipped to the footprint of the Sentinel 1 ascending orbit

2.2 Data

2.2.1 Sentinel 1 data

The study uses Sentinel 1 C-band data from the European space agency (ESA). Sentinel 1A was launched in April 2014 but earlier observations within the study area were characterized by huge gaps that made it unsuitable for multi-temporal InSAR MTI analysis. Consistent observations were only realized after the launch of Sentinel 1B in April 2016. It guaranteed consistent observations and decreased the revisit time to 12 days from the earlier 24 days. The Sentinel 1 data are acquired in interferometric wide (IW) mode and each image consists of 3 sub swaths that can act as an independent image. IW is imaged through ScanSAR mode called Terrain Observation with Progressive Scan (TOPS) that aims to improve uniform Signal to Noise Ratio (SNR). The product is distributed with a swath of 250 km with a resolution of 5*20 in range and azimuth respectively (Geudtner et al., 2014). Table 1 presents a summary of the data used.

Table 1 Summary of the Sentinel 1 SAR data

	Ascending	Descending
Number of Images	127	99
Relative Orbit	130	79
Track number	1173	597

2.3 ALOS PALSAR 1

Advanced Land Observing Satellite (ALOS), PALSAR L-band SAR was launched in May 2006 and operated until 2011 by the Japan Aerospace Exploration Agency (JAXA). For our study area, 13 images were available from July 2007 to October 2010 characterized by inconsistent revisit time. The data was acquired from ESA ALOS PALSAR Dissemination Service in a raw format both single polarization (FBS) and dual-polarization (FBD). Both acquired in ascending mode along path 566 with a spatial resolution of 10m.

2.3.1 Groundwater level data

The location of boreholes within Nairobi County was obtained from Water Resources Authority (WRA). The authority tasked with the management and issuance of permits for groundwater abstraction. Nairobi County falls within the Nairobi Aquifer System (NAS). The NAS data were subset to get the data within the study area. Fig. 2 shows the spatial distribution of boreholes and temporal evolution. A total of 1185 boreholes were found to fall within the study area, the data covers a period of 1930- 2018. It should be noted that the number of boreholes presented is underestimation of the actual number of boreholes. The exact number of boreholes in Nairobi is not known but estimated to be above 5000, different studies reporting different estimates due to illegal borehole drilling (Nato, 2015). Chakava et al. (2014) reported that surveys conducted by WRA in 2011 found the number to be 2139 boreholes which was still a gross underestimation. The current number of boreholes could be more than 5000 given that each day, WRA receives an average of five boreholes applications per day at Nairobi sub-region Office Oiro et al. (2020) not considering the illegal borehole drilling. Previous studies are however in agreement that, the number of boreholes has been on the rise, with an exponential increase during the last two decades characterized by decreases in the water table. The boreholes are concentrated in the built-up areas specifically residential areas.

2.4 InSAR Processing

2.4.1 Sentinel 1 Processing

The interferometric synthetic aperture radar Scientific Computing Environment (ISCE) was used to generate stack focused SLC images. Coregistration was carried out following the Network-Based Enhanced Spectral Diversity approach (Fattahi et al., 2016) which ensures higher accuracy required for images acquired in TOPS mode to avoid phase discontinuities (Prats-Iraola et al., 2012). The SLC stack was then preprocessed to generate interferograms needed for multi-temporal analysis. Interferometric pairs were chosen to minimize

Fig. 2 Spatial and temporal distribution of boreholes within Nairobi county for the period 1930-2018

the geometric and temporal baselines which can easily be achieved because of the short revisit time of Sentinel 1 data and the orbital tube that ensures that the geometric baselines are constrained. The SBAS network adopted for this study is shown in Fig. 3. For MTI we adopted the modified SBAS Hooper (2008) implemented in the Stanford Method for Persistent Scatterers/Multi-Temporal InSAR (StaMPS/MTI) package. It works on single look complex interferograms to select slowly decorrelating filtered phase pixels instead of the multi looked interferograms as implemented in the conventional SBAS (Berardino et al., 2002). The scatters are initially selected based on the amplitude dispersion difference $D_{\Delta,A}$ which is defined as,

$$D_{\Delta,A} = \frac{\sqrt{\frac{\sum_{i=1}^N (|m_i| - |s_i|)^2}{N}}}{\frac{1}{2N} \sum_{i=1}^N |s_i|} = \frac{\delta_{\Delta,A}}{\mu_{\Delta,A}} \quad (1)$$

