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Impact of Nasser Lake on gravity reduction and geoidal heights for Egypt

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A B S T R A C T

In the course of the IAG African Geoid Project, it is needed to study the impact of the lakes on the gravity reduction and geoidal heights. The aim of this paper is to study the impact of the water in Nasser Lake on gravity reduction and geoidal heights for Egypt. The determination of the gravimetric geoid is based on the well-known remove-restore technique. The problem of the lakes occurs because the popular programs widely used in practice (e.g., TC-program (Forsberg, 1984)) assume that all positive elevations are filled with rock topography, and all negative elevations are filled with ocean water. This is, however, not true for the case of Nasser Lake, which lies completely above sea level, at about 180 m elevation, with a water depth of about 20 m. The paper presents an approach on estimating the impact of Nasser Lake on gravity reduction and geoidal heights using TC-program with some tricky cases. The results show that the impact of Nasser Lake on both gravity anomalies and geoid undulation is limited to the area of the lake. The impact of Nasser Lake on the gravity anomalies is in the order of sub mgal, while the impact of Nasser lake on the geoid undulation is significant and reaches few centimeters.

1. Introduction

In order to apply Laplace equation, there should be no masses outside the geoid (Heiskanen and Moritz, 1967). This implies removing, mathematically, the topographic masses and their compensating masses. This process is known in physical geodesy as gravity reduction. The remove-restore technique (Forsberg, 1984) is widely used in practice. Abd-Elmotaal and Kühtreiber (2003) have proposed a more accurate remove-restore technique by introducing the so-called window technique. In both techniques, the effect of the topographic masses are removed using TC-program (written originally by Forsberg (1984)) or its modified version (written by Abd-Elmotaal and Kühtreiber (2003)). As TC-program uses unclassified Digital Height Models (DHMs), it assumes that all positive elevations are filled with rock topography, and all negative elevations are filled with ocean water.

In the case of Nasser Lake, the situation is quite different. The whole lake is located above the sea level. Thus it has positive elevations. TC-program thus treats the water masses inside the Nasser Lake as rock topography instead of water masses. Accordingly, the main aim of the current investigation is to determine the impact of the Nasser Lake on both the gravity reduction and the geoid undulation.

The study area is defined and an overview of the Nasser Lake is given. The available Digital Height Models for the current investigation are described. The Stokes' technique of the geoid determination, within the remove-restore scheme, is outlined. The used images for determining the lake and the necessary image analysis has been given. The approach of determining the impact of the Nasser Lake on the gravity reduction and the geoid undulation using TC-program is explained and then implemented.

It should be noted that the area of Lake Nasser attracts a number of interesting studies. Some studies were interested in computing a local geoid for the Nasser Lake area (see, e.g., Tscherning et al., 2001). Other studies were tackling the important topic of the crustal deformation in the area of Lake Nasser (cf., e.g., Zahran and Abdel-Monem, 2006).

2. Study area – Nasser Lake

Nasser Lake is one of the largest artificial freshwater reservoirs in the world. It is considered as the largest artificial reservoir in Africa by volume (excluding continental lakes, e.g., Tanganyika). The Lake is located in southern Egypt and northern Sudan. Strictly, "Lake Nasser" refers only to the much larger portion of the lake that is in the Egyptian territory (83% of the total area), (cf. Fig. 1). The Sudanese prefer to call their smaller portion of the lake "Lake Nubia". This study concerns the whole area of the lake. The lake was created after the construction of the High Dam across the River Nile waters during the 1960s. The lake lies between latitudes $21.75°N \leq \phi \leq 24°N$, extends over 500 km long upstream of the High Dam, and has a width of 35 km at its widest point (near the Tropic of Cancer). At 182 m water level (above mean sea level), the lake has an average width of about 12 km and covers a

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Fig. 1. Lake Nasser location.

surface area of 5237 km^2 with a storage capacity of some 150–165 km^3 of water (Zwieten et al., 2011).

Nasser Lake is valuable for Egypt as it represents a large reservoir for the country's freshwater resources. The location of the lake is characterized by an extremely arid climate, with a wide diurnal variations and almost no precipitation. The volume of the water in the lake fluctuates greatly annually and seasonally depending upon the net annual volume of water it receives and the operation of the High Dam. Fig. 2 shows the lake level fluctuation as inferred from satellite altimetry (LEGOS/GOHS) from 1992 to 2011. The highest recorded water level during this period was 181.2 m (above mean sea level) in November 1999, while the lowest level recorded so far was 167.2 m in July 1993. In this study, satellite images, namely Landsat-7 ETM+ images, are used to determine the boarders of the lake as described in Section 7.

