Groundwater Storage Changes Detected from Gravity Recovery and Climate Experiment (GRACE) Data in Nile Delta Aquifer.

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Abstract

Gravity observations can be used to monitor the groundwater storage variations, through the traditional techniques, which are very difficult due to high cost and strong labor intensity. The system Gravity Recovery and Climate Experiment (GRACE) measures gravity anomalies on the earth to estimate changes in Terrestrial Water Storage (ΔTWS) for a regional area with low cost and wide coverage. GRACE data available from 2003 to 2011 but as a result of just two piezometric maps were available, so in this study, the changes in GRACE gravity data of 2003 and 2006 were used to monitor the Ground Water Storage changes (ΔGWS) in Nile Delta aquifer, which extended from 30^o to 31^o N and 30^o to 31^o E of Egypt. (ΔGWS) are obtained by subtracting the soil moisture water obtained from the hydrological models GLDAS (Global Land Data Assimilation System) from (ΔTWS), the effective parameter for study area is soil moisture. This work has the potential to improve Nile Delta Aquifer's groundwater resource management and validate it by comparing (ΔGWS) extracted from GRACE against (ΔGWS) from two piezometric maps provided by Research Institute for Ground Water (RIGW). The results indicate that the maximum and the minimum differences between traditional techniques from piezometric maps and GRACE satellite- GLDAS model calculations are 25 and -11 mm respectively with standard deviation about 15 mm.

Keywords**:** GRACE, Groundwater, Aquifer, Gravity field, Piezometric and GLDAS

1. Introduction

Groundwater is a necessary resource for many water users in Egypt. As the next war will be on water, especially after the problems happened between the Nile Basin countries and how much Egypt suffers from restrictions in its share of the Nile River water in addition to the urgent need for increasing the cultivated area. Ground water recharge is water that has infiltrated the ground, and moved through pores and fractures in soil and rock to the water table (the depth at which soil and rocks are fully saturated with water). The amount of water that seeps into the ground will vary widely from place to place, depending on the slope of the land, soil type, vegetation, and amount and intensity of rainfall for example, infiltration rates in sandy soil are higher than clay soil or pavement. Recharge is greatest in the spring and falls because the ground is not frozen and plants do not consume large amount of water **(Gotkowitz.M., 2010)**. Recharge maintains the supply of fresh water that flows through the groundwater system to wells, streams, springs, and wetlands. Not all precipitation becomes groundwater recharge some of it runs off the land surface to streams or storm sewers, some evaporates, and some is taken up by plants **(Johnson.S., 2012)**.

Ground water is stored in aquifers, which are water-bearing rock formations that hold water in the inter-particle pore space and cracks within rock material, to locate ground water accurately and to determine the depth, quantity and quality of the water, a target area must be thoroughly tested and studied to identify hydrologic and geologic features important to the planning and management of the resource. Rates of groundwater recharge are difficult to quantify, since other related processes, such as evaporation, transpiration and infiltration processes must first be measured or estimated to determine the balance. To improve water resources management it is critical to develop monitoring systems that provide accurate and timely information on the status of water reservoirs, including water in soil and aquifers. Satellites, in this case (GRACE), have the potential to address the observational gap of monitoring regional water storage changes. The GRACE mission provides approximately monthly changes in (ΔTWS) on the basis of measurements of the Earth's global gravity field **(Tapley et al., 2004; Wahr et al., 2004).**

ΔTWS, as inferred from the gravity measurements, represents a vertically integrated measure of water storage that includes groundwater, soil moisture, surface water and snow. Therefore, in order to infer one component from ΔTWS (e.g., groundwater storage), other components (e.g., surface water, soil moisture) need to be measured or estimated. A number of studies have validated GRACE derived ΔTWS with results from land surface models and with monitored soil moisture and groundwater storage changes. These studies showed that GRACE can be used to evaluate land surface model simulations and to estimate changes in components of the water budget (e.g., evapotranspiration, soil moisture, groundwater, snow water, and basin discharge) **(e.g., Rodell et al., 2004b; Syed et al., 2005; Yeh et al., 2006; Rodell et al., 2006; Niu and Yang, 2006; Hu et al., 2006; Swenson et al., 2008b).**

