High-Precision GPS Monitoring of the Land Subsidence in the Nile Delta: Status and Preliminary Results

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Abstract

Land subsidence is a crucial spatial phenomena harmfully affects dens populated areas. Several delta regions of rivers worldwide suffer from noteworthy land subsidence and deformation. In the Nile delta, quite a few researches have been carried out to estimate the land subsidence rates and spatial distribution. However, results have been shown that the Nile delta encounters a substantial subsidence in the last few decades. Out of many geodetic monitoring methods (e.g. tide gauge data analysis, repeated levelling data, radar remote sensing imageries) GPS proves to be the most precise approach for land subsidence and deformation, that can fulfill the millimeter level of accuracy. This paper summarizes the undergoing research study to utilize high-precision GPS geodetic techniques to monitor land subsidence and horizontal deformation in the Nile delta area. Repeated GPS observations for six stations over the Delta covering the period 2012-2015 have been compiled, processed, and analyzed. Preliminary results, in terms of vertical and horizontal land deformations rates, patterns, and spatial coverage, are presented. It has been found that the vertical land movements at these six locations range from +4.9 to -6.5 mm/year, while the horizontal ground movements vary from 4.2 to 6.6 mm/year in the north-east direction. It is recommended that further detailed multi-disciplinary studies should be performed to explore the relationships between land subsidence and other environmental factors such as soil compaction and variations of groundwater levels. Finally, it is recommended that the accomplished results should be taken into consideration by decision makers in any existing and upcoming development plans of the Nile Delta.

Keywords: Ground deformation, Land subsidence, GPS, Nile Delta, Egypt

Introduction

Land subsidence is a natural hazard affects several large urban areas all over the world, particularly in coastal and rivers' delta regions. Geometrically, land subsidence can be defined as the downward displacement of land surface relative to a specific reference surface, such as the Mean Sea Level (MSL), the geoid, or a reference ellipsoid, or relative to a certain assumed stable point outside the prone subsidence area. Such natural hazard phenomena can be attributed to natural and/or human activities, such as tectonic activities (e.g. earthquake and faulting), volcanic activities, landslide, underground mining activities, excessive groundwater or oil/gas extraction, natural consolidation of alluvium soil, and load of huge constructions. Impacts of land subsidence might be categorized into infrastructure, environmental, economic, and social impacts (e.g. Abidin et al, 2015). In some cases, such a phenomena results in catastrophic effects as what happened in Cairo, particularly in El-Dewica area, where landslide of large blocks of rocks from Mokattam mountain has led to the destruction of almost 50 houses in 2008 (Poscolieri et al. 2011).

Crustal movements and land subsidence can be monitored by several techniques including levelling, Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS), and the Synthetic Aperture Radar (SAR) such as the Interferometry SAR (InSAR). Several studies have utilized such techniques for land subsidence all over the world (e.g. Atanasova 2015, DEPI 2014, Kalkan 2014, and Serpelloni et al. 2007). InSAR provides the capability of subsidence monitoring over large areas in a cost effective manner on a few-millimeters level of precision. On the other hand, levelling can reach a millimeter level of accuracy in monitoring huge infrastructure, e.g. dams, but it becomes time consuming in monitoring large areas. Thus, GNSS techniques would be the optimum and most accurate geodetic tool regarding deformation and subsidence over large areas.

In Egypt, geodetic deformation monitoring activities have begun in the 1980s, particularly after the occurrence of Aswan earthquake in 1981. For example, Rayan et al. (2010) have analyzed observations of a network of 11 GPS stations around lake Nasser in south Egypt, and have found that the horizontal crustal movements are in the order of 20 mm/year. Additionally, Aly et al. (2009) and Poscolieri et al. (2011) have utilized InSAR images covering the grater Cairo area during the period 1993-2000, and have found that the average rate of land subsidence is approximately 7 mm/year. Similar results with a rate of subsidence of 2-8 mm/year have been recently reported also for the Nile Delta region over the period 1992-1999 (Zaid et al., 2014). It has been shown that highest subsidence occurred at Damietta branch of the Nile, while moderate rates observed around Manzala lagoon (Becker and Sultan, 2009). In Sinai peninsula, the average velocity of crustal motion has been estimated, from GPS surveys, as 31 mm/year northward (El-Fiky 2005). Mohamed (2005) has analyzed continuous GPS observations at the Alexandria tide gauge station over the period 2001-2003 and has estimated land subsidence to be 0.47 mm/year.

