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Estimating water volume variations in lakes and reservoirs from four operational satellite altimetry databases and satellite imagery data

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ABSTRACT

Water levels in lakes and reservoirs can currently be obtained from four different satellite altimetry databases: (i) Global Reservoir and Lake Monitoring (GRLM), (ii) River Lake Hydrology (RLH), (iii) Hydroweb and (iv) ICESat-GLAS level 2 Global Land Surface Altimetry data (ICESat-GLAS). This paper proposes a new method for estimating water volume changes in lakes and reservoirs from these four databases in combination with satellite imagery data, without any in-situ measurements and bathymetry maps. Three lakes/reservoirs with different characteristics were studied, i.e. Lake Mead (U.S.A.), Lake Tana (Ethiopia) and Lake IJssel (The Netherlands). Compared to in-situ water levels, satellite altimetry products provided accurate water level variations for Lake Mead and Lake Tana but not for Lake IJssel. The long-term lowest water level in each satellite altimetry database was used as the reference level for water volume estimation. All water levels were converted to the Water Level Above the Lowest Level (WLALL), and the series of Landsat TM/ETM + imagery data were selected to extract corresponding surface areas for establishing area–WLALL relationships. Subsequently, the relationships of the Water Volume Above the Lowest water Level (WVALL) and WLALL were obtained through the analytical integration of area–WLALL relationships. The WVALL–WLALL relationships are site-specific and database-specific and can be used to convert water levels from the four databases directly into water volumes above the identified minimum levels for the same lake. Validation showed that estimated water volumes agreed well with in-situ measurements (R^2 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.

1. Introduction

Lakes and reservoirs store fresh water, and make it available to domestic, industrial, irrigation, hydropower, wetlands, and environmental water use sectors. Many large reservoirs have been constructed recently (Avakyan & Iakovleva, 1998; Gleick, 2003) and more will follow during the current century. Allocation of water is a tradeoff between water available in lakes and reservoirs and the water demands from those various sectors, and it is important to know the water availability at all times. Regular and accurate monitoring of water storage variations in lakes and reservoirs is essential for equitable water allocation to water use sectors, ecosystem services and for a better understanding of the climate changing impacts (Birkett, 1995; Crétaux & Birkett, 2006; Crétaux et al., 2011). The volume of water stored in lakes or reservoirs is dependent on the balance between inflow (i.e. precipitation, river inflow, discharge from communities and industries, and seepage) and outflow (i.e. evaporation, groundwater percolation, withdrawals, and river outflow). It is not feasible to compute volume fluctuations from all these flows and their associated uncertainties. Direct measurements of levels and volumes are therefore necessary.

The water level in lakes and reservoirs is traditionally measured by means of in-situ gaging stations installed near river mouths, bridges, weirs and sluices. However, the number of in-situ gaging stations has decreased in recent years around the globe (Alsdorf et al., 2007; Calmant et al., 2008; Crétaux & Birkett, 2006; Frappart et al., 2006a). Many remotely located lakes and reservoirs have never been gaged, especially in developing countries (Medina et al., 2008; Zhang et al., 2006). Even in places where gaging stations exist, measured data are not always freely available to other institutions and to the general public. Often the public is kept uninformed about water levels because it is sensitive national and international information that affects the livelihoods of large groups of people. Routine information on water levels is not often disclosed to water and environmental professionals. The lack of data exchange unnecessarily complicates collaboration between government departments, international river basin authorities and beneficiaries such as irrigation districts, municipal water supply departments, water boards, and electricity boards.

The volume of water stored in lakes and reservoirs cannot be measured directly. Traditionally, the water volume in a lake or reservoir is estimated based on in-situ water levels and bathymetry maps. A

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bathymetry map can be obtained from hydrologic surveys, using sonar sensors on ship transects to measure the underwater topography. However, these kinds of surveys are time-consuming, labor intensive and costly (Peng et al., 2006). Therefore, bathymetry maps are usually non-existent or difficult to obtain for a given lake or reservoir.

Satellite radar/laser altimetry is a technique that can be used to estimate water levels of open water bodies. The background on the principles of satellite radar and laser altimetry is given in Section 2. Both satellite radar and laser altimeters are profiling tools rather than imaging devices, which means they can only record measurements along their ground tracks without the ability of a true global coverage (Alsdorf et al., 2007; Birkett & Beckley, 2010). Different satellite altimetry missions are flying at different orbits, which results in the different spatio-temporal coverage of lakes and reservoirs. Satellite radar altimetry has been used successfully to derive water levels of continental surface water bodies such as inland seas, lakes, rivers and wetlands (Calmant et al., 2008; Crétaux & Birkett, 2006). Although the main objective of the Geoscience Laser Altimeter System (GLAS) on the ICESat (Ice, Cloud, and land Elevation Satellite) mission was to measure the elevation changes of polar ice sheets between 2003 and 2009, ICESat-GLAS derived water levels in lakes have shown an accuracy of better than 10 cm when compared with lake gage data (Bhang et al., 2007). The ICESat-GLAS level 2 Global Land Surface Altimetry data (GLA14) (labeled as ICESat-GLAS hereafter) was recently used to derive water levels for lakes (Phan et al., 2012; Swenson & Wahr, 2009; Zhang et al., 2011a, 2011b). It is worth comparing the merits and limitations of both satellite radar altimetry and laser altimetry. The main strength of satellite laser altimeter (i.e. ICESat) is that it can measure at 172 m intervals along-track with a narrower footprint size of about nominal 70 m compared to the radar altimeters with a footprint size of several kilometers (Zwally et al., 2002). This practically implies that small lakes can be encompassed with ICESat only. The footprint of radar altimeters changes as a function of the sea/lake state, the wave height or the corrugated land (Rosmorduc et al., 2011), however, the infrared laser (1064 nm) from ICESat acts like a flashlight — whatever is illuminated in the spot does not affect the footprint size (personal communication with Timothy J. Urban, 2013). It should be noted that for ICESat the nominal 70 m footprint was the design, but in reality ICESat footprints were elliptical with sizes about 50–105 m. The detailed information on the footprint size during the whole ICESat operation periods is given at: http://nsidc.org/data/icesat/pdf/glas_laser_ops_attrib.pdf. Satellite radar altimeters can work under all-weather conditions with little hindrance by cloud, vegetation cover or canopy (Birkett & Beckley, 2010). For laser altimeters, the forward scattering caused by thin clouds and low-level atmospheric effects, and saturation from high-energy returns over bright smooth flat surfaces can cause centimeter to meter errors for range measurement by the laser altimetry (Brenner et al., 2007). Satellite radar altimeters work continuously with a regular repeat period of 10, 17, or 35 days. ICESat was changed in the fall of 2003 from continuous measurement to a campaign mode resulting in a 91-day repeat with a 33-day sub-cycle (Abdalati et al., 2010). The detailed information on the operational periods for the campaigns of ICESat is given at: http://nsidc.org/data/icesat/laser_op_periods.html. The campaign mode in the laser altimeter ICESat measurement series induces a temporal interval that is not consistent to radar altimetry.

At present, besides ICESat-GLAS, three other databases based on satellite radar altimetry for selected water bodies are operationally accessible. They are (i) the Global Reservoir and Lake Monitoring (GRLM) database (ii) the River Lake Hydrology (RLH) database by The River and Lake Project, and (iii) the Hydroweb database (see Table 1). These four databases 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). The detailed information on the agency responsible for the ICESat and its technical characteristics can be found at http://nsidc.org/data/icesat/, such details for the mentioned five radar altimeters are available at: http://www.altimetry.info/html/missions. The four products are based on different track extent due to the use of different satellite altimetry data. The ongoing development and specific objectives of these products result in the different target (lake or reservoir) availability. It should be noted that the water levels from the four products are with respect to different datum/reference systems (Table 1), rendering it impossible to combine the absolute values from the different products for better temporal intervals. The combination from different altimeters for better temporal sampling and the difficulties involved for inland water bodies have been discussed in Birkett et al. (2011), Calmant et al. (2008) and Frappart et al. (2006a).

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 (Frappart et al., 2005, 2008, 2011), the lower Mekong River Basin (Frappart et al., 2006b) and the Lower Ob' Basin (Frappart et al., 2010). Few studies attempted to derive water volume variations in lakes and reservoirs using the combination of satellite altimetry and imagery data. Crétaux et al. (2005) reconstructed volume variations in the inland lake Big Aral Sea using the digital bathymetry model and water levels derived from T/P altimetry data. Peng et al. (2006) derived the water level–volume relationship for Fengman Reservoir, China, using in-situ water levels and surface areas derived from Landsat imagery data. Zhang et al. (2006) converted water levels derived from T/P altimetry data to water storage in Lake Dongting, China, using the water level–storage relationship which was established from T/P altimetry water levels and in-situ water storage measurements. Smith and Pavelsky (2009) computed water storage changes in nine lakes of the Peach–Athabasca Delta, Canada using in-situ water levels and remotely sensed surface areas. Medina et al. (2010) estimated water volume variations in Lake Izabal using in-situ water levels and ENVISAT Radar Altimeter (RA-2) and Advanced Synthetic Aperture Radar (ASAR) images. The above methods rely entirely on the availability of bathymetry maps or in-situ water levels or water volumes which are difficult to obtain or non-existent for most remote lakes. Recently the GRACE satellite gravimetry has been used in combination with satellite altimetry and optical imagery data to study the water volume variations in the very large inland water bodies, e.g. a study by Singh et al. (2012) for the Aral Sea. However, the characteristics of GRACE restrict its meaningful application to study areas not smaller than 200,000 km^2 (Singh et al., 2012), which is a big limitation for hydrological study of many lakes and reservoirs with relatively smaller surface areas.

These satellite altimetry databases are becoming attractive for operational applications in water resources management. In this study, the main objective is to propose and evaluate a method that combines operational satellite altimetry databases with satellite imagery data to estimate water volume variations in lakes and reservoirs. The fact that in-situ measurements and bathymetric data are not needed makes it appealing to a large variety of users in the water and environmental management sector. The in-situ observed water levels and water volumes are available for quantitatively assessing the accuracy of satellite altimetry databases and the estimated water volumes.

2. Background on satellite altimetry

Satellite altimeters transmit a series of pulses towards the Earth's surface in the nadir direction and receive the echo reflected by the surface. The different kinds of pulses render two types of altimeters: radar altimeters and laser altimeters. Radar altimeters use microwave pulses (e.g. Ku-band, C-band and S-band) (Rosmorduc et al., 2011). Laser altimeters use laser pulses at visible and near-infrared wavelengths. The general principle for measurements is similar for satellite radar and laser altimetry. Whereas the laser altimeter is sensitive to clouds, the radar altimeter is an all weather measurement system. The time for the pulse to be reflected by the surface back to the

Table 1
Four different satellite altimetry databases and their characteristics.

