Scientific Research Publishing

Integrating Radar Altimeters and Optical Imagery Data for Estimating Water Volume Variations in Lakes and Reservoirs (Case Study: Lake Nasser)

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Abstract

Monitoring of variations in water for lakes and reservoirs is a requirement for meeting human needs and assessing ongoing climatic changes. However, regular gauging networks fail to provide the information needed for water volume data. The aim of this study is to evaluate an approach to estimate water volume variation for the southern part of Lake Nasser in Egypt without *in-situ* gauge measurements and bathymetry maps. Combination of both Hydroweb satellite altimetry and Landsat 8 satellite imagery data was used. As compared to *in-situ* water levels, satellite altimetry provided accurate water levels variations for Lake Nasser; the RMSE was 0.28 m, with excellent agreement (R^2 is 0.98). The lowest water level of altimetry database *i.e.* 174.57 m was used as a reference level for estimating water volumes variations for the study duration 8/2014-6/2015. All water altimetry levels were converted to differences of recorded water level above the lowest altimetry Level (ΔWL). Series of Landsat 8 imagery data were selected to extract surface areas corresponding to radar altimetry water levels dates. Areas-ΔWL relationship model was established as a polynomial function: A = f(ΔWL), and therefore, the relationship of the water volume above the lowest water level for the study time (ΔV) and ΔWL was obtained through the analytical integration of (Area-ΔWL) model. Another approach (Heron method) was also applied for estimating water volume variations. Validation of these two approaches showed that estimated water volume variations above reference water level using both methods *i.e.* integration and Heron agreed well with *in-situ* measurements of volume variation deduced from recent bathymetry map and *in-situ* water levels (R^2 for both methods =

0.98). The RMSE for integration method is 323.89 MCM and for Heron method was 318.09 MCM, being approximately 13.2% of the mean volume variations above the lowest reference water level for mean surface area ≈658 km². Another byproduct for these approaches was the modeling for a remote detecting water level. Once the F(L) relationship is set up for a given region, future Landsat images can be utilized to track water levels freely of radar altimetry. Finally it can be concluded that remote sensing resources (satellites radar altimeters and optical satellite images) that are openly accessible these days represent a great opportunity to remotely monitor reservoir water capacity and help in examining and observing hydrological and water driven procedures.

Keywords

Radar Altimetry, Water Volume Change, Landsat 8, Lake Nasser, Egypt

1. Introduction

Regular and accurate monitor of variations in water for lakes and reservoirs would be necessary for equitable allocation of water and for a better understanding of the impact of climate change [1] [2] [3]. The traditional method of measuring water level is by gaging station installed near river mouths, bridges, weirs and sluices. Recently the use of gage stations has decreased around the globe [2] [4] [5] [6]. The stored water volume in reservoirs and lakes cannot be measured directly, and traditionally. A bathymetry map can be obtained from hydrologic surveys, using sonar sensors on ship transects to measure the underwater topography. But this kind of survey is time-consuming, labor intensive and costly [7]. Therefore, bathymetry maps are difficult to obtain for a given lake or reservoir. Satellite radar/laser altimetry is a technique that can be used to estimate water levels for water bodies. Both satellite radar and laser altimeters are profiling tools rather than imaging devices, which means that they can only record measurements along their ground tracks without the ability of a true global coverage [4] [8].

Different satellite altimetry missions are flying at different orbits, resulting in the different spatio-temporal coverage of lakes and reservoirs. Satellite radar altimetry has been utilized effectively to derive water levels of continental surface water forms; for example, inland seas, lakes, streams and wetlands. [2] [5]. At present, besides ICESat-GLAS, three other databases based on satellite radar altimetry for selected water bodies are operationally accessible. They are: 1) Global Reservoir and Lake Monitoring (GRLM) database; 2) the River Lake Hydrology (RLH) database by The River and Lake Project; and 3) the Hydroweb database. These four data bases involve the ICESat laser altimetry mission and five radar altimetry missions i.e. T/P (Topex/Poseidon), Jason-1, Jason-2 (also known as OSTM (Ocean Surface Topography Mission)), GFO (Geosat Fellow On) and ENVISAT (Environmental Satellite).

Notwithstanding some limitations, altimetry is a method that needs a turned out possibility for hydrology science since that information would be freely accessible worldwide, and it is considered as the only source of information for most lakes in remote areas. Several satellite altimetry missions were launched since the late 1980s: GEOSAT (1986-1988), ERS-1 (1991-1996), Topex/Poseidon (1992-2005), ERS-2 (1995-), GFO (2000-2008), Jason-1 (2001-) Jason-2 (2008-) and ENVISAT (2002-). ERS-1, ERS-2 and ENVISAT have a 35-day temporal resolution (duration of the orbital cycle) and 70 km inter-track spacing at the equator. Topex/Poseidon, Jason-1 and Jason-2 have a 10-day orbital cycle and 350 km equatorial inter-track spacing. GEOSAT and GFO have a 17-day orbital cycle and 170 km equatorial inter-track spacing.

