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Estimation of Reservoir Discharges from Lake Nasser and Roseires Reservoir in the Nile Basin Using Satellite Altimetry and Imagery Data

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Abstract: This paper presents the feasibility of estimating discharges from Roseires Reservoir (Sudan) for the period from 2002 to 2010 and Aswan High Dam/Lake Nasser (Egypt) for the periods 1999–2002 and 2005–2009 using satellite altimetry and imagery with limited *in situ* data. Discharges were computed using the water balance of the reservoirs. Rainfall and evaporation data were obtained from public domain data sources. *In situ* measurements of inflow and outflow (for validation) were obtained, as well. The other water balance components, such as the water level and surface area, for derivation of the change of storage volume were derived from satellite measurements. Water levels were obtained from Hydroweb for Roseires Reservoir and Hydroweb and Global Reservoir and Lake Monitor (GRLM) for Lake Nasser. Water surface areas were derived from Landsat TM/ETM+ images using the Normalized Difference Water Index (NDWI). The water volume variations were estimated by integrating the area-level relationship of each reservoir. For Roseires Reservoir, the water levels from Hydroweb agreed well with *in situ* water levels (RMSE = 0.92 m; R^2 = 0.96). Good agreement with *in situ* measurements were also obtained for estimated water volume (RMSE = 23%; R^2 = 0.94) and computed discharge (RMSE = 18%; R^2 = 0.98). The accuracy of the computed discharge was considered acceptable for typical reservoir operation applications. For Lake Nasser,

the altimetry water levels also agreed well with *in situ* levels, both for Hydroweb (RMSE = 0.72 m; R^2 = 0.81) and GRLM (RMSE = 0.62 m; R^2 = 0.96) data. Similar agreements were also observed for the estimated water volumes (RMSE = 10%–15%). However, the estimated discharge from satellite data agreed poorly with observed discharge, Hydroweb (RMSE = 70%; R^2 = 0.09) and GRLM (RMSE = 139%; R^2 = 0.36). The error could be attributed to the high sensitivity of discharge to errors in storage volume because of the immense reservoir compared to inflow/outflow series. It may also be related to unaccounted spills into the Toshka Depression, overestimation of water inflow and errors in open water evaporation. Therefore, altimetry water levels and satellite imagery data can be used as a source of information for monitoring the operation of Roseires Reservoir with a fairly low uncertainty, while the errors of Lake Nasser are too large to allow for the monitoring of its operation.

Keywords: satellite altimetry; Landsat; reservoir discharge; Lake Nasser; Roseires Reservoir; Nile Basin

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1. Introduction

Hydrological data are key information for water resources management. However, such data are frequently not readily available, particularly in transboundary river basins, either because of not being measured or limited accessibility to the data by the riparian states. Information of river flow, reservoir storage and water use in a given riparian country is obviously of high importance for the whole basin. Such data is often not fully shared, particularly in water-scarce basins, e.g., the Nile, Indus, Tigris and Euphrates river basins [1]. The decline of hydrological networks in the world, particularly in developing countries, adds to the challenges of having accurate and representative hydrological data in river basins [2].

The Nile Basin covers an area of 3.3 million km^2, is 6500 km long and is shared by 11 countries (Figure 1a). From south to north, the Nile traverses through varying climates, including the equatorial lakes, savannah, Sahara and, ultimately, the Mediterranean climate at its outlet. The basin is experiencing increasing water demands by the growing population, creating strong competition over the (fixed) water resource. Large dams have been constructed in the lower part of the basin (Egypt and Sudan), and new dams are planned or under construction in many locations, e.g., Bujagali Dam in Uganda, the Grand Ethiopia Renaissance Dam (GERD) in Ethiopia, and the Setit Dam in Sudan. Large dams change the water regime and availability not only locally, but at the basin scale, which then necessitates transboundary water management for optimal utilization of the resources. In fact, this has been the trigger for the formation of the Nile Basin Initiative (NBI), started in 1999, to support sustainable development and the equitable utilization of, and benefits from, the Nile water resources [3].

As at 2013, the riparian countries had not yet reached consensus on a data sharing protocol. The Comprehensive Framework Agreement (CFA) was signed by six out of the eleven Nile countries. The CFA intends to provide a legal and institutional framework for basin water resources management, including data sharing protocols [4]. The countries share only few hydrological data among themselves [5].

Figure 1. Locations of (**a**) Nile Basin; (**b**) Lake Nasser, Egypt; (**c**) Roseires Reservoir, Sudan and the gauging stations.
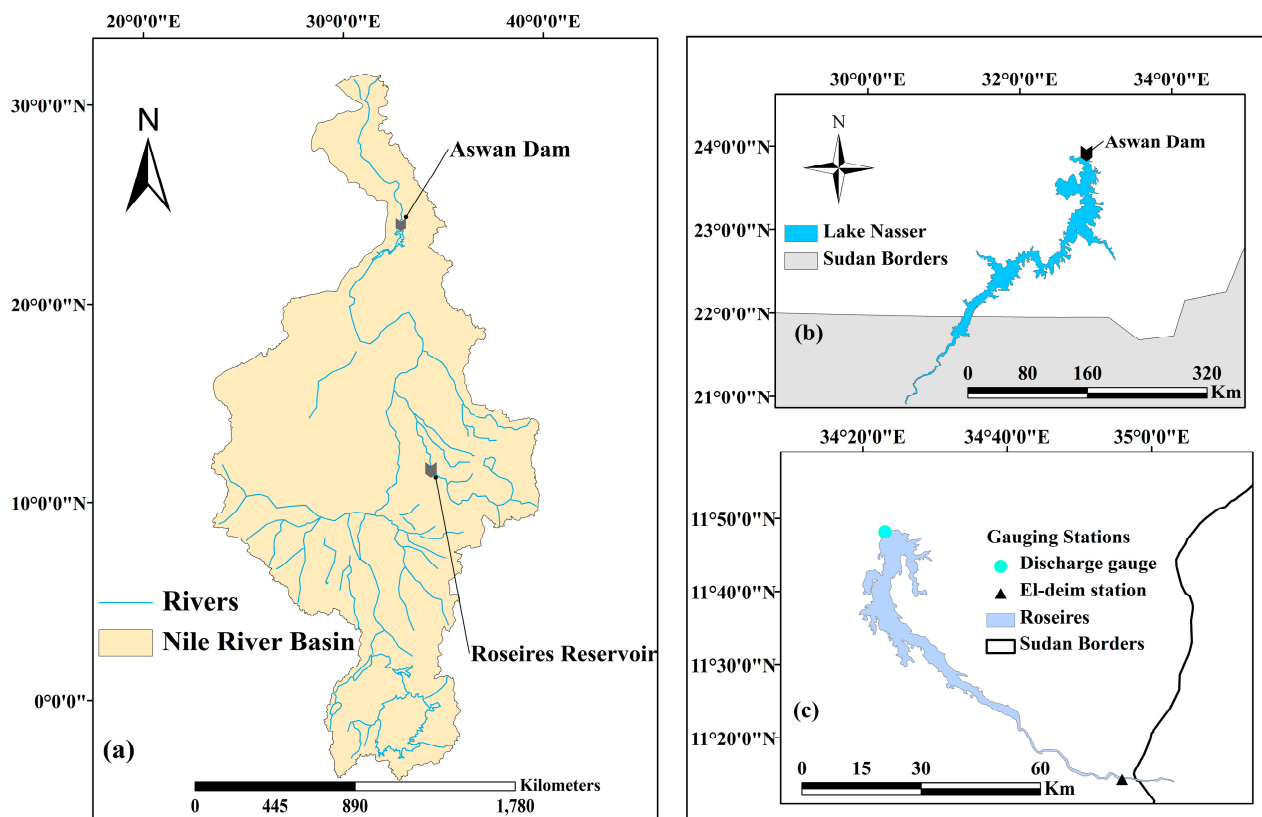
Satellite remote sensing is emerging as a potential technique to support hydrological monitoring and, hence, inform water resources management in river basins [1,6]. Satellite altimetry, a remote sensing technique, has been successfully used to derive water level data in lakes, reservoirs, rivers, floodplains and wetlands, providing data for more than 15 years [7].

