Hydrological Signals due to the Seasonal Variation of Lake Nasser and its Effect to the Surrounding Crust as Deduced from the Tidal Gravity Observations

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Abstract

Impounding of Lake Nasser started in 1964 and reached the highest water level so far in 1978 with a capacity of 133.8 km^3. It is extending 500 km in southern Egypt and northern Sudan, thus forming the second largest man-made lake in the world. The water level fluctuates between 168m and 178m, the cycle being divided into four different periods of inflow, stability, discharge, and stability again. The variation of the mass of the water of the reservoir changes the potential field either by loading or by change of the ground water level. To detect these signals two years of continuous gravity measurements (from the year 2002 to the year 2004) have been used from a tidal station installed very close to the Lake. A combined plot of water level variation and residual gravity shows that the residual gravity follows water level variations with a time delay. Two methods have been used in the current study to evaluate the gravity variations in the tidal records due to variations of water level at Lake Nasser. In the first method, the data were divided into blocks, each block represents an epoch of a certain water level in the lake. These blocks reflect the situation in the lake during the decrease, stability, and increase of water level. The tidal parameters at different blocks with different water levels show some changes. These changes reach up to 4% in amplitude factors, and 0.5° in phase shifts. The variations in the elastic parameters follow to some extent the variations of water level in the lake. In the second method, cross-correlation was applied between residual gravity and change of water level in the lake. Generally, a moderate correlation coefficient (0.556) between residual gravity variation and water level variation, and a weak correlation coefficient (0.480) between residual gravity and ground water variation were recognized. Correlation coefficients of selected blocks follow to some extent the values of water level variation on one side and ground water variation on the other side. The study shows that variations of the Lake level affect the surrounding crust significantly. Variation of the lake has to be modelled and considered in the geodetic and gravity observations in this region if higher accuracy is to be achieved.

1. Introduction

The filling of large reservoirs changes the stress regime, either by increasing vertical stress (compression) by loading or increasing pore pressure through the decrease of effective normal stress (Snow, 1972; Bell and Nur, 1978; Simpson, 1986; Roeloffs, 1988). At Lake Nasser, water level fluctuates four times during the year, according to the cycle of charge (inflow) and discharge (outflow), followed each by a period of stabilisation. The variations of water level in the lake affect the dynamic stability of the area, either by variable induced loading or variation in the underground water level. On the other hand, the analysis of tidal gravity observations at Aswan tidal station, which is very close to Lake Nasser, shows discrepancies between the observed and synthetic tidal parameters. These discrepancies may be due to variations in water lake level. In the region of Lake Nasser, the Nubian sandstones cover a large area, with a porosity of about 25%. So, any change in water level in the lake changes the underground water level. Seepage of water of the lake into the underground depends on the types of rocks in the underground, their state of weathering and tectonic influences (formation of clefts and cavities of different sizes). The run-off depends on the properties of superficial material, the evaporation on meteorological parameters (air temperature, humidity of air, and wind) and plant cover, etc. In hydrologic modelling, generalized input data and parameters are commonly used, which are representative for a certain area or a certain period of time. In addition, models for gravimetric purposes should describe with high accuracy the actual hydrologic situation in the area under consideration and its variation with time. At Lake Nasser area, in the epochs of recharge the increase of the water level of the lake leads to outflow from lake to underground, increasing the ground water level. On the other hand, in the epochs of decreasing water level the inflow from underground water to the lake leads consequently to decreasing ground water level. Thus, ground water level should follow to a great extent the lake level variation. However, structural setting of the area of Lake Nasser indicates that:

a. The number of faulting systems at the north western part of the lake causes a complicated hydro-dynamical behaviour.
b. Decrease of the sediment thickness towards the east leads to a decrease of this effect in eastern direction.