Recently, satellite radar altimetry was combined with satellite imagery to derive volume variations of surface water in large river basins such as the Negro River Basin [9] [10] [11], and the [12]. Few studies were carried out to derive variations of water volume in lakes using the combination of imagery and altimetry data. [13] reconstructed volume variations in the inland lake Big Aral Sea using the digital bathymetry model and water levels derived from T/P altimetry data. Reference [14] computed water storage changes in nine lakes of the Peach-Athabasca Delta, Canada using *in-situ* water levels and remotely sensed surface areas. Recently the GRACE satellite gravimetry has been used in combination with altimetry and satellite imagery data to study the variations of water volume in the very large inland water bodies, e.g. a study by [15]. These satellite altimetry databases are becoming attractive for operational applications in water resources management.

The purpose of the study is to evaluate an approach which combines two freely available Landsat images and radar altimeters data (processed into water levels), to estimate the water volume variations for the southern part of lake Nasser, without *in situ* measurements and bathymetry data. Two methods were applied for water volume variations estimation: Heron method and integration model method. These methods will help decision makers to estimate the relative water volume variations for the sake of water and environmental management rather than absolute values without *in-situ* water level measurements and bathymetric maps. The *in-situ* observed water levels and water volumes were used for assessing the accuracy of satellite altimetry databases and the estimated water volume variations.

2. The Study Area

Lake Nasser extends from southern Egypt to the northeast part of Sudan, with length of about 500 km and maximum width 35 km. The total area surveyed is approximately 50,000 feddans. In general, the geographic boundary is between latitude 21˚ and 24˚30' north and longitude 31˚30' and 33˚ east. This research is limited to the Egyptian portion of Lake Nasser that extends along 50 km from Sudan border (Figure 1).
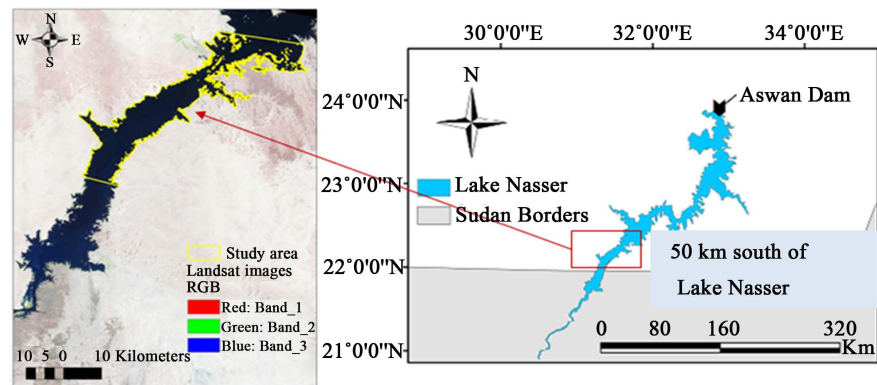
Figure 1. Study area in Lake Nasser.

3. Data Sets

3.1. Daily Measured Water Levels

Measurements of water level between August, 2014 and June 2015at one gauging station for Lake Nasser were obtained from Nile Research Institute (NIR) database for assessment purpose. Figure 2 demonstrates measured water levels trend. With standard deviation about 1.4 for this short duration between (2014-2015).

The corresponding Surface regions and also water volumes were computed with the use of surface volume tool under ArcGIS environment. Thus being based on a recently created bathymetry map obtained from hydrologic surveys, using multi-beam echo sounder which is a device used to determine the depth of water and the nature of the water stream bed (underwater topography). Figure 3 shows the multi-beam acquisition software and the diagram of multi beam scanning area [16]. Figure 4 demonstrates the resulted bathymetry level points for the study area

3.2. Radar Altimetry Data

Hydroweb available satellite water height comprised different satellite altimetry: Topex/Poseidon, Jason 2, Gfo, Envisat, Saral. These data were obtained for free from [17]. Figure 5 demonstrates a snapshot for the database of Lake Nasser that includes the near real water level and surface area, water volume through the years 1992 to 2016.While Figure 6 shows the trend of radar altimetry water levels through only 2014-2015 period. Both data (text and graphs) were downloaded from Hydroweb which include: (decimal year, date, time, height above surface of reference, standard deviation, area in km^2, volume with respect to volume of the first date in km^3, Flag).