Where N is the number of images, S_i and M_i are the amplitudes of the slave and master, so that $\delta_{\Delta,A}$ is the standard deviation of the difference in amplitude between master and slave and $\mu_{\Delta,A}$ is the mean amplitude. For this study amplitude dispersion index of 0.4 was chosen. The spatially correlated components present in the interferograms are estimated through bandpass filtering while the spatially uncorrelated components are separated through correlation with baseline. The subtraction leaves out the decorrelation noise which is quantified as a temporal coherence expressed as,

$$\gamma_x = \frac{1}{N} \left| \sum_{i=1}^N \exp \sqrt{-1} (\psi_{x,1} - \tilde{\psi}_{x,1} - \Delta \tilde{\phi}_{\theta,x,i}) \right| \quad (2)$$

Where $\psi_{x,1}$ is the wrapped phase, $\tilde{\psi}_{x,1}$ is the spatially uncorrelated term and $\Delta \tilde{\phi}_{\theta,x,i}$ is the spatially correlated terms. The interferograms were then corrected for spatially-uncorrelated look angle error then it was finally unwrapped using the approach proposed by (Hooper, 2010), a 3D cost function unwrapping algorithm. The tropospheric delay was estimated through time series filtering. The procedure was repeated for both the ascending and ascending data. To determine the nature of the deformation signal, the velocity estimates from

both the orbits were combined to estimate the vertical and east-west components. The velocity estimates were first interpolated into a regular grid to ensure that pixels are present in both the tracks and cover similar extents. The vertical component and the east-west component was determined following equation 1. The North-South component was not determined due to the low sensitivity of InSAR measurements in the north-south direction.

$$\begin{bmatrix} \cos \theta_{asc} & -\sin \theta_{asc} \cos \alpha_{asc} \\ \cos \theta_{dsc} & -\sin \theta_{dsc} \cos \alpha_{dsc} \end{bmatrix} \begin{bmatrix} d_v \\ d_E \end{bmatrix} = \begin{bmatrix} d_{los_{asc}} \\ d_{los_{dsc}} \end{bmatrix} \quad (3)$$

Where θ is the incidence angle and α is the heading angle of the satellite, d_v is the movement in a vertical direction while d_E is the movement in the horizontal direction. Due to varying nature of the look angle of the Sentinel 1, we used the incidence angle for each of the pixel location in determining the vertical and horizontal components.

Fig. 3 SBAS network for ascending and descending orbit for Sentinel 1 data

2.4.2 ALOS InSAR Processing

We also used data from ALOS Palsar 1 L-band data for the period 2007-2010. 12 images from the ascending mode, co-polarized data from both FBS and FBD modes were used. Envi Sarscape (Sahraoui et al., 2006) was used to convert the raw ALOS images into single look complex images and for the SBAS time series processing in this study. A small baseline network was generated considering that all the images were connected into the network Fig. 4, given the longer baselines for L-band data, it is least affected by geometric decorrelation (Sandwell et al., 2008), also our study area is majorly composed of build-up areas hence longer temporal baselines are still appropriate for this region. Multi look interferograms were generated, filtered using the Goldstein filter (Goldstein and Werner, 1998) to increase the noise to signal ratio and unwrapped through Minimum Cost Flow (MCF). The 90 m Shuttle Radar Topography Mission (SRTM) DEM was used to remove the topographic influence. The interferograms were then refined to remove orbital errors through the polynomial fitting of degree 3 using the ground control points. Atmospheric noise was then estimated and accounted through time series filtering. The deformation rate inversion was determined assuming vertical direction based on the results of the Sentinel 1 analysis.

Fig. 4 SBAS network for ALOS PALSAR data

2.5 Borehole data processing

Time series analysis for borehole data was carried out to check the variation of the water rest levels (wrl) from the year 1927-2018. For each year we picked the maximum value of wrl within the mapping unit to represent the wrl for that particular year as shown in Fig. 5. To determine the correlation of the water abstraction and the deforming regions, we analyzed the trend of the wrl. Though the two data sets do not overlap in terms of acquisitions time, the rate of change in water rest levels which is spatially varying can show the correlation

between the deforming region and the groundwater abstraction. The borehole data were also superimposed to the velocity estimates map to check the spatial distribution and its relation to the subsiding regions. Due to the mismatch of the two data sets, correlation analysis was carried out using the water rest levels for the year 2015-2018 and the estimated velocity rates from the InSAR estimates.

Fig. 5 Temporal variation of the water rest level for Langata, west of Nairobi.

