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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

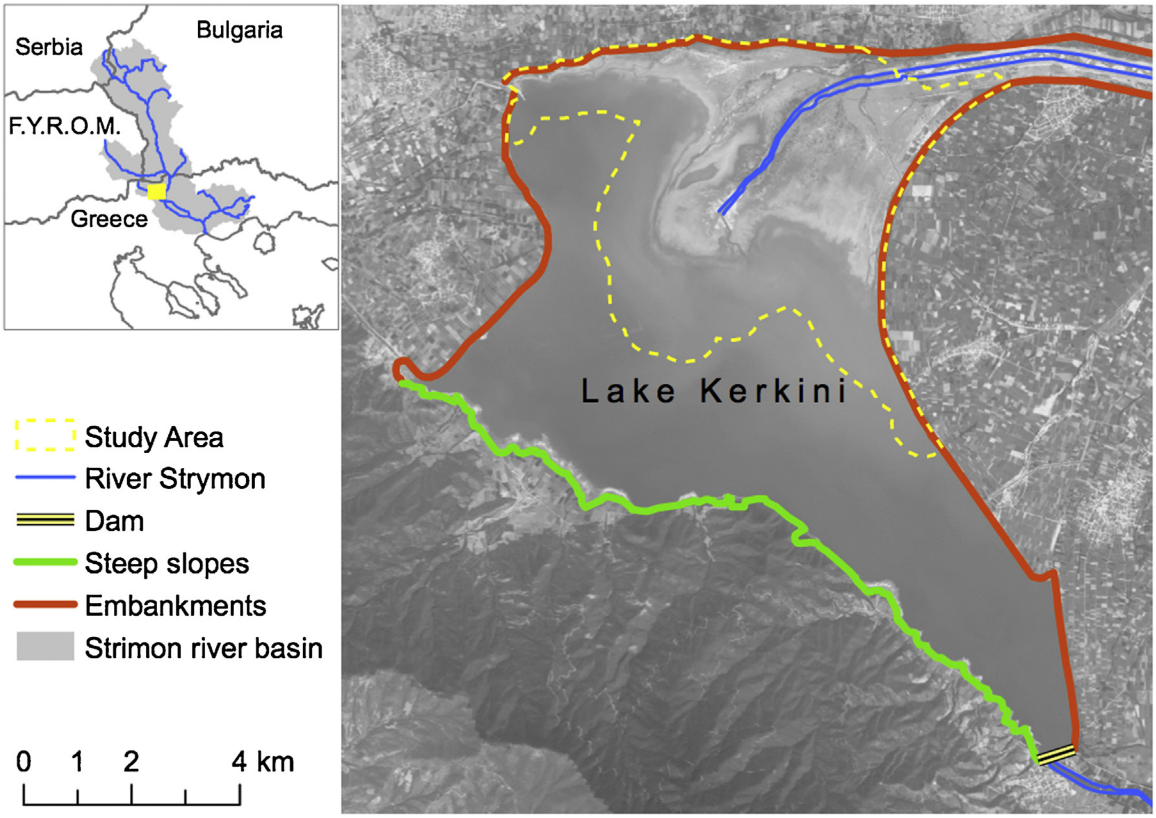

Fig. 1. Location of study area, Lake Kerkini and its main features.