Databases	Used satellite data	Period	Intervals	Geoid/reference system
GRLM	T/P, Jason-1, Jason-2, ENVISAT	1992–present	10-day	9-year T/P mean level
RLH	ENVISAT, Jason-2	2002–present	35-day	Mean level
Hydroweb	T/P, Jason-1, Jason-2, GFO, ENVISAT	1992–present	Monthly	GRACE GCM02C geoid
ICESat-GLAS	ICESat	2003–2009	Campaign mode	EGM2008 geoid

altimeter is measured and is used to obtain the distance between the satellite and the earth's surface assuming that the pulse is propagating at the speed of light, i.e. "Range" (Calmant et al., 2008). The "Range" is estimated based on the returned waveform which represents the time evolution of the energy reflected by the surface to satellite using waveform retracking algorithms. The aim of the waveform retracking is to fit a mathematical model to the received waveforms, and retrieve geophysical parameters including the "Range". It should be noted that different retracking method could cause several tens of centimeter differences (Birkett & Beckley, 2010) and even up to several meters (Frappart et al., 2006a) in the final estimated range. Detailed discussion on the waveform retracking methods can be found in Frappart et al. (2006a) and Gommenginger et al. (2011) for radar altimetry and Brenner et al. (2003) for laser altimetry in terms of ICESat. Since the electromagnetic waves can be decelerated as they travel through the atmosphere and ionosphere, various corrections should be applied to the Range to compensate for such delay effects. The altimetric height of the reflecting surface is determined by the difference between the altitude of satellite orbit and the range measurement, taking into account various instrument and geophysical corrections to range:

$$\text{Height} = \text{Altitude–Range–Corrections}. \quad (1)$$

Specific for inland water bodies including lakes and reservoirs, classical corrections should include instrumental, ionosphere, wet and dry tropospheric, solid earth and pole tide corrections for radar altimetry (e.g. Birkett, 1995; Frappart et al., 2006a; Medina et al., 2008). For laser altimetry, the above-mentioned classical corrections are also applicable except the ionosphere correction which is negligible (Frappart et al., 2006a; Urban et al., 2008). In addition, the saturation correction and the atmospheric forward scattering correction are two important corrections for laser altimetry which are not applicable to radar altimetry (Urban et al., 2008). The resulting altimetry height in Eq. (1) is with respect to a reference ellipsoid (ellipsoidal height), and the height is the mean value within the altimeter footprint (Crétaux & Birkett, 2006). The ellipsoidal height can be further converted into orthometric height by removing a geoid height above the reference ellipsoid. The geoid is the gravitational equipotential surface approximately coinciding with mean sea level in the absence of all forces other than gravity and centrifugal forces. The geoid height can be calculated from Earth Gravitational Model (EGM). Crétaux and Birkett (2006) reported that a low-resolution terrestrial geoid like EGM96 (Lemoine et al., 1998) can be utilized for continental water bodies. With a defined orbit, altimeter satellites provide the range measurements at intervals of several kilometers or tens of meters depending on the ground track spacing. Satellites overfly a given ground area with a regular repeat period, thus the time-series of surface height variations can be derived for a specific ground area along the satellite ground track during the lifetime of the satellite mission. The comprehensive and detailed discussion on the principles and applications of satellite altimetry can be found in Fu and Cazenave (2001) and Vignudelli et al. (2011). Zwally et al. (2002) discussed such details for laser altimetry in terms of ICESat.

3. Study areas

Three differing lakes/reservoirs with available in-situ measurements were studied i.e. Lake Mead (U.S.A.), Lake Tana (Ethiopia) and Lake IJssel (The Netherlands). Lake Mead is a narrow and deep lake with a declining water level trend (level dropped 40 m between 2000 and 2010). Lake Tana is a vast circular-shaped and shallow lake with seasonal water level fluctuations of about 1.6 m. Lake IJssel is a regular-shaped and shallow lake with very small water fluctuations (~0.2 m) due to the controlled discharge into the Wadden sea. The average water level in Lake IJssel is maintained at around −0.2 m NAP (Normaal Amsterdams Peil) datum during the period mid-April to end-September. During the remaining months, the level is at −0.40 m NAP (Bottema, 2007). The physical characteristics of these three lakes are listed in Table 2. The data sources are from Kebede et al. (2006) for Lake Tana, and from Holdren and Turner (2010) for Lake Mead. The characteristics of Lake IJssel are obtained from Wikipedia (http://en.wikipedia.org/wiki/IJsselmeer) and the bathymetry map provided by the Ministry of Water Resources and Public Works, The Netherlands. The differences in physical characteristics between these three lakes enabled us to evaluate the performances of satellite altimetry products and the proposed method for water volume variations in the different types of lakes/reservoirs. Fig. 1 presents the three lakes with gaging stations and the ground track coverage of satellite altimetry missions overflying them. The ground track coverage of satellite radar altimeters i.e. T/P, Jason-1, Jason-2, GFO and ENVISAT were derived from the Pass Locator at www.aviso.oceanobs.com/en/data/tools/pass-locator. The ground track coverage of ICESat was derived after extracting the geographical locations of footprints from ICESat-GLAS (see details in Section 4.2.4).

4. Data sets

4.1. In-situ measurements

For Lake Mead, in-situ daily water levels at one gaging station (Fig. 1(a)) and the corresponding surface areas and water volumes for the period 2000 to 2010 were obtained from the U.S. Bureau of Reclamation (USBR). These in-situ daily surface areas and water volumes were computed by USBR using the corresponding water level (L)–surface area (A) and L–water volume (V) relationships derived

Table 2
Physical characteristics of the three studied lakes.

Characteristics	Lake Mead	Lake Tana	Lake IJssel
Country	U.S.A.	Ethiopia	The Netherlands
Latitude	35°59′–36°37′N	11°35′–12°18′N	52°31′–53°05′N
Longitude	114°50′–113°55′W	37°00′–37°38′E	5°02′–6°00′E
Maximum length (km)	180	84	64
Maximum width (km)	15	66	30
Length of shoreline (km)	885	385	258
Maximum depth (m)	158	14	8
Mean depth (m)	56	9	5
Lake area (km^2)	637	3156	1100
Water volume (km^3)	35.5	28.4	5.5

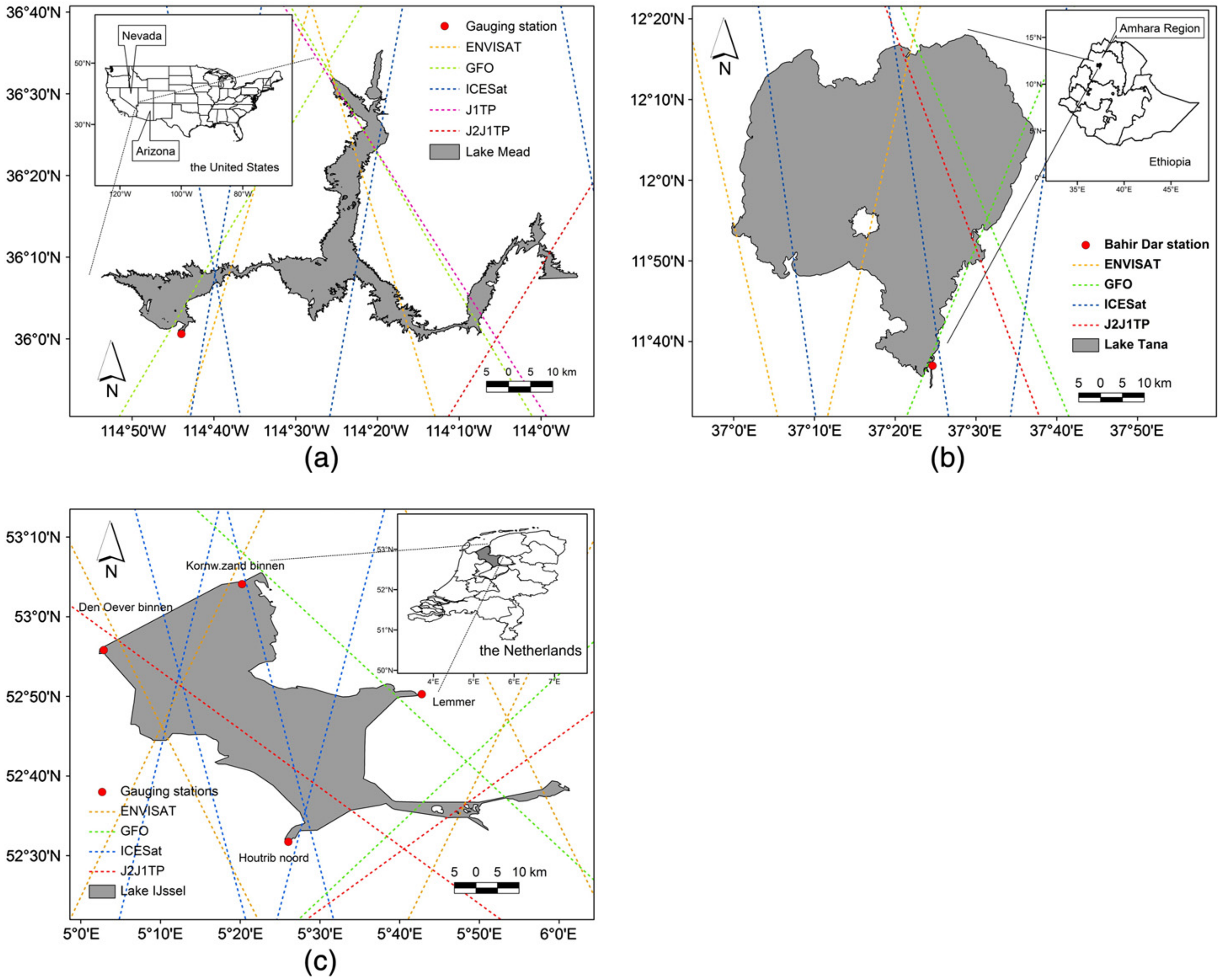

Fig. 1. Locations of Lake Mead (a), Lake Tana (b), Lake IJssel (c), gaging stations, and ground tracks of satellite altimetry missions. The boundary of Lake Mead at full capacity was obtained from Twichell et al. (2003). J2J1TP denotes the shared track by Jason-2, Jason-1 and T/P; J1TP refers to the shared track by Jason-1 and T/P.

from the bathymetric survey of Lake Mead. The L–A and L–V equations were derived as:

$$A = 0.08\ L^2 - 50.95\ L + 8087.48 \tag{2}$$

$$V = 0.03\ L^3 - 27.82\ L^2 + 8887.11\ L - 969993.18 \tag{3}$$

where, the units for L, A and V are m, km^2 and 10^6 m^3, respectively.