2. General Geology

The area of Lake Nasser belongs to the so-called Arabo-Nubian Massif. The area is characterized by four main geomorphological and geological units. These are: Aswan Hills, old Nile Valley and High Dam Reservoir, Lake Nasser, Nubian Plain, and Sinn El-Kaddab Plateau (Fig. 1). The Aswan Hills extend along the eastern bank of Lake Nasser and are characterized by their rugged topography. Precambrian basement rocks are exposed within the hills along the crust of the uplifts (Issawi, 1968).The old Nile valley and the High Dam reservoir are located along the western edge of Aswan hills. Lake Nasser extends mostly over the low lands in the west of the old Nile valley. Embayments were formed covering low lands to the west, the greatest one covers the former "Wadi Kalabsha". The Nubian Plain covers most of the low lands west of the old Nile valley. It has a relatively flat surface covered by Foreland sediments, ranging in age from Late Cretaceous to Eocene. These sediments overlie unconformably the Pre-Cambrian rock unit. The Nubian formation is composed of fine- to coarse-grained sandstone, with some shale and siltstone intercalations. It thins towards the High Dam and Lake Nasser. In some places, sandstone hills, composed of resistant beds, interrupt to the flat surface of the Nubian plain. The Sinn El–Kaddab Plateau is a vast limestone capped table land that extends westwards. The eastern margin is a steep east-facing escarpment called "Sinn El-Kaddab Escarpment". Lake Nasser area is characterized by three main features (Issawi, 1968; 1978). The most important one is faulting. The largest of which are Kalabsha and Seiyal Faults, trending mainly in an E-W direction. Faults in the N-S direction are also predominant. Two other systems of subordinate faults, the NW-SW and the NE-SW also exist. The area is affected by up-arching due to uplifting of basement rocks. Folding is less predominant structure in the study area. Small domes and several basins were created according to the up-arching of the basement.

3. Geophysical Studies

On November 14th, 1981, a moderate earthquake with magnitude 5.6 occurred in the unpopulated area of Kalabsha, along the Kalabsha Fault, 70 km southwest of Aswan City (Kebeasy et al., 1982; 1987). Since then, seismicity continued to occur in the area, but with different magnitudes. The epicentres of these earthquakes were located near the epicentre of the main earthquake of November, 1981, along the eastern part of Kalabsha Fault, mainly near to the wide area of the lake (Kebeasy et al., 1987). Several study programs were initiated at Lake Nasser region. These programs include: monitoring of seismicity, underground water behaviour, strong motion effects on important structures, geological as well as geophysical investigations and monitoring of co-seismic crustal deformation by means of geodetic methods (Vyskočil and Tealeb, 1985; Vyskočil, 1987). Other programs for geophysical measurements were initiated by NRIAG, since 1986. These programs include mapping of the subsurface structures using seismic reflection and refraction techniques (Kebeasy and Ghareib, 1991) as well as magnetic and geoelectric measurements (Vyskočil and Tealeb, 1995).The November 14th, 1981, earthquake is located in Kalabsha area, about 70 km to the south of the High Dam site. The spatial distribution of the earthquakes forming the seismicity map of Aswan area (Fig. 2) shows that the seismicity is concentrated in five main clusters (Fat-Helbary, 1995). These five cluster are: Gabel Marawa, east of Gabel Marawa, Khor El-Ramla, Abu-Derwa, and Old Stream. Most of these zones are attributed to Lake Nasser and can be strongly affected by environmental changes of the lake.