2. Study area

The Nile Delta aquifer consists of the Pleistocene graded sand and gravel, changing to fine sand and clay to the north. In the floodplain of the Nile, the aquifer is semi-confined, as it is overlain by Holocene silt, clay and fine sand. In the northwestern part of the area, a calcareous loamy layer acts as a semi-confining zone outside the floodplain. The thickness of this zone ranges between 0 and 20 m. In the desert fringes, the semi-confined layer is missing and phreatic conditions prevail. The total thickness of the aquifer increases from Cairo northward to about 1,000 m along the Mediterranean coast **(El Tahlawi .M. R. and Farrag. A. A., 2008)**. The Nile River is the mostly source for feeding supply to this aquifer. The boundary of study area (φ =30 to 31N and λ = 30 to

31E). Apart of Nile Delta aquifer which is common in RIGW piezometric maps for two years 2002 and 2006 (Figure 1).

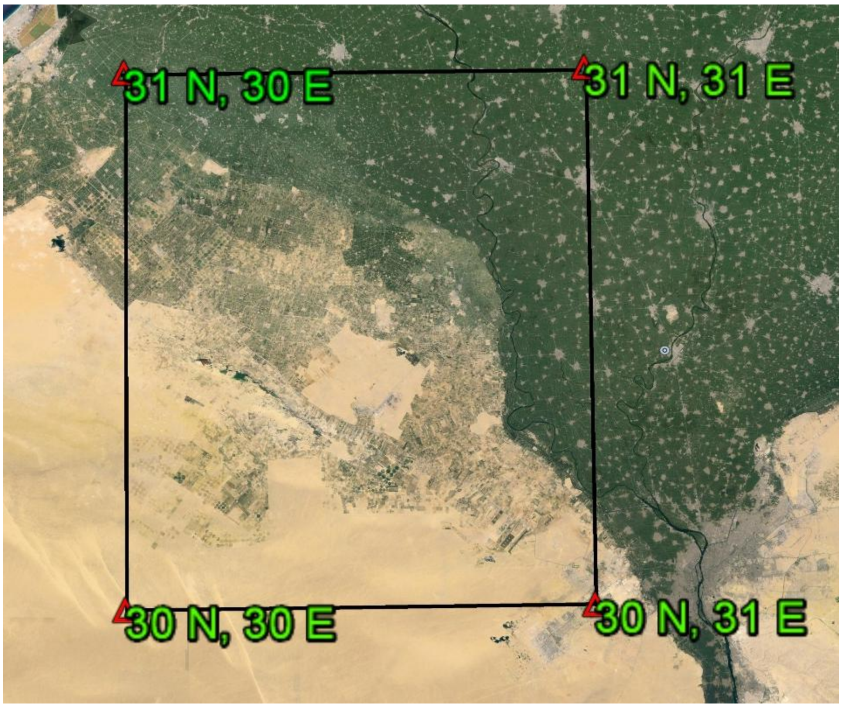

Figure (1): The Area of Interest (AOI)

3. Methodology

Shallow-layer groundwater within a few centimeters of the surface may be detected by Synthetic Aperture Radar (SAR) microwave radiometry or Thermal Infra-Red (TIR) imagery in certain geologic settings. However, groundwater aquifers located deep below more than one meter under the land surface cannot be detected directly by electromagnetic remote sensors and are usually surveyed with gravitational techniques **(Klemas.V and Pieterse.A. 2015)**. Satellite gravity mission GRACE provides time variable gravity field models that reflect the Earth’s gravity field variations due to mass transport processes. The standard of Earth’s gravity anomalies mountains equal higher gravity and deltas mean lower gravity. Monthly time series of anomalies of GRACE-derived total TWS, modelled soil-water storage and estimated groundwater storage **(Rodell.M., Velicogna.I. & Famiglietti.J., 2009)**.

Time-variable gravity anomalies are converted into equivalent units of height in millimeters and provides explanation for short term changes on earth like variations in water or ice. Because of limited ground-based data, GRACE satellite data may be very valuable for monitoring water storage changes.

(Longuevergne, L., Wilson, C. R. , Scanlon, B. R. and Cretaux, J. F.,2012) have shown that accurate GRACE water storage estimates have importance beyond practical hydrology, given the politics and conflicts associated with drought and trans boundary water allocation and management. Accurate assessment of total water storage and its variations within a basin thus requires careful attention to the reservoir component.