The Nile delta area posses a complex geological and hydrological structures so that land subsidence and land uplift are existed interchangeably on the spatial coverage of the area. Fugate (2014) has reported vertical ground motions ranging from uplift of approximately 7.5 mm/year to subsidence of almost 8.5 mm/year over the northern region of the Nile Delta in the period 1993-2000. Within the central Delta area, vertical land movements of ± 5 mm/year have been reported for the period 1993-2000 (e.g. Aly 2006). Additionally, the vertical movements in the Greater Cairo metropolitan area were estimated in the range from -7 mm/year to +3.8 mm/year in the period 2003-2009 (Poscolieri et al., 2011). Similar situations of integrated complex land subsidence/uplift have been reported in other geographic locations(e.g. Sneed et al., 2002).

It worth mentioning that no recent precise geodetic measurements have been conducted within the entire Nile delta to capture present-day subsidence (Aly 2006). This paper demonstrate a precise GPS-based strategy for monitoring land subsidence in the Nile delta region, and presents the accomplished preliminary results.

The Nile Delta

The study area, as shown in Figure 1, extends from longitude 29.6^{o} E to longitude 32.3^{o} E, and from latitude 29.8^{o} N to latitude 31.6^{o} N. The study area extends more than 300 kilometer along the Mediterranean costs from Port Said on the east to Alexandria on the west, and extends almost 200 kilometers perpendicular south to the coastline to Cairo. Thus, its total area equals approximately 25,000 square kilometers. With more than fifty million people, the Nile delta might be considered as one of the most densely populated areas worldwide. The topography of the study area (Figure 2) ranges from elevation -72 meter to 197 meter, with an average of 5.9 meter. As can be seen from that figure that the dominant elevation is less than 10 meter in the northern and middle parts of the delta. Moreover, it can be realized that the northern region of the delta area has an elevation less than almost 5 meter. That fact necessitates performing vulnerability analysis studies regarding the sea rise global phenomena and its hazardous impacts on the Nile delta region (Dawod and Mohamed, 2008). However, researchers emphasis the fact that land subsidence in the Nile Delta might be more environmentally hazardous than the sea level rise phenomena (e.g. Zaid et al., 2014).