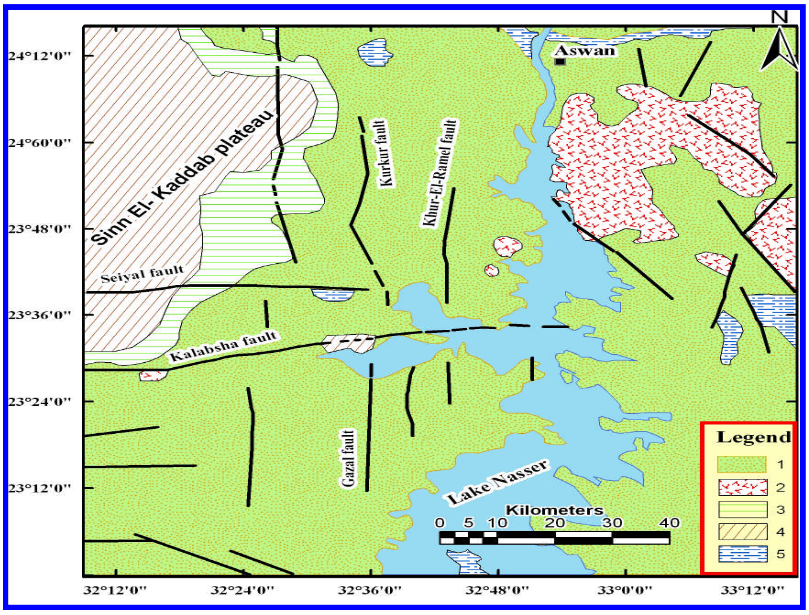

Figure 1: Geological map of Lake Nasser region modified by WC (Woodward-Clyde Consultants, 1985). Legend: 1- Latest Cretaceous sandstones and shale of Nubian Formation.
2- Precambrian metamorphic and plutonic rocks.
3- Latest Cretaceous rocks, mainly shale of the Dakhla Formation.
4- Paleocene to Eocene-age marine limestone.
5- Undivided Quaternary sediment.

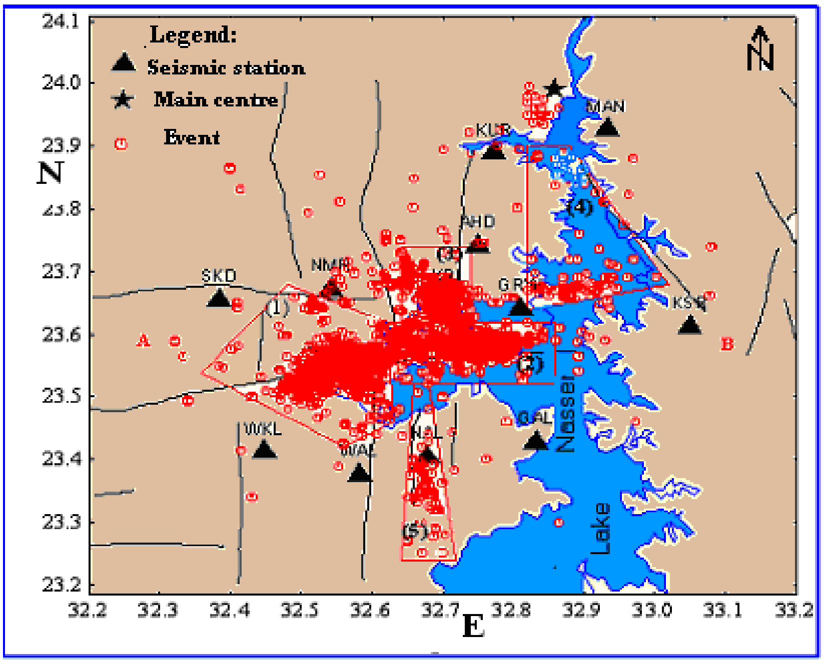

Figure 2: Seismicity map of the Aswan area around Lake Nasser (Fat-Helbary, 1995).

Gravity observations were carried out and repeated at different epochs along the points of the regional network to study the temporal gravity variations around the northern part of Lake Nasser.

Fig. 3 (Zahran, 2005) shows gravity variations along the network at the period from November 2001 to November 2002. The Figure indicates the gravity variations around the lake over a period of one year. This variation is in the order of tens of microgals. Temporal gravity variations along the regional network around Lake Nasser obey to a great extent to water level variations of the lake. It shows significant mass redistribution around the active faults, which can contribute to the seismological activities. Seasonal variations of the level of Lake Nasser modify the stress regime of the area and, thus, variations of the gravity field and crustal deformations are to be expected (Zahran, 2005).