3.3. Optical Satellite Images for Surface Area Estimation

Landsat 8 data with cell size of 30 m were used (for criteria of suitability and low cost) to derivate surface areas for the lakes and reservoirs. Landsat8 data were downloaded from [18]. The dates of altimetry-derived water levels and the satellite images should be coincide exactly. However, most of the time this was not
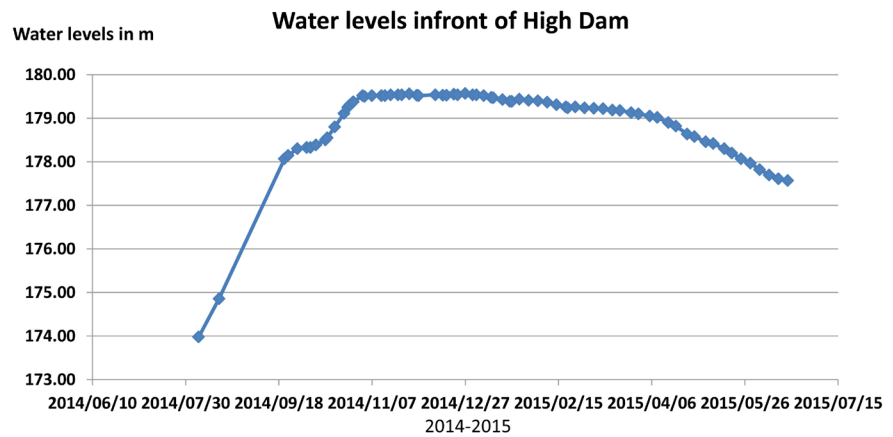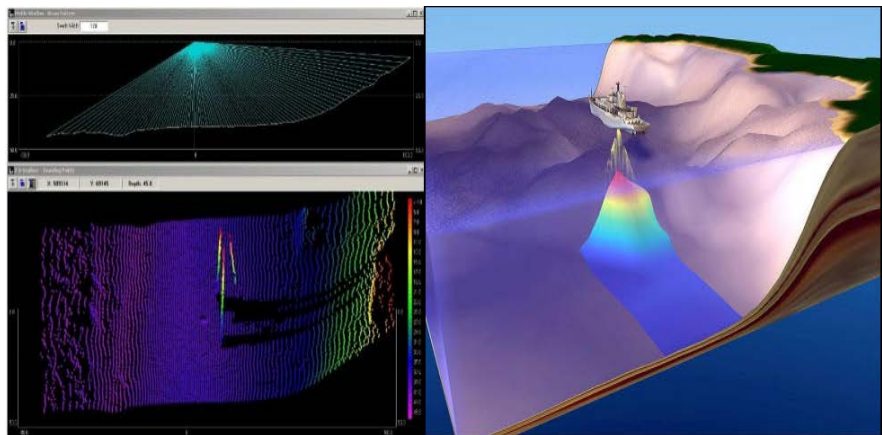
Figure 2. Measured water levels data.

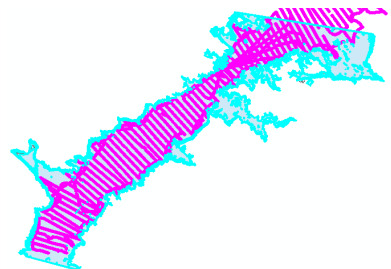**Figure 3.** The multi-beam echo sounder [16].

Figure 4. Bathymetry level points for the study area (NRI data).

the case; firstly because of the different crossover repeated cycles of Landsat (16 days) and altimeter satellites (10 - 35-day or campaign mode) and secondly, some Landsat data could not be used because cloud cover affected the quality of the data. An analysis of daily *in-situ* measurements showed that variations in water levels during a short period (five days) are minimal. In this study: Landsat images for the best 2 days before or after the dates of altimetry-derived water levels were used to derive water surface areas at the corresponding water levels. Two observation time series were used: first, lake surface areas, which extracted from Landsat 8 and second, water levels which deduced from radar altimeters.

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# Center for Space research, university of Texas, austin, USA
# ref: Tapley B, Ries J, Bettatpur S, et al., (2005),
# GGM02 - an improved Earth Gravity field from GRACE, J.geod. 79: 467-478
#
# first date: 1992  9 27 yr month day  2.0 hours 35 minutes
# last date: 2015  2 20 yr month day  0.0 hours 20 minutes
#
# data file format
# (1): decimal year (2) date = aaaa/mm/dd (3): time = hh/mn
# (4): heigth above surface of ref (m), (5): standard deviation from heigth (m)
# (6): area (km2), (7): volume with respect to volume of first date (km3)
# (8): flag
#
# The water level, surface and volume algorithm developed at Legos, Toulouse, France
#
# citation: Cretaux J-F., Jelinski W., Calmant S., et al., 2011.
# SOLS: A lake database to monitor in the Near Real Time water level
# and storage variations from remote sensing data, Advances in space Research, 47, 1497-1507
#
2011.9660 ; 2011/12/19 ; 14:09 ;   173.84 ;   0.16 ; 2321.56 ;   1.06 ; ;
2011.9910 ; 2011/12/28 ; 17:09 ;   173.82 ;   0.11 ; 2319.50 ;   1.02 ; ;
2012.0160 ; 2012/01/06 ; 20:32 ;   173.80 ;   0.09 ; 2317.44 ;   0.97 ; ;
2012.0440 ; 2012/01/17 ; 02:29 ;   173.64 ;   0.14 ; 2300.97 ;   0.60 ; ;
2012.0790 ; 2012/01/29 ; 21:56 ;   173.40 ;   0.35 ; 2276.26 ;   0.05 ; ;
2012.0940 ; 2012/02/04 ; 09:41 ;   173.49 ;   0.08 ; 2285.52 ;   0.26 ; ;
2012.1240 ; 2012/02/15 ; 09:12 ;   173.40 ;   0.09 ; 2276.26 ;   0.05 ; ;
2012.1550 ; 2012/02/26 ; 17:31 ;   173.21 ;   0.20 ; 2256.70 ;  -0.38 ; ;
2012.1830 ; 2012/03/07 ; 23:28 ;   172.96 ;   0.15 ; 2230.96 ;  -0.94 ; ;
2012.2100 ; 2012/03/17 ; 20:38 ;   172.68 ;   0.15 ; 2202.13 ;  -1.56 ; ;
2012.2380 ; 2012/03/28 ; 02:35 ;   172.51 ;   0.18 ; 2184.63 ;  -1.94 ; ;
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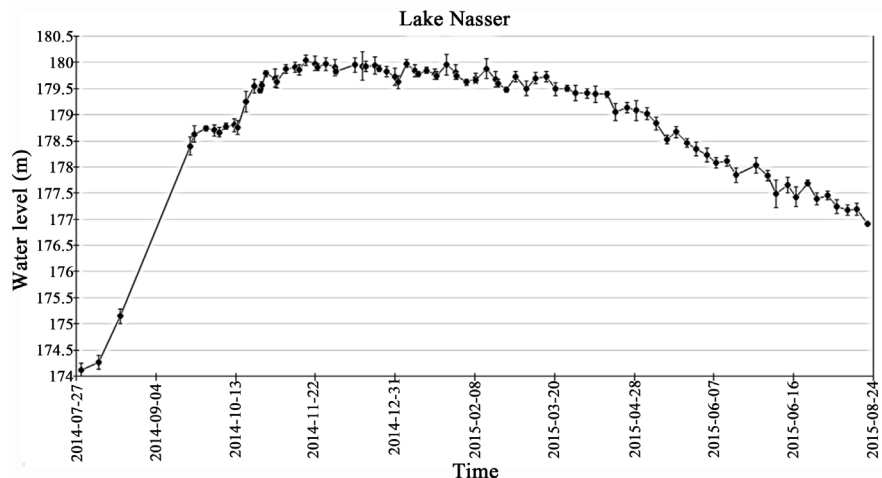**Figure 5.** Snap shot of altimeter water levels data which is download from Hydroweb site.

