ICESAT-DERIVED WATER LEVEL VARIATIONS OF ROSEIRES RESERVOIR (SUDAN) IN THE NILE BASIN

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ABSTRACT

The information of water level variations in lakes and reservoirs is essential for many applications such as water resources management. The conventional in-situ measurements of water levels based on gauge station are often rarely available or difficult to be shared to the public especially for lakes in the developing countries and trans-boundary basins. Satellite altimetry provides an alternative solution to obtaining water level variations in lakes. In this study, the laser altimetry product GLAS/ICESat L2 Global Land Surface Altimetry (ICESat-GLA14) data was used to derive water levels in a narrow long-shaped reservoir in the Nile Basin, i.e. Roseires Reservoir in Sudan. A total of 19 water levels were derived from ICESat-GLA14 during the period 2003-2009. Compared with the in-situ measurements, all 19 ICESat-derived water levels had a $R^2$ of 0.88 and RMSE of 138.80 cm. After excluding two water levels (occurred on June 21, 2004 and June 8, 2005) with very large standard deviation (> 1 m), other 17 ICESat-derived water levels were in excellent agreement with in-situ measurements with $R^2$ of 0.99 and RMSE of 16.96 cm. In practical situation, the high standard deviation can be considered as an indicator for unreliable water level which is better excluded for further application. Two problematic water levels showed high overestimation of the in-situ measurements, and they occurred at the lowest water level situations and during rainy season. The exact reason for such high overestimation needs to be investigated in the future study.

Index Terms— ICESat, altimetry, lake and reservoir, water level, Nile Basin.

1. INTRODUCTION

Lakes and reservoirs store fresh water, and make it available to domestic, industrial, irrigation, wetlands, and environmental water use sectors [1]. Allocation of water is a tradeoff between water available in reservoirs and the water demands. A standard monitoring of water level variations in lakes and reservoirs is thus essential for better water resources management. In addition, the knowledge of long-term water level variations can also improve understanding of the effects of upstream climate change and anthropogenic activities on terrestrial water resources [2]. However, the conventional in-situ measurements of water levels are often rarely available or difficult to obtain for many lakes and reservoirs. Fortunately, satellite radar and laser altimetry has been used successfully to derive the water level of continental surface water bodies such as inland seas, lakes, rivers and wetlands e.g. [1-4]. The details on the principles of satellite altimetry can be found in [5] specifically for radar altimetry and [6] specifically for laser altimetry in terms of ICESat (Ice, Cloud, and land Elevation Satellite). Compared to satellite radar altimetry with larger footprint size (can be up to several kilometers), the laser altimetry satellite ICESat can measure at 172 m intervals along-track with a narrower footprint size of about 62 m [6]. This advantage renders ICESat potentially more suitable for several narrow long-shaped lakes and reservoirs where signals from radar altimetry can often include land surface rather than solely water surface. However, ICESat can be affected by weather situation/cloud interference, and the campaign mode in the laser altimeter ICESat measurement series led to an inconsistent temporal interval when compared to the radar altimeters [1]. Our previous study [1] showed when compared to in-situ measurements, ICESat-derived water levels had a better accuracy for Lake Mead (U.S.A) which is a long and very narrow lake.

The Nile Basin has a length of 6500 km, which is shared by 11 countries. The whole basin covers an area of 3.3 million km$^2$. Large dams have been constructed in the lower part of the Nile basin (Egypt and Sudan), and new dams are planned or under construction in many locations. Large dams change the water regime and availability not only locally, but at basin scale, which necessitates trans-boundary water
management for optimal utilization of the resources. However, data lacking and sharing is still a big challenge for better water management in the Nile Basin. Satellite data can provide a practical solution to this challenge. Therefore, the objectives of this study include: (1) to derive water level variations in a narrow-long shaped reservoir, i.e. Roseires Reservoir (Sudan) in the Nile Basin using ICESat altimetry data; (2) to evaluate the accuracy of ICESat-derived water levels using in-situ measurements.

2. STUDY AREA

The Roseires Reservoir in Sudan was selected as study area due to the availability of in-situ water levels for accuracy assessment. The Roseires Reservoir (11°37'N, 34°23'E) is located on the Blue Nile at 550 km southeast of Sudan's capital Khartoum, and 110 km from the Ethiopia-Sudan border. The location and the shape of Roseires Reservoir are shown in Figure 1. Roseires Reservoir has a maximum length of 80 km, maximum depth of 68 m and mean depth of 50 m. The surface area is about 290 km² and the water storage is approximate 3 km³. It was constructed in 1966 for irrigation (Gezira Scheme) and hydropower generation (280 MW). Currently, the reservoir capacity has decreased by 40% due to sedimentation. However, construction is ongoing to increase the capacity to 7.4 billion m³ with an increased height of 10 m up to level 493 m above mean sea level (AMSL) [7]. The average annual rainfall is about 700 mm. The rain often falls between June and October.

