Determining bathymetry of shallow and ephemeral desert lakes using satellite imagery and altimetry

M. Armon[1], E. Dente[1,2,3], Y. Shmilovitz[1,2], A. Mushkin[2], T. J. Cohen[4], E. Morin[1], and Y. Enzel[1]

[1]The Fredy and Nadine Herrmann Institute of Earth Sciences, the Hebrew University of Jerusalem, Israel.

[2]The Geological Survey of Israel, Israel.

[3]Shamir Research Institute, University of Haifa, Israel.

[4]School of Earth and Environmental Sciences, University of Wollongong, Australia.

Corresponding author: Moshe Armon (moshe.armon@mail.huji.ac.il)

Key Points:

- A new methodology to produce bathymetry maps of shallow desert lakes was developed, based on globally available datasets
- The methodology enables mapping the bathymetry of lakes with sub-basins or partially flooded lakes; both major limitations of other methods
- The derived bathymetry error is ~30 cm, rather than ~2.5 m for other globally available data

Abstract

Water volume estimates of shallow desert lakes are the basis for water balance calculations, important both for water resource management and paleohydrology/climatology. Water volumes are typically inferred from bathymetry mapping; however, being shallow, ephemeral and remote, bathymetric surveys are scarce in such lakes. We propose a new, remote-sensing based, method to derive the bathymetry of such lakes using the relation between water occurrence, during >30-yr of optical satellite data, and accurate elevation measurements from the new Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2). We demonstrate our method at three locations where we map bathymetries with ~0.3 m error. This method complements other remotely sensed, bathymetry-mapping methods as it can be applied to: (a) complex lake systems with sub-basins, (b) remote lakes with no in-situ records, and (c) flooded lakes. The proposed method can be easily implemented in other shallow lakes as it builds on publically accessible global data sets.

Plain Language Summary

Lakes in desert environments are often remote, shallow, and only get filled once in a long while. They are an important water resource, and could be used to decipher past environmental conditions. However, detailed maps of lake-floor terrain, which are required to effectively study these lakes are typically not available. The deepest parts of the lakes are filled with water more frequently than their shallow margins. Thus, we suggest here to relate water occurrence in those lakes with accurate satellite-based elevation measurements, to obtain a valuable lake-floor terrain map. We demonstrate the usefulness of our method by comparing results with other globally available data. Previous methods struggle with complex-terrain lakes or lakes that are partially flooded during their survey; while our method yields high-resolution accurate maps even in such lakes.

1 Introduction

A major characteristic of drylands is endoreism, internal drainage (de Martonne, 1927). The lower and usually drier parts of these drylands are often occupied by ephemeral or seasonal shallow desert lakes (Nicholson, 2011). Thousands of such lakes exist globally with the largest being Lake Eyre (Australia, alias Kati Thanda; surface area of >9000 km^2 when full). Such lakes are significant for opportunistic species that have no other water resources (e.g., D'Odorico and Porporato, 2006; Noy-Meir, 1973). Mapping of lake floors is key in calculating water balance (e.g., Cohen et al., 2015; Enzel and Wells, 1997), important in water resources management, and in deciphering paleoehydrology (e.g., Crétaux et al., 2016; Quade et al., 2018). However, being shallow, dry and remote, bathymetric surveys (e.g., as in Bye et al., 1978) have been scarce in such lakes.

A different approach to bathymetry mapping is through remote-sensing (Gao, 2015; Jawak et al., 2015). The Shuttle Radar Topography Mission (SRTM) has provided high resolution (~30m) global digital elevation models (DEMs) that could, in principal, present bathymetry of such desert lakes. Yet, radar altimetry cannot produce accurate DEMs if the area is flooded or where lake floors are exceptionally bright and/or smooth (Berry et al., 2007; Brenner et al., 2007), which are common conditions.