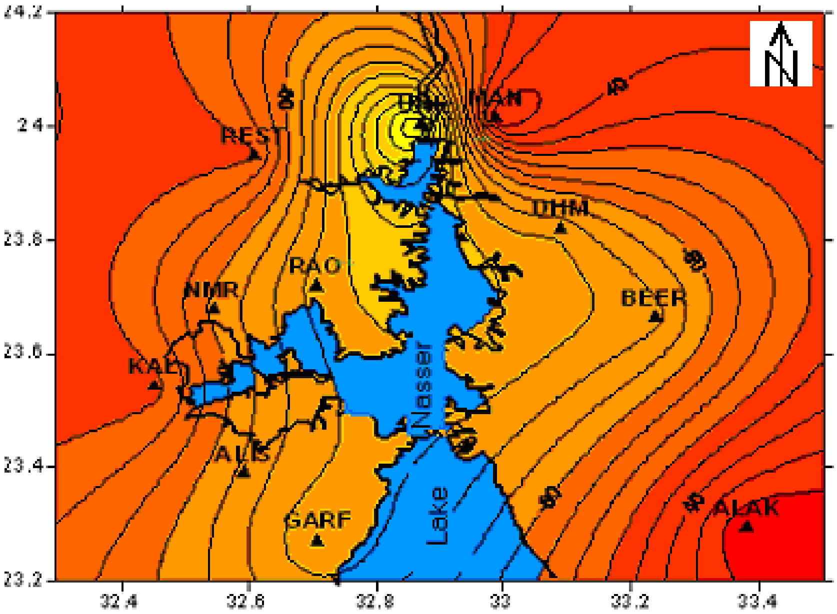

Figure 3: Gravity variations around Lake Nasser from Nov. 2001 to Nov. 2002; difference of contour lines is 20 µGal (Zahran, 2005).

4. Gravity Residuals and Water Level Variations at Lake Nasser

Fig. 4 gives a combined plot of the water level variations at Lake Nasser and residual gravity due to the tidal analysis of data from Aswan tidal station, Hassan et al., 2009. Fluctuations in gravity residues indicate that the tidal factors are not stable. It can be easily noticed that there is a significant change in residual gravity related to water level variation. It can be also noticed that the peak of maximum water level does not coincide with the peak of the maximum residual. This indicates that the response of the crust around the lake to water level variation is not instantaneous. The delay of the residual gravity regarding to water level variation may be due to slowly migrating water in the permeable sandstone. The available data about the variation of underground water level were obtained from March to December 2004 from a well in the area of Nubian sandstones. Fig. 5 shows the variations of Lake water level, underground water level, and residual gravity during the year 2004. From this figure, it can be seen that a steep change in underground water level led to an increase in residual gravity. Clear correlations between residual gravity and change of water level at Lake Nasser can be recognized, and also with change in the underground water level. Moreover, it can be noticed that high residual gravity is obtained at the periods of high underground water level, and low gravity residuals are obtained at periods of low underground water level.

5. Induced Loading Effect

Two methods have been used to evaluate the gravity variation in the tidal record due to the variable load of the lake. In the first method, the data were divided into blocks; each block corresponds to one of the four meteorological seasons (comp. Tab. 1). These blocks reflect more or less the situation in the lake during periods of decrease, stability and increase of the water level. Comparison of some of the selected tidal waves, accurately separated at different blocks could reflect the response of the

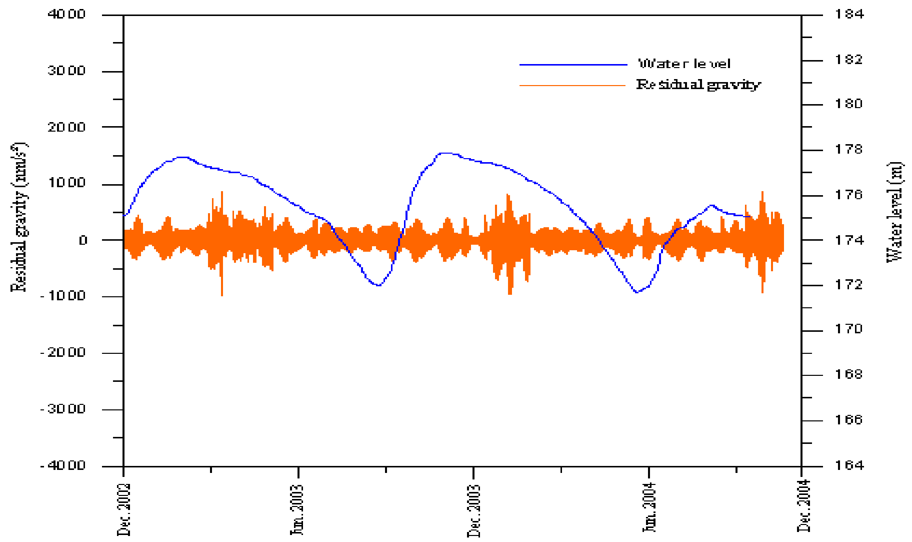

Figure 4: Fluctuation of water level and residual gravity from 2002 to 2004, Lake Nasser area, Aswan, Egypt.