Terrestrial water storage (ΔTWS), a combination of changes in snow water equivalent (ΔSWES), surface water (ΔSWS), soil moisture (ΔSMS) and groundwater storage (ΔGWS) **(Tapley et al., 2004; Günter, 2008; Schmidt et al., 2008).**

Stokes coefficient of spherical harmonics from GRACE represent the global gravity field and changes over time with unprecedented accuracy **(Bettadpur, et al., 2007)**. It is common to expand the height of the geoid above the Earth's mean spherical surface *N* as a sum of spherical harmonics **(Wahr J. M., 2007)**.

$$N = a\sum_{n=2}^{\infty}\sum_{m=0}^{n}[\bar{C}_{nm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda]\bar{P}_{nm}(\cos\vartheta) \quad \text{....(3-1)}$$

$$N = a\sum\sum[\bar{C}nm\cos m\lambda + \bar{S}nm\sin m\lambda]\bar{P}nm\,(\cos\theta) \quad \text{...(3-2)}$$

In which a: is the equatorial radius of the Earth, (**φ, λ, h**): are (geodetic latitude, geodetic longitude, ellipsoidal height) of the point.

$\bar{C}_{nm}$, $\bar{S}_{nm}$ are the fully normalized spherical coefficients of degree n and order m, $\bar{P}_{nm}$: is the fully normalized Legendre function of degree n and order m and θ is colatitude of the point.

Suppose there is a time-dependent change in the geoid ΔN. we can represent the change (Δ) in N from one time to another, or as the difference between N at one time and a time average of N. ΔN can be represented in terms of changes in the spherical harmonic geoid coefficients **(ΔC_{nm} and ΔS_{nm})** as:

$$\Delta N(\theta, \Phi) = a \sum_{n=2}^{\infty} \sum_{m=0}^{n} [\Delta \bar{C}_{nm} \cos m\lambda + \Delta \bar{S}_{nm} \sin m\lambda] \bar{P}_{nm}(\cos \vartheta) \text{..... } \textbf{(3-3)}$$

the change in surface density is defined as (mass/area), Δσ as the radial integral of Δρ through this layer:

$$\Delta\sigma(\theta,\varphi) = \int_{\text{thin layer}} \Delta\rho(r, \theta, \varphi) \qquad \text{....}\textbf{(3-4)}$$

$$\Delta\sigma = \frac{a\, \rho_{av.}}{3} \sum_{n=2}^{\infty} \sum_{m=0}^{n} \frac{2n+1}{1+k_n} [\Delta \bar{C}_{nm} \cos m\lambda + \Delta \bar{S}_{nm} \sin m\lambda] \bar{P}_{nm}(\cos \vartheta) \text{.. } \textbf{(3-5)}$$

In which   is the average density of the earth (5517 kg/m^3) **(Wahr & Molenaar, 1998).**Terrestrial water storage can be calculated using monthly GRACE spherical harmonic coefficient according to the following form **(Chen Y. , 2007) & (Han, et al., 2005)**. ρ_{water} is the density of water (assumed throughout this paper to be 1000 kg/m3), and is included here so that , ΔC_{nm} and ΔS_{nm} are dimensionless. Note that $\Delta\sigma / \rho_{water}$ is the change in surface mass expressed in equivalent water thickness. By noting that the P_{nm} variables are normalized **(Wahr & Molenaar, 1998) & (Swenson, S., & Wahr, J., 2002)**.

$$\Delta h_{TWS} = \frac{\Delta\sigma}{\rho_{water}} \qquad \text{...... } \textbf{(3-6-a)}$$

$$\Delta h_{TWS} = \frac{a\, \rho_{av.}}{3\rho_{water}} \sum_{n=2}^{\infty} \sum_{m=0}^{n} \frac{2n+1}{1+k_n} W_n [\Delta \bar{C}_{nm} \cos m\lambda + \Delta \bar{S}_{nm} \sin m\lambda] \bar{P}_{nm}(\cos \vartheta) \ \textbf{(3-6-b)}$$

Release 05 unconstrained monthly solutions of CSR for the Period 2003 to 2006 from the GRACE database was used. Spherical harmonic coefficients were converted into grid (0.5° × 0.5°) of equivalent temporal gravity using a Gaussian smoothing function with a radius of 300 km and cutoff degree 50. The data obtained from the GRACE mission will contain errors resulting from the satellite instrumentation and from the truncation of the infinite series at a certain Legendre degree. The satellite errors are getting larger proportionally to the degrees. The aim of the filtering is reducing the amplitude of the higher degrees, thus reducing the satellite errors at the loss of spatial resolution. The errors can be reduced by spatially averaging the data leading to a better representation of the gravitational potential at the expense of spatial resolution. De-striping has been done using smoothing filter suggested by (**Swenson, 2008)** to minimize the effect of an error whose telltale signal are N-S stripes in GRACE monthly maps. Temporal gravity variations have been transformed into water thickness variations. The gravity field results are equally sensitive to water at all depths: surface water, soil moisture, and groundwater etc.