To improve lake-bathymetry maps, recent studies either integrate remote-sensing data with a spatial interpolation of in-situ measurements (Feng et al., 2011; Leon and Cohen, 2012) or combine between optical imaging and radar (e.g., Sun and Ma, 2019) or laser altimetry (Arsen et al., 2013; Li et al., 2019; Ma et al., 2019). These satellite imaging methods are based on determining isobaths (equal depth lines) of a lake, through snapshots during different lake stages. Then, shorelines in each specific image are assigned a height through accurate elevation measurements; such as laser altimetry. This determines bathymetry only to the depth of the lowest shoreline identified, using a spatial interpolation of a few isobaths. It also overlooks the possible variance in elevation of a specific shoreline, which can be significant in large lakes (Arsen et al., 2013; Feng et al., 2011). Li et al. (2019) suggested using a long-term (410 images during >30-yr) water occurrence index, instead of a few specific isobaths, and relating it with measurements from a limited dataset of airborne lidar altimetry. This overcomes shoreline elevation variations and makes spatial interpolation unnecessary. However, they assumed a linear relation between isobath areas, sampled at specific points, and elevation. Applying their methodology to a deep reservoir (Lake Mead; >100m deep) only revealed the bathymetry of the upper part of the lake; the deeper bathymetry was extrapolated with geometrical considerations, calibrated using in-situ data (Li et al., 2019). A further complication arises where water occurrence is not based directly on elevation, primarily where a lake is composed of a few sub-basins, which yields more than one possible relation between water occurrence and elevation. Accordingly, present-day methodologies and freely available datasets cannot provide accurate, high-resolution bathymetry of often-flooded, shallow desert lakes, especially for lakes having more than one sub-basin.

Thus, to derive the bathymetry of desert lakes, there is a need for: (a) an efficient and reliable way to recognize the water occurrence at a high resolution, (b) a technique to overcome diverse water occurrences-elevation relations in different sub-basins, (c) a way to derive the bathymetry when lakes are inundated, and (d) a robust method to validate the resultant bathymetry. To tackle these challenges, we developed a simple and easily implemented methodology that derives bathymetry of shallow desert lakes. This paper focuses on three desert lakes, ranging in area from 0.2×10^3 km^2 to 6×10^3 km^2. Lake bathymetries are acquired using the relation between globally-available high-resolution (30 m) water occurrence maps, and elevation data from NASA's new Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2).

Following is a description of the methodology and its application over Lake Eyre, which consists of a few sub-basins. We show the derivation of a bathymetric map for the lake and validate it versus the global SRTM and the best bathymetric map available for the region (Section 3). Having better results than the SRTM, we set to derive the bathymetry of a remote lake in the Sahara (Sabkhat El-Mellah) that has no other bathymetric map (Section 4) and of Lago Coipasa in the Altiplano for which we separately derive the bathymetry under dry and inundated conditions.

2 Methodology

Desert lakes are often fed by floods with monthly to decadal frequencies. Most of the coarser particles are deposited upstream, and thus, lake floors are mainly covered with fine low-permeability sediments, making evaporation the primary output (Nicholson, 2011). Water occurrence in these lakes is <100% of the time, and often <30%. Thanks to a detailed analysis of 3×10^6 Landsat images by Pekel et al. (2016), the frequency of water occurrence over 30 m pixels between 1984 and 2015 is easily accessible worldwide. Water occurs more often over the deeper parts of the lake, where complete evaporation takes longer, and less often over the higher lake margins. Thus, there should be a straightforward relation between water occurrences (i.e., the relative frequency of water in a pixel) and lake floor elevation over such lakes. This, in turn, allows measuring height over specific locations within the lake, from which we can infer the entire lake floor elevation.

ICESat-2 provides dense and accurate elevation measurements (0.7 m point spacing; accuracy and precision of <5 cm and <13 cm, respectively) over land, and even underwater. Thus it yields accurate, narrow (~14m) height profiles of Earth surface, since its launch in September 2018, with a 91-day revisiting frequency (Brunt et al., 2019; Markus et al., 2017). Underwater measurements can penetrate up to ~1 Secchi depth (Parrish et al., 2019), i.e. up to a few meters or even a few dozens of meters (Ma et al., 2019), depending on the optical properties of the water.

To derive bathymetry maps we rely on the relation between Water Occurrence and Laser Profile elevation (hereon WOLP) using four (to five) steps (described schematically in the supporting information Figure 1 [S1]): (a) acquiring a lake water occurrence map from the global water occurrence (Pekel et al., 2016); (b) extracting ICESat-2 elevation data (ATL03 product) that coincide with the lake (defined as regions with >0% water occurrence) (Figure 1a); (c) fitting a mathematical function describing the relation between water occurrence values and elevations (Figure 1b) based on all available scans in the lake extent; and (d) applying the fitted function areally, to translate the water occurrence map into lake-floor elevation over the entire lake basin (Figure 1d). For lakes consisting of sub-basins, an additional step is needed between steps c and d, in which we identify lake sub-basins from water occurrence, as detailed in Section 3 (e.g., Figure 1c). This methodology provides a bathymetric map of lakes that were flooded to some extent between 1984 and 2015, with a resolution of ~30 m.

To evaluate our methodology, we use available topographic data to demonstrate differences between our results and available bathymetric (or topographic) maps. Where the SRTM is the best external source, we use cross-validation, putting aside one ICESat-2 scan each time and validating the bathymetry based on all other scans. Owing to the high accuracy of the ICESat-2 data, we demonstrate the small expected error using our methodology.