3 Results

3.1 Rates of subsidence and spatial pattern for Period of 2007-2010

From the SBAS processing of ALOS data, several locations were observed to subside as shown in Fig. 6. The highest rate of subsidence is recorded at an industrial site, North East of Nairobi (point f) at the rate of approx. 47mm/yr, other significant deforming regions are also observed at Ngara estate off Moi airbase airport point (point c) at a rate of 30mm/yr, Kibera(point a') at a rate of 35mm/yr, Upperhill (point a) at a rate of 19mm/yr, Westlands at the rate of 14mm/yr, Mathare North estate at a rate of 17mm/yr (point i) . All the deforming regions are located in built-up areas and based on their spatial extends it can be treated as localized deformations.

Fig. 6 The LOS Velocity estimates derived from ALOS processing for the year 2007-2010

3.2 Rates of subsidence and spatial pattern for Period of 2017-2021

Based on Sentinel 1 processing from both the ascending and descending orbit, several locations were also identified as subsiding with additional new sites identified as subsiding. The LOS estimates from both the ascending and descending orbits show consistent spatial patterns and magnitude for the locations experiencing significant subsidence. The correlation of velocity estimates from the ascending and descending orbits is shown in Fig. ?? . The highest rate of subsidence is registered in the west of Nairobi (region aa') with an approximate value of approx. 48mm /year. It is located within a region with the largest areal deformation, the region comprises part of Langata, Kibera and Upperhill, the deforming region, unlike other subsiding locations, is large covering an area of approximately 2000ha. Other regions that exhibit significant deformations are residential estates that include Mathare North stretching to Garden estate (region ijk), Westlands near Consolata shrine stretching to parklands (point b), Ngara estate off Moi Airbase airport point (point c), Kasarani estate stretching to Roysambu (region ei), Fourways Junction Mall(point k), and Ruaka near Two Rivers Mall(point g), in Fig. 7. Additionally, other localized deformations are recorded in East of Nairobi near Fedha estate (point d) and at the edges of Dandora landfill (point m) which is the third-largest landfill in Africa, deformation is not recorded at the landfill itself due to low coherence attributed to changing surface characteristics of the dumpsite that is

Fig. 7 The LOS velocity estimates from the ascending(a) and descending(b) processing of Sentinel 1 data clipped to the footprint of ascending track and their correlation()

still active. Aside from those locations that are experiencing subsidence, it can be generally observed that most of the parts in Nairobi do not experience any deformation, the uplift recorded is isolated and can be regarded as outliers as shown in the scatter plot matrix in Fig. 7. Other regions

3.3 Comparison for 2007-2010 and 2017-2021

The comparison of the spatial pattern and rates of deformation for the two observations periods show mixed results. There exist locations, namely Westlands(poin b), Ngara(point c), Kibera-upperhill(section aa') that subsidence was witnessed during the two observations periods, The difference being an increase in the spatial extent and rates of the deforming re-

gions. Additionally, it can be observed that the spatial extent of the two subsiding regions(b and aa') have exponentially increased, and given the same trend, the two deforming units could merge. We also observed that from 2017 to 2021, new subsiding locations with considerably high deformation rates were observed that were not recorded during 2007-2010 period. The locations include Embakasi near Fedha estate(point d), Kasarani(point e) and Ruaka (point g). The three locations were not previously occupied but now serve as residential estates, we show for instance by use of google images the temporal occupation of location e in Fig. 8 . Another notable observation is point f that falls within premises of East African Breweries Limited(EABL) it was previously deforming at the highest rate for the period 2007 to 2010 but recorded insignificant deformation for the period 2017 to 2021. The average rates of velocity have increased for all the subsiding locations as shown in table 2. It should however be noted that for the period 2007-2010 the SBAS network is not robust enough compared to the Sentinel 1 network due to the limited number of ALOS images. The fact that the two sets of data show some consistent spatial pattern of deformation further reinforces that there exist locations that are significantly subsiding.

Table 2 comparison of LOS velocity estimates

Point	2007-2010	2017-2021
a	-5.79	-47.79
b	-9.41	-31.29
c	-11.62	-27.1
d	1.2	-22.76
e	-0.87	-32.48
f	-36.63	5.95
g		-26.5
i	-14.24	-17.02
j	-13.08	-19.06
k	4.01	-17.37
l	-15.08	-22.47
m	-4.72	-10.97

Fig. 8 Google Earth images for the year 2006 and 2021 for point e on Fig. 6

3.4 Direction of subsidence

The direction of deformation is majorly vertical based on the combination of the LOS estimates from ascending and descending orbit of Sentinel 1 data as shown in Fig. 9. The lateral deformation is insignificant, its estimates are in the range of the accuracy of LOS estimates with no particular pattern. Except for some locations within point aa' that recorded the highest deformation that could be interpreted as the consequence of intense subsidence recorded in this region that might have caused horizontal movement.