The water level data derived from satellite altimetry have been combined with *in situ* measurements to estimate water storage in lakes and reservoirs, with successful applications in different parts of the world. The water volume variation of Lake Dongting in China was estimated using a relation developed between water level from satellite altimetry and *in situ* water storage [8]. Medina *et al.* [9] also estimated the volume variation of Lake Izabal in Guatemala from relations utilizing *in situ* measurements, satellite altimetry and imagery data. Duan and Bastiaanssen [10] proposed a method using only satellite altimetry and imagery data to estimate the volume variations of Lake Tana (Ethiopia) and Lake Mead (USA). This latter method can be used in the absence of *in situ* data. This method has been used in this study to estimate volume variation for Roseires Reservoir and Lake Nasser.

Altimetry data have also been used to estimate river discharges, e.g., for the Ob River [11], Chari/Ouham confluence near Lake Chad Basin [12], Amazon [13] and Ganga-Brahmaputra rivers [14]. In these studies, the river discharges were derived from rating curves developed from altimetry water levels and *in situ* discharge measurements. In the absence of *in situ* measurements, Leon *et al.* [15] utilized altimeter water level in a flow routing model (Muskingum–Cunge) to estimate the discharge of the upper Negro River in the Amazon basin (Brazil). The literature shows that discharge of rivers can

be derived from rating curves. However, for lakes, the water level-discharge relationship does not significantly exist or, even if it exists, it may not be available for sharing. Swenson and Wahr [16] estimated the various components of Lake Victoria in East Africa using water balance. The lake's level/storage, evaporation and precipitation were derived from satellite (e.g., altimetry, TRMM and GRACE) and the water inflow from models. The study presented here also uses the water balance, but uses satellite imagery and altimetry, public data on rainfall and evaporation and limited *in situ* data to estimate the discharge of a lake/reservoir. Therefore, this research seeks to add to the methods of estimating lake/reservoir discharges.

In summary, the literature shows many applications of using satellite altimetry and imagery data in combination with *in situ* measurements to derive hydrological information for water resources management. The degree of success is case specific, depending on the frequency and quality of satellite data in relation to the size and shape of the given water body.

This study aims at testing satellite data (altimetry and imagery) combined with limited *in situ* measurements for the operation of two large reservoirs in the Nile Basin: Roseires Reservoir and Aswan High Dam/Lake Nasser (Figure 1). The key question was: How accurate can satellite altimetry and imagery data estimate changes in storage volume and, combined with *in situ* measurements of reservoir inflow, reservoir discharges?

The paper is organized as follows: Section 2 gives a brief description of the two study sites. Section 3 presents all of the data used and their processing for the two reservoirs (altimetry, imagery and *in situ* measurements). The methods used for water balance and data validation are discussed in Section 4, and Section 5 presents the results and discussion. Finally, key conclusions and lessons learned are reported in Section 6.

2. Description of the Study Areas

Roseires Reservoir (Sudan) and Lake Nasser (Egypt) serve crucial functions to the population of both countries (Figure 1). They have been selected for this study because: (i) altimetry data have not been used yet to derive reservoir discharge; (ii) they are located in a transboundary river basin (Nile), where data exchange among riparian countries is limited, even though Sudan and Egypt have an agreement on data sharing (1959 agreement); and (iii) altimetry and satellite imagery data, as well as *in situ* data on inflows and outflows (for validation) were available for both sites.

2.1. Roseires Reservoir

Roseires Reservoir is located on the Blue Nile at Damazin, 550 km southeast of Sudan's capital, Khartoum, and 110 km from the Ethiopia-Sudan border (Figure 1c). The reservoir is located at the southeastern part of Sudan, whose topography is made up of steppes and low mountains. The altitude ranges from about 350 m at Khartoum to 490 m above mean sea level (AMSL) at the Ethiopian-Sudan border. The reservoir was constructed in 1966 for irrigation (Gezira Scheme) and hydropower generation (280 MW). The physical characteristics of Roseires Reservoir are presented in Table 1. The reservoir capacity has decreased by 40% due to sedimentation [17]. However, in January 2013, works were completed that heightened the dam wall by 10 m, increasing the reservoir's storage capacity to 7.4 billion m^3 [18].

Table 1. Characteristics of the two reservoirs studied: Roseires Reservoir and Lake Nasser.

Characteristics	Roseires Reservoir (Sudan)	Lake Nasser (Egypt)
Max length (km)	80	500
Max width (km)	9	12
Maximum depth (m)	68	110
Mean depth (m)	50	70
Reservoir area (km^2)	290	6000
Water volume (km^3)	3	162
Average annual inflow (km^3/y)	49	70
Average residence time (y)	0.06	2.30
Major water uses	Irrigation, hydropower	Irrigation, hydropower

The temperature within the environs of the reservoir ranges from 27 to 46 °C. Rainfall normally occurs between June and October, with an annual average of 0.7 m/y (Damazin station). The annual average water inflow at El-deim is 49 km^3/y.

The operation of Roseires Reservoir distinguishes four stages. During the first stage (rising flood) from July to August, the reservoir level is drawn to a minimum level of 470 m (AMSL). In the second stage, between 1 and 26 September, the reservoir is filled, depending on the water inflow from El-deim. During the third state, the full retention level is maintained, while the fourth stage marks the start of the emptying of the reservoir [17]. Now that the dam wall has been heightened, filling is expected to start earlier each year.

2.2. Lake Nasser

Lake Nasser is one of the greatest man-made lakes in the world, formed after the creation of the Aswan High Dam (AHD) in 1971 on the Nile River (Figure 1b). The lake is located in a desert region. The Arabian/Eastern Desert is located east of the Nile, while the low-lying sand dunes and depressions are found in the Western Desert. The dam was built to provide hydropower (2100 MW) and a steady water supply for irrigation in Egypt (55.5 km^3/y). The lake has a length of about 500 km, 330 km in Egypt and 170 km in Sudan. Table 1 gives further characteristics of Lake Nasser.

The lake is vital to Egypt, as it stores and regulates Nile water, being the main source of freshwater for about 85% of its population. The lake is located in a very hot, dry climate with an annual evaporation ranging from 2.1 to 2.6 m/y [19]. The annual rainfall over the lake is negligible [20].

The operation rules of Nasser reservoir aim at ensuring adequate water supply and the safety of the Aswan High Dam. At the beginning of the water year (1 August), the water level is kept at 175 m AMSL to fulfil high and low flow requirement. When the water level upstream reaches an elevation between 178 m and 183 m, excess water is directed to the Toshka Depression and, if necessary, by means of the emergency spillways on the western bank of the Nile [21]. The maximum retention at 180 m AMSL is obtained in November and, subsequently, the reservoir levels decrease from January to July as water is released.

3. Input Datasets

3.1. In Situ *Data for Roseires Reservoir*

In situ daily water levels (h), water inflows (Q_{in}), outflows (Q_{out}) and volumes (V) for Roseires Reservoir for the period 2002–2010 were obtained from the Ministry of Water Resources, Sudan. The *in situ* water level is referenced to Alexandria Datum (*i.e.*, above mean sea level). The level is taken from graduations on the dam wall. The inflow data is measured at El-deim station close to the Sudan-Ethiopia border. The (observed) outflow from the reservoir is monitored from a short distance downstream of the dam. The bathymetry survey of 2005 with reservoir levels and water volumes were used to derive the volume-level relationship, as given by Equation (1). Note that Equations (1) and (2) below (Section 5.2) have very sensitive decimal places and must be used as such. The bathymetric table shows that the minimum level is 467.00 m, with a corresponding volume of 13.70 m^3 million, while the maximum level was 481.00 m, with a volume of 1934.73 m^3 million. The data nicely spread between the minimum and maximum level every 1.00 m. The equation gave an excellent fit ($R^2 = 0.9995$).

$$V = 0.16565h^3 - 223.30002h^2 + 100,166.89815h - 14,949,451.43946 \tag{1}$$

where:
V = Storage volume in Mm^3,
h = observed reservoir level in m AMSL.