3. DATASETS

3.1. In-situ water levels

The daily measured water levels for Roseires Reservoir during the period 2002-2010 were obtained from the Ministry of Water Resources, Sudan. The water level was measured at the dam wall and referenced to Alexandria Datum (i.e., above mean sea level). The location of the gauge station for measuring water level is shown in Figure 1.

3.2. ICESat-GLAS level 2 Global Land Surface Altimetry data

The ICESat is the first laser altimeter satellite with the Geoscience Laser Altimeter System (GLAS), which was launched on 12 January, 2003 and ended up in 2009. It primarily measures the elevation changes of the Greenland and Antarctic ice sheets as part of NASA’s Earth Observation System (EOS) of satellites. The ICESat’s secondary objective is the determination of cloud and aerosol height profiles, land topography and vegetation canopy heights, sea ice roughness, sea ice thickness, ocean surface elevations and surface reflectivity [6]. Fifteen ICESat/GLAS standard data products (GLA01 to GLA15) are released by The National Snow and Ice Data Center (NSIDC) and are available at: http://nsidc.org/data/icesat/. The product GLA14 GLAS/ICESat L2 Global Land Surface Altimetry data provides surface elevations for land including rivers and lakes and reservoirs. For simplicity, we labeled these data as ICESat-GA14 in the following text. In this study we used the latest Release 33 of the ICESat-GA14 product during the whole period 2003-2009. A relative bigger spatial box covering the whole lake was defined for Roseires Reservoir. The spatial box was used to select all tracks of ICESat-GA14 data which overflies over Roseires Reservoir.

4. METHODS

ICESat-GA14 product provides pointed-like footprint elevation measurements along the tracks of ICESat. We need to conduct further processing to obtain water levels for lakes or reservoirs of interest. In this study, the processing procedures by our previous study [1] were adopted for converting ICESat-GA14 pointed-like elevation to water levels referenced above the EGM2008 geoid ([http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/](http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/)). Firstly, The NSIDC GLAS Altimetry elevation extractor Tool (NGAT), which is freely available at [http://nsidc.org/data/icesat/tools.html](http://nsidc.org/data/icesat/tools.html), was used to extract footprints with date, time, latitude (i_lat), longitude (i_lon), elevation (i_elev), geoid height (i_gdhHt), saturation elevation correction (i_satElevCorr) from ICESat-GA14 product. The descriptions of the extracted information mentioned above can be found in the GLAS Altimetry Data Dictionary at:
The ICESat footprints were converted into an ArcGIS shapefile to the ground track of ICESat, as shown in Figure 1. The water level above the geoid for each footprint was then computed as “elevation – geoid + saturation elevation correction”. All computed water level footprints completely within the boundary of Roseires Reservoir were extracted. The boundary of Roseires Reservoir at the lower water level situation has already been generated from Landsat TM image using the Normalized Difference Water Index (NDWI) method in our another previous study [7]. Then the extracted water levels footprints were averaged for the same date with the outliers excluded. The standard deviation was computed. The outlier removal procedure based on the standard deviation by [4] was followed in this study. After the processing procedures, a time-series of water levels with respect to EGM2008 geoid was finally obtained for Roseires Reservoir during the period 2003-2009. The accuracy of ICESat-derived water levels was also evaluated by validation using corresponding in-situ measurements.

Validation of the ICESat-derived water levels was done by comparison with in-situ measurements. In-situ measurements from the gauging station have their own reference datum (e.g. local mean sea level), while ICESat-derived water levels are referenced to EGM2008 geoid. For accuracy assessment, the ICESat-derived water levels are simply shifted vertically (adding a shift constant that correct for the different geoids or references) to fit in-situ measurements following the method by [5]. The RMSE (root mean square error) of the water level differences are computed to signify error. The $R^2$ (coefficient of determination) was also used to evaluate the agreement between in-situ measurement and ICESat-derived water levels [1]. It should be noted that the ICESat-derived water levels are average values along the ground tracks overflying and within the Roseires Reservoir. Whereas, the in-situ water level measurements are only based on a point in the gauge station. The gauge station is also some distance away from the ICESat tracks (Figure 1). This discrepancy between in-situ measurements and ICESat derived water levels will inevitably introduce uncertainty into the validation results.