3. Digital height models DHMs

In the context of the remove-restore technique (Forsberg, 1984), a set of fine and coarse DHMs is needed for the terrain reduction computation. The $3'' \times 3''$ fine Digital Height Model EGH13S03 and the $30'' \times 30''$ coarse Digital Height Model EGH13S30 (Abd-Elmotaal et al., 2013) are available for this investigation. These DHMs cover the full window of $(19°N \le \phi \le 35°N; 22°E \le \lambda \le 40°E)$. Fig. 3 illustrates the $3'' \times 3''$ fine EGH13S03 for the Lake Nasser area $(20°N \le \phi \le 26°N; 30°E \le \lambda \le 36°E)$. The heights within the Nasser Lake area range between −1776 m and 1961 m with an average of about 289.1 m and a standard deviation of 293.8 m.

4. Remove-restore technique

The remove-restore technique consists of two steps. The first step is performed to remove the effect of the topographic-isostatic masses and the effect of the global geopotential model from the source gravitational data. In the second step, the effect of the topographic-isostatic masses and the effect of the global geopotential model to the resulting geoidal heights are restored. For example, in the case of gravity data, the reduced gravity anomalies in the framework of the remove-restore technique are computed by (see e.g., Rapp and Rummel (1975), Forsberg (1993), and Sansó (1997))

$$\Delta g_{red} = \Delta g_F - \Delta g_{GM} - \Delta g_{TI}, \tag{1}$$

where Δg_F stands for the free-air anomalies, Δg_{TI} is the effect of topography and its compensation on the gravity anomalies, and Δg_{GM} is the effect of the reference field on the gravity anomalies. Thus, the final computed geoid N within the remove-restore technique can be expressed by

$$N = N_{\Delta g} + N_{GM} + N_{TI}, \tag{2}$$

where N_{GM} stands for the contribution of the reference field, $N_{\Delta g}$ stands for the contribution of the reduced gravity anomalies, and N_{TI} is the contribution of the topographic-isostatic masses (the so-called indirect effect).

The above *traditional* remove-restore techniques faces a theoretical problem of the double consideration of some of the topographic-isostatic masses around the computational point. A possible solution of this problem has been made by introducing the *window* remove-restor technique (Abd-Elmotaal and Kühtreiber, 1999, 2003).

The remove step for the window remove-restor technique is given by

$$\Delta g_{win\text{-}red} = \Delta g_F - \Delta g_{GM} - \Delta g_{TI\,win} + \Delta g_{wincof}, \tag{3}$$

where $\Delta g_{win\text{-}red}$ stands for the window-reduced anomalies, $\Delta g_{TI\,win}$ refers to the effect of the topographic-isostatic masses for a fixed full data window and Δg_{wincof} is the contribution of the harmonic coefficients of the topographic-isostatic masses of the data window. The harmonic coefficients of the topographic-isostatic masses can be computed using the expressions given in Abd-Elmotaal and Kühtreiber (2003), or more precisely using the expression given in Abd-Elmotaal and Kühtreiber (2015).

The restore step for the window remove-restor technique is given by

$$N = N_{\Delta g\,win} + N_{GM} + N_{TI\,win} - N_{wincof}, \tag{4}$$

where $N_{\Delta g\,win}$ stands for the contribution of the window-reduced gravity

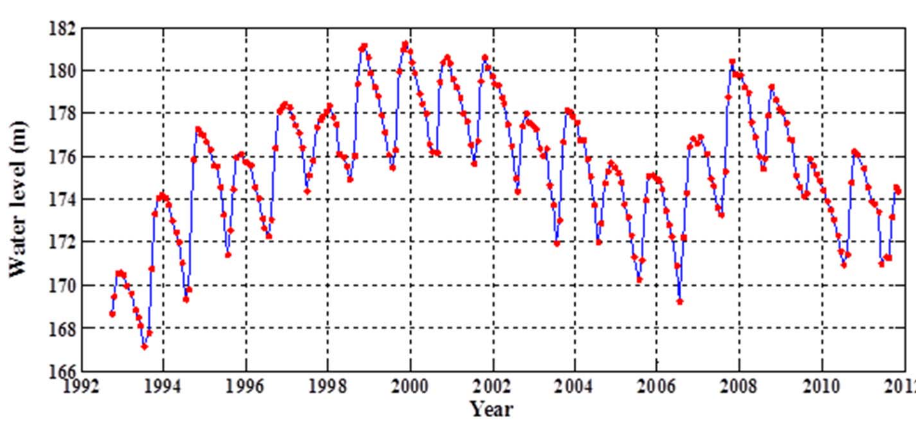

Fig. 2. Lake level variation of Lake Nasser from satellite altimetry (LEGOS/GOHS) (reference point: $\phi = 22.60°, \lambda = 32.10°$).