3 Lake Eyre

Lake Eyre (Figure 2c, e) has a watershed covering almost 1% of the global land area (>1.1×10^6 km^2). It has a complex lake floor with a minimum elevation of -15.2 m relative to the Australian Height Datum (AHD) (Kotwicki and Isdale, 1991). The great flood of 1974 was utilized to perform bathymetric surveys over the lake, yielding a 0.5-m-contour-interval bathymetric map and detailing features >1 km^2 (Bye et al., 1978). Leon & Cohen (2012) (hereon LC12) combined data from this bathymetric map with SRTM data and ICESat-1 laser altimetry (with 170 m point spacing) to form the best bathymetric map of the lake that we are aware of. Because of its vast size, complex bathymetry, and a good reference map, we chose to apply our methodology over Lake Eyre. To have a continuous map, we only mapped Lake Eyre North (the larger and more frequently flooded part of the lake).
To overcome complexity arising from the different relations of water occurrence and elevation in each of the sub-basins (Figure 1b), we divided Lake Eyre North into five sub-basins using the water occurrence map (Figure 1a, S2). This enabled identification of pseudo watersheds, similar to determining watersheds in a topographic map (Supporting Information 1 [SI1]; Schwanghart and Scherler (2014)). We then performed steps b to d of our methodology, separately for each sub-basin (as exampled in Figure 1c). If more than one ICESat-2 scan intersected a watershed, we used data from all available scans. To form a single map out of the different sub-basins, regions close to the pseudo water divide were assigned values using step c from all neighboring sub-basins, inversely weighted according to their distance from the divide (SI1).

We validated the WOLP bathymetry map (Figure 1d) against SRTM data and the LC12 bathymetry over the entire region (Table 1, Figures 2a, 2b), and against ICESat-2 scans over the measured profiles (Figure S3). The WOLP bathymetry lies within ±0.5 m of LC12 elevations for 74% of the region (90% is within ±1 m), i.e., it lies within one elevation contour of Bye et al. (1978). Most of the remaining areas (deviating >1 m) are situated next to the lake margins, where the LC12 map is mostly based on SRTM data, which were acquired during a lake inundation interval, and are therefore not reliable over major parts of the lake (Leon and Cohen, 2012). In ~83% of the area SRTM data were replaced by a constant elevation value (-15 m AHD). The root mean square difference (RMSD) of the SRTM data versus the LC12 map is 1.77 m, and only 25% of the SRTM data are within ±0.5 m of LC12, whereas the WOLP bathymetry has a RMSD of 0.52 m (Table 1). Moreover, the mean RMSD for each of the sub-basins using cross-validation of the different ICESat-2 scans is 0.21-0.57 m (Figure S4), indicating that the WOLP map error is even smaller than it seems when comparing it to the LC12 map.
Hypsometric curves emphasize differences between these analyzed bathymetries (Figure 3), and are important for water volume estimates (SI2). Whereas the SRTM wet area sharply increases above the minimum elevation, because of the constant (-15 m) elevation polygon, the WOLP and the LC12 wet area curves present a gradual increase with depth (Figure 3a). Accordingly, water volumes are lower by ~75% both in the WOLP and LC12 bathymetries compared to the SRTM. Both the WOLP and the LC12 exhibit similar hypsometry in depths of <1 m (dissimilar to the SRTM). According to these maps, the southwestern sub-basin (Belt Bay) is the first to be filled (in accordance with MODIS imagery of floods, Supplementary movie 1 [SM1]). Differences between WOLP and LC12 bathymetries increase above lake depths of 1 m, when the southeastern sub-basin (Madigan Gulf) fills according to WOLP bathymetry. In the LC12 map, the sill between the southern sub-basins is higher and therefore the flooded area increases only above water depth of 2 m. Large differences exist between WOLP and LC12 at the lake's margins; there, LC12 bathymetry rises ~5 m above the lake bottom (Figure 3a). These differences seem to be related to the SRTM-dependent mapping of the lake margins in LC12. At a depth of 3.1 m, the WOLP flooded area reaches its maximum extent, featuring an area of 6.1×10^3 km^2 and a volume of 8.9 km^3, ~33% higher than the respective area and volume calculated based on the LC12 map (Figure 3a). Nevertheless, it is important to note that WOLP bathymetry represents only regions that were flooded between 1984 and 2015, and that the largest flood in recent history occurred in the 1970's. Therefore higher shorelines, as in LC12 or Cohen et al. (2018), could not be mapped with WOLP.