Figure 6. Radar altimetry water heights graph download from Hydroweb (2014-2015).

4. Methodology

Landsat 8 Satellite data were selected to match the dates of altimetry-derived water levels. and these images were geometry corrected and were subset to the domain of collected *in situ* bathymetry map obtained from recent hydrologic surveys using sonar sensors by NIR (in 2013). Classification technique was used to determine the surface area of Lake Nasser study area. This method of classification helps to distinguish accurately the water boundary of the study area in Lake Nasser, where the nature of the land cover of the south part of Egypt is mostly desert and water (**Figure 7**).

4.1. Water Volume Variation Estimation

Two methods for water volume variation estimation were adopted in this study, and they are described as follows.
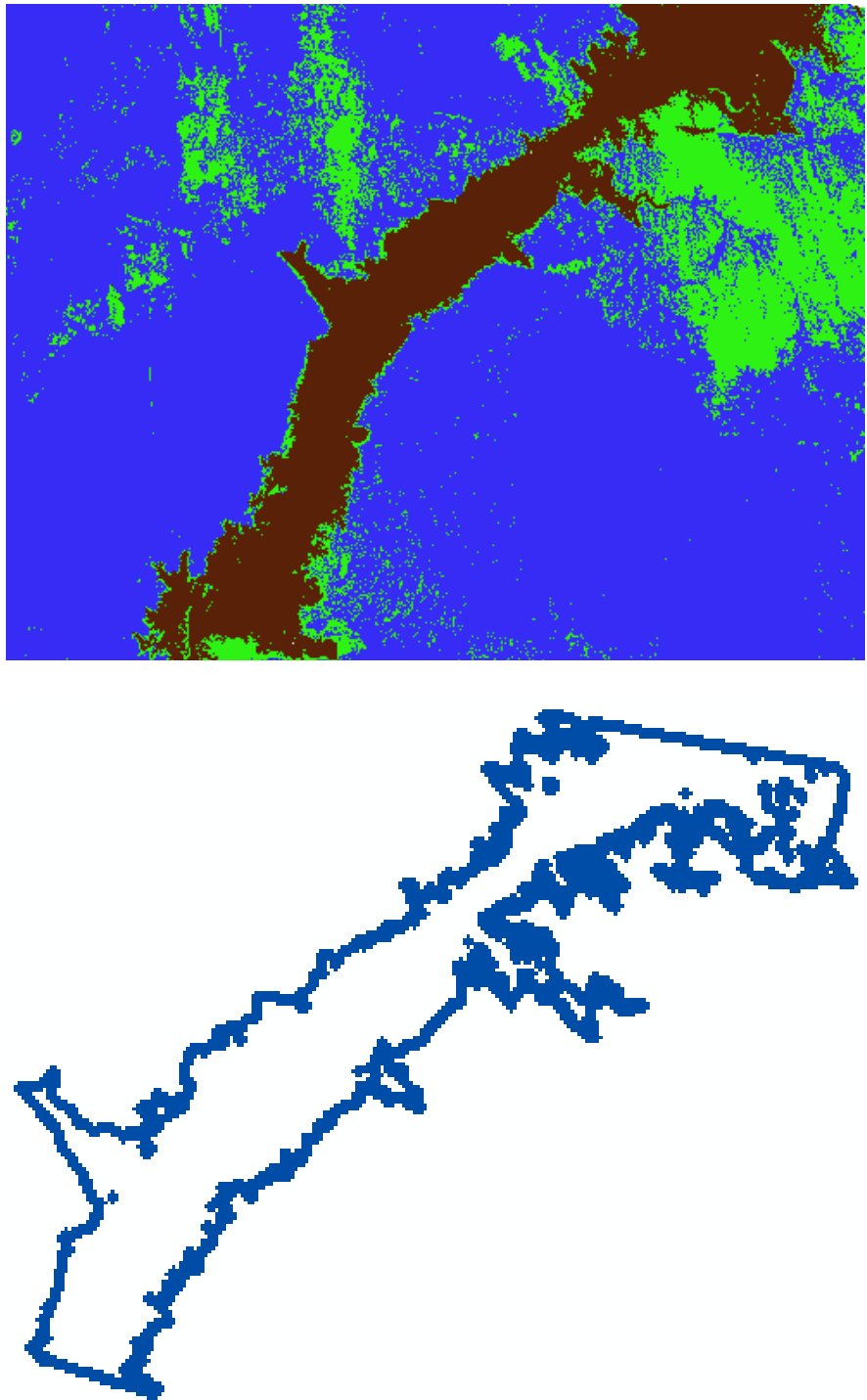
Figure 7. Resulted classes from unsupervised classification & Lake Nasser study area.

