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Use of MODIS satellite images for detailed lake morphometry: Application to basins with large water level fluctuations

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ABSTRACT

Lake morphometry is essential for managing water resources and limnetic ecosystems. For reservoirs that receive high sediment loads, frequent morphometric mapping is necessary to define both the effective life of the reservoir and its water storage capacity for irrigation, power generation, flood control and domestic water supply. The current study presents a methodology for updating the digital depth model (DDM) of lakes and reservoirs with wide intra and interannual fluctuations of water levels using satellite remote sensing. A time series of Terra MODIS satellite images was used to map shorelines formed during the annual water level change cycle, and were validated with concurrent Landsat ETM+ satellite images. The shorelines were connected with in-situ observation of water levels and were treated as elevation contours to produce the DDM using spatial interpolation. The accuracy of the digitized shorelines is within the mapping accuracy of the satellite images, while the resulting DDM is validated using in-situ elevation measurements. Two versions of the DDM were produced to assess the influence of seasonal water fluctuation. Finally, the methodology was applied to Lake Kerkini (Greece) to produce an updated DDM, which was compared with the last available bathymetric survey (1991) and revealed changes in sediment distribution within the lake.

1. Introduction

The morphometry of a lake basin has a major impact on ecosystem structure and function through its influence on thermal regimes, mixing patterns, nutrient cycling and the extent of deep water anoxia (Wetzel, 2001). For reservoirs, however, the role of basin morphometry and its stability are of paramount importance over the effective life of reservoirs and resulting water storage capacity for irrigation, power generation, flood control and domestic water supply. In contrast to the relatively slow rate of infilling of lake basins, reservoirs often experience rapid sedimentation reflecting both the extremely large watershed to lake area ratio and pronounced water level fluctuations and associated shoreline erosion multiple times annually to sustain engineered system functions (Thornton et al., 1996).

Traditionally, lake bathymetric maps were developed from individual points along set transects where the position was triangulated by compass and water depth then measured with weighted ropes. Individual depth contours were subsequently constructed for the basin from multiple transects and related to average lake stage. In recent decades, most lake mapping has combined sonar depth finders and geographic positioning systems along multiple random transects across lakes using motorized boats (Kendra and Singleton, 1987; Moreno-Amich and Garcia-Berthou, 1989). Although the latter maps are accurate and less time consuming and can be used to chart distributions of macrophytes and fish, most lakes are still characterized by a single depth map, often decades or centuries old.

Because of great potential for rapid infilling by upstream sediments, often producing internal deltas and overall differential sedimentation patterns within the reservoir from shoreline erosion, bathymetric maps must be updated regularly to determine trajectories in effective life of reservoirs for their intended

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purpose. For reservoirs experiencing major water level fluctuations and where bottom sediments remain firm upon desiccation, bathymetric maps can be constructed for the exposed lake bottom using geodetic surveying of the exposed lake bed (Kress et al., 2005), and point measurements based on real-time or post-processed kinematic GNSS (Global Navigation Satellite System) measurements for horizontal determination along with a surveying rod for depth determination (Wilson et al., 1997).

Satellite images, especially in the near-infrared and microwave wavelengths, are useful in mapping the extent of a surface water body because of the high absorption of the former and the specular reflectance of the latter (Smith, 1997). In both cases, a surface water body appears very dark and has high contrast with the surrounding land cover. Techniques applied to lake morphometry include: a) on-screen digitizing (Sheng et al., 2006), b) index estimation, such as the Normalized Difference Water Index (NDWI) or the modified NDWI (MNDWI) (McFeeters, 1996), c) density slicing based on a value that defines the water-land threshold (Wang et al., 2014) and d) numerous image classification methods (Baup et al., 2014; Smith, 1997).

In addition to imaging remote sensing systems, satellite altimeter data have been used to monitor temporal variation in the extent of surface water bodies. Despite providing high-accuracy measurements (better than 4–5 cm in an absolute sense and within few mm in a relative sense) (Shum et al., 1995), satellite altimetry has several limitations for inland water monitoring including degradation of the altimeter signal due to land intrusion, scattering of the altimeter waveform and minimum size and orientation of a water body for satellite detection relegating altimeter measurements to being useful for profiling rather than surface mapping (Troitskaya et al., 2012).