For Lake Tana, daily measured water levels at Bahir Dar station (Fig. 1(b)) between January 1, 1992 and August 31, 2006 were obtained from the Ministry of Water Resources, Ethiopia. The relationships between water level (L)–surface areas (A) and L–water volume (V) were inversely derived from Wale et al. (2009) which was based on a recently created bathymetry map. The L–A and L–V equations are:

$$A = 4.94\ L^2 - 17560.14\ L + 15618856.76 \tag{4}$$

$$V = -8.44\ L^3 + 45243.55\ L^2 + 80844047.65\ L + 48150659439.10. \tag{5}$$

Hence the daily surface areas and water volumes were derived by converting daily measured water levels using Eqs. (4) and (5). We referred to these surface areas and water volume estimates as in situ measurements and used them to validate the estimated surface areas and water volumes in this study.

For Lake IJssel, measured water levels at 10-minute intervals from 2002 to 2010 at four stations, i.e. Den Oever binnen, Kornwerderzand binnen, Hourtrib noord and Lemmer (Fig. 1(c)), and a bathymetry map were obtained from the Ministry of Water Resources and Public Works, The Netherlands.

4.2. Satellite altimetry products for water level

4.2.1. Global Reservoir and Lake Monitor (GRLM)

The GRLM database is prepared by the United States Department of Agriculture Foreign Agricultural Service (USDA/FAS) in cooperation with NASA and the University of Maryland. The database is available at: http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/. The database mainly utilizes data from T/P, Jason-1, Jason-2 and GFO and recent additional ENVISAT satellites to monitor time-series of water level variations for presently ~228 of the world's largest lakes and reservoirs in a near-real time manner (i.e. update on a weekly basis) for operational application. The details on processing procedure and data format for the GRLM can be found in Birkett et al. (2011). Currently GRLM provides a merger of T/P, Jason-1 and Jason-2 (TPJO.1 version) time-series relative water level variation with respect to the mean 9-year T/P level at 10-day intervals for 80 lakes/reservoirs. An ENVISAT time-series of relative water level variation with respect to the mean level of a given ENVISAT reference cycle at 35-day intervals for 148 lakes/reservoirs is also provided. For each lake/reservoir included in GRLM, there are two time-series of water level variations, i.e. the raw data and the smoothed data with a median type filter to eliminate outliers and reduce high frequency noise. However, smoothed data are only for visualization, they are not expected to be used for quantitative analysis. The raw data of TPJO.1 version including water levels and estimated errors for Lake Tana and Lake IJssel from GRLM were used in this study.

4.2.2. River Lake Hydrology product (RLH)

The River and Lake project by ESA and Montfort University is based on altimetry data mainly from ERS, ENVISAT and additionally from Jason-2 to provide water levels for lakes, reservoirs and rivers. The database is available at: http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main. The full details on product generation procedures are described in the River and Lake Product Handbook v3.5 (2009). Two types of products, i.e. the River Lake Altimetry (RLA) and River Lake Hydrology (RLH) are available. RLA is for experienced users of altimetry data while RLH is designed for hydrologists with no detailed knowledge of radar altimetry. RLH provides the relative water level variations with respect to the corresponding climatological mean level. The climatological mean level is calculated by averaging all the water levels (referenced to the EGM96 (Earth Gravitational Model) geoid Lemoine et al., 1998) for the whole data available period. The RLH product format is a time-series of water level variations and associated standard deviations for a given target for each ground track rather than a single time-series for a given target. Thus, for some large targets where several tracks overfly, several time-series water levels are provided; and for targets where a track is divided due to islands, several time-series are also provided. Only data (water levels and standard deviations) for Lake Tana are available from RLH and were used in this study.

4.2.3. Hydroweb

Hydroweb is developed by LEGOS/GOHS (Laboratoire d'Etudes en Oceanographie et Geode'sie Spatiale, Equipe Geodesie, Oceanographie, et Hydrologie Spatiales) in France. Hydroweb provides time-series of water levels of large rivers, about 150 lakes/reservoirs, and wetlands around the world using the merged T/P, Jason-1, Jason-2, ENVISAT and GFO data. Hydroweb is available at: http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/. Presently Hydroweb also provides variations of surface area and water volume for ~27 lakes/reservoirs but without any detailed explanatory documentation of procedures for each specific target. Based on the personal communication with Jean-Francois Crétaux (2012), Hydroweb uses various data sources, i.e. bathymetry maps, Landsat, CBERS-2, SRTM data and ENVISAT radar images, depending on the data availability to calculate water volume variations. The basic NDWI (Normalized Difference Water Index) method (McFeeters, 1996) was used for classification of water bodies if applicable.

The processing procedures of Hydroweb are described in Crétaux et al. (2011). Water levels in Hydroweb are referenced to the GRACE GGM02C geoid using the GGM02C model complete to degree and order 150 (Frappart et al., 2006b; Tapley et al., 2005). In addition, if the different tracks of a satellite or different altimeter satellites overfly the same lake or reservoir, the Hydroweb water levels are "monthly" values derived by merging measurements from all tracks (Crétaux et al., 2011). Therefore, for a given lake/reservoir, only a single time-series of water level is generated and provided. The water levels from Hydroweb can be for a specific day (i.e. the exact date when a satellite altimetry mission overflies the target) or "monthly", depending on whether a single or multiple tracks or satellites overfly the target. It should be noted that "monthly" Hydroweb water levels do not represent the average value of a real month (30/31 days). The specific days in each month that were used to generate each monthly value are not given in the Hydroweb product; thus we could not compute the "monthly" values from in-situ measurement. Instead the average in-situ measurement values of all days in a month were computed to generate real monthly values to validate Hydroweb monthly products.

Monthly water levels with standard deviations for Lake Mead and Lake Tana are available from Hydroweb and were used in this study.

4.2.4. ICESat-GLAS level 2 Global Land Surface Altimetry data (ICESat-GLAS)

The product GLA14 ICESat-GLAS level 2 Global Land Surface Altimetry (ICESat-GLAS) data provides surface elevations for land including rivers and lakes and reservoirs, plus laser footprint geolocation, range measurements, and geodetic, instrumental and atmospheric correction parameters (Zwally et al., 2003). The product is available from the National Snow and Ice Data Center (NSIDC) at http://nsidc.org/data/icesat/. In this study we used the Release 33 product for the whole period 2003–2009 to derive water levels in lakes and reservoirs.

Unlike GRLM, RLH and Hydroweb which provide water level variations for certain lakes and reservoirs directly, ICESat-GLAS product provides elevation measurements along the tracks of ICESat rather than for specific targets. Hence, further processing is needed to obtain water levels for water bodies of interest. In this study, the processing procedures are described as follows:

a. The NSIDC GLAS Altimetry elevation extractor Tool (NGAT) developed by NSIDC was used to extract footprints with latitude, longitude and elevation and geoid height from the ICESat-GLAS product. The geoid height is based on the updated geoid model EGM2008 (http://nsidc.org/data/icesat/data_releases.html). These points were converted into an ArcGIS shapefile to show the ground track of ICESat (Fig. 1).
b. The water level above the geoid for each footprint was taken as the difference between elevation value and geoid height.
c. All water level points of lakes were taken within the boundaries of the lakes, and the extracted water levels were averaged for each track with the outliers excluded. We used Landsat TM/ETM + imagery to obtain the lake boundary. For outlier removal, the two-step procedure by Zhang et al. (2011b) was used: first, obvious outliers with abnormal high/low values were removed by a simple visual inspection of each water level profile; then based on the acceptable standard deviation (STD) threshold, those outliers causing higher standard deviation were removed. The STD threshold of 10 cm used by Zhang et al. (2011b) was followed for Lake Tana and Lake IJssel. Due to the narrow shape of Lake Mead (Fig. 1(a)), the numbers of ICESat measurements within Lake Mead were very limited (78/11 footprints at the best/worst situations). For some tracks, it was difficult to clearly determine and remove outliers because of the limited number of measurements and their scatter. The threshold was relaxed to 30 cm when the desirable 10 cm could not be achieved for those tracks.
d. All computed water levels for a specific lake or reservoir were combined in time sequence to construct the time-series of water levels during the available data period.

After the processing procedures, we obtained the time-series of water levels with respect to EGM2008 geoid with associated standard deviations for Lake Mead (39 values), Lake Tana (13 values) and Lake IJssel (21 values) within the period of available in-situ measurements. For Lake Mead, there were only 11 water levels with STD greater than 10 cm, ranging from 11 to 22 cm. The average STD of all 39 water levels was 9 cm and within the desirable 10 cm.

4.3. Landsat TM/ETM + imagery

Landsat TM/ETM + data with spatial resolution of 30 m and long-term availability since the launch in 1984 were used to extract the surface areas for the lakes and reservoirs investigated. The data were downloaded from http://glovis.usgs.gov. The satellite images should coincide exactly with the dates of altimetry-derived water levels. However, most of the time this was not the case firstly because of the different crossover repeat cycles of Landsat (16-day) and altimeter satellites (10–35-day or campaign mode); 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 (within 5 days) are minimal. Landsat TM/ETM + images for the best 5 days before or after the dates of altimetry-derived water levels were used to derive water surface areas at the corresponding water levels. Desirably, at least 10 TM/ETM + images acquired during different moments for each lake or reservoir are needed to estimate the water surface areas during periods of the highest and lowest water levels captured by satellite altimetry, but the selection of imagery data was adjusted according to practical situations. It should be noted that the Scan Line Corrector (SLC) compensating for the forward motion of the satellite in the ETM + sensor failed on May 31, 2003. As a consequence, ETM + data acquired after the SLC failure (labeled as SLC-off data) have wedge-shaped gaps and missing pixels which resulted in approximately 22% of missing image data for each scene (Chen et al., 2011). In this study, SLC-off images were only used when other data were not available. For Lake Mead, no SLC-off image was used while SLC-off data had to be used for Lake Tana. For the selected SLC-off data, we used a readily available simple gap-filling extension toolbox (landsat_gapfill.sav) in the ENVI software (http://www.exelisvis.com) to fill the gaps. This gap-filling toolbox provides two options: one is the single-image gap-filling using a triangulation interpolation method, and the other is two-image gap-filling method which is known as the local linear histogram matching technique chose by USGS (http://landsat.usgs.gov/documents/SLC_Gap_Fill_Methodology.pdf). In this study, the single-image gap-filling method was finally used due to two problems encountered for the two-image gap-filling method: difficulty in finding two well-matching images and the extra uncertainty possibly caused by the temporal variability in two images which represent different water level situations. As described later in Section 5.1, the reasonable accuracy of the final estimated surface areas (4.64% RMSE) for Lake Tana suggests that the gap-filling worked well. Many recently developed gap-filling techniques (e.g. Chen et al., 2011; Zeng et al., 2013) could be used for improvements in gap-filling in the future studies. Since February 2008, Landsat has been brought to orbit and this data mission will ensure that free data on open water surfaces will continue to become available.