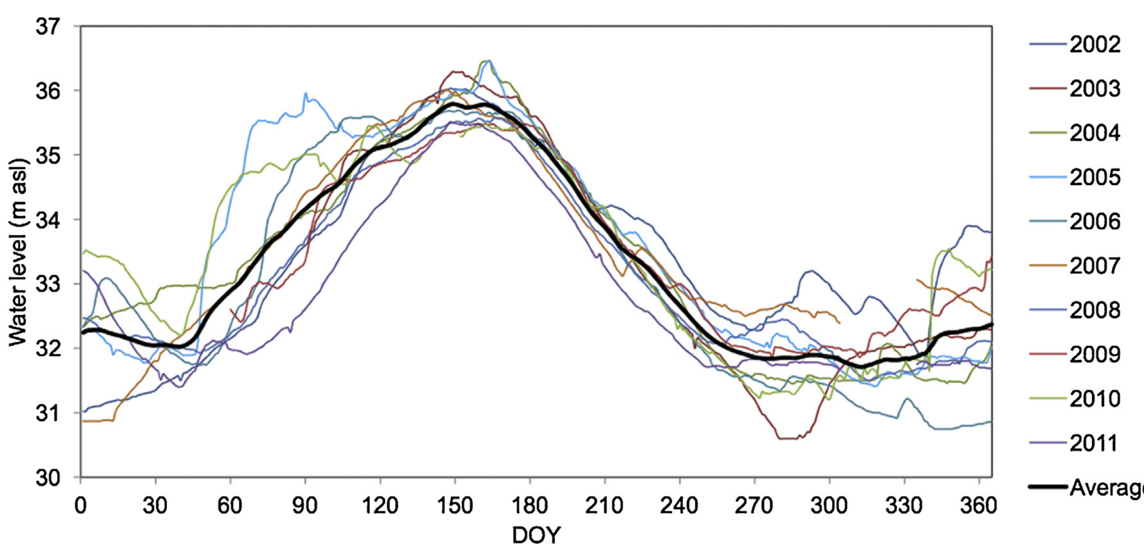

Fig. 2. Annual water levels of Lake Kerkini.

1977–1984 and 1984–1991 because of active watershed reforestation and implementation of anti-erosion measures (Psilovikos and Margoni, 2010).

2.2. Data

MODIS on board Terra satellite (launched in December 1999) is the main source of satellite images used in this study because of appropriate wavelengths and acquisition frequency. MODIS product MOD09Q1 at 250 m resolution was used to create the time series. It is a composite product (i.e., the highest quality pixels of the respective 8 day time period are selected to form the image), which offers the following advantages: removal of cloud cover gaps, avoidance of low viewing angles and highlighting of low quality pixels. In addition, Landsat ETM+ (Enhanced Thematic Mapper Plus) images of 30 m spatial resolution were utilized for clarifications and validation.

For the area of Lake Kerkini, all available MODIS and ETM+ images for 2007 were collected, comprising 46 MODIS and 7 ETM+ cloud free images. The pre-processing steps for MODIS included conversion of the original .hdf file format into .geotiff and extraction of bands 1 and 2 (red and near-infrared, respectively) using

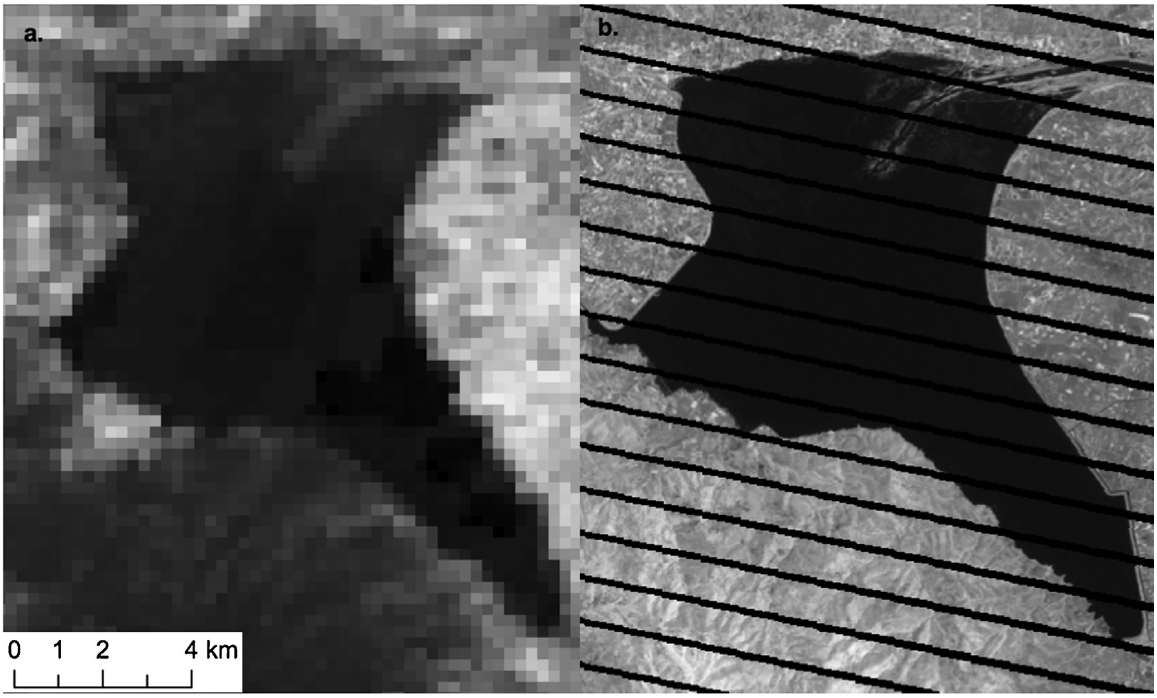

Fig. 3. Gray scale images of the near-infrared band demonstrating the lake area: a. Terra MODIS (16/05/2007) and b. Landsat ETM+ (15/05/2007).