$$\Delta TWS = \Delta GW + \Delta SM + \Delta SWE + \Delta SW \qquad \textbf{... (3-7)}$$

Where, ΔTWS Terrestrial water storage, ΔGW Groundwater storage, ΔSM Soil moisture, ΔSWE Snow water equivalent and ΔSW Surface water. For this study area Nile Delta aquifer lie in semi-arid area at west of delta of Egypt, there is no Snow water at this desert area, moreover Surface water is neglected because of narrow width. Then the equation can be expressed as:

$$\Delta TWS = \Delta GW + \Delta SM \qquad \textbf{... (3-8)}$$

To isolate the ground water we subtract monthly water storage estimates predicted by land surface models getting from GLDAS_NOAH (description in next page) from total water storage variations. Then, the ΔGW Groundwater storage changes can be represented as:

$$\Delta GW = \Delta TWS - \Delta SM \qquad \textbf{… (3-9)}$$

4. Datasets

Three datasets were used in this research with the following characteristics:

4.1 GRACE Data

The GRACE monthly spherical harmonic coefficients were downloaded for the globe from Center of Space Research (CSR), University of Texas at Austin available at (http://www.csr.utexas.edu/), then the area of interest (AOI) was excluded and converted into a grid of (0.5°×0.5°).

4.2 GLDAS Hydrology Model

One of the most widely used global continental hydrology models is GLDAS/Noah **(Rodell et al. 2004)**. The NOAH model with 1° resolution from 2003 to 2006 was used according to the available piezometric maps. The GLDAS model is available at (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=GLDAS10_M)

4.3 Piezometric Maps

The available piezometric maps were provided from RIGW of groundwater level observations for just two years 2002 and 2006. Contour label represent the level of groundwater surface. Positive value is above mean sea level and vice versa. Thirty points were choose in each cell.