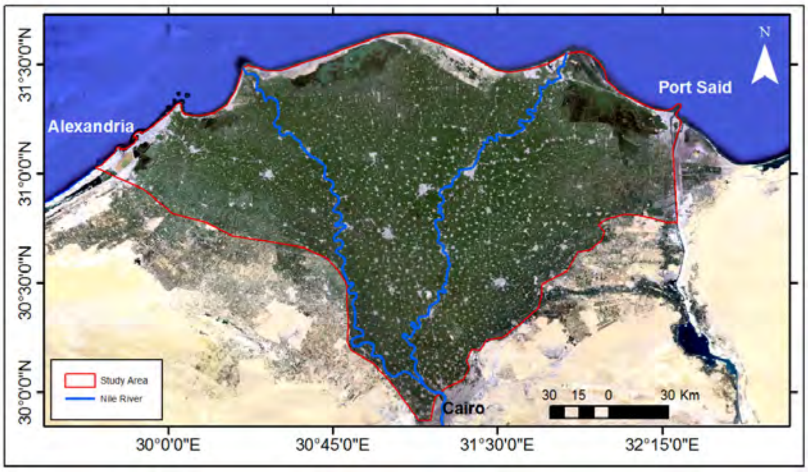


Figure 1: The Study Area

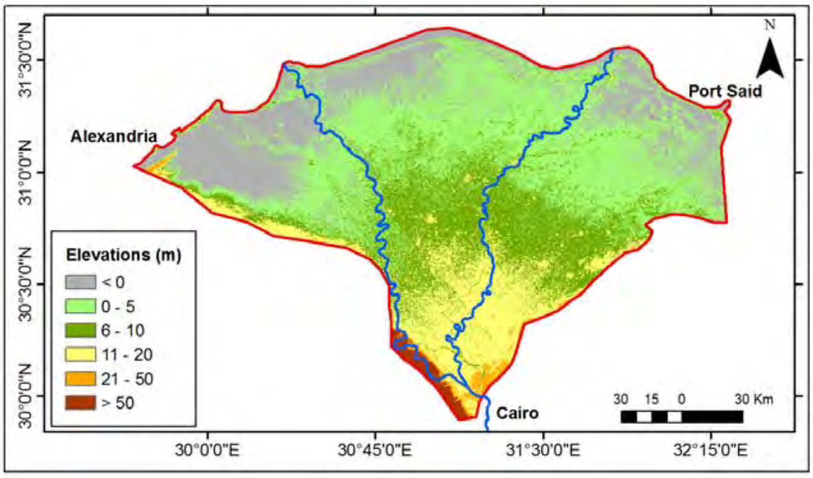


Figure 2: Topography of the Study Area

Available Data

The utilized dataset compresses GPS raw data of 6 stations of the Virtual Reference Stations (VRS) belong to the Egyptian Survey Authority (ESA). ESA has established these 40 Continuously Operating Reference Systems (CORS) in 2010. Each station is equipped with a dual-frequency GPS receiver fixed on the top of an ESA building, and every station sends its raw data in real time to the central ESA office in Cairo. The utilized stations are: Cairo, Tanta, Baltim, Port Said, Abu

El-Matameer, and Abu Kebeer (Fig. 3). The stations and the dataset have been chosen according to the availability and continuity of GPS data. Therefore, three sessions have been selected for each station in the period 2012-2015, where each session contains a 48-hour continuous GPS dataset in the RINEX (Receiver-INdependent EXchange) format (Table 1).

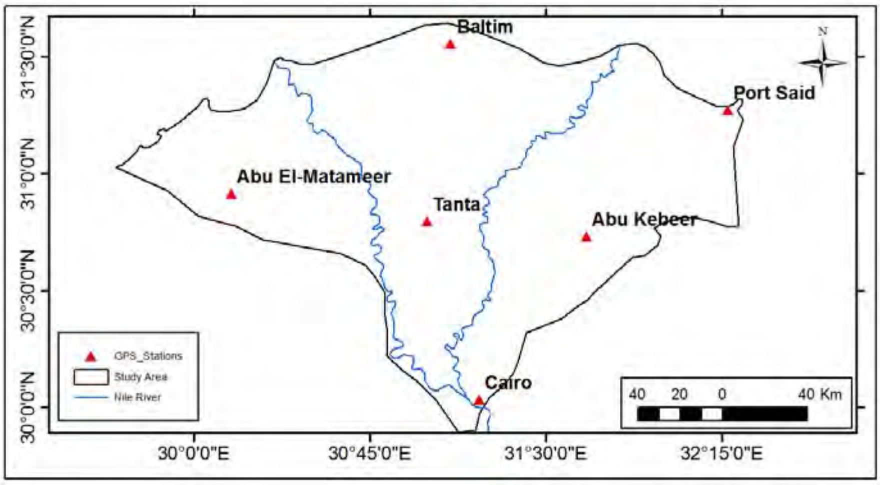


Figure 3: The Utilized GPS VRS Stations

Table 1: The Available GPS Data

Station	1-2012	1-2013	7-2013	1-2014	7-2014	1-2015
Cairo	X				X	X
Port Said	X				X	X
Abu Kebeer	X		X		X	X
Tanta	X	X	X			
Baltim	X		X	X		
Abu El-Matameer	X	X		X		