5. Methodology

5.1. Surface area estimation

Various land use/cover classification methods (from conventional unsupervised methods (e.g. Duan et al., 2009) to more advanced artificial neural networks (ANN) and support vector machine (SVM) classifiers (e.g. Song et al., 2012)) can be used to classify the extent of water bodies. We conservatively considered the careful digitization be the most accurate method, although it is time-consuming and tedious. The MNDWI (Modified Normalized Difference Water Index) method proposed by Xu (2006) has been widely used and proved robust to extract water bodies (Ji et al., 2009; Lu et al., 2011). The MNDWI is calculated as the ratio of the Green band subtracted from the middle infrared (MIR) band to the sum of the Green band and the MIR band. The equation is expressed as follows:

$$MNDWI = (Green–MIR)/(Green + MIR). \quad (6)$$

Water features have positive MNDWI values because of their higher reflectance in the Green band than the MIR band while non-water features (soil and vegetation) have negative NDWI values due to their lower reflectance in the Green band than the MIR band (Xu, 2006). A threshold value for MNDWI (e.g. simply a value of zero) can be set to separate water features from non-water features. Ji et al. (2009) concluded that the threshold should be manually adjusted according to atmospheric absorption and lake water quality for a more accurate extraction of the size of water bodies. In this study, we adopted the MNDWI method followed by a manual digitization. This kind of combination should preserve the efficiency of MNDWI method and accuracy by a careful digitization. Following the manual adjustment procedure by Xu (2006) and recommendation by Ji et al. (2009), different MNDWI threshold values were tested and the resulting water feature/non-water feature separations, especially near the water body boundary, were visually checked. The threshold values of 0 and 0.1 were found suitable for Lake Mead and Lake Tana, respectively. For each satellite image, the mistaken water features near the water body boundary (inundated areas present water features but should not belong to lake) were further removed by the aided digitization through visual interpretation. Finally, the water surface areas were calculated as the sum of the areas of the pixels identified as water bodies. In this study, a total of 49 Landsat images were processed (21 for Lake Mead and 28 for Lake Tana). The in-situ surface areas derived from the bathymetric survey (Section 4.1) were used to validate the estimated surface areas. The estimated surface areas are in good agreement with in-situ measurements ($R^2 = 0.99$ for Lake Mead; $R^2 = 0.89$ for Lake Tana), and the percentage of RMSE in terms of the mean measured surface area is 2.19% for Lake Mead and 4.64% for Lake Tana (Table 3).

5.2. Water volume estimation

The total volume (V) of water depends on a specific fixed minimum volume of water contained in lakes and reservoirs (V_{con}), and a variable component that varies with the water levels (V_{var}):

$$V = V_{con} + V_{var}. \quad (7)$$

The hypothesis to be tested is whether satellite measurements can capture V_{var} by dynamic measurements over a long enough period, such as for instance 10 years. This is the most challenging part of volumetric assessments. V_{con} refers to the water stored between a certain fixed water level and the bottom. The single value for V_{con} can be obtained from topographic maps before a reservoir was constructed and more rarely from bathymetric maps. Determination of V_{con} has several difficulties. The underlying topography is uneven and it fluctuates significantly; thereby increasing error bands. In addition, the underlying topography changes continuously and elevations increase due to sedimentation and other human activities (Feng et al., 2011; Peng et al., 2006). 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 to the reference level to separate V_{con} and V_{var}. The resulting water volume V_{var} is referred to as Water Volume Above the Lowest water Level (WVALL) in this paper. Considering that the objective of this study is to estimate the relative water volume variations for the sake of water management rather than absolute values, values of V_{con} can be disregarded.

In this study, the lowest water level in each satellite altimetry product was determined first. Subsequently, the lowest water level was subtracted from all water levels obtained from each satellite altimetry product to obtain the Water Level Above the Lowest Level (WLALL). The relationship between WLALL and corresponding surface area (area–WLALL) was established using regression analysis. Because the water volume is the integration of the functional relationship between surface area and water level, the WVALL–WLALL

Table 3
Statistics for the estimated surface areas from Landsat images for Lake Mead and Lake Tana when compared to in-situ measurements from bathymetric survey.

Study area	No.	R^2	$Mean_{measured}$ (km^2)	$Mean_{estimated}$ (km^2)	RMSE (km^2)	RMSE/$mean_{measured}$ (%)
Lake Mead	21	0.99	410.80	404.26	8.98	2.19
Lake Tana	28	0.89	2913.71	3044.91	135.30	4.64

"No." refers to the number of estimated surface areas derived from Landsat images. "$Mean_{measured}$" and "$Mean_{estimated}$" are the mean values of in-situ measurements and estimated surface areas from Landsat images, respectively.

relationship can be obtained by analytically integrating the function of area–WLALL with the condition that WVALL is equal to zero when WLALL is zero. In order to clearly explain how to perform such analytical integration, let us imagine that the area–WLALL relation can be described as a second-polynomial function: $A = f(L) = aL^2 + bL + c$, where A is the surface area in km^2, L is WLALL in m, and a, b, c are coefficients determined by regression analysis. Then the WVALL–WLALL function which is the integration of $f(L)$ against dL can be written as: $V = f(L) dL = aL^3/3 + bL^2/2 + cL + d$, where V means WVALL, and a, b, c and d are coefficients. The a, b and c are the same values in area–WLALL function, and d can be solved as 0 given the condition $V = 0$ when $L = 0$. The resulting equation can be used to convert the time-series of WLALL to WVALL for the analysis of water volume variations in lakes or reservoirs.

5.3. Validation

The validation of satellite altimetry-derived water levels is generally done by comparison with in-situ measurements from gaging stations (Birkett, 1995; Birkett & Beckley, 2010; Crétaux & Birkett, 2006; Medina et al., 2008). It should be noted that altimetry-derived water levels are average values along the ground tracks overflying the targets, and the tracks are usually some distance away from the gaging stations. The exact values of distance between overflying tracks and in-situ gaging stations are not reported here for conciseness, but Fig. 1 with scale bar gives a rough idea on the distances. In addition, in-situ water levels from gaging stations have their own reference datum (e.g. local mean sea level), while water levels from different satellite altimeter products are based on different geoids or references (see Table 1). So we cannot directly compare the absolute values of water levels from satellite altimeter products with in-situ measurements. Only the water level variations can be derived from the operational databases. The validation method by Birkett and Beckley (2010) is commonly used, and thus adopted in this study. In this method, the altimetry-derived water levels are simply shifted vertically (adding a shift constant that correct for the different geoids or references) to fit in-situ measurements. The RMSE (root mean square error) of the water level differences is computed to signify error. Siddique-E-Akbor et al. (2011) also used a similar procedure to bring the satellite altimetry derived water levels into a target datum for inter-comparison. The R^2 (coefficient of determination) was also used to evaluate the agreement between in-situ measurement and altimetry-derived water levels. To validate the estimated water volumes, the measured water volumes were converted to WVALL as estimated volumes. The conversion was carried out by subtracting the water volume value for the same date that the lowest water level occurred in satellite altimetry water level products. Two statistical indicators, R^2 and RMSE were used to validate the estimation.

6. Results and discussion

6.1. Water levels

Water levels for Lake Mead were obtained from Hydroweb and ICESat-GLAS. There were 75 monthly water level values available in the Hydroweb database covering the period from 2000 to 2010. For ICESat-GLAS, 39 water levels corresponding to the ICESat campaign date were obtained during the whole operational period of ICESat (2003–2009). Fig. 2 compares water level time-series between in-situ measurements and those from Hydroweb and ICESat-GLAS. It should be noted that water levels from both Hydroweb and ICESat-GLAS were shifted vertically to the same datum with in-situ measurements by adding a shift constant following Birkett and Beckley (2010) (Table 4). Both water level time-series from Hydroweb and ICESat-GLAS were in good agreement with in-situ measurements in phase and amplitude with R^2 of 0.99 (Table 4). However, the maximum water level during the whole period was underestimated by Hydroweb (Fig. 2(a)). As clearly shown in Fig. 2(a), the water level in Lake Mead dropped about 40 m during the period 2000–2010. This continuous drop in water level was caused by two main reasons: the sustained decreased in runoff from the upstream Colorado River due to the extended drought, and the increasing water demands caused by population growth in the Lake Mead Basin (Holdren & Turner, 2010; Li et al., 2010). From Fig. 2, the lowest water level that occurred in each time-series was also identified correctly. Because Hydroweb water level time-series and ICESat-GLAS time-series cover different periods (2000–2010 versus 2003–2009) and at different time intervals (monthly versus campaign dates), the date of the lowest water level observed with Hydroweb and ICESat-GLAS products was different. In Hydroweb time-series, the lowest water level occurred in October, 2010; in ICESat-GLAS time-series the lowest water level occurred on October 2, 2009. The RMSE between water levels from Hydroweb and in-situ measurements was 64.1 cm (Table 4). Lake Mead was not included in previous studies where altimetry water levels were compared with in-situ measurements, but the RMSE for Lake Powell was reported to be 80 cm (Crétaux et al., 2011). Because Lake Powell has a similar shape (long and very narrow) and size as Lake Mead, the results revealed consistency. As described in Section 5.3, the distance between in-situ gage station and the tracks of satellite altimeter missions inevitably contributed to the RMSE. In addition, the high RMSE from satellite radar altimetry for such small bodies could be partly due to the inclusion of land and island information in the radar footprint for range measurements, and also due to the poor model-based wet tropospheric range correction (Birkett & Beckley, 2010). ICESat-GLAS was better than Hydroweb with a RMSE of 35.0 cm. This could be partly due to the smaller footprint of the satellite laser altimeter (ICESat) than radar altimeters (data used for Hydroweb). Hence, ICESat-GLAS could be more suitable for small and narrow lakes but the time interval is inconsistent, corresponding to campaign dates.

