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Deriving three dimensional reservoir bathymetry from multi-satellite datasets

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ABSTRACT

We evaluate different techniques that rebuild reservoir bathymetry by combining multi-satellite imagery of surface water elevation and extent. Digital elevation models (DEMs) are processed in two distinct ways in order to determine 3-D reservoir bathymetry. They are defined as (a) linear extrapolation and (b) linear interpolation. The first one linearly extrapolates the land slope, defining the bottom as the intersection of all extrapolated lines. The second linearly interpolates the uppermost and lowermost pixels of the reservoir's main river, repeating the process for all other tributaries. A visible bathymetry, resulting from the combination of radar altimetry and water extent masks, can be coupled with the DEM, improving the accuracy of techniques (a) and (b). Envisat- and Altika-based altimetric time series is combined to a Landsat-based water extent database over the 2002–2016 period in order to generate the visible bathymetry, and topography is derived from the 3-arcsec HydroSHEDS DEM. Fourteen 3-D bathymetries derived from the combination of these techniques and datasets, plus the inclusion of upstream and downstream riverbed elevations, are evaluated over Lake Mead. Accuracy is measured using ground observations, and show that metrics improve as a function of added data requirement and processing. Best bathymetry estimates are obtained when the visible bathymetry, linear extrapolation technique and riverbed elevation are combined. Water storage variability is also evaluated and shows that best results are derived from the aforementioned combination. This study contributes to our understanding and representation of reservoir water impoundment impacts on the hydrological cycle.

1. Introduction

Today, water security is a major issue in many regions in the world where humans face a changing climate. Manmade reservoirs and their operation play a key role in water storage and supply, and have a major impact on the water budget at the regional scale (e.g., Getirana, 2016; Wang et al., 2011). Reservoir operation rules or other related information, such as water levels and outflows, are not usually available for large scale modeling purposes. In that sense, numerous studies have proposed different techniques to infer reservoir dynamics worldwide through remote sensing. Water levels are commonly inferred through laser or radar altimetry (Birkett et al., 2010; Cretaux et al., 2011; Okeowo et al., 2017), water extent from land cover imagery, such as Landsat, MODIS and radar images (Jung et al., 2010; Jung et al., 2011; Messager et al., 2016) and storage by combining both of them (Duan and Bastiaanssen, 2013; Gao et al., 2012; Smith and Pavelsky, 2009; Zhang et al., 2014). Other studies have combined water extent with DEMs in order to determine the water storage variability in large river basins (e.g. Cretaux et al., 2015; Papa et al., 2013; Salameh et al., 2017).

Hydrological models have been critical in the understanding of the global water availability (e.g., Getirana et al., 2017), but most of these models neglect anthropogenic impacts. Few exceptions represent reservoirs as simple "buckets", where no bathymetric information is required, simulating water multi-use based on generic empirical equations (e.g., Doll et al., 2009; Haddeland et al., 2006). Recent progress in surface water dynamic modeling allows us to obtain a more physically based representation of reservoir operation impacts on the river network system (e.g., Mateo et al., 2014). However, global DEMs, commonly used to derive model parameters, inform us with the surface water elevation rather than the bathymetry, which is defined as the measurement of water body depths. Recent efforts have been put

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towards the development of more accurate global DEMs, accounting for different sources of errors and interferences (e.g. Yamazaki et al., 2017). Although some studies have suggested ways to improve flow directions in flat DEMs due to floodplains (e.g. Getirana et al., 2009a; Getirana et al., 2009b), water bodies are yet to be accurately accounted for in DEM processing. That imposes a major limitation in determining the actual reservoir water volume and depth, their variability and impacts on river systems. Determining the bathymetry of shallow waters is defined as one of NASA priorities in the 2017–2027 Decadal Survey for Earth Science and Applications from Space for a more accurate representation of the Earth topography (National Academies of Sciences, 2017). As a result, accurately representing the impacts of reservoir operation on the surface water dynamics can be achieved with improved DEMs where the bathymetry is properly represented.

Although some studies present techniques to estimate reservoir volume and depth through statistical relationships (e.g., Heathcote et al., 2015; Hollister et al., 2011; Sobek et al., 2011), remotely inferring 3-D reservoir bathymetry has been underexplored. Tseng et al. (2016) introduced a novel methodology to estimate water levels combining water extent time series with a three-dimensional bathymetry obtained through the linear extrapolation of DEMs. The technique was successfully applied to Lake Mead, and results were compared against ground observations. DEM extension through a linear extrapolation is a robust solution providing a first order representation of what the bathymetry could be, and easily transferrable to other reservoirs. However, unless the DEM was acquired during a low water period (Zhang et al., 2016), the inaccuracy of the 3-D bathymetry can be high, since the bottom, defined by the intersection of all extrapolated lines, can be unrealistic.