4.1.1. Analytical Integration

This method is a precise lake volume derivation based on polynomial function fitting, F, using scatter between the surface area (A) and water level (L) measurements which consider as a robust fitting relation. Since any increase in water level must be accompanied by increase in water area. $A = F(L)$ and volume can be obtained by simply integrating (Equation (1)).

$$\Delta V = \int_{l1}^{l2} f(L)\mathrm{d}l \tag{1}$$

The approach is useful if the full range of water levels cannot be observed. In other words the variations from reference level of water will be studied and evaluated as follows:

As stated by [19], the total volume (V) of water depends on a specific constant minimum volume of water contained in lakes (V_{fixed}), and a variable component that varies with the water levels (V_{var}) as describe in Equation (2):

$$V = V_{\text{fix}} + V_{\text{var}} \tag{2}$$

V_{fix} refers to the water stored between a certain constant water level and the bottom. The single value for V_{fix} can be obtained from topographic maps before a reservoir is constructed or rarely from bathymetric maps. Determination of V_{fix} has several difficulties. The underlying topography is uneven and it fluctuates significantly; thereby increasing error factors. In addition, the underlying topography changes continuously and elevations increase due to sedimentation and other human activities [7] [20]. The determination of V_{var} is for practical purposes more appealing.

The lowest water level derived from satellite altimetry during the study period can be set as reference level to separate V_{fix} (which disregarded in the scope of this study) and V_{var}. The resulting water volume V_{var} is referred to as water volume above the lowest water level *i.e.* 174.57 in this study. The lowest water level value in satellite altimetry data was subtracted from all water level values obtained from altimetry data to obtain the variation of water level above the lowest water level (ΔWL). The function relate (ΔWL) and corresponding lake surface area (area-ΔWL) was established using regression analysis. Because the water volume is the integration of the functional relationship between lake surface area and water level, thereby the (ΔWV - ΔWL) relationship, where ΔWV is the volume variation above lowest reference water level, can be obtained by analytically integrating function of (area-ΔWL)with the condition that ΔWV is equal to zero when ΔWL is zero. Assume that the area-ΔWL relation can be described as a polynomial function for example: $A = f(L) = aL^2 + bL + c$, where A is the surface area in km^2, L is ΔWL in m, and *a*, *b*, *c* are coefficients determined by regression analysis. Then the (ΔWV - ΔWL) function which is the integration of *f*(*L*) against d*L* can be written as: $\Delta WV = \int f(L)\mathrm{d}L = aL^3/3 + bL^2/2 + cL + d$, where d can be solved as 0 given the condition (ΔWV = 0 when *L* = 0). The resulting equation can be used to convert the time-series of (ΔWL) to (ΔWV) for the analysis of volume variations in lakes or reservoirs.

4.1.2. Heron Method

Pyramidal frustum volume was derived 2000 years ago by Heron (Greek mathematician, native of Alexandria, 10-70 AD) as in Equation (3):

$$V = \left((L1 - L2)/3\right) * \left(A1 + A2 + \left(\sqrt{A1 * A2}\right)\right) \tag{3}$$

Two water levels: $L1$ and $L2$ with corresponding surface areas $A1$ and $A2$ are using in this relation and limnologists are still using Formula (3) to compute the volume of lakes.

5. Results and Discussions

Comparison between measured water level time-series and those of radar altimetry must be first evaluated to ensure the accuracy of radar altimetry water levels data (for the period 2014 to 2015), to be based for water volume variation estimation. The resulted correlation coefficient R^2 = 0.98 and RMSE = 28 cm (Figure 8).

The next two figures demonstrate the relations between: surface areas (in km^2) deduced from optical satellite images and 1-radar altimetry and 2-measured water levels. R^2 for the first relation was 0.96, and for the second was 0.99. These excellent correlation values give a confidence of the deduced surface areas from the satellite images (Figure 9 and Figure 10).