For Lake Tana, all four satellite altimetry products provided water levels. For each product, only water levels within the period of in-situ measurements (January 1, 1992–August 31, 2006) were used for validation. GRLM provided 482 water levels for Lake Tana at a consistent interval of 10 days. From RLH product, 34 water levels could be obtained covering the period October 16, 2002 to August 16, 2006 with a consistent interval of 35 days. Hydroweb provided 168 monthly water levels. From ICESat-GLAS, only 13 water levels corresponding to campaign dates were obtained for Lake Tana covering October 16, 2003 to June 26, 2006. Comparisons of water level time-series between in-situ measurements and those from GRLM, RLH, Hydroweb and ICESat-GLAS are shown in Fig. 3. The shift constant values are presented in Table 4. The observation of large shift constant values for GRLM and RLH is because both the original GRLM and RLH data are referenced to the mean level (see Table 1, and Sections 4.2.1

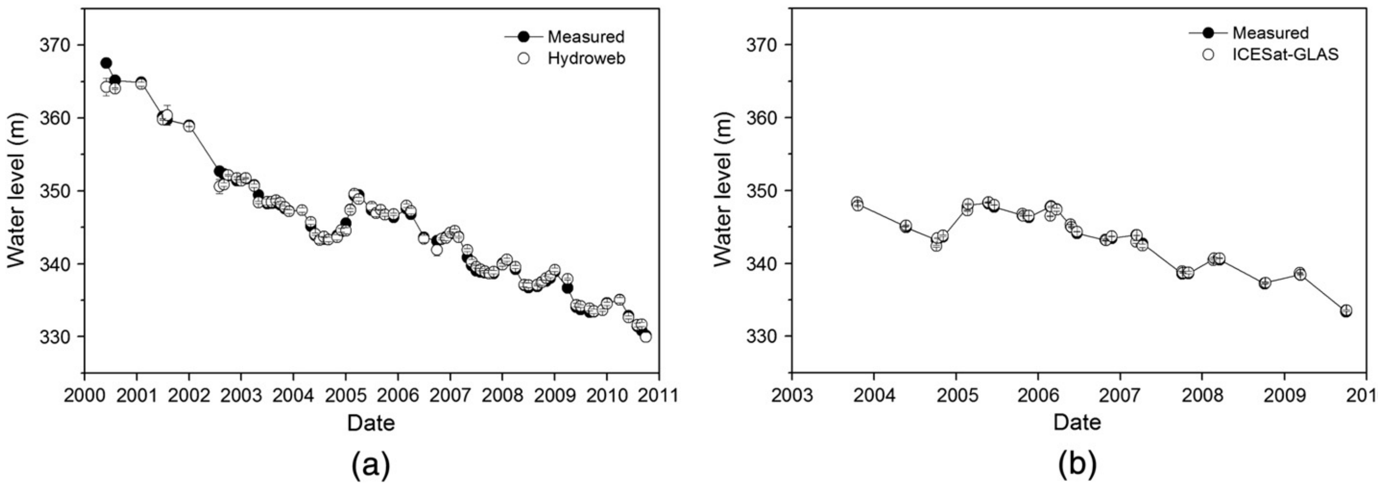

Fig. 2. Comparison between measured water levels and satellite altimetry water levels with standard deviation as error bar (a) Hydroweb and (b) ICESat-GLAS for Lake Mead between 2000 and 2010.

and 4.2.2). It should be noted that in Fig. 3(a) and (c) the observed sudden drop in water level in 2002 is mainly due to the construction of the Chara Chara weir at the outlet in Bahir Dhar commencing from 2000 (Chebud & Melesse, 2009). The drop in water level could be also due to the fact the year 2002 was a dry year with less rainfall in the Lake Tana Basin (Duan & Bastiaanssen, 2013). Time-series from each satellite altimetry product agreed well with in-situ measurement with R^2 of 0.95 to 0.97 (Table 4). However, the standard deviation (STD) from RLH appears to be relatively large as shown by the error bar included in Fig. 3(b). As shown in Fig. 1(b), the effective track of ENVISAT mission (which RLH data are mainly derived from) over-flied the island within Lake Tana. Therefore, we guess that the higher STD could be due to the inclusion of some land-contaminated ENVISAT measurements (which happed around the island within Lake Tana) in the averaging computation of all measurements along the ENVISAT track for the final water level. The raw data of ENVISAT should be used to analyze the exact reasons for the higher STD in RLH. The lowest water level in each time-series was also correctly identified (i.e. occurred on June 18, 2003 in GRLM; May 14, 2003 in RLH; June, 2003 in Hydroweb; June 20, 2004 in ICESat-GLAS). It should be noted that for some cases water levels derived from satellite altimetry could be abnormally low (or high) which will affect the determination of the lowest water level as the reference for further water volume variation estimation. For example in GRLM as shown in Fig. 3(a), the water level on February 28, 1996 is abnormally low, but this could be identified as an outlier easily and removed from further analyses based on the long-term water level time-series. Thus, for the accurate determination of the lowest water level as a reference it is best to use a long enough water level time-series. The RMSE between each satellite altimetry database and in-situ measurements was similar, ranging from 10.5 to 16.2 cm. This could indicate that satellite laser altimetry (i.e. ICESat) with a narrower footprint does not perform significantly better than satellite radar altimetry for big lakes or reservoirs where the contamination of land/coastline within the footprint is no longer a big issue.

For Lake IJssel, water levels were obtained from GRLM and ICESat-GLAS only. Lake IJssel rarely freezes and has no tide effect, but it suffers from north-western wind effect resulting in short-term water level fluctuations (P. H. A. J. M. van Gelder, personal communication, 2012). Considering this possible wind effect and the availability of four stations at 10-minute intervals, we carried out a strict selection of in-situ water levels for validations of satellite altimetry products, i.e. only the mean water level of four gaging stations at 10-minute intervals with a standard deviation within 10% of the mean value were used. A small standard deviation indicates stability of the water level of the entire lake, thus the possible wind effect can be excluded. The exact date (to the hour and minute) for each water level from GRLM and ICESat-GLAS was used to select the corresponding 10-minute mean in-situ water levels. Finally 78 and 7 in-situ water levels passed the aforementioned strict selection for validation of GRLM and ICESat-GLAS, respectively. Fig. 4 compares the time-series of in-situ measurements and shifted water levels from GRLM and ICESat-GLAS. For GRLM as shown in Fig. 4(a), the water level variation seemed to follow a similar line with the in-situ measurement in general, but there were still discrepancies in amplitude and phase and the agreement was low with R^2 of 0.49 although the RMSE was 7.9 cm (Table 4). Birkett et al. (2011) described the desirable accuracy to be better than 10% of expected total seasonal fluctuation and the accepted accuracy must allow for a discernible capture of fluctuation. Lake Mead showed a general declining trend of about 40 m, and the RMSE (64.1 or 35.0 cm) is only 1.6% or 0.9% of the targeted large fluctuation. For Lake Tana, the RMSE of 10.5–16.2 cm is 6.6–10.1% of the target seasonal fluctuation of 1.6 m. The small ratio of RMSE to the target fluctuation could be the reason why the fluctuation in phase and amplitude was accurately captured for Lake

Table 4
Statistics for satellite altimetry water levels for the three studied lakes when compared to in-situ measurements.

Study area	Database	Period	No.	R^2	RMSE (cm)	Shift constant (m)	Measured mean water level (m)
Lake Mead	Hydroweb	2000–2010	75	0.99	64.1	−0.7922	344.2
	ICESat-GLAS	2003–2009	39	0.99	35.0	0.2457	343.3
Lake Tana	GRLM	1992–2006	482	0.95	16.2	1786.4612	1786.2
	RLH	2002–2006	34	0.96	11.5	1786.1699	1785.8
	Hydroweb	1992–2006	168	0.95	13.3	−1.5055	1786.2
	ICESat-GLAS	2003–2006	13	0.97	10.5	−0.7298	1785.8
Lake IJssel	GRLM	2002–2010	78	0.49	7.9	−0.3619	−0.3
	ICESat-GLAS	2003–2009	7	0.06	87.0	0.5726	−0.3

"No." means the number of water level values from satellite altimetry products within the period of available in-situ measurements for validation.

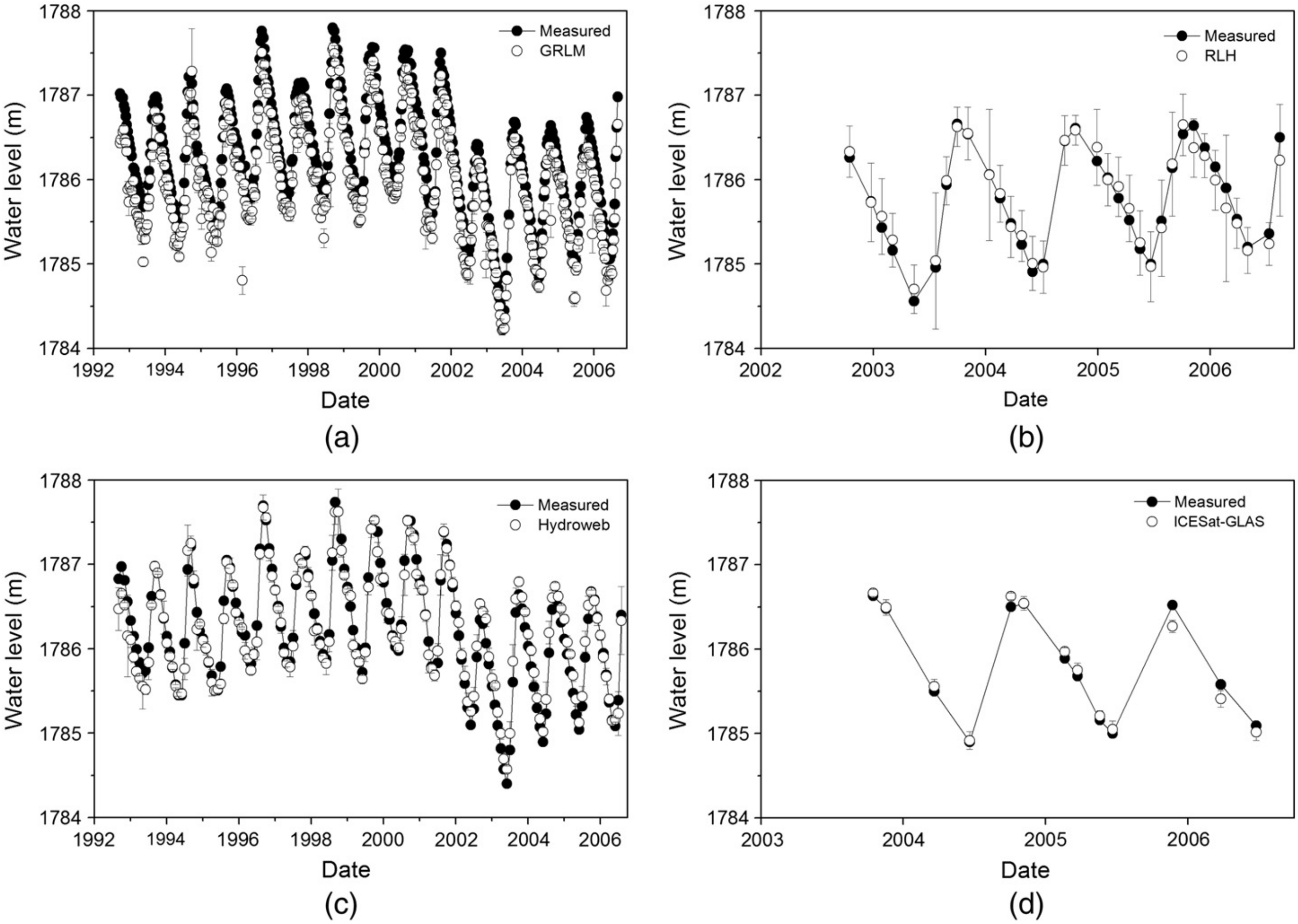

Fig. 3. Comparison of satellite altimetry products and measured water levels for Lake Tana between January 1, 1992 and August 31, 2006. (a) GRLM (b) RLH (c) Hydroweb and (d) ICESat-GLAS. Error bars are estimated errors for GRLM, standard deviations for RLH, Hydroweb and ICESat-GLAS.