4 Application for non-mapped and inundated lakes

Sabkhat El-Mellah is a small, northwestern Sahara ephemeral lake (~170 km^2) (Figure 2e, f). It is fed in the High Atlas Mountains and is flooded only once every few years (Mabbutt, 1977). There is no bathymetric map of this lake that we are aware of. A comparison of the WOLP bathymetry (Figure S5) to the SRTM data (Figures 2d, S6) indicates generally a similar pattern (location of the deepest part of the lake and its margins, large scale slopes, etc.). However, variations of the SRTM data over Sabkhat El-Mellah are approximately ±2 m (Figures 3b, S6), while lake depth is ~5 m, yielding an uncharacteristic discontinuous and rough lake floor (e.g., Quade et al., 2018). The mean cross-validation RMSD of WOLP bathymetry is much lower (0.32 m; Table 1, Figure S7). The WOLP map exhibits a much higher flooded area in comparison with the SRTM data (Figure 3b). E.g., at a 1 m lake depth, the WOLP lake area is 0.15×10^3 km^2 versus 0.08×10^3 km^2 according to SRTM data.

The same methodology was applied over Lago Coipasa (or Salar de Coipasa; surface area up to 2400 km^2), which is a high altitude (3660 m), shallow saline lake, occasionally filled with water (Placzek et al., 2006) (Figure 2e, i). However, during February 2019, the lake was flooded (SM2), thus, ICESat-2 scans taken afterward exhibit both the water surface and the lake floor in its inundated region.

Recent studies highlight the ability of ICESat-2 scans to penetrate water and yield bathymetric profiles (Forfinski-Sarkozi and Parrish, 2016; Ma et al., 2019; Parrish et al., 2019). Therefore, we derived two different bathymetric maps of Lago Coipasa, one using all available "dry" scans (i.e., before February 2019; Figure S8), and the other (Figure S9) using only post-flood scans ("wet" scans), manually omitting the ICESat-2's water surface readings (SI3). The difference between the "dry" bathymetry and the SRTM data, and the difference between the "dry" and "wet" maps are shown in Figures 2g and 2h, respectively. Given the difficulty in determining water density, we did not correct the effect of the changing refraction coefficient between water and air on underwater elevation measurements. However, to avoid location errors, we used only nadir data, which are expected to have the least spatial error. The expected vertical error where water depth is ~0.7 m (SI3), as in this 2019 flood, is <0.18 m (Parrish et al., 2019) or even less (as shown in Ma et al., 2019).

Similar to Lake Eyre, the WOLP-SRTM difference map (Figure 2g) illustrates that Lago Coipasa was inundated during the SRTM scan, and the wet part of the scan was replaced with a fixed elevation value. The SRTM data over the lake area varies within ~±5 m (RMSD=2.84 m; Figures 3c and S10), meaning that over a ~1.5 m deep lake, such as Lago Coipasa, SRTM-based water volume calculations for all practical matters are absurd. In contrast, both the "dry" and the "wet" WOLP bathymetries yield a much smaller mean cross-validation RMSD value (0.28 m and 0.47 m, respectively; Table 1, Figures S11, S12).

The fixed-elevation polygon in the SRTM data for Lago Coipasa is bounded by high (>2 m) artificial walls. This is exhibited in the hypsometry by a sharp increase and then a fixed wetted area of 0.87×10^3 km^2 (Figure 3c). In lake depths of <1 m, the "dry" bathymetry presents a detailed gradual increase in lake area and volume, filling most of the maximum lake extent. The "wet" WOLP area at 1 m depth is smaller than the "dry" area due to a 1.3 m deeper lake bottom in the "wet" bathymetry (Figure 3c; SI2). Both the "dry" and "wet" scans did not cross the northernmost part of the lake, which is characterized by the highest water occurrence (and presumably deepest water column). For this reason, we stress that future crossing of ICESat-2 over this specific region of the lake could improve its bathymetry.

Compared with the "dry" bathymetry, 58% of the "wet" lake area lies within ±0.5 m of the "dry" bathymetry (RMSD = 0.39 m). Thus, relying on the "dry" bathymetric map, which seems reasonable in light of the results shown for Lake Eyre, we suggest that even when using only the "wet" scans, the WOLP bathymetry yields better results than the currently available global product (SRTM). This leads us to propose the usage of the methodology presented here for any of the world's shallow desert lakes.

5 Discussion

The largest source of uncertainty in the WOLP bathymetry stems from the selected fitting equation between water occurrence and elevation (step c). However, this selection affects mainly the extremities of data, i.e., the extrapolation of elevation to values that were not observed by the ICESat-2 (areas with gray dots in Figures 1c, S5, S8, S9). Thus, in cases where ICESat-2 data covers the water frequency extremities, WOLP bathymetry is accurate, as demonstrated by the cross-validation results. Large enough lakes should be covered by at least a few ICESat-2 scans (e.g., Figure 1a) and therefore, scans are expected to cover a wide range of water occurrences. This wide range can yield an accurate bathymetry for almost all of the lake extent.