3.2. In Situ Data for Lake Nasser

Ten-day mean measurements for *in situ* water levels (h), water inflows (Q_{in}) and outflows (Q_{out}) for the periods 1999–2002 and 2005–2009 and daily *in situ* water levels and volumes for the period 2007–2009 were obtained from the Ministry of Water Resources and Irrigation (MoWR), Egypt. *In situ* data were not received for the period 2003–2004. The *in situ* data are with respect to Alexandria Datum (*i.e.*, AMSL). To allow for daily interpolation, the 10-day mean measurements were assumed to occur on Days 5, 15 and 25 of each month, and linear interpolation was performed for the intermediate days. This interpolation may introduce some uncertainty in the validation results, but this is expected to be small. The water inflow is recorded at Dongola station in Sudan and is computed by a rating curve equation.

The daily *in situ* water levels and volumes for the period 2007–2009 were used to derive the volume-level relationship for the lake. The relation was further used to convert *in situ* water levels to *in situ* volumes for the whole period of 1992–2002 and 2005–2009. The converted *in situ* volumes were used to validate the volumes from satellite measurements. The derived relation is given in Equation (2). This is based on 731 data points, with a minimum level of 173.30 m (volume: 112,600 million m^3) and maximum level of 180.11 m (volume: 150,193 million m^3). The data gave an excellent fit ($R^2 = 1.0$)

$$V = 5.56806h^3 - 2,858.00945h^2 + 493,925.51557h + 28,630,490.83329 \tag{2}$$

3.3. Altimetry Water Level Datasets

Altimetry water levels from the Hydroweb and Global Reservoir and Lake Monitoring (GRLM) databases were used in this study. These databases were chosen because of the temporal resolution, level of processing and data availability for the two study areas. Readers are referred to Duan and Bastiaanssen [10] for a discussion of all four satellite altimetry water level databases for lakes and reservoirs.

Hydroweb is prepared by LEGOS/GOHS (Laboratoire d'Études en Géophysique et Océanographie Spatiale/Equipe Geodesie, Oceanograhie et Hydrologie Spatiale) in Toulouse, France. The altimetry data were derived from Topex/Poseidon, ERS-1 and 2, Envisat, Jason-1 and GFO satellites. The data are average monthly water level time series [22]. The reference of the water level is the GRACE Gravity Model 02 (GGM02) geoid. The procedure for water level processing in Hydroweb is described in detail by Cretaux *et al.* [23].

The Global Reservoir and Lake Monitor data (GRLM) are prepared by the United States Department of Agriculture's Foreign Agricultural Service (USDA-FAS) in collaboration with NASA and the University of Maryland. The database uses data from Topex/Poseidon (T/P), Jason-1, Jason-2 and Envisat, and the data are at time interval of 10-days [24]. The reference of water levels from GRLM is with respect to the mean 9-year T/P water level. Therefore, they are expressed in relative water levels. The procedure for water level processing in GRLM can be found in [25]. The water levels of Lake Nasser are available in both databases, while water levels of Roseires can be found only in Hydroweb.

3.4. Landsat TM/ETM+ Imagery Data

Landsat TM/ETM+ imagery data were used to extract the water surface areas of the two reservoirs: Roseires and Lake Nasser. TM/ETM+ imagery data were chosen because of their long-term data availability (since 1984), free access and high spatial resolution (30 m). One scene of a Landsat image can entirely cover Roseires Reservoir, while three scenes are needed to completely cover Lake Nasser. The acquisition dates of images for the two reservoirs are given in Section 5. The data were downloaded freely [26].

Two problems were encountered when using Landsat images: cloud cover and domain, and were worked around as discussed in this section. Landsat images with dates coinciding with that of altimetry water level measurements were chosen to extract the reservoir's water extent. The selection of coinciding dates was not always possible, because of high cloud cover and different revisit periods of the Landsat and altimeter satellites. In such cases, the closest dates were selected since the climate variations in some month(s) would not change much. In Hydroweb, water levels in a close or the same month and year with images were chosen, while in the GRLM database, specific days were chosen. Some of these dates had a big difference (*i.e.,* 10 to 60 days) with respect to the date of altimetry water levels . Undoubtedly, this introduces an error in the estimation of the reservoir area. In the acquisition of the images of Roseires, it was observed that the boundary of Roseires Reservoir overlapped with the edge of some image scenes, reducing the availability of one complete scene. This situation also limited the acquisition of close or coinciding dates to derive the area-level relationship. The merging of three

Landsat images to cover Lake Nasser with different acquisition dates also introduces errors in the delineation of the lake area.

The Landsat-7 satellite has had a problem with its Scan Line Corrector (SLC) since 31 May 2003, resulting in SLC-off ETM+. This failure has led to about a 22% data loss due to the increased scan gap [27]. Therefore, gap filling was done for images after May 2003, using Local Linear Histogram Matching (LLHM). The LLHM uses a Landsat TM or ETM+ SLC-on image to fill the SLC-off image [28]. The images chosen for the gap filling were cloud-free images and had comparable seasonal conditions. The Landsat-7 image gap filling was done for both Roseires Reservoir and Lake Nasser, since some of the acquisition dates were after May 2003.

3.5. Rainfall and Evaporation

Long-term mean values of monthly rainfall data for Roseires Reservoir and Lake Nasser were obtained from the International Water Management Institute (IWMI) On-line Climate Summary Service Model [29]. Generally, the IWMI On-line Service Model data is based on data obtained from weather stations around the world for the period 1961–1990. Using mean values of rainfall and evaporation is expected to generate negligible error in the water balance of the two reservoirs. Rainfall volume on Roseires Reservoir is very small, because the reservoir area is at a minimum during the rainy season, while on Lake Nasser, the rainfall rate is negligible. Open water evaporations from the two reservoirs were calculated using the Penman [30] formula. All parameters in the Penman formula, *i.e.*, temperature, relative humidity, wind speed and relative sunshine duration, were obtained from long-term mean monthly values of the IWMI online climate summary service model. This is expected to cause a small error in evaporation volume, which is at least much smaller than the uncertainty of the reservoir area.

4. Methods

4.1. Altimetry Water Level Measurements

As given in Section 3.2, altimetry water levels for the two reservoirs were acquired from two databases (Hydroweb and GRLM). The mean difference (constant shift) between the *in situ* and altimetry water levels was computed and then simply added to altimetry water levels [10,31]. This ensures the attainment of a common datum, which allows the comparison of the two data series. For validation, the commonly used indicators, *i.e.*, the coefficient of determination (R^2) and the root mean square error (RMSE), were computed.

Alternatively, Global Navigation Satellite System (GNSS) data provide a datum shift for altimetry data for certain specific locations. However, there were no network stations of GNSS for our studies of the two reservoirs, and therefore, these were not used [32].

4.2. Delineation of Reservoir Surface Area

The extents (surface areas) of the two reservoirs were delineated from Landsat satellite images using the Normalized Difference Water Index (*NDWI*) [33] as given by Equation (3):

$$NDWI = \frac{(GREEN - NIR)}{(GREEN + NIR)} \tag{3}$$

where *GREEN* and *NIR* are the green and near-infrared red bands, respectively. The water features have positive values due to their higher reflectance of the green band compared to the *NIR* band, while vegetation and soil features have zero or negative values because of their higher reflectance of the *NIR* band compared to the green band. The Modified Noramlized Difference Water Index (MNDWI), which replaces the *NIR* band in Equation (3) with the mid-infrared red (MIR) band, has been reported to perform better than *NDWI* [34]. However, we found that the MIR band (Band 5) for both study areas had poor qualities; the boundaries of the image scenes shift when the MNDWI is applied. Therefore, *NDWI* was used to delineate the reservoir areas in this study. Band 2 of Landsat TM/ETM+ (green), and Band 4 (*NIR*) were used in Equation (3). With the aid of visual inspection and *NDWI* ranging from 0.01 to 1, water bodies of both study areas were extracted. The range was based on the general observation of detecting water bodies within a trial and error range from 0 to a positive value. The reservoir surface area was then calculated as the sum of the areas of the pixels identified as water bodies.