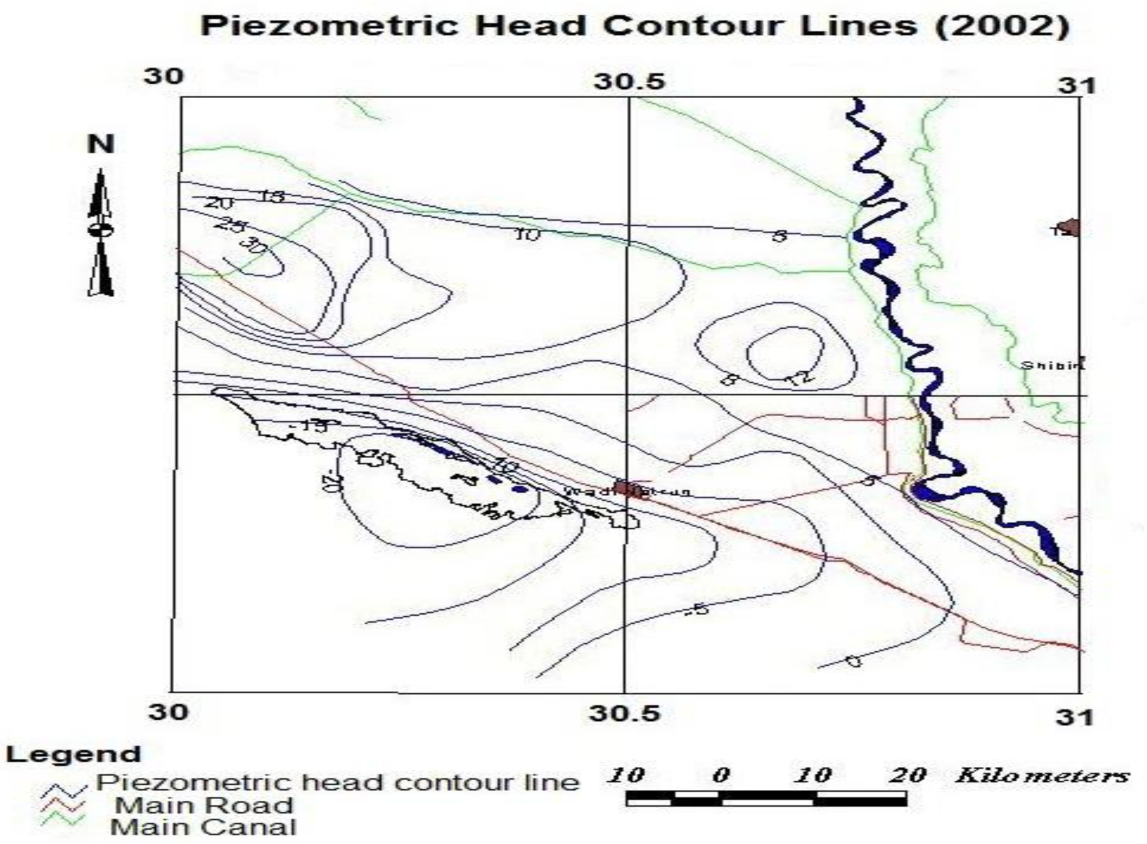

Figure (2): RIGW Piezometric Contour Map for Year 2002.

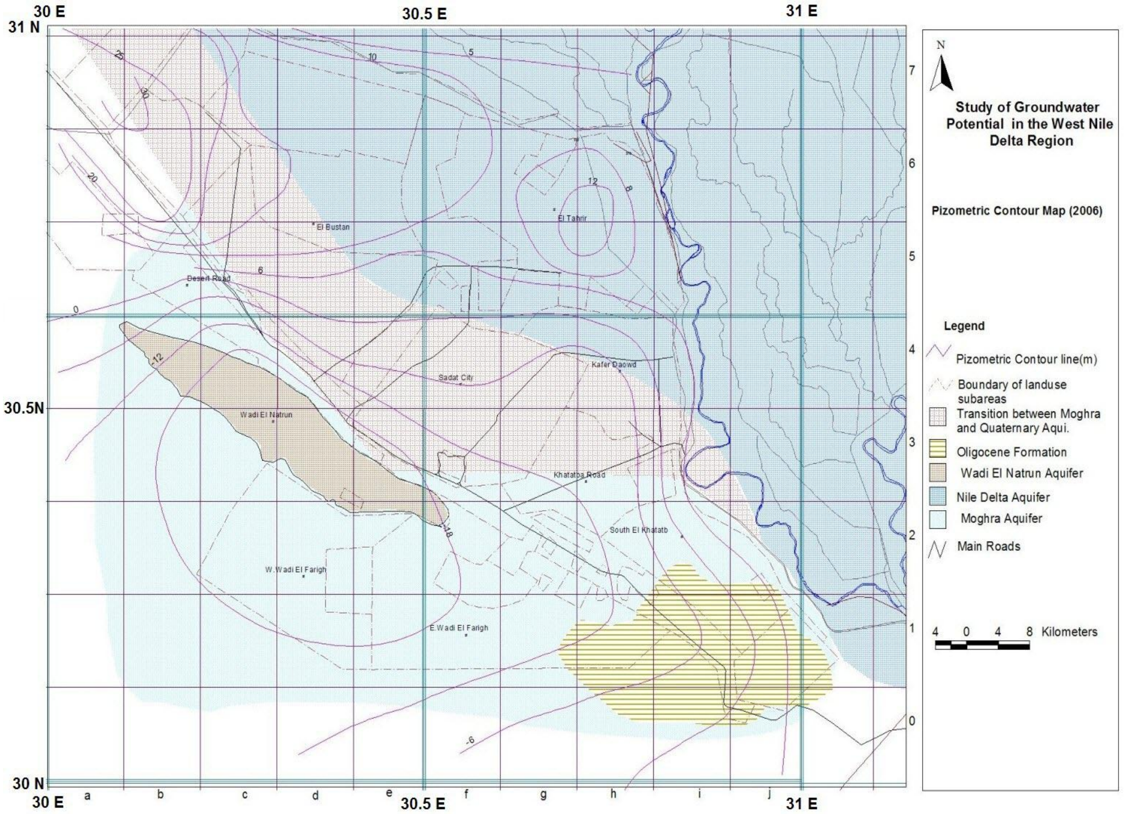

Figure (3): RIGW Piezometric Contour Map for Year 2006.