The relationship between resulted (ΔWL) which was deduced from altimetry data and corresponding surface area (Area-ΔWL) was established using regression analysis for the study period (from 8/2014 till 6/2015).This relation was
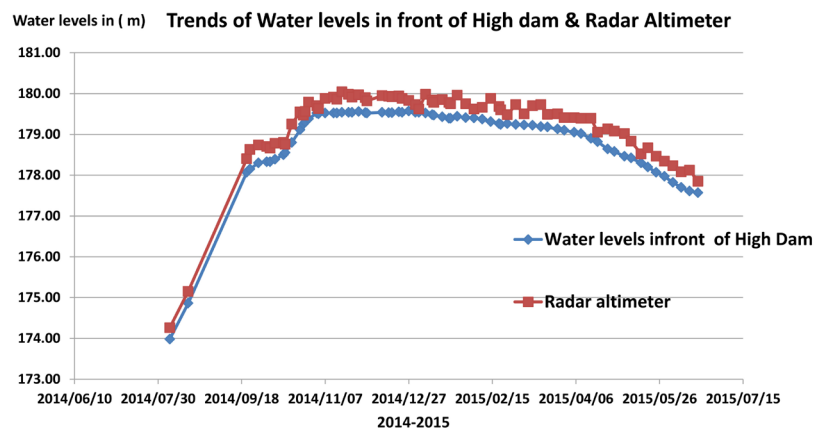

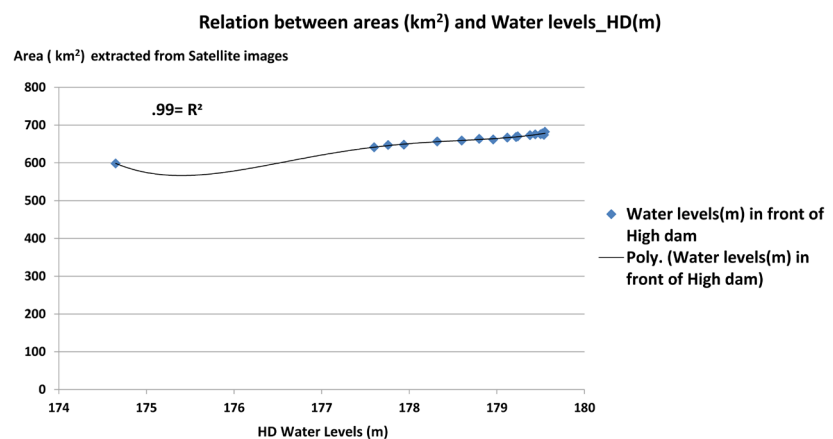**Figure 8.** Comparison between measured water levels and satellite altimetry water levels.

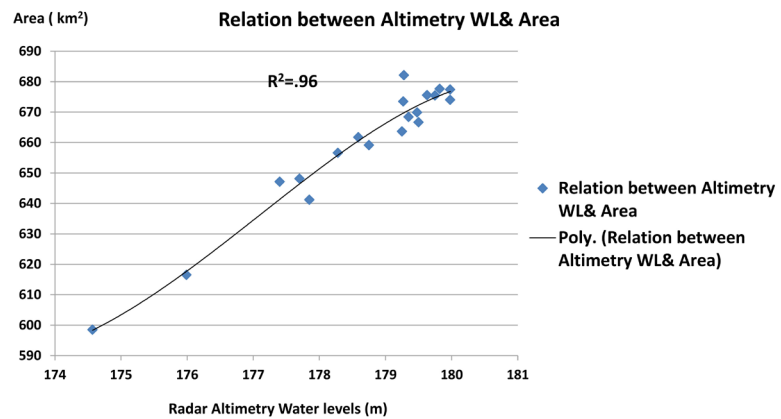**Figure 9.** Relation between surface areas and *in-situ* water levels.

Figure 10. Relation between surface area and satellite altimetry water levels.

described as a fourth-polynomial function (Equation (4)) with $R^2 = 0.979$ (**Figure 11**).

$$\text{Area} = 0.223(\Delta\text{WL})^4 - 2.644(\Delta\text{WL})^3 + 9.693(\Delta\text{WL})^2 + 4.236(\Delta\text{WL}) + 598.4 \quad (4)$$

Determination of volume variation (using integration model) relative to minimum altimetry water level (as reference) can be deduced by Integration of $f(L)$ against $\mathrm{d}l$, and can be developed as follows:

$$\Delta\text{WV} = \int \text{Area}\,\mathrm{d}l = \int F(\Delta\text{WL})\,\mathrm{d}l$$
$$= \int 0.223(\Delta\text{WL})^4 - 2.644(\Delta\text{WL})^3 + 9.693/2(\Delta\text{WL})^2 + 4.236(\Delta\text{WL}) + 598.4 \quad (5)$$

$$\Delta\text{WV} = 223/5(\Delta\text{WL})^5 - 2.644/4(\Delta\text{WL})^4 + 9.693/3(\Delta\text{WL})^3$$
$$+ 4.236/2(\Delta\text{WL})^2 + 598.4(\Delta\text{WL}) + \text{constant} \quad (6)$$
$$(\text{constant} = 0 \text{ at } \Delta\text{WV} = 0 \text{ at reference level})$$