Processing and Results

The Precise Point Positioning (PPP) technique was applied in this research in order to achieve the most-precise coordinates, particularly heights, for each GPS station. The basic idea behind PPP is the estimation of precise satellites orbits and satellite clock errors based on observations from a high quality global fiducial network, and then the utilization of such information to solve the station parameters of any site world-wide (Seeber, 2003). The PPP position determination is based on the processing of the following ionosphere-free combination of the un-differenced code and phase observations (Xu, 2007):

$$\lambda\Phi = \rho - (\delta t_r - \delta t_k)c + \lambda N + \delta_{trop} + \delta_{tide} + \delta_{rel} + \varepsilon_{pc} \quad (1)$$

$$R = \rho - (\delta t_r - \delta t_k)c + \delta_{trop} + \delta_{tide} + \delta_{rel} + \varepsilon_{cc} \quad (2)$$

where

$$N = f_1 N_1 - f_2 N_2 \quad (3)$$

$$\lambda = \frac{c}{(f_1^2 - f_2^2)} \quad (4)$$

where,

R	is the pseudorange,
ρ	is the geometric range,
c	is the speed of light,
f_1 and f_2	are the GPS L1 and L2 frequencies,
N_1 and N_2	are the phase ambiguity terms on L1 and L2 frequencies,
Φ	is the carrier phase,
λ	is the wavelength of the combination,
δt_r, δt_k,	are the clock errors of the receiver and satellite respectively,
δ_{trop}, δ_{tide}, δ_{rel}	are the troposheric, tidal, and relativistic effect respectively,
ε_{cc} and ε_{pc}	denote the residuals after the combination of code and phase respectively.

The above equations show that the unknown parameters to be estimated in PPP include position coordinates, phase ambiguity terms, receiver clock offset, and the troposheric effect. Precise satellite orbits and clock products with the centimeter-level accuracy needed for PPP are now widely available from a number of public organizations. One of these well-known organizations is the International GNSS Service (IGS). Consequently, the processing workflow consists of several steps (Figure 4). First, in each session, the raw GPS data of an IGS station have been downloaded as a control point. Second, Precise satellite orbits, for both GPS and GLONASS satellites, have been obtained too. Next, using PPP strategy, precise geodetic heights have been estimated for each station in each session in the International Terrestrial Reference Frame (ITRF2008) epoch 2012. Lastly, comparing station's heights enables the determination of vertical movement rate between two successive sessions at each station (e.g. Sneed et al., 2002).