Laser altimetry errors, estimated to be ~0.3 m for a single photon return, and much lower (0.05-0.07 m) for an average of neighboring photon returns (Jasinski et al., 2016), are not expected to impact our results significantly. A larger uncertainty lies between points that have a similar water occurrence but different elevation, as is the case if there are small and local topographic minima. Using more scans may decrease the variations, although some of them may be intrinsic, e.g., where transmission-losses or springs are common. Water occurrence minima can be too small to be identified as a different sub-basin. Thus, our method is limited to sub-basins that are large enough to be resolved with ICESat-2, as in Lake Eyre (Figure 1, SI1). In deriving the Lake Eyre bathymetry, we used at least four scans for each sub-basin, yielding an error of only 0.2-0.6 m (Table 1, Figure S4).

Another limitation to our methodology comes from the maximum water penetration of the ICESat-2 laser. This limits the ability to derive bathymetry in lakes that have a water depth of tens of meters or more. In such circumstances, a partial bathymetry could still be derived for the outskirts of the lakes using our methodology, or as presented in Li et al. (2019) or in Ma et al. (2019) for the shoulders of Lake Mead. However, we focus here on shallow desert lakes, in which, by definition, this is not a major obstacle.
Sediment deposition could also increase the uncertainty of the derived bathymetry. Here, we use satellite imaging water occurrence from >30-yr period (Pekel et al., 2016), implying that if the lake floor was altered during this time interval, present-day ICESat-2 scans can yield only an averaged bathymetry of this period. However, newer global water occurrence datasets could emerge in the near future, enabling both derivation of newer bathymetries, and higher resolution maps (e.g., 10-20 m pixels from Sentinel-2).
Apart from these limitations, taking a long series of satellite imagery extends a great opportunity. If only specific dates are used to identify isobaths (or shorelines), the error propagates to the bathymetric map. Using statistics based on many years, single image errors diminish. Such errors include water piling-up on one side of the lake due to winds (Arsen et al., 2013), misclassification of water boundaries or crossing isobaths (Long et al., 2019), and specific date imaging having only partial coverage of a lake, because of imaging geometry or cloud obscuration. Moreover, the use of specific date imagery requires a spatial interpolation between isobaths, thus concealing small features in between isobaths.
Out of the three lakes analyzed above, Lake Eyre is probably the most closely monitored, yet the nearest river gauge is situated many hundreds of kilometers upstream. Therefore, there is no accurate in-situ data for water input volumes. ICESat-2's high spatial resolution (~70 cm) combined with high-resolution water occurrence map (e.g., 30 m in the map of Pekel et al., 2016) yields an accurate, high-resolution bathymetry, even over flooded or complex desert lakes. Such maps could help in determining the water discharge into remote desert lakes and their evaporative losses, providing much-needed data in remote areas, serving as a basis for mass and energy balance calculations over such lakes, and for water management strategies.

6 Conclusions

Using a new methodology which links long-term water occurrence and accurate height measurements, each independently derived from satellite remote-sensing, we mapped the bathymetry of three shallow lakes in drylands across the globe. We verified the bathymetries using a previous bathymetric map, SRTM data, and through cross-validation. This easy-to-implement methodology yields a high-resolution bathymetry of shallow desert lakes that were flooded sometime during 1984-2015, using globally available datasets.

- As an example of a complex shallow lake system, we used Lake Eyre, consisting of multiple sub-basins. Despite its complexity, verification versus the best available DEM showed that the methodology is successful, as long as each sub-basin is covered by an elevation measurement scan.
- The methodology was also applied to two lakes with no previous bathymetry maps, one in the Sahara (Sabkhat El-Mellah) and the other in the Altiplano (Lago Coipasa). Results proved low cross-validation RMSD values (~0.3 m) compared with the SRTM data (~2.5 m).
- Applying the methodology in Lago Coipasa separately to "dry" and to "wet" ICESat-2 scans, relying on laser penetrability, we showed that bathymetry can even be produced during lake inundation.

The presented methodology can be applied to a large portion of the shallow lakes around the globe. It enables mapping of inundated lakes (a major obstacle for widely used methods), small lakes, and large and complex lake systems.