Estimated ΔWV in million cubic meters (MCM) was calculated by substituting the corresponding ΔWL in Equation (6). The ideal way to verify the estimated water volume variations would be a test on a lake, were there is both long-term satellite coverage and simultaneous measured ground truth obtained by sonar bathymetry and gauges water level. Unfortunately the available ground truth data concerning the water levels are limited to (2014-2015), in spite of the availability of a reasonable number of Landsat images matching the times of radar altimetry data. To validate the resulted estimated water volumes variations, the measured water volumes were converted to ΔWV measured as estimated water volumes variations. This conversion was carried out by subtracting the water volume value for the same date that the lowest altimetry water level occurred from all measured water volumes values. Other approach was applied to estimate water volumes variations (based on altimetry water levels and satellite surface areas) by using Heron method, which is described in Equation (3). The estimated ΔWV using Integration method, Heron method, and measured ΔWV values were demonstrated in **Table 1**. R^2 and RMSE were determined to validate the estimated ΔWV for the two methods.

Root mean square errors for estimated ΔWV using integration and Heron

Relation between (Variation above ref_altimetry water levels (174.57) and surface area)
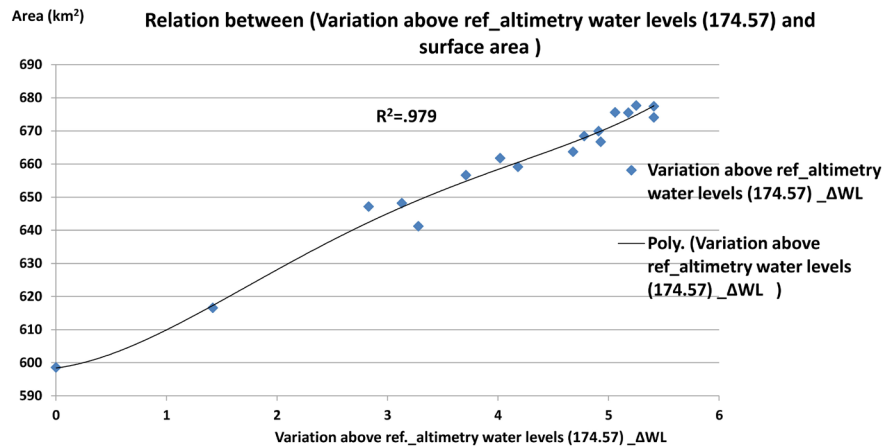

Figure 11. Relation between surface area & altimetry ΔWL.

Table 1. Estimated and measured ΔWV in MCM.

Estimated ΔV in MCM using integration model	Estimated ΔV in MCM using Heron method	Measured ΔV in MCM
0.0000	0.0000	0.0000
864.1219	884.1889	914.5171
1753.0406	1762.1512	1850.1118
1946.1168	1950.4932	1941.5877
2043.1615	2032.7182	1786.4655
2323.1938	2327.4096	2201.2364
2526.7296	2532.0249	2582.0204
2632.3074	2627.4616	2341.8795
2964.4716	2952.1895	2480.8515
3031.2980	3026.3750	2826.7853
3118.3619	3112.3298	2730.7379
3131.7751	3117.2149	2653.7375
3219.0814	3221.5179	2936.5240
3299.8543	3297.6047	2885.6361
3347.0512	3347.7846	2956.5289
3455.1449	3440.2604	2927.7132
3455.1449	3449.1731	2937.7575

methods were 323.98, and 318.09 MCM respectively and $R^2 = 0.98$ for both methods (**Figure 12** and **Figure 13**).

Another byproduct is proposed for this study; Once the $F(L)$ relationship is established for a given area, hence future Landsat images can be used to track water levels independently of radar altimetry.

It is important to mention that these results were consistent with those deduced by [21] for Lake Tana in Ethiopia ($R^2 = 0.99$) for both relations: between water levels and areas deduced from Landsat satellite images; and those between
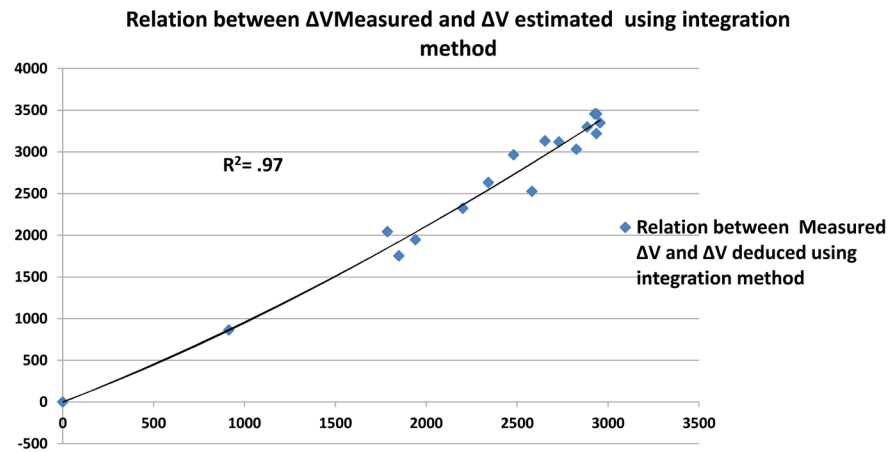
Relation between ΔVMeasured and ΔV estimated using integration method

Figure 12. Relation between estimated ΔWV using integration method and measured ΔWV.