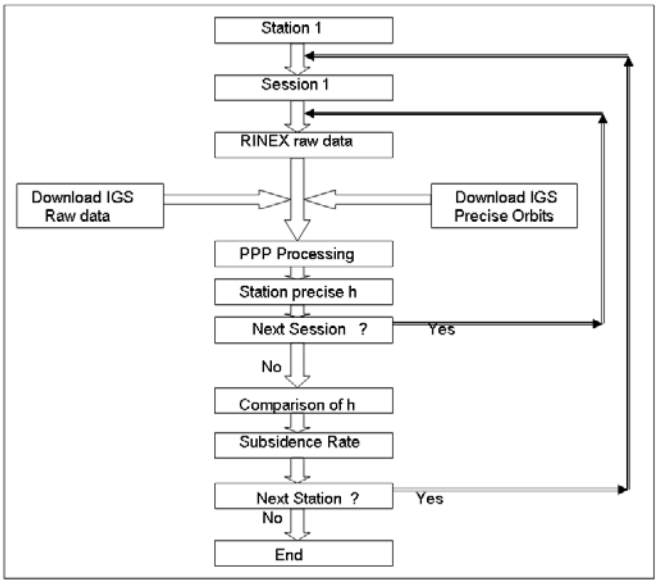


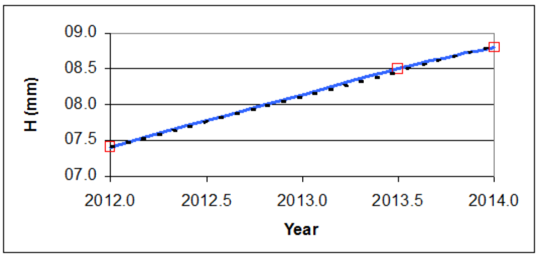
Figure 4: The Data Processing Workflow

Using the Trimble TBC 3.2 GPS data processing package, ellipsoidal heights have been computed for each station at each session with a precision of ± 0.002 m. The rates of vertical land movements have been, then, estimated through linear regression. The attained results are represented in Table 2 and depicted in Figure 5. It can be realized that subsidence exist in Port Said and Tanta, while the remaining four stations show uplift. Additionally, it is observed that the vertical deformation at both Baltim and Abu El-Matameer are relatively small compared to the rate of the other stations. Moreover, it can be seen that the GPS station at Tanta shows the maximum subsidence annual rate with almost 7 mm/year. The last column of Table 2 shows the value of coefficient of determination (R^2), which constitutes a statistical measure about the amount of variations in the original data that the regression formula could explain. The higher the value of that coefficient, the more-precise the regression equation developed. It can be realized that R^2 value of four stations (namely Cairo, Tanta, Baltim, and Port Said) are close to one, which means that the linear regression model precisely describe the land vertical movements at these locations. On the other hand, stations Abu El-Matameer, and Abu Kebeer produce moderate R^2 values, which indicates that their vertical movements might not follow a precise linear pattern with respect to time. These concluded remarks could be also visualized clearly in Figure 5.

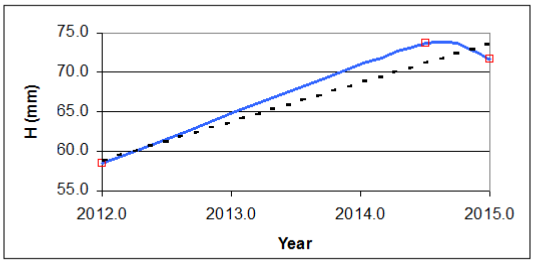
Furthermore, a spatial model of vertical movements in the Nile Delta (Figure 6) area has been developed using the Krigging statistical method within the Arc GIS software. From this figure, it can be concluded that the average vertical movement, over the study area, equals -0.74 mm/year. Additionally, it can be realized that the middle region of the Delta suffer from land subsidence, particularly at its eastern borders, while the north-western and the south-eastern areas show an uplift. These findings agree, on a general basis, with those reported by earlier studies (e.g. Fugate 2014 and Aly 2006). However, detailed research studies should be carried out in order to investigate the relationship between the attained preliminary results and the soil compaction and groundwater extraction characteristics in the Nile Delta region. Recent research studies have utilized an integration of GPS, InSAR, spirit levelling, and groundwater-level data to monitor land subsidence (e.g. USGS 2013). Additionally, the correlation between geological characteristics and land vertical movements in the study area should be explored in details. For example, Becker and Sultan (2009) suggested that higher land subsidence in the north-east borders of the Delta might have a casual relationship with the distribution of young (<3500 year old) sediments that were deposited during recent development of the Damietta branch of the Nile and have been compacted since then.

Table 2: Vertical Land Movements Rates 2012-2015

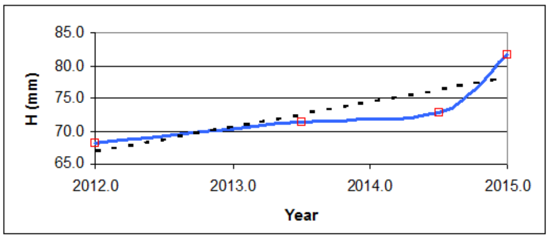
Station	Vertical Movement Rate (mm/year)	R^2
Cairo	+ 4.94	0.92
Port Said	- 4.72	0.94
Abu Kebeer	+ 3.69	0.73
Tanta	- 6.51	0.99
Baltim	+ 0.71	0.99
Abu El-Matameer	+ 0.55	0.41