Acknowledgments and Data

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Figures and table

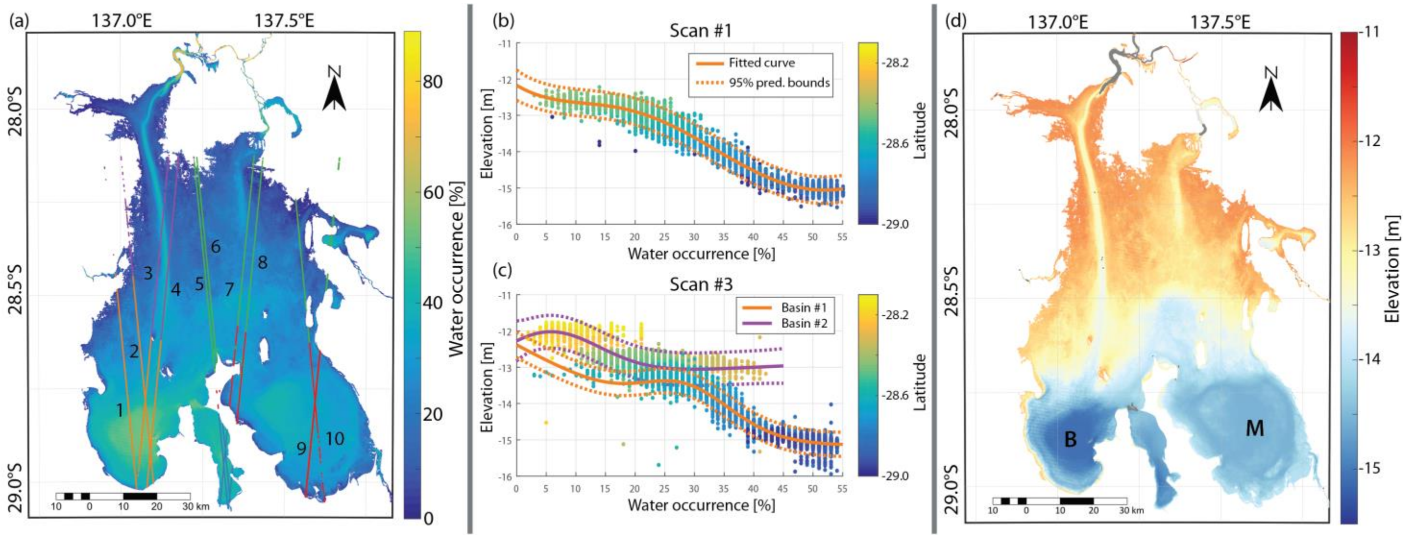


Figure 1. An example of bathymetry derivation in Lake Eyre North (a schematic representation of this process is in Fig S1). (a) Water occurrence from Pekel et al. (2016) and ten ICESat-2 scans over the lake (labeled) used to derive elevations. Scans are colored by the 5 identified pseudo-watersheds (SI1). (b) The relation between water occurrence and elevation measurements from ICESat-2 scan #1 with a two-term gaussian fit and its 95% prediction boundaries. Colors represent latitude. (c) The same as in b, but for scan #3. The fit here is divided according to the watersheds. (d) Derived bathymetry map based on the methodology presented in Section 2. Gray dots represent regions in which water occurrence is greater than the highest occurrence overpassed by ICESat-2. B = Belt Bay. M = Madigan Gulf.