4.3. Storage Volume Estimation

A surface area-water level relation (based on satellite measurements) was integrated to obtain volume-level relations for each reservoir. First, the lowest water level (h_{min}) of the altimetry time series data was identified. The lowest water level was then subtracted from all water levels (h) obtained from each satellite altimetry data (*i.e.*, $h - h_{min}$). The ($h - h_{min}$) can also be known as the water depth d above h_{min} [10]. It is assumed that the storage volume is zero at h_{min}, *i.e.*, when $d = 0$, $V = 0$, but $A \neq 0$, where A is surface area of the reservoir/lake. However, in reality, there is a storage volume in the reservoir at d, at least equal or larger than the dead storage. This is to allow water volume computations independent of the dead storage. For comparison, the *in situ* volumes have also been converted to volumes above the lowest water level (h_{min}). The conversion was done by subtracting the *in situ* volume for the same date that the lowest water level occurred in the satellite altimetry products.

Therefore, time series of two variables (surface area and water level) were prepared. The surface area (A) of a reservoir/lake delineated from the TM/ETM+ images for a given date is associated with altimetry water level measurements (h), converted to ($h - h_{min}$) of the same (or closest) date. A second-polynomial function ($A = f(d) = ad^2 + bd + c$) was obtained by correlating the surface area (A) in Mm^2 and water depth (d) in m, a, b, c being constants determined by regression analysis. The A-d relation was then integrated to obtain the volume-level relation ($V = f(d) = ad^3/3 + bd^2/2 + cd + e$); where V is the water volume above h_{min}. The A-d relation was integrated with the condition that the water volume (V) is equal to zero when water depth (d) is zero. The constants a, b, and c are the same values as in the A-d relation, and e is solved as zero (0) given the condition $V = 0$ when $d = 0$.

4.4. Water Balance of Reservoirs

The discharge from a reservoir/lake has been computed from the water balance equation of Equation (4), assuming negligible groundwater interactions:

$$Q_{in} + A\ (P - E) - dS/dt = Q_{out} \tag{4}$$

where:

Q_{in} = inflow in Mm³/day

Q_{out} = reservoir discharge in Mm³/day

P and *E* = precipitation and open water evaporation in m/day, respectively

dS/dt = change in storage volume with time in Mm³/day

A = the reservoir's water surface area in Mm² (=km²).

The inflow, Q_{in}, was obtained from *in situ* measurements. The reservoir discharge, Q_{out}, was computed based on altimetry water level measurements, Area-level and volume-level relations (*i.e.*, dS/dt) were derived from Landsat and altimetry data. Q_{out} is computed on decadal time steps (10-day) for GRLM and monthly for Hydroweb. The computed discharges Q_{out} of Equation (4) were then validated against observed discharges. The objective here is to assess the accuracy of the discharge computed from a reservoir if it is based on satellite data of water levels and storage volume.

5. Results and Discussion

5.1. Results for Roseires Reservoir

5.1.1. Altimetry Water Level Measurements

The time-series of monthly water levels from Hydroweb and *in situ* measurements for Roseires Reservoir is shown in Figure 2. The Hydroweb water levels have been shifted vertically to the datum of the *in situ* measurements by adding a constant shift [31]. The shift of −1.54 m is the mean difference between the two data series for the period of nine years from 2002 to 2010 (Table 2). Figure 2 shows that water levels from Hydroweb agreed well with the *in situ* water level measurements (R^2 = 0.96), in particular for high reservoir levels. However, water levels from Hydroweb overestimate reservoir levels during the flood season (when water levels are kept low), as was the case in 2004 and 2005, but not during the 2006 flood. Note that usually, the reservoir is at the maximum level by the end/beginning of the year and at minimum level during the flood season, June, July and August. Because of the very high flow during the flood season of 2006, which exceeded the gate capacity of Roseires Dam, the reservoir level rose above minimum levels, the so-called compulsory storage [35]. The under estimation at high water levels and over estimation at low levels could be attributed to the adjustment from the constant shift.

Table 2. Statistics of altimetry-derived water levels for Roseires Reservoir and Lake Nasser.

Study Areas	Dataset	Period	No. *	Interval	R^2	RMSE (m)	Shift Constant (m)	Mean Shifted Water Level (m)
Roseires	Hydroweb	2002–2010	63	monthly	0.96	0.92	−1.54	479.75
Lake Nasser	Hydroweb	1999–2002 2005–2009	89	monthly	0.81	0.72	−0.12	176.89
	GRLM	1999–2002 2005–2009	215	10-day	0.94	0.62	179.43	177.12

* Refers to the number of data points used.

Figure 2. Time series of altimetry water levels from Hydroweb (blue), ranging from 473 m to 485 m, compared to *in situ* measurements (red), ranging from 470 m to 484 m, for Roseires Reservoir during the period 2002–2010. The water levels from Hydroweb have been shifted vertically by −1.54 m to correct for the datum. The error bars in blue represent the standard deviation of altimetry water levels from the Hydroweb database.
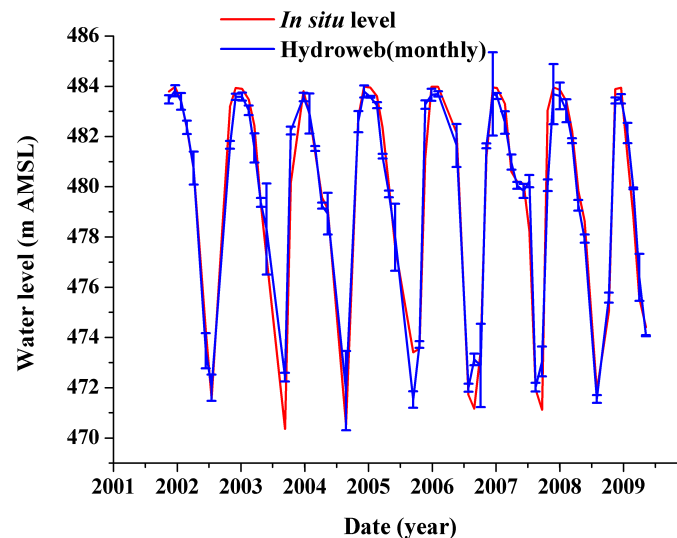
The RMSE of Hydroweb water levels against *in situ* water levels for Roseires was 0.92 m, which is about 7% of the seasonal variation (~14 m), and R^2 is 0.96, showing good agreement with *in situ* measurements. The literature reports a wide range of RMSE for different lakes and reservoirs worldwide. In general, the RMSE is small for large lakes, e.g., 3 to 7 cm for Lake Victoria, East Africa [31], but increases to several decimeters for smaller lakes, e.g., 26 cm for Lake Woods and 105 cm for Lake Powel [23]. The accuracy of altimetry water levels has been attributed to the size of the target water body, the surrounding topography and the roughness of the surface [23]. With larger rivers, RMSE ranges from 10 to 20 cm, e.g., Amazon River [36], and increases over narrower rivers and/or in the presence of vegetation [6]. The satellite laser altimetry, Ice, Cloud and Elevation Satellite (ICESat) derived water levels for Roseires Reservoir reveal an RMSE of 17 cm [37]. The improved accuracy of water levels from ICESat as compared to Hydroweb could be due to the smaller footprint of satellite laser altimeter (ICESat) than satellite radar altimeter (Hydroweb).

5.1.2. Reservoir Area and Volume

Nine pairs of coincident water levels from Hydroweb and Landsat TM/ETM+ imagery data were selected to determine surface area-level and further volume-level relations for Roseires (Table 3). Based on these nine pairs, the area-level relationship for Roseires was derived by regression analysis, as shown in Figure 3. The scatter could be attributed to two reasons: (i) different acquisition dates of altimetry data and satellite images, in particular during transition periods (filling or emptying of the reservoir); and (ii) the inherent uncertainties of both altimetry measurements (discussed in Section 5.1.1) and the area delineation from the *NDWI* images. However, a representative *A-d* relation could be derived ($R^2 = 0.87$). The volume-level relation was obtained by the integration of Equation (5).

The resulting function, as shown in Equation (6), was used to convert water levels from Hydroweb to calculated volumes for Roseires Reservoir.

$$A = 0.34d^2 - 5.04d + 147.30 \tag{5}$$

$$V = 0.11d^3 - 2.52d^2 + 147.30d \tag{6}$$

where:

A = area of reservoir derived from Landsat imagery (km^2).

d = water depth (m).