Mead and Lake Tana. Considering the minimal magnitude of fluctuation of 0.2 m for Lake IJssel, a higher accuracy may be required. An accuracy of 7.9 cm (39.5%) by GRLM seems to be insufficient to capture the small fluctuation. The precision (or minimum total error) of satellite radar altimetry-based water levels for lakes was reported to be about 4–6 cm (Birkett & Beckley, 2010; Crétaux & Birkett, 2006), the high noise-to-signal ratio (4–6 cm precision versus 20 cm water level variation) could be the main reason for the poor performance of GRLM for Lake IJssel. As shown in Fig. 4(b), an unexpected poor result was observed for ICESat-GLAS with little agreement with in-situ measurement

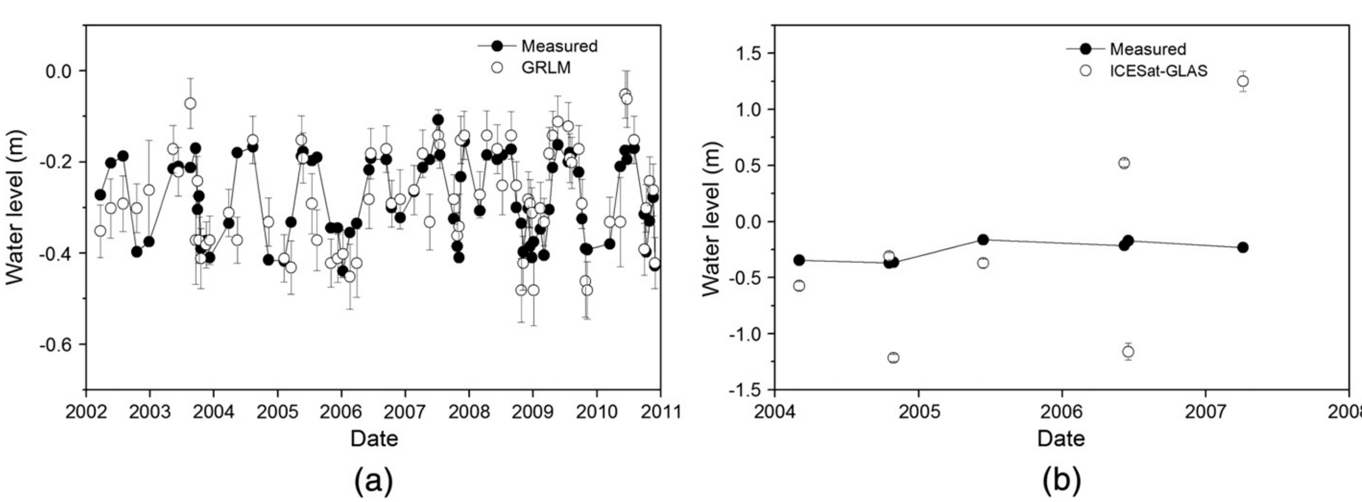

Fig. 4. Comparison of satellite altimetry products and measured water levels for Lake IJssel between 2002 and 2010. (a) GRLM and (b) ICESat-GLAS. Error bars are estimated errors for GRLM, standard deviation for ICESat-GLAS.

($R^2 = 0.06$) and a high RMSE of 87.0 cm (Table 4). The unexpected poor result from ICESat-GLAS could be due to the atmospheric effects such as cloud interference on laser altimetry. However, the quality flags for cloud (*i_cld1_mswf* and *i_MRC_af*) included in the ICESat-GLAS product were labeled as invalid for all tracks on Lake IJssel. The possible influence of a saturation effect (Urban et al., 2008) was rejected as we checked the saturation quality flag (*i_satCorrFlg*) included in ICESat-GLAS and found that most ICESat elevations were labeled as "no saturation effect". The very limited number of elevations labeled as "saturation effect" was already removed for final water level computation. Details of these three quality flags can be found in the GLAS Altimetry Data Dictionary (2012). The mentioned saturation effect refers to the phenomenon that the energy in the altimeter return pluses exceeds the GLAS receiver linear dynamic range, which will result in clipped-peak waveforms and further cause the negative bias in the estimated surface elevations or water levels (GLAS Altimetry Product Usage Guidance, 2013; Urban et al., 2008).

Given that (1) the objective of this paper was to propose a method for estimating water volume changes; (2) only high-level satellite altimetry databases were used which could not provide enough information (i.e. values for each item in Eq. (1) and details on the adopted methods for retracking and corrections), we could not further investigate the exact reasons for the poor results of Lake IJssel as well as some outliers in GRLM (Fig. 3(a)) and the high STD in RLH (Fig. 3(b)) for Lake Tana in this paper. This highlights the need for two future studies. Firstly raw satellite radar and laser altimetry data should be used to separately check each item (e.g. range measurement and corrections) which was used to generate the final water levels. This separate analysis can help to explain the poor results for Lake IJssel and outliers in GRLM and high STD in RLH. Secondly, more lakes/reservoirs with small fluctuation (<0.5 m) need to be studied to test the performance of satellite altimetry, as also stressed by Birkett and Beckley (2010). Such studies will show whether Lake IJssel is an exceptional case with poor results or whether the results reflect the general limitation of satellite altimetry for lakes with such small fluctuation. Given the poor water level results, water volume estimation was not conducted for Lake IJssel.

It is worth mentioning several practical issues for the investigated four satellite altimetry databases. As mentioned in Section 2, the water levels are derived using the Eq. (1), thus the accuracy/quality of the final-product water levels depends on the accuracy/quality of each item (in particular "Range" and corrections) in Eq. (1). The data from three radar altimetry databases (GRLM, RLH and Hydroweb) are already processed and the user could not do some refinement in order to improve the quality of the data. In addition, the values for each item in Eq. (1) are not given which renders the user inability to diagnose the quality of data. In some situations, several lakes and reservoirs which are actually measured by satellite radar altimetry could not be included in GRLM, RLH and Hydroweb databases due to the ongoing development and specific objectives of these three databases. In that case, one has to process the raw satellite radar altimetry data to derive water levels. The practical procedures can be found in many papers (e.g. Birkett et al., 2011; Medina et al., 2008; Ponchaut & Cazenave, 1998). The Basic Radar Altimetry Toolbox (BRAT) can be helpful for processing such raw data, which is freely available at: http://www.altimetry.info. Another issue relates to the sparse temporal sampling (at best 10-day intervals, see Table 1) of these databases. One may wonder whether it is possible to combine water levels from different databases for improved temporal sampling. Strictly speaking, the reasonable combination should be conducted using the raw data from different altimeters and after the biases between different altimeters must be accounted for (Birkett et al., 2011; Calmant et al., 2008; Frappart et al., 2006a). The sufficient number of coincident crossover measurements is required to determine the biases between different altimeters, which often cannot be achieved for inland water bodies where different altimeters cross over different locations at different times (Birkett et al., 2011; Frappart et al., 2006a). The combination of different altimeters has been well applied for the oceans, the readers interested in the combination techniques are referred to Le Traon and Ogor (1998) and Ducet et al. (2000). With the assumption that no spatial variation in water level at a given day, the practical solution to combining three databases GRLM, RLH and ICESat-GLAS (Hydroweb cannot be combined as it provides monthly-average data) for several large or "lucky" lakes where multiple altimeters crossed over is to find an adequate number of coincident data to compute the datum conversion constant among the three databases to account for the difference in the different reference systems (Table 1). The procedure by Siddique-E-Akbor et al. (2011) can be used to bring a given database (e.g. GRLM) into a reference database (e.g. ICESat-GLAS). In the case of this study, far limited number of coincident data was observed among GRLM, RLH and ICESat-GLAS for Lake Tana (only 2 coincident data between GRLM and RLH, no for others), therefore we cannot combine them into a complete time-series in a reasonable way.

6.2. Water volumes

For Lake Mead, the lowest water level in Hydroweb occurred in October, 2010 with an original value of 330.7519 m. The original value is the absolute value obtained from satellite altimetry products rather than a vertically shifted value to fit in-situ measurements. Only satellite measurements were used for water volume estimation in this study without any in-situ data. All 75 original water levels from Hydroweb were converted into WLALL by subtracting the minimum value in October, 2010. Subsequent estimates of water volumes were also based on the lowest water level i.e. the value in October, 2010. For validation purposes the in-situ measurements of water volumes were thus also converted into WVALL, i.e. water volumes above the water level measured in October, 2010. For ICESat-GLAS, the lowest water level occurred on October 2, 2009 with an original value of 333.2855 m. Subsequently, all 39 ICESat-GLAS water levels were converted into WLALL, and in-situ measurements were also converted into corresponding WVALL. It should be noted that the lowest water level is different for different satellite altimetry products. No inter-comparison in water volume estimations can be carried out for different satellite altimetry water levels, unless they coincide on the same day.