Remote sensing has been used successfully to estimate water level of un-gauged lakes using high and medium resolution optical satellite images and auxiliary data. Baup et al. (2014) used satellite altimetry data along with high resolution satellite images to estimate the volume of a small lake in southwestern France. Open water mapping of Lake Urmia in Iran utilized radar altimetry data and satellite images for developing analytical modeling equations to calculate volume, area and elevation characteristics (Sima and Tajrishy, 2013). Abileah et al. (2011) employed a volume-area-level relationship using Landsat, TOPEX/Poseidon and Jason data to monitor reservoir capacity in Egypt. In a similar manner, very high resolution images of RapidEye satellite combined with high resolution topography, were used to map water level changes in Lake Fürstenseer in northeast Germany (Heine et al., 2015). Smith and Pavelsky (2009) used both remotely sensed surface-area from MODIS images and in-situ measurements of water-surface stage to provide accurate estimations of storage changes of 9Canadian lakes. Finally, Chemin and Rabbani (2016) developed an automated methodology to monitor volumetric characteristics of small lakes (<100 ha) using the concept of water Level Virtual Gauges (wLVGs), which involves identification of the waterline from Landsat images along slope tracks upstream of water bodies.

Laser altimeter, Landsat and MODIS (Moderate Resolution Imaging Spectroradiometer) data have been used to validate the bathymetry of shallow lakes (Arsen et al., 2014) and document expansion of reed beds (*Phragmites australis*) in a shallow lake undergoing progressive water loss (Crisman et al., 2014). The frequent observations by the MODIS sensor has been utilized in monitoring wetlands inundation and seasonal hydrological variations at 16 day intervals in the Florida Everglades, USA (Ordoyne and Friedl, 2008), while the wide coverage of MODIS images was useful for mapping wide areas such as the Yangtze River basin downstream of the Three Gorges Dam to study the size dynamics of several lakes, providing results with accuracy comparable to that obtained with Landsat images (Wang et al., 2014).

Although optical remote sensing provides access to relatively inexpensive, high quality data that can be used to characterize lake morphometry, cloud coverage, especially during the rainy season hinders development of long term databases on changing morphometry. This can be overcome with high temporal resolution remote sensing satellites, which allow daily observation and compositing of images. The current study presents a methodology for using a time series of Terra MODIS and Landsat ETM+ satellite images for updating digital depth models (DDM) of lakes and reservoirs displaying wide intra and interannual fluctuations of water levels. Particular attention is paid to understanding spatial patterns of sediment deposition within Lake Kerkini, Greece, a shallow reservoir characterized by an extremely large watershed, high sedimentation and profound water level fluctuations.

2. Materials and methods

2.1. Study site

Lake Kerkini (41°13′N, 023°08′E) is a reservoir on the transboundary Struma/Strimon River in northern Greece, close to the border with Bulgaria (Fig. 1). Most of its 11,967 km^2 watershed lies in Bulgaria (8734 km^2 i.e. 73%), with decreasing contributions from Former Yugoslav Republic of Macedonia, Serbia and Greece. Kerkini was constructed on the site of a former lake and swamp in 1932 for downstream flood protection. A few decades later, several large scale land reclamation projects including embankments at the reservoir and river channel, and irrigation and drainage networks facilitated use of the reservoir for irrigation of downstream lands.

At its maximum extent, Kerkini lake has a surface area of 72 Km^2 but it often declines to 54 Km^2 after a four meter drop in water level, reflecting both seasonal changes in river inputs and manipulated water levels for management purposes (HSPN, 2015; Mpartzoudis, 1993). Mean monthly river inflows range from 21 m^3/sec to 140 m^3/sec (dry and wet periods, respectively), with mean annual inflow water volume estimated at 2613 hm^3 (Ganoulis and Zinke Environmental Consulting, 2004). In addition, water volume in Kerkini is actively manipulated to meet the needs of irrigation of 833 km^2 of the downstream plain of Serres (Alexandridis et al., 2008), a small hydroelectric plant of 8.35 MW installed on the reservoir outlet, and provision of flood protection downstream during excessive flows during spring (Manos et al., 2004). During the annual flood season (late winter-early spring), water level is maintained at a low level to provide maximum habitat for migratory birds and to absorb potential high incoming flows. During this period, water is mainly used for hydropower production. Maximum capacity of the lake (36 m a.s.l.) is reached in late spring and used to meet irrigation demands of the downstream plain. Water is diverted through open channel networks during summer, and by the end of the irrigation period (early autumn), the lake stands at its average minimum water level of 32 m a.s.l. (Fig. 2).

Owing to its extremely large watershed to lake area ratio (166:1), Kerkini has experienced problems with sedimentation of river borne sediments from its inception. Annual delivery of such sediment to the lake approximates 12.0×10^6 m^3/year (Stefanidis and Stefanidis, 2012), forming a large internal delta where the river empties into the lake that is colonized by an alluvial forest and recognized as a priority habitat by the European Habitats Directive (92/43/EEC). In 1982, the embankments along the lake shore were raised from 33 m a.s.l to 39 m a.s.l. in response to basin infilling with inorganic sediment and a reduction in water storage and conservation value. Sediment delivery to the lake was reduced from 9.9×10^6 to 6.8×10^6 m^3/year between the periods