V = volume in Mm^3.

Table 3. Water depth with corresponding imagery data and delineated surface area for Roseires Reservoir.

| No.	Altimetry Water Levels			Landsat TM/ETM+ Images		
	Date	Original (m)	d (m) [a]	Date	Sensor	Area (km^2)
1	July 2009	473.09	0.02	14 September 2009	ETM+	148.10
2	August 2008	474.59	1.52	27 September 2008	ETM+	162.00
3	March 2010	477.93	4.87	9 March 2010	ETM+	167.90
4	April 2009	479.48	6.41	23 April 2009	ETM+	175.70
5	March 2009	480.80	7.74	22 March 2009	ETM+	211.90
6	February 2010	481.48	8.41	12 January 2010	TM	239.00
7	March 2008	482.52	9.45	4 April 2008	ETM+	217.30
8	January 2010	483.68	10.61	4 January 2010	ETM+	252.20
9	November 2007	485.24	12.17	28 November 2007	ETM+	246.60

"Original" is the original value obtained from Hydroweb. [a] The water depth referred to above is lowest altimetry water level, h_{min}.

Figure 3. The area (A) and water depth (d) relationship of Roseires Reservoir from paired altimetry water levels and the area derived from Landsat images.
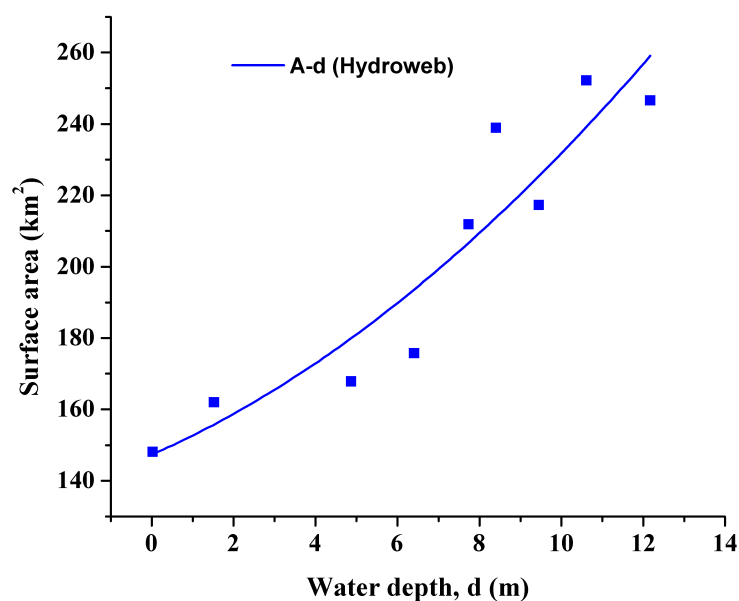
The monthly series of calculated from volume satellite data and calculated volume from *in situ* data for Roseires Reservoir from 2002 to 2010 are shown in Figure 4. The calculated volumes from satellite data were obtained by applying Equation (6) to altimetry water level data. The calculated volumes from satellite data were relative to the reference volume, which corresponds to the lowest water level (h_{min}) from Hydroweb. The calculated volumes from *in situ* data were derived by subtracting the *in situ* water volume that corresponds to the lowest altimetry water level from all *in situ* water volumes obtained from Equation (1). As can be seen from Figure 4, the operation pattern could be reproduced by satellite-derived data. The RMSE was 355 Mm^3 (*i.e.*, 23% of the mean volume of 1529 Mm^3), while R^2 was 0.94. The calculated volume based on satellite data consistently underestimated water volumes when the reservoir was at a maximum and overestimated at minimum levels. At low water levels, all of the calculated volumes (*in situ*) had negative values, except for August 2006, when the lowest water level occurred. August 2006, was used as the reference water level for the *in situ* water volume, since the date corresponds to the lowest water level (h_{min}) from Hydroweb. However, for other dates, even lower *in situ* water levels were measured. This reference water level value is thus greater than the other low water levels, hence the existence of negative volumes at low levels. These negative volumes do not affect our discharge estimation, since this is calculated from water volume differences between two time periods rather than the absolute values of water volumes for a specific time (see Section 5.1.3 on discharge estimation).

Figure 4. Monthly series of calculated volume (*in situ* data and satellite data) above the reference level for Roseires Reservoir between 2002 and 2010. The *in situ* volume (red) was derived from the *V-h* relationship obtained from a bathymetry survey of 2005, (Equation (1)), but relative to the reference volume. The satellite volume (blue) is derived from the *V-d* relationship using satellite measurements, *i.e.*, Landsat imagery and altimetry water level (Equation (6)).
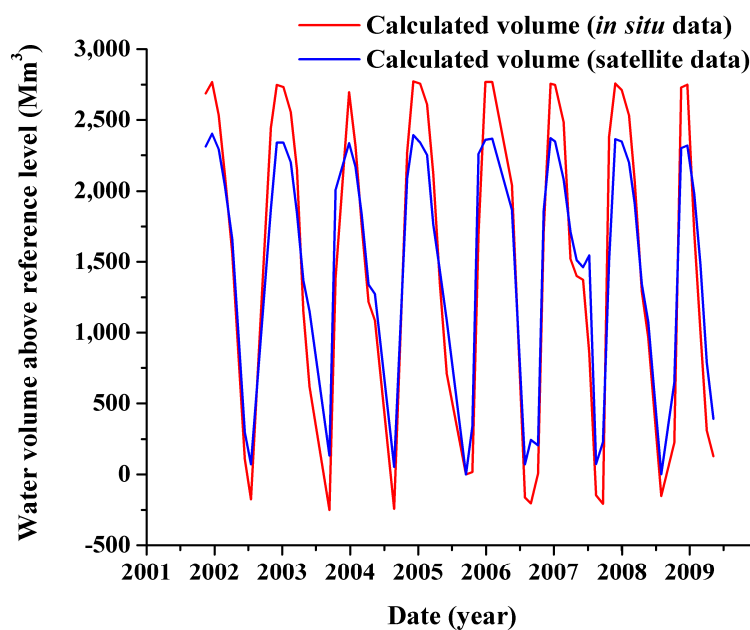
5.1.3. Reservoir Discharge

For validation, observed discharges from Roseires Reservoir based on a rating curve were compared with those computed by the water balance (wb) equation (Equation (4)). First, Q_{out} was computed using all *in situ* measurements (Q_{in}, *P*, *E*, *A*, *dS/dt*), labelled as *Q* (wb *in situ* data) in Figure 5. Here, *dS/dt* is based on *in situ* water level measurements, and the volume-level- relation is derived from bathymetric survey. Subsequently, Q_{out} was computed using satellite (sat.) data of *A* and *dS/dt* and *in situ* data of Q_{in}, *P*, *E*, labelled as *Q* (wb sat. data-Hydroweb). Here, *dS/dt* is based on altimetry water level measurements and the volume-level relation from satellite data with respect to the time step of the altimetry database (10-day or monthly). As shown, the three differently computed outflows are in excellent agreement with each other, e.g., *Q* (wb sat. data-Hydroweb) correlates well with *Q* (observed), $R^2 = 0.98$. The RMSE between the two datasets is 671 Mm^3/month, corresponding to 18% of the observed mean discharge. This can be considered an acceptable accuracy, given that the uncertainty of discharge measurement is between 5% and 10%, while errors up to 15% to 20% were reported for large rivers [14]. Discharge measurement errors of 4%–17% were reported for the Amazon River [13], and 17% for the Ob' river [11].