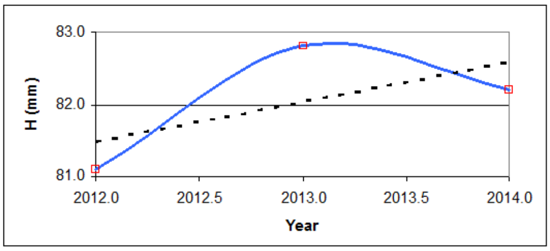
Baltim



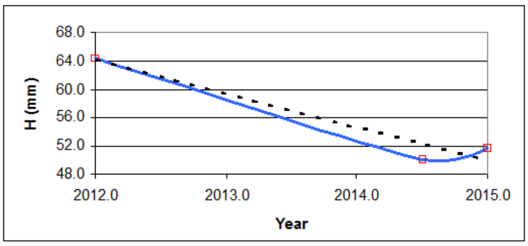
Cairo



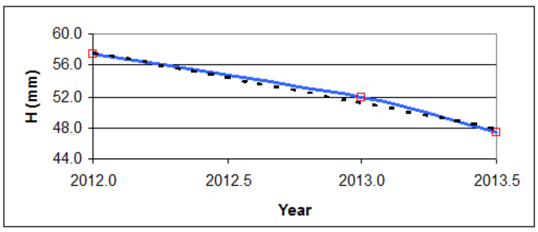
Abu Kebeer



Abu El-Matameer



Port Said



Tanta

Figure 5: Linear Trends of Vertical Movements

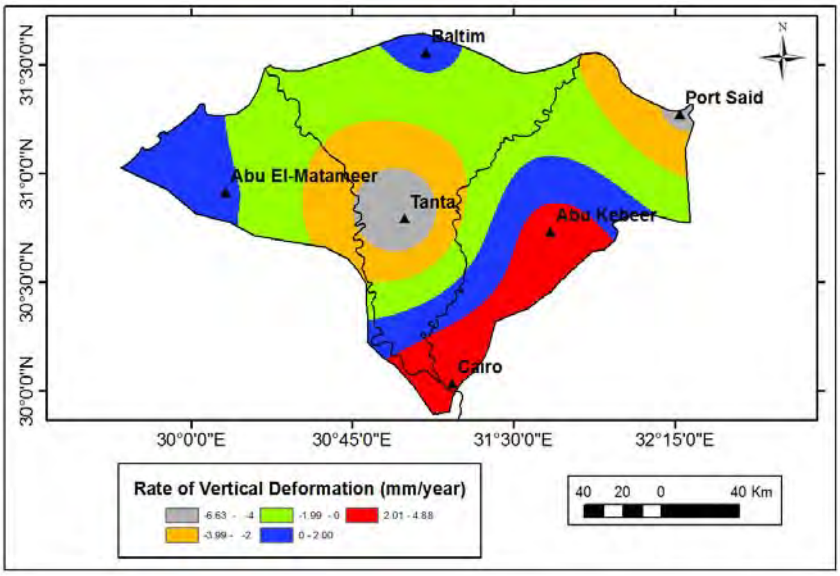


Figure 6: Vertical Ground Movements Annual Rates

Next, the horizontal land movements in the study area have been investigated as well. For each GPS station, the projected 2D coordinates (UTM east and north) have been computed at each session with a precision of ± 0.001 m. The changes in horizontal coordinates have been estimated, and the rate of horizontal movements have been obtained (in terms of amount and direction), as presented in Table 3. As well, a spatial model of horizontal movements in the Nile Delta area has been developed (Figure 7). From the accomplished findings, it can be realized that the horizontal ground movement at Tanta station is relatively small compared to the other stations. The horizontal deformation rates are in the range of 4-7 mm/year with a mean equals 5.6 mm/year, which still can be classified as small horizontal movements. Similar results have been reported by Rayan (2003). Again, further detailed research studies should be performed to explore the relationship between these attained preliminary results and the geological characteristics of the Nile Delta region.