We address this issue by proposing and comparing different techniques for estimating 3-D reservoir bathymetry exclusively based on satellite data. They can be combined, increasing the level of data requirement and processing. Data sources include the Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS; Lehner et al., 2008), Envisat and Altika radar altimeters, and Landsat-based water extents. Lake Mead, located in Nevada, USA, is considered as the study case due to the large ground-based data availability, including bathymetric measurements, used for evaluation. It is also the largest reservoir in the U.S., with a maximum water capacity of 32.2 km^3. More specifically, we focus on the lower portion of the lake, the Boulder Basin (see Fig. 1 for location), which has a maximum water capacity of 10.5 km^3.

2. Datasets

2.1. Water extent

Water extent time series was derived from Landsat historical datasets (i.e. Landsat 4, 5, and 7 ETM+) for the 1982–2005 period, totaling 585 water extent maps (Tseng et al., 2016). Water pixels were classified from each of the Landsat datasets based on their green and shortwave infrared bands, known as the Modified Normalized Difference Water Index (MNDWI; Xu, 2006). For this study, water masks were generated to include all the pixels that have a value larger than 10% (considered “water”) in this Landsat frequency map. The Landsat series has a nominal spatial resolution of 1 arcsec using the WGS84 datum.

2.2. Water level

Water level time series were derived from both satellite and ground observations. We obtained daily historical water elevation from 1983 to 2016 for Lake Mead, at Hoover Dam, from Bureau of Reclamation Records. The water elevations are referenced to the adjusted United States Geological Survey (USGS) datum (i.e. locally known as Power House Datum), 0.55 ft lower than National Geodetic Vertical Datum 1927 (NGVD27) (USDI, 2011). Satellite-based water levels were derived from both Envisat and the SARAL/Altika radar altimeters. Envisat was launched by the European Space Agency (ESA) in 2002 had a cross-track interval ~80 km at the Equator and 35-day revisit period, which shared the same orbital elements with preceding ERS-1/-2 missions. The SARAL/Altika launched in February 2013 that follows Envisat is used to extend the altimetry time series. Here, we used the latest version of reprocessed Envisat Sensor Data Record (SGDR V2.1) provided by the *Centre National d'Etudes Spatiales* (CNES) Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) service, corresponding to cycle 6–93. The pass #406 near the Overton Arm of northern Lake Mead (Fig. 1) is selected to retrieved water elevations of both products. Overlapped range between satellite ground track and

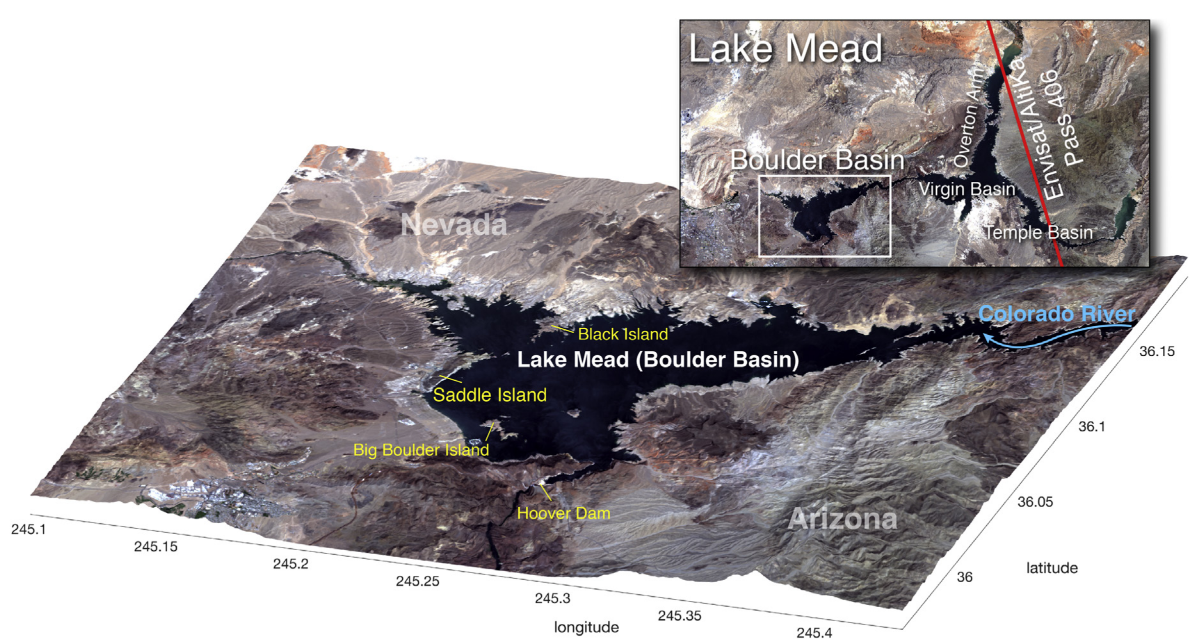

Fig. 1. Geographical information of Lake Mead in the USA and the Boulder Basin aimed in this study. This figure is derived from a Landsat-8 OLI image taken on August 14, 2017.