Figure 5. Roseires Reservoir discharges between 2002 and 2010. Red is *Q* (observed) based on rating curve; green is *Q* (wb *in situ* data) based on *in situ* data; blue is *Q* (wb sat. data-Hydroweb) based on satellite data.
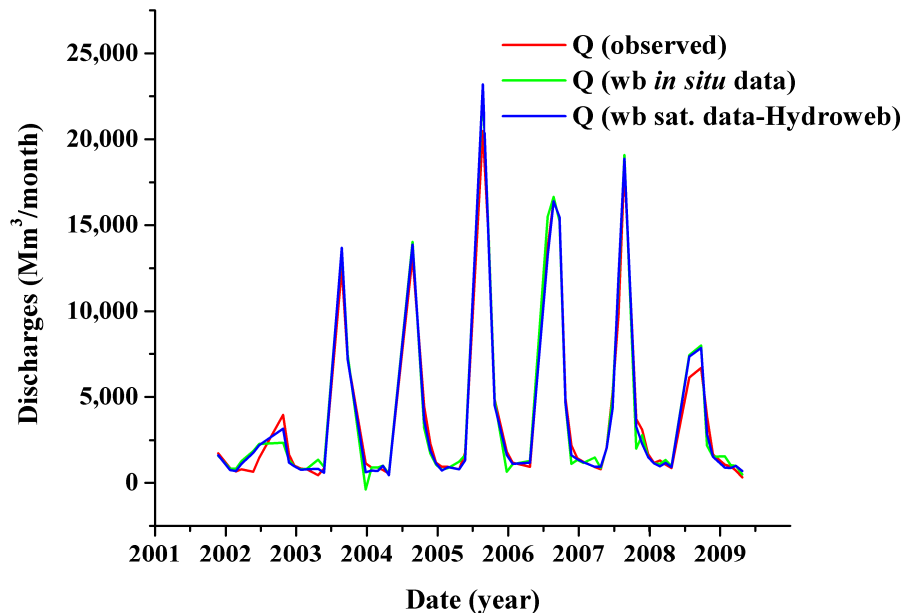

To understand the errors introduced by satellite *versus* other sources of errors, the two observed discharges were compared, *Q* (observed) from the rating curve and *Q* (wb *in situ* data). The mean difference between the two discharges resulted in 16%. This shows that the error of the discharge using satellite data relative to the discharge (all *in situ* data) can be in the order of 2%, assuming linear error propagation.

5.2. Results of Lake Nasser

5.2.1. Altimetry Water Level Measurements

The water level data for Lake Nasser from Hydroweb (monthly) and GRLM (10-day) covered the periods 1999 to 2002 and 2005 to 2009. To attain a common datum for comparison, the water levels of Hydroweb and GRLM were shifted vertically with −0.12 m and 179.43 m, respectively (Table 2). The shifted values varied largely in magnitude, because the Hydroweb products were absolute water levels, while the GRLM products were water level variations referenced to the mean nine-year T/P water level. Figure 6 shows the time-series of *in situ* measurements, Hydroweb and the GRLM. It compares the *in situ* levels and shifted altimetry water levels, and the gap is a result of the lack of *in situ* data from 2003 to 2005. In the absence of *in situ* data for this period, Section 5.2.2 shows the possibility of estimating water volume from Hydroweb water levels to cover this gap.

Figure 6. Time series of altimetry water levels from Hydroweb (blue) and GRLM (green) compared to *in situ* measurements (red) for Lake Nasser during the periods 1999–2002 and 2005–2009. The error bars in blue and green represent the standard deviation of water levels for Hydroweb and GRLM, respectively.
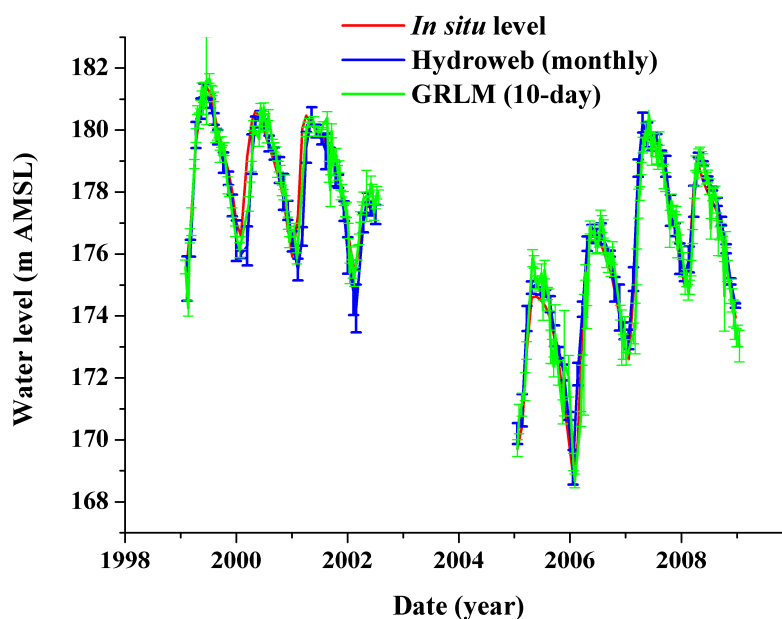
In Figure 6, both altimetry water levels are in good agreement in phase and amplitude, especially at high reservoir levels. It could be observed that the Lake Nasser levels showed a clear decline between 2002 and 2007. This could be attributed to the drought in East Africa affecting the major sources of the Nile River, *i.e.*, the White Nile from Lake Victoria and the Blue Nile from the Ethiopian Plateau [16]. The huge size of Lake Nasser reservoir (two-times annual flows) allows a long memory of response to inflow variability. Inflow was declining until 2005, but higher flows entered the lake from 2006 onward.

The RMSE of monthly data from Hydroweb against *in situ* water levels was 0.72 m, which is about 6% of the annual fluctuation (~13 m), while R^2 is 0.81 (Table 2). Similarly, the RMSE of altimetry data from GRLM against *in situ* water levels was 1.22 m, and R^2 is 0.82. In general, the raw GRLM data has outliers, which were identified by comparison with *in situ* data. The mean square errors

(MSE) between the two datasets exceeding 3 m were considered major outliers and were removed. Consequently, 20 outliers were taken out of the 235 data points of GRLM. The RMSE after the removal was 0.62 m, which is about 5% of the annual fluctuation, and the R^2 was 0.94 (Table 2). The lower accuracy for Lake Nasser compared to Roseires could be attributed to the narrow and long shape of the former, which allows only small areas to be covered in the footprint of satellite altimetry, leading to the altimetry product being contaminated by land [25]. Land contamination for inland water is normally removed through customized processing of altimetry data, which is beyond the scope of this current study. Details on the removal of land contaminations have been discussed by developers of GRLM [25] and Hydroweb [23]. Furthermore, the difference in the places where the *in situ* gauge and altimetry satellites measure water levels would add some uncertainty. The single point-based *in situ* gauge station cannot reflect the spatial variation of water levels. The satellite altimetry measures along the track, which has a certain distance from the *in situ* gauge station.

5.2.2. Reservoir Area and Volume

Table 4 presents the selection of Landsat images matched with altimetry water level dates and the derived surface areas for Lake Nasser. Six monthly water levels from Hydroweb and areas derived from Landsat Images were paired to estimate the *A-d* relationship. Similarly, eight GRLM water levels and areas were paired to determine the *A-d*. Due to the narrow and long shape of Lake Nasser, three scenes were merged to obtain one complete scene for the lake. Two of the image scenes have similar dates, and each scene has its specific water level and extent. The acquisition dates for two of the scenes, Path 175 Row 44 and Path 175 Row 45, are the same; hence only one column is maintained as for both in Table 4. To reduce the error of water extent (area) arising from scene merging, the maximum allowed reservoir water level difference between the selected images scenes was assumed to be 0.6 m. Landsat images spanning from 1999 to 2002 were mostly used for area estimation, as they were free of image gaps, *i.e.*, easier to process compared to the SLC gap-filling procedure. Few Landsat SLC-off images were used, since the gap filling of three SLC-off image scenes using SLC-on images for Lake Nasser was time consuming.

The Equations (7), (8), (9) and (10) represent the *A-d* and *V-d* relationships derived from Hydroweb and GRLM. Equation (7) and (9) were integrated to obtain Equation (8) and (10) respectively. The lowest water levels (as the reference for water volume estimation) for Hydroweb and GRLM were different; therefore, their derived equations are database specific. Equations (8) and (10) were used to convert the water levels to water volumes.