According to the lowest-highest sequence of WLALL from both Hydroweb and ICESat-GLAS, 11 and 10 Landsat TM/ETM + images coinciding with the dates of the water levels were selected to estimate corresponding surface areas. Table 5 lists these original water levels, WLALL values, corresponding selected images, and estimated surface areas using the MNDWI method. Regression analyses using pairs of WLALL and surface area (11 pairs for Hydroweb and 10 pairs for ICESat-GLAS) showed that the WLALL–surface area relationship can be expresses by two second-degree polynomials, with an R^2 of 0.99 for both Hydroweb and ICESat-GLAS (Fig. 5). Furthermore, a third-degree polynomial function of WVALL and WLALL was generated using the standard analytical integration (the function is included in Fig. 5). Finally, 75 and 39 values of WVALL were obtained by converting all WLALL using the corresponding WVALL–WLALL function for Hydroweb and ICESat-GLAS, respectively. The behavior of the time-series of water volume variations is similar with the water level variations shown in Fig. 2 except the difference in the absolute values, thus the time-series of water volume variations was not presented for conciseness, rather a common 1:1 line figure was presented to give a more clear comparison between in-situ and estimated values. Fig. 6 presents the comparisons between in-situ measurements and estimated WVALL using Hydroweb and ICESat-GLAS water levels. The estimated WVALL was in good agreement with in-situ measurements in amplitude and phase with a high R^2 of 0.99 for using both Hydroweb and ICESat-GLAS water levels (Table 6). There was little difference in the mean values of estimated WVALL and in-situ data. The RMSE was 344.45 and 175.74 10^6 m^3 i.e. 6.3%

Table 5
Summary of WLALL from Hydroweb and ICESat-GLAS water levels for Lake Mead and selected corresponding imagery data and estimated surface areas.

Water level sources	No.	Water levels			Landsat TM/ETM images		
		Date	Original (m)	WLALL (m)	Date	Sensor	Areas (km^2)
Hydroweb	1	2010-10	330.75	0.00	2010-10-14	TM	330.61
	2	2010-06	333.41	2.66	2010-06-24	TM	339.58
	3	2009-06	335.13	4.38	2009-06-21	TM	346.55
	4	2008-10	338.21	7.46	2008-10-24	TM	366.85
	5	2007-08	339.98	9.23	2007-08-03	TM	379.76
	6	2007-05	342.67	11.92	2007-05-15	TM	384.87
	7	2005-01	345.34	14.58	2005-01-17	TM	423.22
	8	2003-05	349.21	18.46	2003-05-20	TM	433.80
	9	2002-12	352.54	21.78	2002-12-27	TM	455.46
	10	2002-01	359.62	28.87	2002-01-17	ETM+	512.12
	11	2000-08	364.82	34.07	2000-08-15	TM	554.65
ICESat-GLAS	1	2009-10-05	333.29	0.01	2009-10-11	TM	349.98
	2	2008-10-09	337.10	3.80	2008-10-08	TM	371.76
	3	2009-03-14	338.18	4.90	2009-03-17	TM	375.53
	4	2008-02-19	340.14	6.92	2008-02-27	TM	380.09
	5	2006-10-30	342.81	9.61	2006-11-04	TM	402.21
	6	2007-03-16	343.60	10.32	2007-03-12	TM	403.32
	7	2004-05-19	344.88	11.53	2004-05-22	TM	407.83
	8	2005-11-20	346.29	13.01	2005-11-20	TM	420.38
	9	2006-02-27	347.53	14.24	2006-02-21	TM	424.10
	10	2005-05-25	348.01	14.84	2005-05-25	TM	426.78

"Original" means the original value directly from the satellite altimetry products; "WLALL" is obtained by subtracting the lowest water level in the time-series during the study period.

and 4.6% of the mean value of in-situ measurements, using Hydroweb and ICESat-GLAS water levels, respectively.

During the available in-situ measurements period (January 1, 1992 to August 31, 2006), the lowest water level for Lake Tana occurred on June 18, 2003 with an original value of −2.01 m in the GRLM water level time-series; and on May 14, 2003 with an original value of −1.470 m in RLH; and in June, 2003 with an original value of 1786.0782 m in Hydroweb. Using ICESat-GLAS the lowest level occurred on June 20, 2004 with an original value of 1785.646 m. Each satellite altimetry time-series was converted into WLALL. Four sets of Landsat TM/ETM + images coinciding with the date of WLALL from each product were selected according to the lowest-highest sequence of WLALL: 11 images for GRLM, 8 images for RLH, 10 images for Hydroweb (at monthly scale) and 6 images for ICESat-GLAS. For GRLM, Hydroweb and ICESat-GLAS, no suitable images could be found to match the date of the lowest water level due to either poor quality of images or too large a date shift/difference. It should be noted that for RLH one selected image was 8 days after the date of the corresponding water level. This image was selected because the corresponding water level was the higher water level in the RLH time-series and would have a large effect on further surface area–level relationship establishment. In addition, for ICESat-GLAS, the small number (13) of water levels added the difficulty to select the coinciding imagery data. The desirable criterion (selecting images that are within 5 days before or after) was thus relaxed to be within 8 days for using ICESat-GLAS data. This impact of relaxing criterion is negligible as we found the variation in surface areas during the 8-day shift period (Table 7) is within 0.2% according to in-situ measurements from bathymetric survey. Four sets of images were further used to derive surface areas using the MNDWI method. Table 7 lists these original water levels, WLALL values, corresponding selected images, and estimated surface areas for each satellite altimetry product for Lake Tana. The WLALL–surface area relationship was obtained through regression analysis using each set of pairs of WLALL and surface area, and the WVALL–WLALL relationship was further determined by analytical integration. Fig. 7 shows the established WLALL–surface area relationship (all with an R^2 larger than 0.92) and analytical

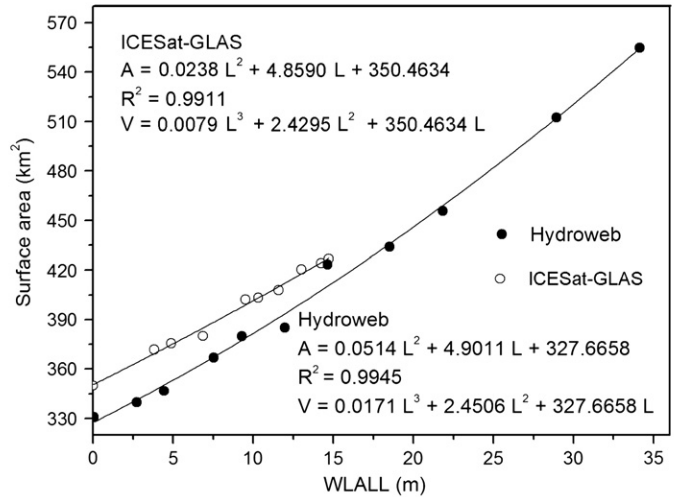

Fig. 5. Surface area (A)–WLALL (L) and analytical integrated WLALL (L)–WVALL (V) relationships for Lake Mead using water levels from Hydroweb and ICESat-GLAS products.

integrated WVALL–WLALL relationship for four satellite altimetry water levels.

These four sets of WLALL values were converted into WVALL values using the established WVALL–WLALL functions. Fig. 8 compares estimated WVALL using satellite altimetry water levels and in-situ measurements. All estimated WVALL agrees well with in-situ data with R^2 larger than 0.95 (Table 6). The RMSE ranges from within 9.4% to 13.1% of mean value of in-situ measurements.

It should be noted that in addition to the errors in altimetry water levels and extracted surface areas, the mismatch in dates between Landsat imagery data and satellite altimetry products can introduce additional errors in the subsequent water volume estimations. This limitation could be overcome by using satellite imagery data from other satellite systems, such as SPOT, ASTER, DMC, CBERS, HuanJing, IRS, RapidEye multispectral imagery and radar images from Radarsat and ENVISAT (ASAR).

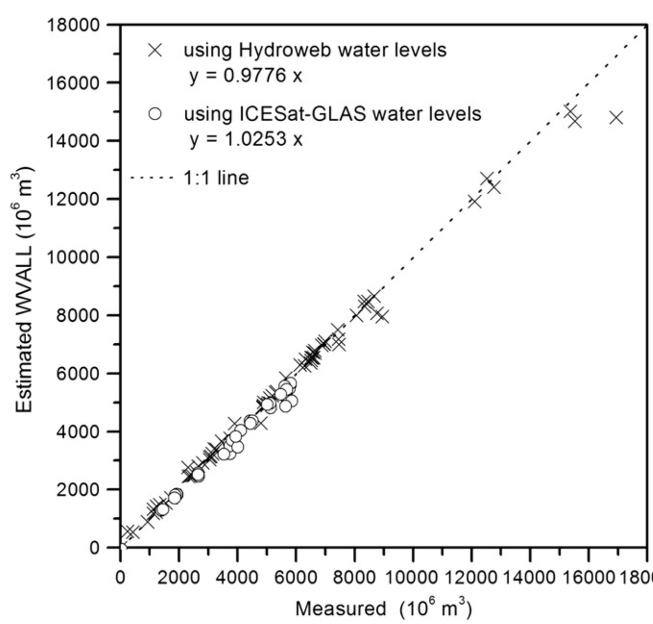

Fig. 6. Comparisons between in-situ measurements and water volume variations estimated from using Hydroweb and ICESat-GLAS water levels for Lake Mead.

Table 6
Statistics of estimated water volumes for Lake Mead and Lake Tana when compared to in-situ measurements.

Study areas	Water level sources	Period	No.	$Mean_{measured}$ (10^6 m^3)	$Mean_{estimated}$ (10^6 m^3)	R^2	RMSE (10^6 m^3)	RMSE/$Mean_{measured}$ (%)
Lake Mead	Hydroweb	2000–2010	75	5440.56	5402.20	0.99	344.45	6.33
	ICESat-GLAS	2003–2009	39	3805.54	3707.82	0.99	175.74	4.62
Lake Tana	GRLM	1992–2006	482	5246.90	5349.20	0.95	494.77	9.41
	RLH	2002–2006	34	3562.79	3236.77	0.96	465.96	13.08
	Hydroweb	2003–2006	168	5403.01	5027.51	0.96	541.03	10.01
	ICESat-GLAS	2003–2006	13	2673.20	2700.64	0.97	309.90	11.59

"No." is the number of estimated water volume values during the study period; "$Mean_{measured}$" and "$Mean_{estimated}$" are the mean values of measured data and estimated result, respectively.

7. Conclusions

Knowledge of water volume variations in lakes and reservoirs is essential for water balance studies and water allocation and water release strategies by the responsible agencies. The main objective of this paper was to propose a new method for estimating water volume changes using only satellite data without in-situ gage measurements. All four presently available satellite altimetry products i.e. GRLM, RLH, Hydroweb and ICESat-GLAS were used to obtain water levels for three lakes/reservoirs with entirely different characteristics: Lake Mead, Lake Tana and Lake IJssel. The availability of water levels for a specific lake/reservoir differs in the four products, but for Lake Tana all four products provided water levels. Satellite altimetry products were in good agreement with in-situ water levels for Lake Mead ($R^2 = 0.99$) and Lake Tana (R^2 ranged from 0.95 to 0.97), but not for Lake IJssel ($R^2 = 0.06$ to 0.49). The exact reasons for the poor results of Lake IJssel should be investigated using raw satellite altimetry data in more depth in the future study.