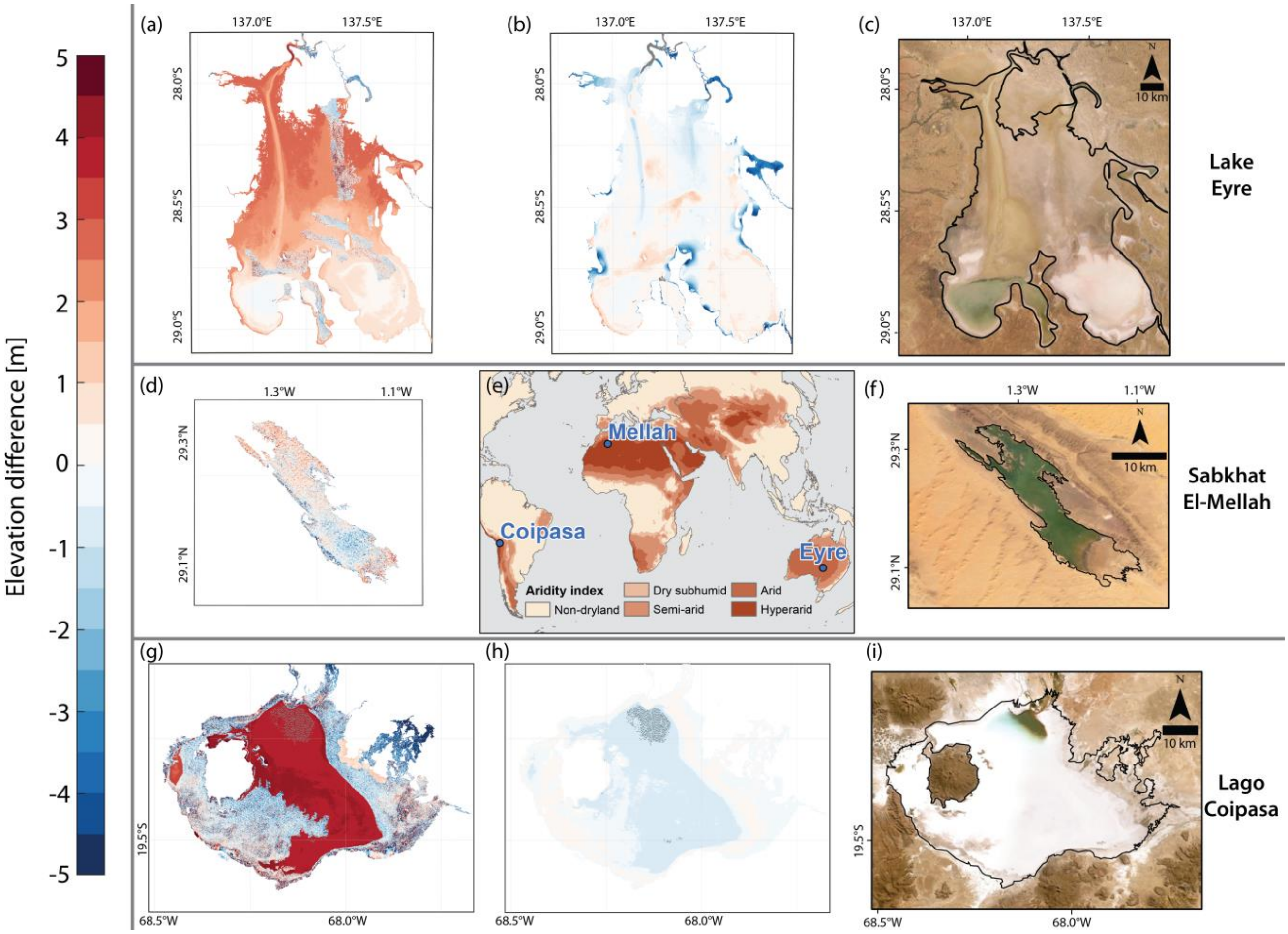
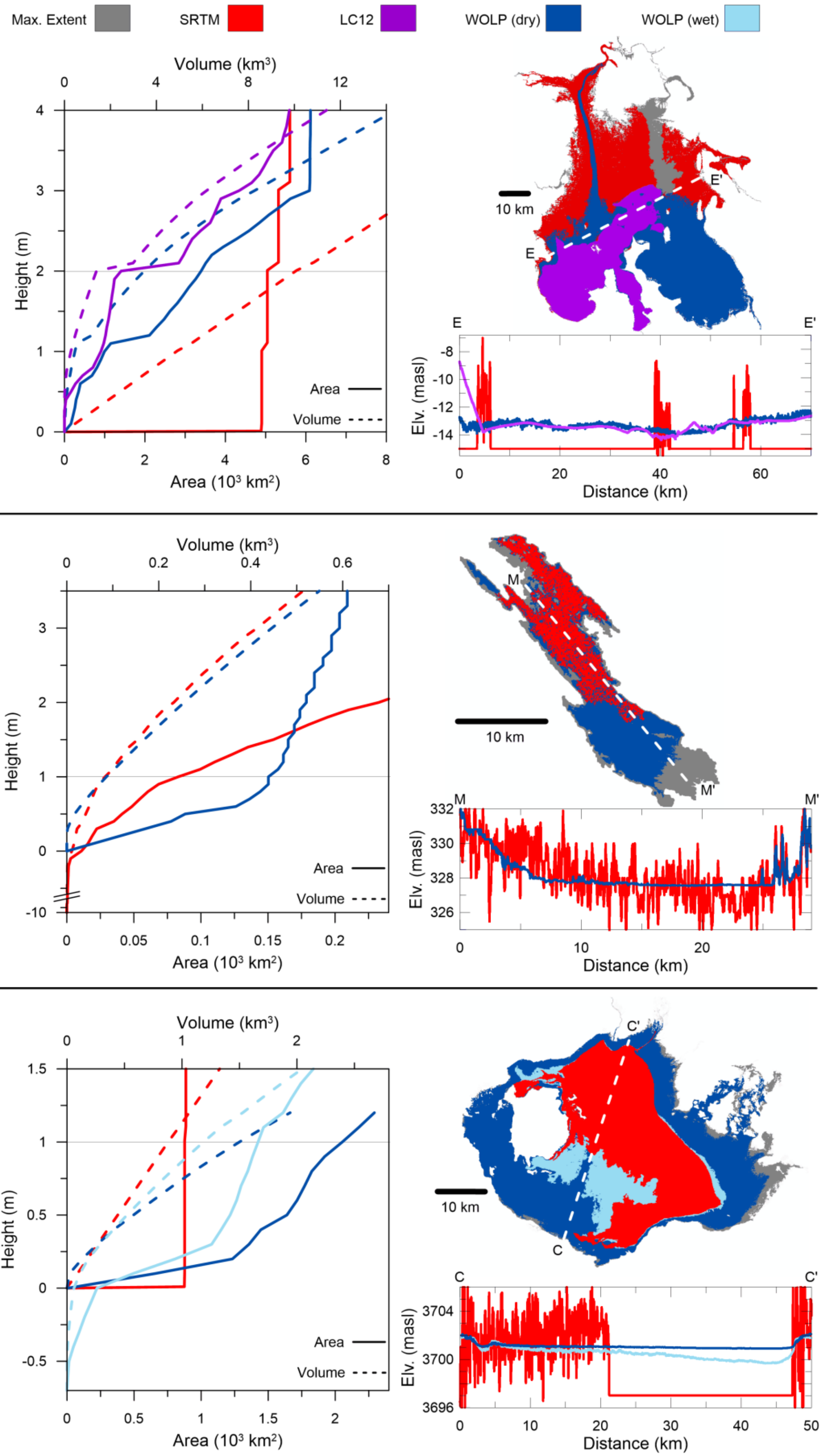