For Hydroweb, the *A-d* relation is given by Equation (7), represented by the blue curve in Figure 7. The R^2 was 0.96.

$$A = 2.49d^2 + 141.52d + 3824.11 \tag{7}$$

$$V = 0.83d^3 + 70.76d^2 + 3824.11d \tag{8}$$

For GRLM, the *A-d* relation with R^2 of 0.99 is given by Equation (9), represented by the red curve in Figure 7.

$$A = 5.43d^2 + 99.06d + 3836.13 \tag{9}$$

$$V = 1.81d^3 + 49.53d^2 + 3836.13d \tag{10}$$

Table 4. Water depth and the corresponding estimated surface areas for Lake Nasser.

Water Level Sources	No.	Altimetry Water Level			Landsat TM/ETM+ Images		
		Date	Original (m)	d (m) [a]	Path 174 Row 44	Path 175 Row 45	Area (km^2)
Hydroweb	1	July 2006	169.24	0.00	9 July 2006	16 July 2006	3846.08
	2	April 2006	172.94	3.70	20 April 2006	27 April 2006	4214.58
	3	July 2002	174.88	5.64	12 June 2002	21 July 2002	4881.45
	4	June 2002	176.07	6.84	12 June 2002	11 June 2002	5012.57
	5	August 1999	176.31	7.07	7 August 1999	6 August 1999	4919.08
	6	December 2002	177.40	8.16	December 2002	28 December 2002	5102.32
	7	March 2002	178.71	9.47	8 March 2002	15 March 2002	5476.42
	8	September 2000	179.35	10.11	10 September 2000	9 September 2000	5274.76
	9	November 1999	181.41	12.17	3 November 1999	10 November 1999	5998.30
GRLM	1	12 July 2006	−10.76	0.00	9 July 2006	16 July 2006	3846.08
	2	4 May 2006	−6.96	3.80	20 April 2006	27 April 2006	4214.58
	3	26 July 2002	−4.17	6.59	12 June 2002	21 July 2002	4881.45
	4	10 August 1999	−2.85	7.91	7 August 1999	6 August 1999	4919.08
	5	16 June 2002	−2.69	8.07	12 June 2002	11 June 2002	5012.57
	6	16 April 2001	−1.52	9.24	8 May 2001	13 April 2001	5177.57
	7	10 September 2000	−0.94	9.82	10 September 2000	9 September 2000	5274.76
	8	19 March 2002	−0.21	10.55	24 March 2002	15 March 2002	5476.42
	9	5 February 2001	0.11	10.87	5 March 2001	8 February 2001	5552.88
	10	17 November 1999	1.92	12.68	3 November 1999	10 November 1999	5998.30

"Original" is the original value obtained from the satellite altimetry products. [a] The water depth refers to above the lowest water level (h_{min}).

Figure 7. The area (A)-water depth (d) relationships for Lake Nasser were derived from altimetry water levels and surface area (Landsat) data of Table 4 for Hydroweb (blue) and GRLM (red).
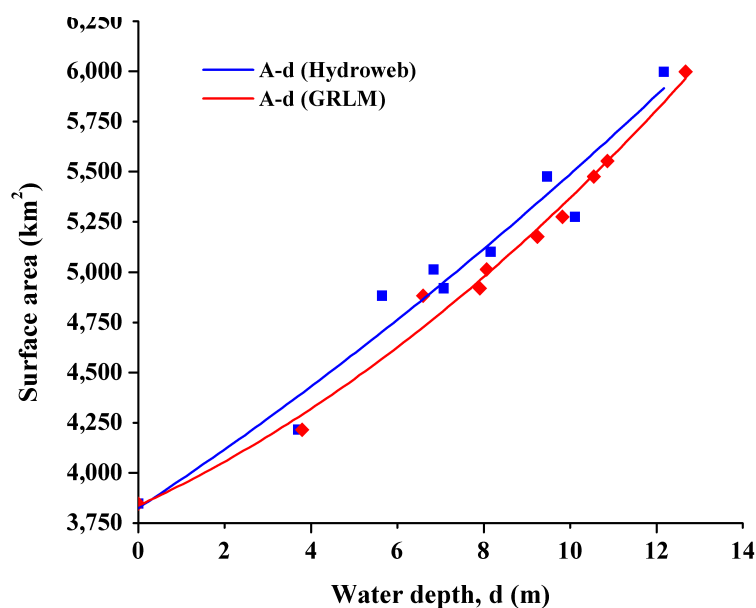
Figure 8 shows time-series of calculated volume from *in situ* data (Equation (2)) and calculated volumes from Hydroweb data (Equation (8)) and GRLM data (Equation (10)) for Lake Nasser during the periods 1999 to 2002 and 2005 to 2007. The calculated volumes from *in situ* data were relative to the reference volume, which corresponds to the lowest water level (h_{min}) from Hydroweb and GRLM. The operation pattern of Lake Nasser has been agreeably reproduced, although Hydroweb and GRLM underestimated the volume at minimum and maximum reservoir levels. The RMSE from Hydroweb data was 5720 Mm^3 (*i.e.*, 15% of the mean volume of 38,847 Mm^3), while R^2 was 0.93. The RMSE based on GRLM data was 3858 Mm^3 (*i.e.*, 10% of the mean volume of 39,377 Mm^3), while R^2 was 0.94. GRLM is slightly better than Hydroweb in terms of smaller relative RMSE for Lake Nasser.

Figure 8. Calculated volume for Lake Nasser above the reference level from *in situ* data and GRLM during the period 1999–2000 and from Hydroweb during the period 1999–2007. Calculated volumes for the gap in the period (2003–2005) show the use of the Hydroweb water level in the absence of *in situ* water levels. The time steps for the volumes (Mm^3) in GRLM and Hydroweb are 10-day (decadal) and monthly, respectively.
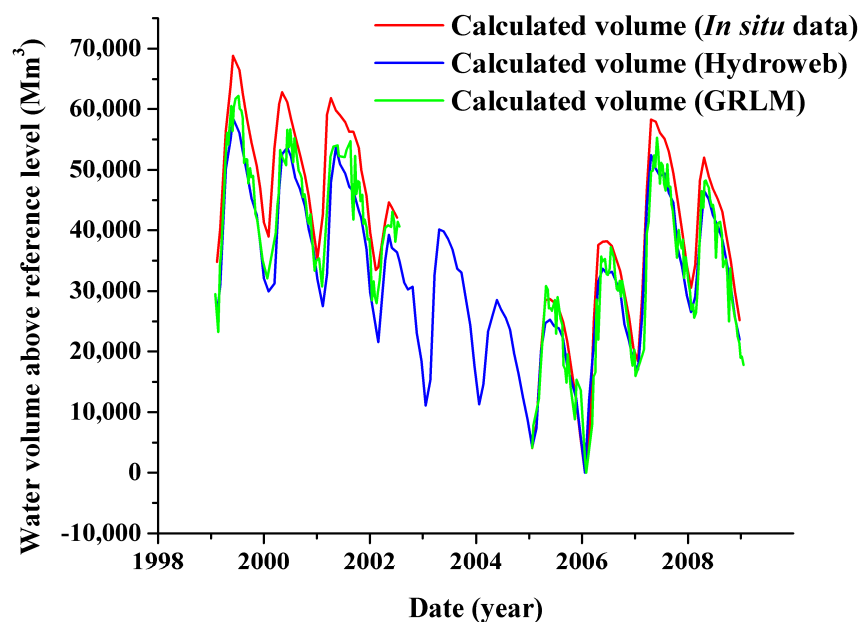

5.2.3. Reservoir Discharge

The discharges of Lake Nasser have been computed by the water balance equation. The comparison of the three discharges is given in Figure 9. *Q* (observed) is the observed discharge based on the rating curve, *Q*(wb sat. data-GRLM) is based on satellite data, while *Q* (wb *in situ* data) is based on *in situ* data.

There was good agreement between *Q* (wb sat. data-GRLM) and *Q* (wb *in situ* data), but large differences between *Q*(observed) and either *Q* (wb sat. data-GRLM) or *Q* (wb *in situ* data). The estimated discharges were overestimated at both low and high water levels. The 10-day discharge *Q* (wb sat. data-GRLM) poorly agreed with the *Q* (observed), giving an RMSE of 139% and an R^2 of 0.36 (Table 5). This error far exceeds the acceptable error in discharge measurements in large rivers.