Table 7
Summary of WLALL using GRLM, RLH, Hydroweb and ICESat-GLAS water level values and corresponding selected imagery data and estimated surface areas for Lake Tana.

Water level sources	No.	Water levels			Landsat TM/ETM images		
		Date	Original (m)	WLALL (m)	Date	Sensor	Areas (km^2)
GRLM	1	2003-05-19	−1.83	0.18	2003-05-18	ETM+	2966.88
	2	2004-05-20	−1.30	0.71	2004-05-20	ETM+	3009.05
	3	2002-07-06	−1.19	0.82	2002-07-02	ETM+	3020.19
	4	2004-04-01	−0.92	1.09	2004-04-02	ETM+	3023.42
	5	1995-03-18	−0.39	1.62	1995-03-17	TM	3039.07
	6	1998-04-11	−0.14	1.87	1998-04-10	TM	3044.65
	7	2002-09-03	−0.12	1.89	2002-09-04	ETM+	3052.12
	8	2004-11-15	0.07	2.08	2004-11-12	ETM+	3063.01
	9	2000-02-04	0.13	2.14	2000-02-03	ETM+	3065.86
	10	2001-02-05	0.30	2.31	2001-02-05	ETM+	3066.37
	11	1998-11-05	0.77	2.78	1998-11-04	TM	3079.91
RLH	1	2003-05-14	−1.47	0.00	2003-05-18	ETM+	2966.88
	2	2004-06-02	−1.16	0.30	2004-06-05	ETM+	2996.40
	3	2003-01-29	−0.61	0.86	2003-01-26	ETM+	3028.71
	4	2002-12-25	−0.44	1.03	2002-12-25	ETM+	3036.13
	5	2005-03-09	−0.25	1.22	2005-03-04	ETM+	3042.02
	6	2006-01-18	−0.18	1.29	2006-01-18	ETM+	3047.67
	7	2005-12-14	0.11	1.58	2005-12-17	ETM+	3052.26
	8	2003-10-01	0.46	1.92	2003-10-09	ETM+	3064.65
Hydroweb	1	2003-05	1786.20	0.12	2003-05-18	ETM+	2966.88
	2	2002-07	1786.94	0.86	2002-07-02	ETM+	3020.19
	3	2002-04	1787.18	1.10	2002-04-29	ETM+	3034.74
	4	1995-03	1787.35	1.27	1995-03-17	TM	3039.07
	5	2000-05	1787.59	1.51	2000-05-25	TM	3051.24
	6	2002-01	1788.01	1.93	2002-01-23	TM	3058.32
	7	2001-02	1788.20	2.12	2001-02-05	TM	3066.37
	8	1998-12	1788.38	2.30	1998-12-06	TM	3071.16
	9	1998-11	1788.67	2.59	1998-11-20	TM	3079.91
	10	1998-10	1789.13	3.05	1998-10-19	TM	3085.51
ICESat-GLAS	1	2006-03-27	1786.14	0.49	2006-03-23	ETM+	3033.96
	2	2005-03-24	1786.48	0.83	2005-03-20	ETM+	3039.50
	3	2005-02-19	1786.70	1.05	2005-02-16	ETM+	3042.63
	4	2005-11-23	1787.00	1.35	2005-11-15	ETM+	3062.22
	5	2004-11-06	1787.27	1.63	2004-11-12	ETM+	3063.01
	6	2003-10-16	1787.39	1.75	2003-10-09	ETM+	3064.65

"Original" means the original value from the satellite altimetry products; "WLALL" is obtained by subtracting the lowest water level in the time-series during the study period.

Satellite altimetry products were combined with Landsat TM/ETM + imagery data to estimate the water volume variations for Lake Mead and Lake Tana. The surface areas were derived from Landsat images using the MNDWI method followed by visual digitization. The accuracy of estimated surface areas was reasonable with RMSE within 5% of the mean in-situ surface areas derived from bathymetric survey. The lowest water level captured in satellite altimetry products over the long-term can be used as a reference level for water volume estimation. All satellite altimetry water levels were converted to WLALL (Water Level Above the Lowest Level) by subtracting the lowest water level for each satellite altimetry product. The WLALL–surface area relationships were established by regression analysis of pairs of WLALL and corresponding surface areas derived from Landsat TM/ETM + imagery data. The WVALL (Water Volume Above the Lowest water Level)–WLALL relationships were further constructed through analytical integration. This allowed us to convert satellite altimetry water levels directly into time-series of water volume variations without becoming reliant on the support from in-situ measurements or bathymetry maps. This is an important advantage for operational application because changes in water storage are related to the releases from the lake or reservoir. All estimated water volumes agreed well with in-situ water volumes for both Lake Mead and Lake Tana, with R^2 higher than 0.95 and RMSE ranging between 4.6 and 13.1% of corresponding mean value of in-situ measurements.

This study demonstrated the feasibility of estimating water volume variations using only freely available satellite data for lakes and reservoirs where reasonable accurate water levels can be obtained from satellite altimetry. However, the availability of reliable in-situ measurements (especially for water volumes) limits us to study the very small number of lakes in this paper. More conclusive accuracy of satellite altimetry databases and proposed method should be assessed comprehensively using more different lakes/reservoirs with good-quality in-situ measurements in the future. Recent studies showed our proposed method also generated reasonable water volume variations for Lake Nasser (Egypt-Sudan) and Roseires Reservoir (Sudan) with R^2 of 0.94 and RMSE within 9-21% when compared with in-situ water volumes (Muala, 2012; Muala et al., submitted for publication). The proposed method can be extended with ease to other lakes or reservoirs which are included in these four databases. Several lakes and reservoirs which are actually measured by satellite radar altimetry could not be included in GRLM, RLH and Hydroweb databases due to the ongoing development and specific objectives of these three databases. It is technically feasible that users could process raw satellite radar altimetry data themselves to obtain water levels and then apply the proposed method to estimate water volume variations without in-situ measurements. Once water volume variation is determined, and combined with precipitation, evaporation and inflow, the water balance of lakes and reservoirs can be used to estimate outflow. When the estimated water volume variations

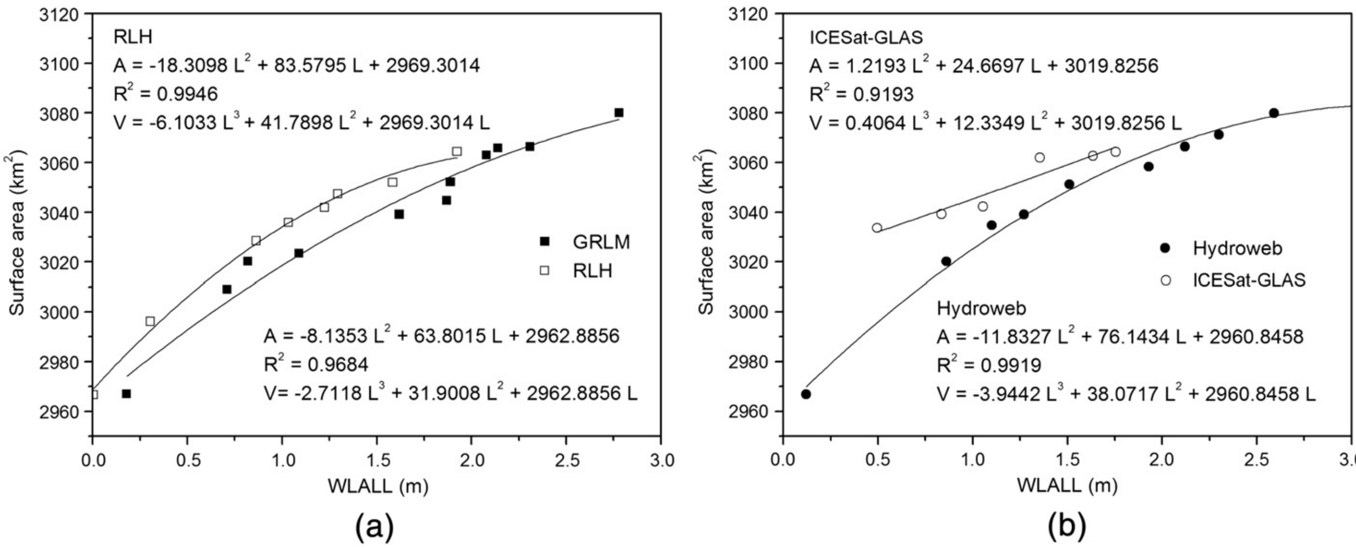

Fig. 7. Surface area (*A*)–WLALL (*L*) and analytical integrated WLALL (*L*)–WVALL (*V*) relationships for Lake Tana using: GRLM and RLH water levels (a); and Hydroweb and ICESat-GLAS water levels (b).

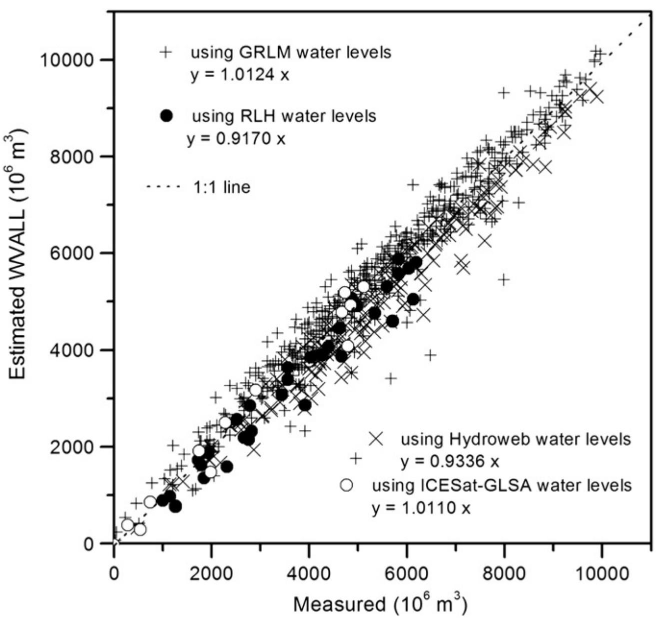

Fig. 8. Comparisons between in-situ measurements and water volume variations estimated from using GRLM, RLH, Hydroweb and ICESat-GLAS water levels for Lake Tana.

using our proposed method were combined with a simple water balance model, Muala et al. (submitted for publication) found that the estimated outflow/discharge from Roseires Reservoir agreed well with in-situ discharges (R^2 of 0.98 and RMSE within 18%). This study underscores the potential of remote sensing as a tool to monitor water volume variations in lakes or reservoirs and contributes to free access to water resources information.

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