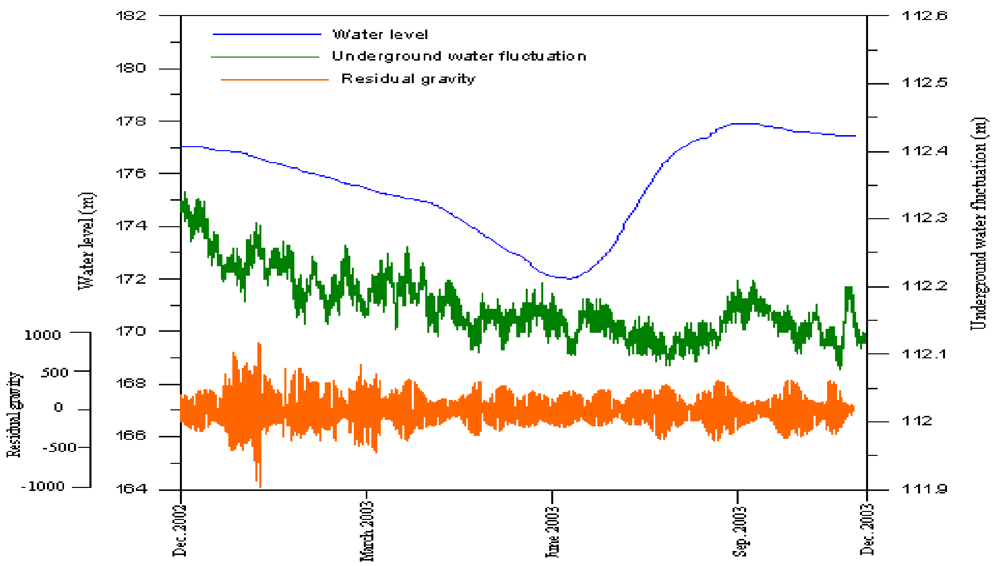

Figure 5: Residuals gravity, water level fluctuations and underground water fluctuations from 2002 to 2003, Lake Nasser area, Aswan, Egypt.

behavior of the crust to the variable load of the lake. In the second method, a quantitative evaluation to the relation between residual gravity and water level will be numerically evaluated by applying the cross-correlation between the residual gravity and the change of water level in the lake during the period of observations (from 2002 to 2004).

Block analysis method

Three main wave groups (Q1, O1, and M2) were chosen because of their large amplitudes which can be easily separated from tidal gravity observations. The observed amplitude factors for the different blocks were compared using the program ANALYZE of the ETERNA 3.3 package (Wenzel, 1996a; 1997). Tables. 1 and 2 show the observed amplitude factors of different blocks during the years 2003 and 2004. It has been noticed that there is a change in the amplitude factors from block to block, in which there is a change in water level. The variations in amplitude factor after block analysis during 2003 are shown in Fig. 6. It can be noticed that the wave O1 shows higher sensitivity to water level changes than Q1. This may be due to the daily variation of the

Table 1: Variation of the observed amplitude factors, after block analysis, during the year 2003, Lake Nasser area, Aswan, Egypt.

Tidal wave / Period	Q1	O1	M2	Water level fluctuation (m)
January to March 2003	1.086 ± 0.031	1.036 ±0.027	1.094 ±0.011	-1.04
April to June 2003	1.045 ± 0.031	0.998 ±0.029	1.059 ±0.010	-1.68
July to September 2003	1.048 ± 0.037	0.985 ±0.019	1.048 ±0.013	-2.64
October to December 2003	1.096 ± 0.029	1.029 ±0.018	1.103 ±0.011	+4.16

Table 2: Variation of the observed amplitude factors, after block analysis, during the year 2004, Lake Nasser area, Aswan, Egypt.