5. Results and Discussion

The area is divided into four cells each cell have $0.5^{o} * 0.5^{o}$ to find the ΔTWS from GRACE monthly temporal gravity variations then subtracting ΔSM (mm) obtained from GLDAS from ΔTWS to find ΔGW. The three values ΔTWS, ΔSM and ΔGW are the mean values of all available months for the years 2003 and 2006 respectively. These steps are applied for each cell and for the both years. The reference is the New Year value and the old year value subtracted from the value of the new one (this concept is considered in all different calculations) that's means positive value is rechargeable and negative value is dischargeable area.

The land water storage in GLDAS model includes the soil moisture. So, the change in groundwater storage can be calculated by subtracting the changes in total water storage caused by changes in soil moisture ΔSM for the corresponding area from GLDAS where its resolution is 1^{o} and its mean values are equal to 11 and 12 mm for 2003 and 2006 respectively.

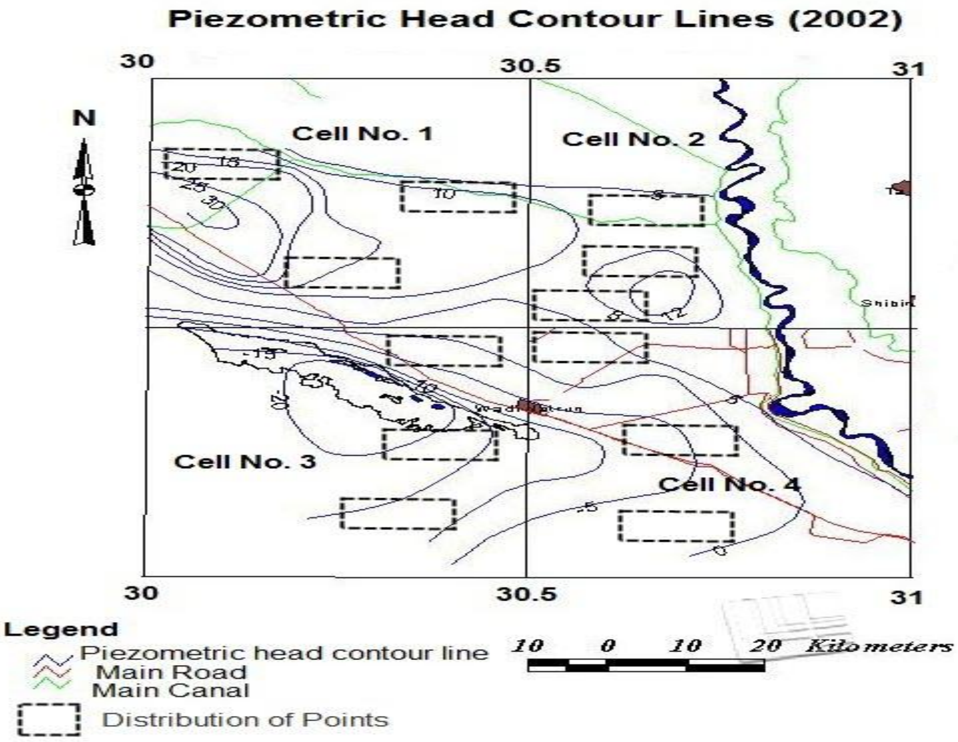

Figure (4): Distribution of Thirty Points at Each Cell.

Table (1): Differences in ΔGW between 2003 & 2006 for Cells 1, 2, 3 & 4

Cell No.	Global Coordinates		Mean for Year 2003			Mean for Year 2006			Difference in ΔGW_{2006} & ΔGW_{2003} (mm)
	LONG	LAT	ΔTWS (mm)	ΔSM (mm)	ΔGW (mm)	ΔTWS (mm)	ΔSM (mm)	ΔGW (mm)	
Cell No.1	30 E	31 N	-74	11	-85	33	12	21	106
	30.5 E	31 N	-70		-81	43		31	112
	30.5 E	30.5 N	-68		-79	44		32	112
	30 E	30.5 N	-71		-82	36		24	107
Cell No.2	30.5 E	31 N	-70	11	-81	43	12	31	112
	31 E	31 N	-60		-71	50		38	110
	31 E	30.5 N	-60		-71	50		38	109
	30.5 E	30.5 N	-68		-79	44		32	112
Cell No.3	30 E	30.5 N	-71	11	-82	36	12	24	107
	30.5 E	30.5 N	-68		-79	44		32	112
	30.5 E	30 N	-66		-77	46		34	111
	30 E	30 N	-68		-79	40		28	107
Cell No.4	30.5 E	30.5 N	-68	11	-79	44	12	32	112
	31 E	30.5 N	-60		-71	50		38	109
	31 E	30 N	-59		-70	49		37	107
	30.5 E	30 N	-66		-77	46		34	111