5. RESULTS AND DISCUSSION

A total of 19 water levels were derived from ICESat-GLA product for Roseires Reservoir between 2003 and 2009. The number of ICESat footprints within Roseires Reservoir were very limited (the average number is 8, 4 for worst situation, 31 for best situation) due to the narrow shape of the reservoir and the direction of overflying track of ICESat (Figure 1). All tracks of ICESat intersect Roseires Reservoir in its narrow part. Given the limited number of footprints, during the outlier removal the standard deviation threshold was set to 30 cm if applicable similar to what we did for Lake Mead with a similar long-narrow shape [1]. Figure 2 shows time-series of water levels from ICESat-GLA 14 product and corresponding in-situ measurements. The inconsistent temporal intervals of ICESat-derived water levels can be clearly observed in Figure 2. ICESat-derived water levels cover only several given months (i.e. February, March, June, October, November and December). The standard deviation for each ICESat-derived water level is also included as error bar in Figure 2. The average standard deviation for all 19 water levels was 27.78 cm. After excluding the two water levels with very large standard deviation, the average standard deviation was 17.82 cm for other 17 water levels. In Figure 2, the ICESat-derived water levels were shifted vertically by adding a constant to the same reference with in-situ water levels. The shift constant value is presented in Table 1. From Figure 2, overall the ICESat-derived water levels are in agreement with the in-situ measurements. The $R^2$ is 0.88 and the RMSE is 138.80 cm. The high RMSE is caused by the large discrepancies in two water levels (June 21, 2004 and June 8, 2005) between ICESat-derived and in-situ measurements. For these two water levels, the associated standard deviations are very big (1.13 and 1.15 m). Actually, in the practical situation, the two water levels are better excluded for further application. The number of footprints within Roseires Reservoir is 9 and 7 for the date June 21, 2004 and June 8, 2005, respectively. The very high dispersion in water level values from those footprints can be considered as an indicator for unreliable measurements. After excluding these two water levels, all other 17 ICESat-derived water levels are in excellent agreement with in-situ measurements. The $R^2$ is 0.99 and RMSE is only 16.96 cm (Table 1). The two problematic water levels showed high overestimation of the in-situ measurements, and they occurred at the lowest water level situation and during the rainy season. Considering two large discrepancies occurred in June within the rainy season, this could suggest that the weather situation/cloud interference on laser altimetry may be a reason for the discrepancy between ICESat-derived water level and in-situ measurements. However, our previous study [7] also found that the radar altimetry product (Hydroweb) also highly over-estimated the water levels in the June, 2004 and 2005, although that comparison was based on monthly scale as Hydroweb provides monthly mean water levels. The radar altimetry will not be affected by weather situation. Therefore, the exact reason for the overestimation by radar altimetry and laser altimetry (i.e. ICESat in this case) in water levels at lowest water level situation and within rainy season is an interesting topic to investigate in the future study. According to the principle of satellite altimetry, the final water level is computed from several items such as “range” and related corrections [1], thus error associated in each item is possible cause to the problematic overestimation. The raw data of satellite altimetry are better to be used to separately diagnose
every item for determining the exact reason for such high overestimation observed at the lowest water level situations and during rainy seasons.

![Figure 2. Comparison of measured water levels and ICESat-derived water levels with standard deviation as error bar for Roseires Reservoir between 2003 and 2009.](image)

**TABLE 1**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>R²</td>
<td>0.88</td>
<td>0.99</td>
</tr>
<tr>
<td>RMSE (cm)</td>
<td>138.80</td>
<td>16.96</td>
</tr>
<tr>
<td>Shift constant (m)</td>
<td>-0.80</td>
<td>-0.34</td>
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<tr>
<td>Measured mean water level (m)</td>
<td>481.23</td>
<td>482.11</td>
</tr>
</tbody>
</table>

“No.” means the number of pairs of in-situ and ICESat-derived water levels for validation.

### 6. CONCLUSIONS

In this study, the GLAS/ICESat L2 Global Land Surface Altimetry data (GLA14) product was used to construct the time-series of water level variations in Roseires Reservoir (Sudan) between 2003 and 2009. The in-situ water levels at a gauge station were used to evaluate the ICESat-derived water levels. The validation results showed that ICESat-derived water levels were in excellent agreement with in-situ measurements with R² of 0.99 and RMSE of 16.96 cm after excluding two water levels with very high standard deviation (> 1 m). With the problematic two water levels included, the RMSE was increased to 138.80 cm. In practical situation, the water levels with high standard deviation can be considered to be problematic and better excluded for further application. The two problematic water levels significantly overestimated the corresponding in-situ measurements, and they occurred at lowest water level situation and during the rainy season. The exact reason for such high overestimation is an interesting topic to be investigated in the future study.

### 7. ACKNOWLEDGMENTS

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### 8. REFERENCES