Tidal Wave / Period	Q1	O1	M2	Water level fluctuation (m)
January to March 2004	1.081 ± 0.029	1.029 ±0.019	1.098 ±0.013	-1.09
April to Jun, 2004	1.052 ± 0.025	0.993 ±0.017	1.066 ±0.013	-2.18
July to September, 2004	1.049 ± 0.030	0.984 ±0.016	1.055 ±0.013	-2.60
October to December, 2004	1.075 ± 0.028	1.017 ±0.018	1.090 ±0.013	+3.52

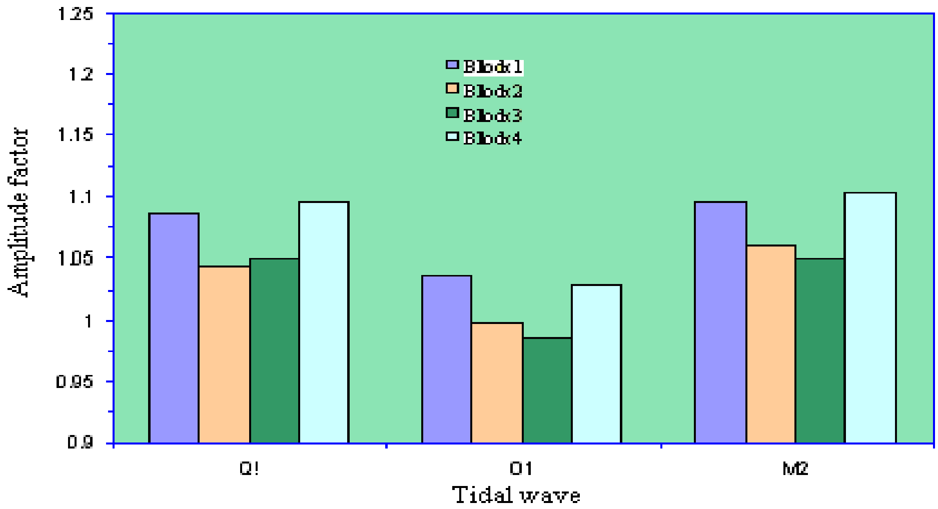

Figure 6: Variation of the observed amplitude factors, after block analysis, during the year 2003, Lake Nasser area, Aswan, Egypt.

variable load of the lake, which has a frequency close to O1 band rather than Q1 band. However, this assumption needs some more verification and study.

Besides, the phase shift for different blocks was compared. Tabs. 3 and 4 show the observed phase shift after block analysis during the years 2003 and 2004. It has been found that there is a change in phase shift from period to period. Variations in phase shift are shown in Fig. 7. As a result of the block analysis, the effect of the variable load of Lake Nasser is obvious in the changes of both amplitude factor and phase shift. With regard to the accuracy of the separated waves, the observed changes in the amplitude factor and- phase shift are significant for O1 and M2.
The Amplitude factors are higher in autumn and spring i.e. during the period of charge and stabilisation of the Lake. This effect reaches 0.4%. There exists a tendency to observe a decrease of 0.5° of the phase differences at the same time.

Table 3: Variation of phase shift, after block analysis during the year 2003, Lake Nasser area, Aswan, Egypt.

Tidal wave / Period	Q1	O1	M2	Water level fluctuation (m)
January to March	1.05 ± 0.50	-0.35 ±0.33	1.96 ±0.30	-1.04
April to June	1.45 ± 0.46	-0.24 ±0.44	2.53 ±0.28	-1.68
July to September	1.46 ± 0.48	-0.24 ±0.33	2.40 ±0.21	-2.64
October to December	1.06 ± 0.47	-0.42 ±0.43	1.99 ±0.29	+4.16

Table 4: Variation of phase shift, after block analysis during the year 2004, Lake Nasser area, Aswan, Egypt.