+ Sign indicates recharge,
-Sign indicates discharge

Table (1) show the cell number one after subtracting the mean of ΔGW (from GRACE-GLDAS) of two years indicating that the area is recharged by an average value about 109 mm. The cell number two after subtracting the mean of ΔGW (from GRACE-GLDAS) of two years indicating that the area is recharged by an average value about 110 mm. The cell number three after subtracting the mean of ΔGW (from GRACE-GLDAS) of two years indicating that the area is recharged by an average value about 109 mm.

The cell number four after subtracting the mean of ΔGW (from GRACE-GLDAS) of two years indicating that the area is recharged by an average value about 110 mm.

The given RIGW piezometric maps for two years 2002 and 2006 are the only available data for groundwater level observations, but the GRACE mission has been launched in March 2002 and the first available data began from year 2003.

Piezometric contour maps were converted into digital format by on screen digitizing from AutoCAD Raster Design then, Triangulated Irregular Network (TIN) interpolation technique used to find groundwater level for thirty points for each cell. The thirty points were chosen to grantee well distribution over the cell.

Table (2): Differences in GW Level between 2002 and 2006 for Cell No.1

Cell No.1	Global Coordinates		Diff in GWL(mm)		
	LONG	LAT	MAX	MIN	Mean
	30:30.5 E	30.5:31 N	340	0	168

Cell number one extended from 30° to 30.5 ° E and 30.5 ° to 31 ° N. The thirty points show that the aquifer is recharged with a mean value 168 mm, the maximum and the minimum recharge rates are 340 mm and 0 mm respectively.

Table (3): Differences in GW Level between 2002 and 2006 for Cell No.2

Cell No.2	Global Coordinates		Diff in GWL(mm)		
	LONG	LAT	MAX	MIN	Mean
	30.5:31 E	30.5:31 N	340	10	146

Cell number two extended from 30.5° to 31 ° E and 30.5 ° to 31 ° N. the thirty points for cell number two show that the aquifer is recharged with a mean value 146 mm, the maximum and the minimum recharge rates are 340 mm and 0 mm respectively.

Table (4): Differences in GW Level between 2002 and 2006 for Cell No.3

Cell No.3	**Global Coordinates**		**Diff in GWL(mm)**		
	LONG	**LAT**	**MAX**	**MIN**	**Mean**
	30:30.5 E	**30:30.5 N**	**440**	**10**	**123**

Cell number three extended from 30^o to 30.5^o E and 30^o to 30.5^o N. the thirty points for cell number three show that the aquifer is recharged with a mean value 123 mm, the maximum and the minimum recharge rates are 440 mm and 10 mm respectively.

Table (5): Differences in GW Level between 2002 and 2006 for Cell No.4

Cell No.4	**Global Coordinates**		**Diff in GWL(mm)**		
	LONG	**LAT**	**MAX**	**MIN**	**Mean**
	30.5:31 E	**30:30.5 N**	**-2490**	**-8100**	**-5665**

Cell number four extended from 30.5^o to 31^o E and 30^o to 30.5^o N. the thirty points for cell number four show that the aquifer is discharged with a mean value -5665 mm, the maximum and the minimum discharge rates are -2490 mm and -8100 mm respectively.

Table (6): Differences in GW Level between Piezometric and GRACE-GLDAS.

Cell No.	**Global Coordinates Range**		**Piezometric Mean Diff in GWL(mm)**	**Modified Piezometric Mean Diff in GWL(mm)**	**GRACE-GLDAS Mean Diff in GWL(mm)**	**Diff between Modified Piezometric & GRACE-GLDAS**
	LONG	**LAT**				
1	**30:30.5 E**	**30.5:31 N**	**168**	**134**	**109**	**25**
2	**30.5:31 E**	**30.5:31 N**	**146**	**117**	**110**	**7**
3	**30:30.5 E**	**30:30.5 N**	**123**	**98**	**109**	**-11**
4	**30.5:31 E**	**30:30.5 N**	**-5665**	**-4532**	**110**	**-4642**

In order to have the both methods (i.e., GRACE-GLDAS and Piezometric maps) temporally consistent, we scaled the piezometric maps values under the assumption of linear evolution through time. This means assuming a simple principle of total period by scaling the piezometric maps data to the time span of GRACE-GLDAS datasets.