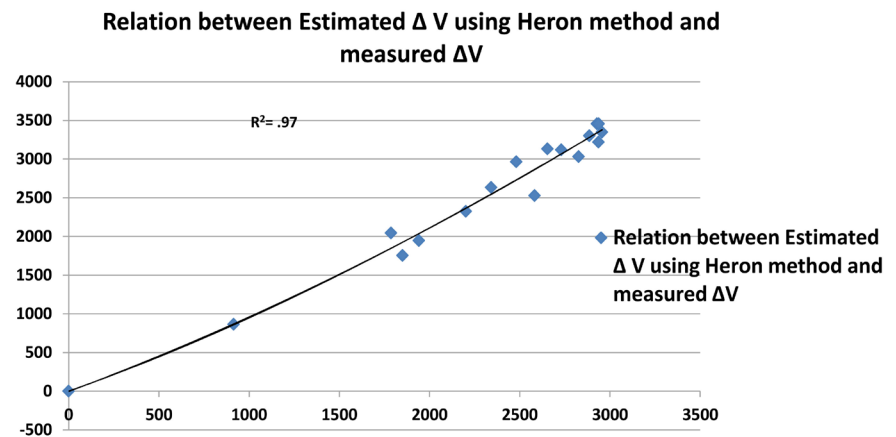**Relation between Estimated Δ V using Heron method and measured ΔV**

Figure 13. Relation between estimated ΔWV using Heron method & measured ΔWV.

water level and water volumes. Also the validation of the study which carried out by [19] for Lake Mead (U.S.A.), Lake Tana (Ethiopia), and Lake IJssel (The Netherlands) showed that the estimated water volumes agreed well with *in-situ* measurements (R^2 ranged from 0.95 to 0.99) and the root mean square error (RMSE) was within 4.6% to 13.1% of the mean volumes of *in-situ* measurements, which is consistent with the evaluation results of Lake Nasser study.

Other issues need to be illustrated: 1) The (ΔWV - ΔWL) relationship is site-specific and radar altimetry database-specific, and can be used, also to convert water levels from the altimetry databases directly into water volumes above the identified minimum reference level for lake Nasser; 2) From Table 1, the calculated volume variations using Integration method were approximately equal those calculated using Heron method, and this is considered as important indicator of high confidence in using the polynomial integration method; 3) The accuracy of water volume variations are affected by the relation between water levels and corresponding surface areas, as when water levels increase, the surface area deduced from satellite images specially at Khors regions will increase more than the middle stream of the

lake which may cause unreal water volumes variations at the lake boundary, hence high water levels may cause errors in calculations of volume variation by applying the polynomial relation between water levels and surface areas as it is clear from Table 1, when water levels increase the difference between *in situ* volume variations and those estimated from integration, Heron methods increase; 4) In this work, the measured water levels were limited to short duration time (2014-2015) so the integration model may changes for long duration and this must be investigated; 5) The surface areas which deduced from satellite images gain some errors due to: atmospheric effects, low spatial resolutions, and the conflict between dates of altimetry data sets and satellite images acquisition dates, and these errors can affect the deduced volume variations accuracy. In general, the integration model needs to be further studied to be more generalized due to site specific and time. Also the future work should focus on improving the model performance.

6. Conclusions

Estimating water volume variations relative to reference water level for the southern part of Lake Nasser in Egypt were determined and evaluated using available free Landsat and radar altimeter datasets, instead of using *in-situ* water gauge and bathymetry maps. Two approaches were examined for water volume variation estimation: The first method based on Areas-ΔWL relationship model (ΔWL is the difference between radar altimetry water levels and the lowest water level during the study time). Areas-ΔWL relationship model was established as a polynomial function: Area = f(ΔWL), hence, the relationship of the water volume variations above the lowest water level for the study time, *i.e.* (ΔV - ΔWL) was obtained through the analytical integration of Areas-ΔWL relationship model. The second method was performed by applying Heron equation:

$$\Delta V = \left((L1 - L2)/3 \right) * \left(A1 + A2 + \left(\sqrt{A1 * A2} \right) \right)$$

Validation of these two approaches showed that: Integration model and Heron agreed well with *in-situ* measurements of volume variation deduced from recent bathymetry map and *in-situ* water levels (R^2 for both methods = 0.98) and RMSE for integration method = 323.89 MCM, while for Heron method, RMSE = 318.09 MCM, and these RMSE values were approximately = 13.2% of the mean volume variation above lowest reference water level for the study period, for mean surface area ≈ 658 km². The initial results for this specific geographic area of Lake Nasser showed promising approaches for monitoring Lake Nasser water volume variation. Further tests are needed to firmly prove these techniques in order to generalize the relationship model of the water volume variations above the lowest water level (ΔV - ΔWL) to be valid for all geographic areas of Lake Nasser, and to enhance the accuracy. In addition, further improvements are expected when additional data from current and future satellite missions are integrated.

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