Tidal wave / Period	Q1	O1	M2	Water level fluctuation (m)
January to March	1.07 ± 0.47	-0.36 ±0.39	1.88 ±0.28	-1.09
April to June	1.51 ± 0.35	-0.24 ±0.31	2.39 ±0.28	-2.18
July to September	1.42 ± 0.47	-0.25 ±0.31	2.41 ±0.30	-2.60
October to December	1.09 ± 0.33	-0.37 ±0.30	1.89 ±0.29	+3.52

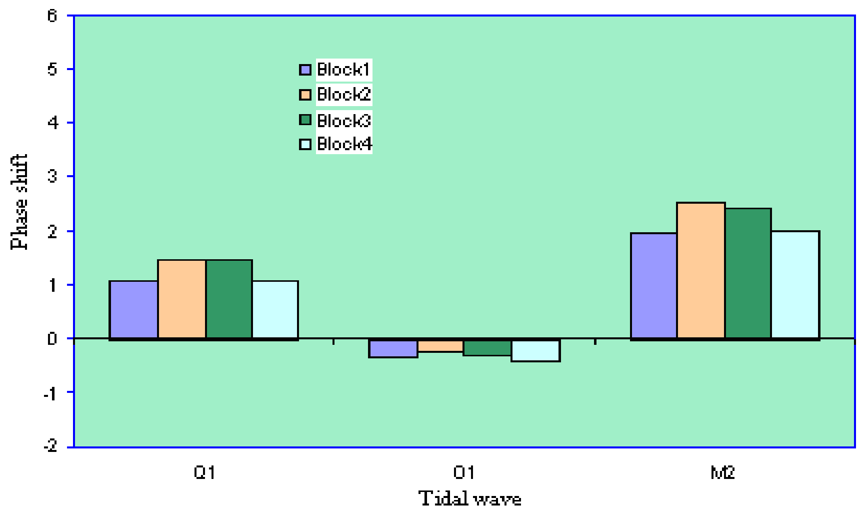

Figure 7: Variation of phase shift, after block analysis during the year 2003, Lake Nasser area, Aswan, Egypt.

Cross-Correlation method

First, the correlation coefficient between the tidal residuals and the lake level changes was computed for the whole period of observations. Hereafter, the correlation coefficient has been computed separately for some selected blocks. The results obtained from these analyses are shown in Tab. 5. The correlation coefficient for the whole period was found to be +0.556. The best relationship between the water level fluctuation and change in gravity could be obtained for the period from October to December, 2003, where the correlation coefficient attained +0.562. In this period, the water level reached its maximum value (177.91 m). The worst relationship could be obtained for the period from July to September, 2004, where the correlation coefficient dropped down to +0.432. In this period, the water level reached its minimum value of 172.02 m. So, it can be noticed from the results in Tab. 5 that there is a clear correlation between the fluctuation of water level and the change in gravity. To estimate the effect of underground water level variation on the residual gravity, again a cross-correlation was computed. The correlation coefficient was found to be +0.480, which means there is a weak relation between the variation of underground water level and residual gravity.

Table 5: Variation of cross correlation coefficient between residual gravity and water level fluctuation, Lake Nasser area, Aswan, Egypt.

Period	**Correlation coefficient**	**Water level Fluctuations (m)**
from Jan., 2003, to Dec., 2004	+0.556	
from January to March 2003	+0.530	-1.04
from April to June 2003	+0.502	-1.68
from July to September 2003	+0.468	-2.64
from October to December 2003	+0.562	4.16
from January to March, 2004	+0.495	-1.09
from April to June 2004	+0.445	-2.18
from July to September 2004	+0.432	-2.16
from Oct., 2004, to Dec., 2004	+0.492	3.52

Table 6: Variation of cross correlation coefficient between residual gravity and underground water level fluctuation, Lake Nasser area, Aswan, Egypt.