Fig. 9 Velocity estimates of horizontal and vertical components .

3.5 Time series analysis

The nature of subsidence is majorly linear for the subsiding locations except for some locations that show varying rates of subsidence where the deformation has since stopped or subsidence has since occurred. We have shown in Fig. 10 the time series displacement rates for the selected points that capture the scenarios explained above. As observed in Fig. 6 and Fig. 7 location a has been subsiding during both observation periods, with higher rates being observed in 2017-2021. Location f which was the most deforming during 2007-2010 has stabilized between 2017 and 2021. Additionally, we noticed two locations that were not deforming during 2007-2010 and are now subsiding, namely region d and e, region d started to subside towards the end of the year 2010 and has been constantly deforming. However point e is the most recent deforming location where deformation is being realized towards mid of the year 2019. We note that there is a gap of seven years and to understand the deformation that occurred in between the two periods. We have processed Sentinel 1 interferograms from the descending orbit for the 11. April 2014 to 27 February 2017 and 27 February 2017 to -20. December 2020. Given that the study area is urban and the orbital tube of Sentinel 1 leading to short geometrical baselines, the coherence of most of the parts is still high for the longer temporal baselines interferograms. From the interferograms, it can be observed that the regions that were recorded to have experienced subsidence in MTI analysis match with those of the interferogram as shown by the concentric circles of the wrapped interferogram in Fig. 11. For fifteen months cumulative subsidence of 21.38 radians was recorded which

Fig. 10 Time series displacement of some selected points on Fig. 6 for 2007-2010 and 2017-2021.

is approximately 95mm, implying that those regions have been subsiding at almost equal rates. It can also be observed that point e started subsiding after the year 2017. It can also be observed that Ngara estate point C was initially deforming at a faster rate compared to other regions but the rate has reduced in comparison with other places. The shape of the largest deforming site A is in the orientation of Nw-SE elongated and with the trend, it appears that there exists the possibility of the two deforming regions aa' and b merging as unit deforming areas.

4 Discussion

4.1 Groundwater exploitation as a driver of subsidence

The spatial pattern of most of the subsiding regions coincides with the locations that have been reported to experience a decrease in the water table. The coefficient of determination between the groundwater level and the velocity estimates is 0.48 as shown in Fig. 12 but it should be noted that the water levels are for the year 2015 to 2018 which is outside the observation period of our study. It shows the contribution of groundwater over-exploitation in the depletion of the aquifer and the consequent subsidence due to a reduction in the pore pressure within the aquifer system. Some of the locations cited to be settling in Nairobi by Mathu et al. (2014), though difficult to compare with our estimates because they were not spatially presented, coincide with the subsiding regions from our estimates. Moreover, the subsiding regions have been found to have higher rates of decrease in water table levels compared to other regions in Nairobi. For instance, some section of region aa' in Fig. 7 with the highest rate of subsidence falls in Langata, a region that has the highest number and density of boreholes characterized by a decrease in the water table at higher rates compared to other places within Nairobi county as noted by Nato (2015) and Ochungo et al. (2019). Chakava et al. (2014) report that this region experiences a water table level decline of 7m per year compared to other regions that decline at the rate of 3 m. Additionally, EABL(location f) installed a water recycling plant towards the end of the year 2007 which has greatly reduced the water demand (Wakhungu et al., 2017; EABL, 2011) and explains why subsidence is not recorded between 2017-2021. The intense subsidence recorded during 2007-2010 could be associated with huge demand of water during this period due to the nature of the process-

Fig. 11 Wrapped(a and b) and unwrapped(c and d) interferograms for 20141104-20170209 and 20170209-20201220 estimated from Sentinel 1 descending orbit showing the evolution of the deforming units.

Fig. 12 Water rest level contours for the period 2015-2018 superimposed on velocity estimates

ing which requires alot of water. Most of the boreholes are constructed by the residential owners to supplement the inconsistent supply of water hence the reason why most of the subsidence is witnessed in the residential areas. Moreover, location (e) in figure 4 is a developing residential area that was not previously densely occupied as can be seen in figure 8 no deformation was recorded for the period 2007-2010, the region starts to deform mid-2019

as shown in the figure. We do not have borehole data at this location but given the norm of the new buildings supplementing piped water with Groundwater, it can be hypothesized that the recently subsiding region is attributed to water abstraction as a result of a change in land use to residential as shown in figure 6. Analysis of the time series of the displacement rates show a linear trend with no periodic change, this shows that a major component of subsidence is due to the inelastic settlement which is in agreement with the hydrogeological modelling of Mathu et al. (2014).