Figure 2. Comparisons of WOLP bathymetries with SRTM data in Lake Eyre (a), Sabkhat El-Mellah (d), and Lago Coipasa (g). (b) Comparison of Lake Eyre bathymetry with the map of Leon & Cohen (2012). (e) Location map of the three lakes, and aridity index (UNEP, 1992) from the Climatic Research Unit of the University of East Anglia (New et al., 2002). True-color satellite imagery of the lakes from Esri\Digitalglobe, and maximum extent of water occurrence in black) from Pekel et al. (2016) (c, f, i). (h) Difference between the “wet” and “dry” bathymetries of Lago Coipasa.



Max. Extent
SRTM
LC12
WOLP (dry)
WOLP (wet)
a
Volume (km³)
Height (m)
Area (10³ km²)
Area
Volume
10 km
E
E'
Elv. (masl)
Distance (km)
b
Volume (km³)
Height (m)
Area (10³ km²)
Area
Volume
10 km
M
M'
Elv. (masl)
Distance (km)
c
Volume (km³)
Height (m)
Area (10³ km²)
Area
Volume
10 km
C
C'
Elv. (masl)
Distance (km)

Figure 3. Hypsometric curves, extent maps and cross-sections for Lake Eyre (a), Sabkhat El-Mellah (b), and Lago Coipasa (c). The maps show filling extent at heights (denoted by a gray line on the hypsometric curves) that exert major differences between bathymetries. Details of the preparation of the hypsometries are in SI2.

Table 1. *Validation results across the lakes*

Lake	Validated map	Reference	Regional / Profile validation	RMSD [m]	Lake depth [m]
Lake Eyre	SRTM	LC12	Regional	1.77	3.2 (WOLP)[§], 4.1 (LC12)[§]
	WOLP (this study)	LC12	Regional	0.52	
	SRTM	ICESat-2	Profile	0.95-2.30*	
	LC12	ICESat-2	Profile	0.20-0.69*	
	WOLP	ICESat-2	Profile, cross-validation	0.21-0.57*	
Sabkhat El-Mellah	SRTM	ICESat-2	Profile	2.04[#]	5.0 (WOLP)[§]
	WOLP	ICESat-2	Profile, cross-validation	0.32[#]	
Lago Coipasa	SRTM	ICESat-2	Profile	2.84[#]	1.2 (WOLP: “dry”)[§]
	WOLP (“dry”)	ICESat-2	Profile, cross-validation	0.28[#]	
	WOLP (“wet”)	WOLP (“dry”)	Regional	0.39	2.2 (WOLP: “wet”)[§]
	WOLP (“wet”)	ICESat-2	Profile, cross-validation	0.47[#]	

*Range denotes the average RMSD for each sub-basin, averaged between the different ICESat-2 profiles in it.
[#]Average among the different ICESat-2 profiles.
[§]Estimated (see SI2).