Table 3: Horizontal Land Movements Rates 2012-2015

Station	Horizontal Movement Rate (mm/year)
Cairo	5.37 NE
Port Said	5.83 NE
Abu Kebeer	6.62 NE
Tanta	4.22 NE
Baltim	5.85 NE
Abu El-Matameer	6.04 NE

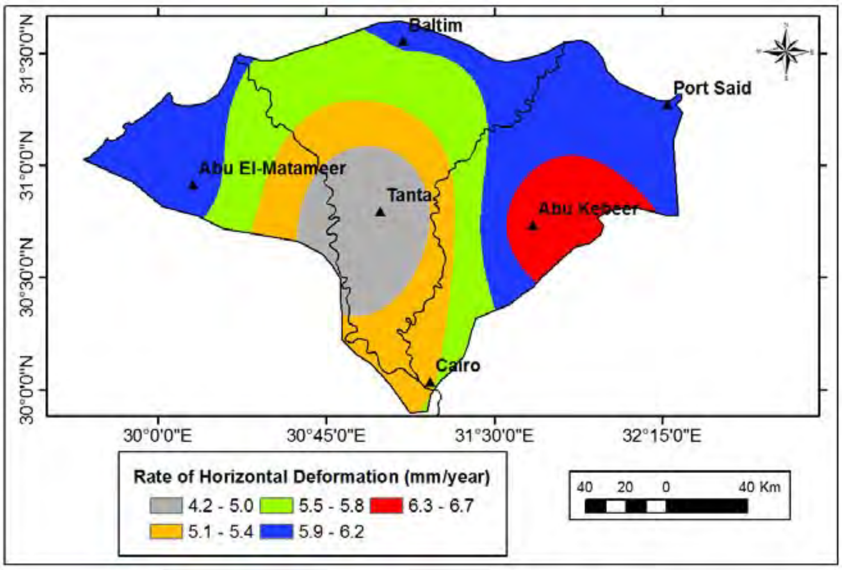


Figure 7: Horizontal Ground Movements Annual Rates

Conclusions

Ground deformation in general and land subsidence in particular significantly influence urban areas on environmental, development, and human basis. This research study has applied recent high-precision GPS datasets for monitoring and detecting both vertical and horizontal ground movements in the Nile Delta region. Repeated GPS observations for six stations over the Delta covering the period 2012-2015 have been compiled, processed, and analyzed. Ellipsoidal heights have been computed for each station at each session with a precision of ± 0.002 m. The attained results show that subsidence exist in Port Said and Tanta, while the remaining four stations show uplift. Additionally, it is observed that the vertical deformation at both Baltim and Abu El-Matameer are relatively small compared to the rate of the other stations. Furthermore, it can be seen that the GPS station at Tanta shows the maximum subsidence annual rate with almost 7 mm/year. On the other hand, the estimated horizontal land movements are in the range of 4-7 mm/year, which still can be classified as small horizontal movements. It should be highlighted that six GPS stations over the entire Nile Delta area might not be the optimum number of stations to precisely monitor ground deformation over that large area. More GPS monitoring stations are recommended to fulfill a homogenous spatial distribution. The proposed stations should agree completely with the international geodetic standards for such a high-precision activity. In addition, further investigations should be carried out in the future utilizing longer time-span datasets in order to accurately map the time-dependant vertical movements in the study area.

Based on the attained primarily findings, few recommendation could be made. Firstly, although geodetic techniques, such as GPS, can monitor and detect ground deformation by a high-accuracy level, they observe such deformation at specific point locations. Performing GPS monitoring at large number of points over a large area might be time-consuming and expansive. Hence, for the Nile Delta region, it is recommended to integrate GPS with SAR satellite imagery method in order to spatially portray the ground deformation pattern with adequate precision. Furthermore, it is a matter of fact that ground deformations are often caused by human activities such as water and oil pumping, and are influenced by natural characteristics particularly the geological, hydrological, and soil conditions. Hence, it is recommended that further detailed multi-disciplinary studies should be carried out to detect the soil compaction features of the Nile Delta, along with the recent variations of groundwater levels. Finally, the accomplished results should be taken into consideration by decision makers in any future development plans of the Nile Delta.

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