4.2 Other causative agents

There exist deforming locations that can not be linked to overexploitation of underground water, for instance, location a' which was found to deform during both the observations period lies within the flood plain of River Ngong. The region is the largest informal settlement in Kenya with an approximate population of 300,000 (Ndemo, 2020; Ren et al., 2020). It was previously marshland land (Ngugi et al., 2012) and has been known to flood (Mulligan et al., 2016). The subsidence at this location is due to consolidation as a result of the construction of congested unplanned structures on the floodplain. Fig. 13 shows the location of the subsiding unit in relation to the flood plain. Another interesting subsiding region that cannot be solely tied to groundwater exploitation is location d, the spatial extend of the subsiding unit is limited and the adjacent residential units are not subsiding, moreover, the water rest levels at this region are shallow compared to other regions. The residential units at this location consist of high rise buildings built close to each other, with each building hosting a large number of tenants (Mwau, 2019). Subsidence at this location could be attributed to consolidation due to the loading effect of the buildings. As it can be observed in Fig. 6 the region was not subsiding during the period 2007-2010, the deformation thereafter can be attributed to loading associated with the high-density of high-rise buildings that were constructed after the year 2007.

Fig. 13 Velocity estimates for region a' and its relation to the Ngong river flood plain and velocity estimates of point d and its relation to building density, image courtesy of Google.

The phenomenon is consistent with other studies that have reported localized subsidence attributed to the higher density of buildings (Xu et al., 2012; Yang et al., 2018). Additionally, the deformation observed at the edges of Dandora landfill(location m) can be attributed to consolidation and the biochemical process, similar observations have been noted in other places like the case of Baek et al. (2019), the continued filling of the waste poses danger to the neighbouring properties. Similarly, the recent major developments in the North west of Nairobi on the previously undeveloped land seems to have triggered subsidence, for instance, the development of the Two Rivers Mall and the subsequent developments within its environs could be attributed to the subsidence at location g. The subsidence witnessed at the two airports (Wilson Airport and Moi Airbase, Eastleigh airports) can be attributed to foundation settlement that is tied to the consolidation of the filling material during construction and the loading effect during take-off and landing. Subsidence due to takeoff and landing of planes has been reported in other cities (Aobpaet et al., 2013; Gao et al., 2016; Mesri and Funk, 2015). Precise deformation monitoring though currently lacking could in future provide major insights on the deformation at these two airports. This is due to the

fact the two airports are located off the two subsiding regions aa' and c and the deformation recorded could be also be attributed to the effect of adjacent deformation.

5 Conclusion

We have shown that indeed the fear of possible subsidence in Nairobi that had been earlier postulated exists. The research findings empirically collaborate with previous hydrological studies that had suggested a possibility of land subsidence in Nairobi. We have quantified the subsidence spatially showing five deforming regions. The subsidence is of higher magnitude in the largest deforming area with a velocity of 60mm/year. The subsidence in most of the locations has been gradually occurring linearly and the nature of deformation is vertical. The subsidence can be attributed to over exploitation of groundwater although subsidence tied to consolidation due loading of the buildings, landfill and developments along Ngong river flood plain also exist. A deformation map is an important geodetic tool for guiding mitigation measures to prevent further subsidence and avoid the destruction of property. For regions that experience subsidence due to over exploitation of groundwater, the map can be used to guide issuing of licenses for drilling or stopping further abstraction. Moreover, the map provides an empirical way for locating the observation wells for monitoring the groundwater levels to provide a true representation of the depletion of the aquifer. The impact of subsidence of the estimated magnitude could lead to the destruction of property and life. The building permits for the construction and the building codes can also benefit from the deformation map by taking into account the expected subsidence. Engineering projects that depend on geodetic control need to be aware of the possibility of significant deformation, especially for the projects that depend on elevation differences for design. Cumulative subsidence of approximately 30 cm over a four year period can significantly alter the structural integrity of sewer lines and drainage networks that depend on gradient flow leading to instances of flow back and or flooding. Given that SOK does not update the geodetic network it implies that vertical geodetic controls that fall within the subsiding locations have been rendered unreliable. InSAR has reversed how geodetic measurements are conducted, instead of using higher resolution geodetic measurements followed by InSAR; it is now common to start with InSAR then high-resolution techniques targeted at already identified deformed areas (Liao et al., 2020). Hence future research will be geared towards hydrogeological modelling with higher resolution geodetic techniques such GNSS or high-resolution InSAR for multi-sensor monitoring for regions identified as deforming. Given the significance of Nairobi to Kenya economy, measures have to be taken to mitigate the effects of recorded subsidence.

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Conflict of interest

The authors declare that they have no conflict of interest.

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