Table (6) ensures that the results obtained from GRACE-GLDAS and piezometric for Nile Delta aquifer are rechargeable according to results of cells number one, two and three. These results agree with the main hydrogeological units in Egypt (RIGW 1988) which indicate that the Nile Delta aquifer is rechargeable **(El Tahlawi .M. R. and Farrag. A. A., 2008)**.

On the other hand, at the cell number four the results of the both datasets are inconsistent however, the general behaviour of Nile Delta aquifer is rechargeable for the surface and subsurface according to RIGW description for the main hydrological units in Egypt which published by **(El Tahlawi. M. R., Farrag . A., 2008)** which indicates that the GRACE-GLDAS results are more reliable.

Figure (5) illustrates the agreements in results between both methods. The maximum and minimum difference are +25 mm and -11 mm respectively.

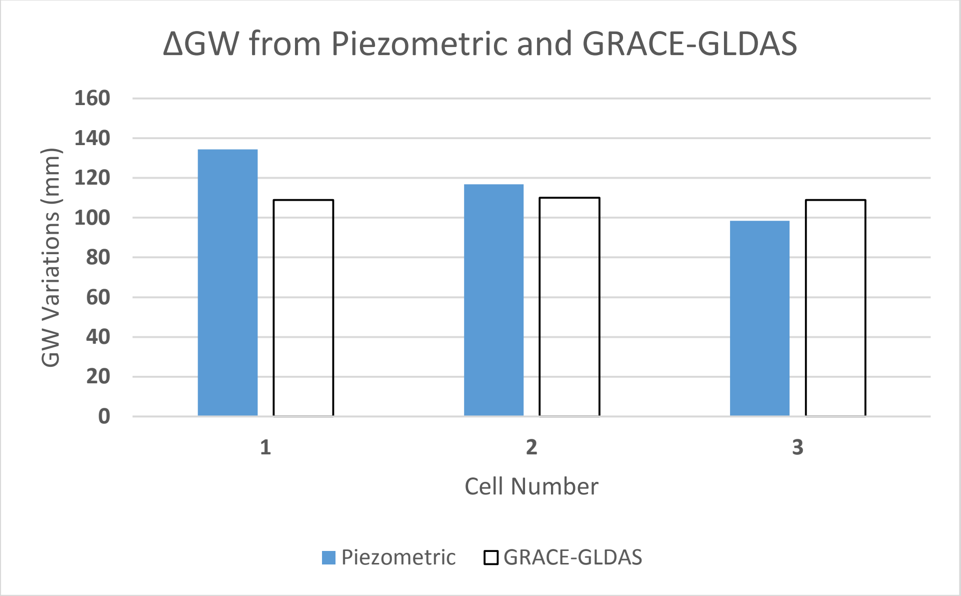

Figure (5): ΔGW by Piezometric Maps and GRACE GLDAS.

The cell four excluded because of huge value in ΔGW by Piezometric maps.

6. Conclusions

(GRACE) satellite, the earth gravity change data have been provided to be used differently to estimate terrestrial water storage (TWS) variations with unprecedented accuracy. GRACE is unique in its ability to monitor changes in total water storage (ΔTWS) from which we can extract (ΔGWS).

At the field scale ground-based gravity observations can be used to assess the state of deep aquifers without the need for costly and impractical (Piezometers). In addition the gravity data provides change in mass of the whole profile (not just the aquifer) and can give an indication of recharge rates.

After evaluating the GRACE data in calculating the groundwater storage changes at Nile Delta aquifer according to available data from RIGW for 2002 and 2006, Nile Delta aquifer is rechargeable according to both results from piezometric maps and GRACE-GLDAS calculations. GRACE-GLDAS are very valuable for regional areas, need more studies for different aquifers in Egypt.

According to **Nile Basin Initiative (NBI), 2012,** there is a high variability in recharge in the groundwater systems in the Nile region, with rates ranging from a few millimetres to over 400 mm/ year. That's support GRACE-GLDAS results. The NBI data verify the results of GRACE-GLDAS and ensure that the cell four has recharge unlike RIGW piezometric map which approve discharge nature of the cell, so we demand more scrutiny for ground piezometric observations for these area.

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