Period	Correlation coefficient	ground water level fluctuations (cm)
From Mar., 2003 to Dec., 2004	+0.480	
From Mar., 2003 to Jun., 2003	+0.352	10
From Jul., 2003 to Sep., 2003	+0.283	7
From Oct., 2003 to Dec., 2003	+0.336	8

6. Time Variation of the Earth's Gravity Field at Lake Nasser Area

Zhang et al. (1996) developed a method to predict time variations of the Earth's gravity field and crustal deformation due to mass loading caused by the impounding of the three Gorges reservoir. Zahran (2005, pers. communication) used Zhang's method to compute the effect of the induce loading on the gravity field during the period of study. Fig. 8 shows gravity field variations as induced by water level variations at Lake Nasser. It can be seen that the variation in gravity follows the variation of the water level in the lake. The maximum gravity variation is 500 nm $/s^2$ due to maximum water level variation. The range of induced load gravity variation is significant for tidal observations and also for repeated gravity variations for geodetic purposes. The high residuals were found to be associated with high water level variations. Moreover, the obtained phase shift between water level variation and residual gravity (Fig. 4) is not clear. This effect may be due to mass changes by water migrating through the rock around the lake in addition to the elastic behaviour.

7. Discussion

A combined plot of water level variation and residual gravity shows that the residual gravity follows water level variation with a time delay. This time shift may be due to the permeability of the rocks and migrating water masses. On the other hand, the differences of the tidal parameters in different blocks under different loading conditions may be due to pore pressure changes, and, thus, modifications of overall elasticity of the rock. There is a moderate correlation between residual gravity variation and lake water level variation, whereas the correlation between residual gravity and underground water variation is weak. Correlation coefficients of selected blocks show that their values follow to a great extent the values of water level variations on one side and on the other side groundwater variation. The effect of induced load in the lake on the gravity field was calculated at different water levels at Aswan tidal gravity station. The range of induced load gravity variation is significant for tidal observations and also for repeated gravity surveys for geodetic purposes.

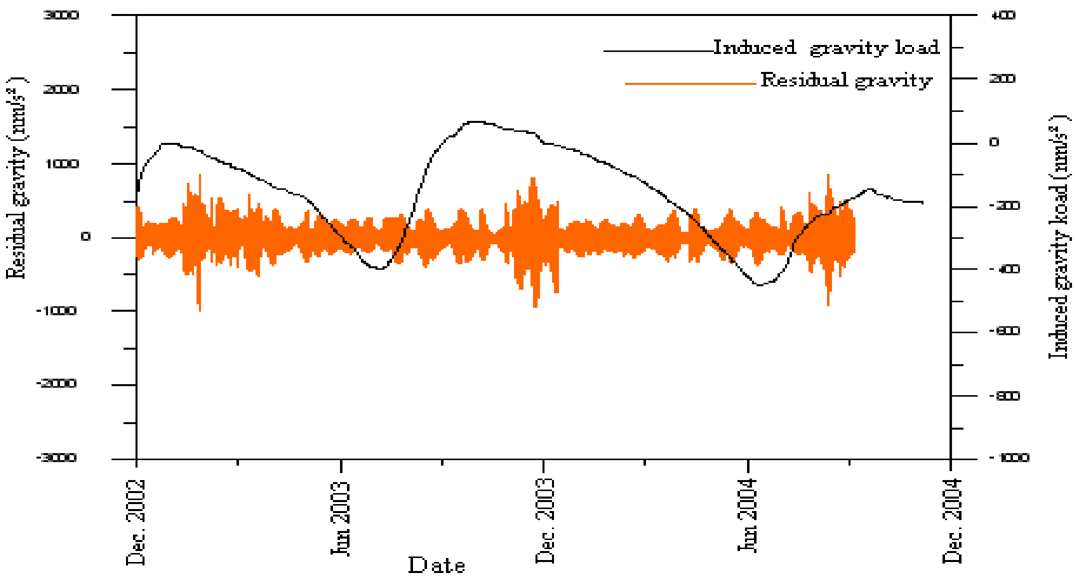

Figure 8: Induced gravity load and residual gravity, Lake Nasser Area, Aswan, Egypt (from 2002 to 2004).

Acknowledgements: The authors are indebted to the Department of Geophysics, Faculty of Science, Cairo University and the National Research Institute of Astronomy and Geophysics (NRIAG) for the encouragement of this work. We thank the Regional Seismological Center at Aswan for providing the facilities for the measurements. Finally we are grateful to the German Academic Exchange Service (DAAD) for supporting the work by travel funds to RMH and GJ.

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