Figure 9. Time series of observed and computed discharges for Lake Nasser during the periods 1999–2002 and 2005–2007. Red is *Q* (observed) based on observed discharge; green is *Q* (wb *in situ* data); and blue is *Q* (wb sat. data-GRLM).
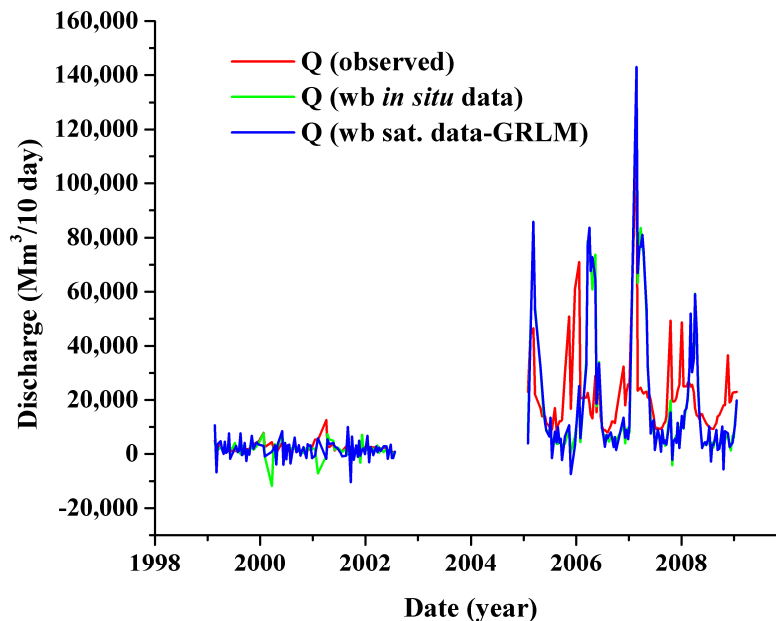
The three sets of discharge data were compared to understand error sources. A comparison of *Q* (wb *in situ* data) and *Q* (observed) also yielded a relatively large error (RMSE = 137%) and poor agreement (R^2 = 0.36). Comparing *Q* (wb sat. data-GRLM) and *Q* (wb *in situ* data) resulted in a much smaller, but still unacceptably high, error (RMSE = 30%), with a very high R^2 of 0.97. This may imply that satellite measurements might not be the major source of error. Discharges derived using Hydroweb (monthly) data in the water balance computations gave a relatively low error compared to GRLM (Table 5).

Table 5. Statistics of discharges using satellite data and *in situ* data in a water balance.

Study Areas	Data	Period	No. [*]	Observed$_{mean}$ [a]	Estimated$_{mean}$ [a]	R^2	RMSE [a]	%RMSE [b]
Roseires	Hydroweb	2002–2010	63	3769	3833	0.99	652	17.79%
	In situ data	"	101	3792	3869	0.98	611	16.11%
Lake Nasser	Hydroweb	1999–2002 2005–2009	89	5467	4235	0.09	3826	69.98%
	In situ data	"	89	5467	4127	0.26	3566	65.21%
	GRLM	1999–2002 2005–2009	215	11,947	11,409	0.36	16,704	138.92%
	In situ data	"	215	11,947	11,358	0.37	16,416	137.41%

[*] Refers to the number of datasets used. [a] Mm^3/month for Hydroweb and *in situ* data and Mm^3/10-day for GRLM and *in situ* data. Observed$_{mean}$ is the mean of the observed discharges, and Estimated$_{mean}$ is the mean of the estimated discharges. [b] Percentage of the RMSE relative to the mean observed data, *i.e.*, (RMSE/the mean observed discharge) × 100%.

The difference between *Q* (observed) and *Q* (wb) might be due to several reasons. Firstly, it could be due to unaccounted spills from the reservoir into the Toshka Depression and to other desert streams.

It is known that when the reservoir level exceeds 178 m, water may flow into Toshka. Bastawesy *et al.* [38] confirm that there were water releases into Toshka within the period 1998–2002. This indicates that Toshka receives excess water in certain times of the year when water level exceeds 178 m. Secondly, the inflow Q_{in} might have been overestimated in this study, as it was measured at about 250 km upstream of the lake and more than 750 km from the outflow gates of the dam. Inflow in this reach may not be accurately captured. Finally, the large size of Lake Nasser compared to its inflow (*i.e.*, its large residence time) increases the uncertainty in computed reservoir releases, compared with that of a reservoir with a smaller residence time (such as Roseires Reservoir); *i.e.*, the same error in water level estimation introduces, in the case of a reservoir with a large residence time, a large absolute error in the computed volume of the water stored, which will translate into a large absolute error in computed outflow, which may result in a very large relative error.

6. Conclusions

As data on reservoirs are often scarce or not in the public domain, this study evaluated the feasibility and accuracy of using satellite altimetry and imagery data to estimate stored water volumes and, combined with limited *in situ* data, discharges from Roseires Reservoir (Sudan) and Lake Nasser (Egypt) in the Nile Basin. These estimated discharges would not only provide information on water releases to downstream users, but also give insight into the reservoir operation strategies.

The water volume of the reservoirs was derived from the integration of a lake-specific area-level relationship. The surface area was estimated from Landsat images using *NDWI*, while the water level was from satellite altimetry. The discharge was computed using the water balance of the reservoir. The other components of the water balance (evaporation and rainfall data) were obtained from the IWMI online database. The *in situ* water levels, *V-d* relations, water inflows and outflows were obtained from the responsible ministries of Sudan and Egypt. The obtained *in situ* water levels, water volumes and discharges were used for the validation of satellite-derived results.

For Roseires Reservoir, monthly water levels from Hydroweb showed a good agreement with *in situ* water levels (RMSE = 0.92 m and R^2 = 0.96). The RMSE of the calculated volume and discharge Q (wb, sat. data) were 23% and 18%, respectively. The discharge is within the acceptable error of 15%–20% for single discharge measurements in large rivers. The outcome shows the potential to use satellite information for reservoir operation, which could be very useful for the contexts of no *in situ* data. The results showed that satellite-derived data can be used as a fairly reliable source of information for water resources management at a river basin scale.

For Lake Nasser, water levels from both GRLM (10-day) and Hydroweb (monthly) agreed well with *in situ* water levels (*i.e.*, RMSE = 0.62 m, R^2 = 0.96 and RMSE = 0.72 m, R^2 = 0.81, respectively). The RMSE of the calculated volume from GRLM and Hydroweb were 10% and 15%, respectively. However, the error of the estimated discharge based on the water balance was quite high. The RMSE of the estimated discharge from GRLM and Hydroweb were 139% and 70%, respectively. Similarly, the same order of magnitude of error was obtained when the discharge was calculated with the water balance equation using *in situ* measurements. Sources of errors could include unaccounted outflows (e.g., reservoir spills to the Toshka Depression and water flows to desert streams) and

overestimation of the water flowing into Lake Nasser. These errors would affect the water balance and influence the computed reservoir discharge.

This research contributes to the derivation of water discharges/releases in reservoir operations where there are limited or no *in situ* data. Specifically, the stored water volumes of Roseires Reservoir and Lake Nasser were successfully estimated, deriving their respective area-level and volume-level relationships using satellite data. Furthermore, by combining satellite-derived information on storage changes with *in situ* inflow data, the water releases from the two reservoirs could be adequately estimated for Roseires Reservoir, but with major limitations in the case of Lake Nasser. In the latter case, some major error sources may in fact not be related to satellite-derived information. It is also concluded that in general, error propagation in the estimation of reservoir releases for reservoir systems with shorter residence times will be smaller than in systems with longer residence times.

These findings are valuable for water resources management, particularly in a transboundary basin, such as the Nile Basin, where data sharing is still limited.

Author Contributions

Eric Muala collected, analysed data and processed most data, including the satellite imagery. All *in-situ* measurements were facilitated, obtained and analysed by Yasir Mohamed. Zheng Duan analysed some data, gave guidance for volume methodology and satellite data processing. Eric Muala was responsible for the research and the write up of the manuscript with contributions from all co-authors. Yasir Mohamed, Zheng Duan and Pieter van der Zaag critically revised the manuscript. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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