MODIS Reprojection Tool (MRT4) software (https://lpdaac.usgs.gov/tools/modis_reprojection_tool). All satellite images were available in Universal Transverse Mercator coordinate system (UTM), thus no projection transformation errors were introduced. ETM+ images suffered from the SLC-off effect (USGS, 2013). Thus, systematic gaps obscured 15% of the land in the study area. Although these gaps covered part of the required information, no attempt to fill-in missing data was taken, as this would have inserted distortions in the resulting images (Alexandridis et al., 2013). A sample of MODIS and ETM+ images is displayed in Fig. 3.

In-situ GNSS measurements were carried out in August-September 2004 within the framework of a monitoring study for Lake Kerkini at low water levels (Malamatinis et al., 2005) employing dual frequency GPS (Global Positioning System) receivers (Leica SR520). The GNSS measurements were conducted in a differential semi-kinematic mode, with the base station situated ~5 km from the rover points occupying a trigonometric benchmark of the Hellenic Geographic Military Service. A minimum occupation time of 10 s after achieving a fixed solution (on the fly) for each point and 10^0 elevation cut-off angle was used. The GPS data post-processing were carried out with Leica's LGO software by reducing the GPS baselines between the rover and the base receivers, building double-differences. This resulted in achieving fixed solutions for the carried phase ambiguities, so that a least-squares adjustment of the GPS vectors could be used to estimate the final point coordinates. Points for which ambiguities could not be resolved even after the post-processing were removed. The final set of in-situ observations covers an area of ~600 ha (1.4 km × 4.1 km) in the northern part of the lake (Fig. 4). The internal accuracy of the GNSS data was estimated at the 0.02–0.03 m and 0.04–0.06 m (one sigma) for the horizontal and vertical position, respectively, while final estimated heights were orthometric heights, i.e., heights above the geoid. The latter were derived from a simple transformation of the GNSS-derived ellipsoidal heights to orthometric heights using a nationwide geoid model for Greece (Vergos et al., 2005a; Vergos et al., 2005b). Altogether, 4770 GPS measurement points were available. The average GPS measurement was used for comparison with each pixel of the produced DDM. In all cases, up to 12 GPS measurement points were averaged per pixel and the standard deviation was less than 0.11 m.

The last available bathymetric survey of the lake was conducted in 1991 (Albanakis et al., 1993; Psilovikos and Margoni, 2010) using a hydrographic boat equipped with sonar and based on the range survey method (Fig. 4).

2.3. Construction of digital depth model of the lake's bed

The concept of delineating the morphometry of a lake bed with remote sensing is based on digitizing the contour lines as they appear at the shoreline on multiple dates. The changing water level (vertical information) is connected with the shoreline (horizontal information) through the shape of the lake's bed (3D information). Knowing water level on the dates of image acquisition is a pre-requisite for producing contour lines with specific elevation information. Then, the resulting contours are interpolated to produce the digital depth model that describes the lake's bed morphometry. Thus, the challenge from an Earth observation point of view is the accurate delineation of multi-temporal shorelines.

Identification of shorelines utilized photo-interpretation of the MODIS satellite images to avoid errors that are inserted by automatic recognition methods (Alexandridis et al., 2009). The high absorption of water in the near-infrared spectrum was employed to map water bodies (Davis et al., 1978). Thus, the near-infrared band (band 2) was displayed in gray scale, using a 2 standard deviation histogram stretch. The identified shorelines were digitized on-screen. A similar approach was adopted to identify and map the shorelines using the ETM+ images at higher spatial resolution, thus providing improved accuracy compared to MODIS. ETM+ derived shorelines were used both for training photo-interpreters and for validation of the shoreline identification accuracy. Each digitized shoreline represents the outline of the water body at a specific water level and date. The date component was used to attribute water level values to the shorelines obtained from daily water level records and subsequently used as bathymetric contours.

The ANUDEM interpolation algorithm was used to produce the digital depth model from the bathymetric contours (Hutchinson,

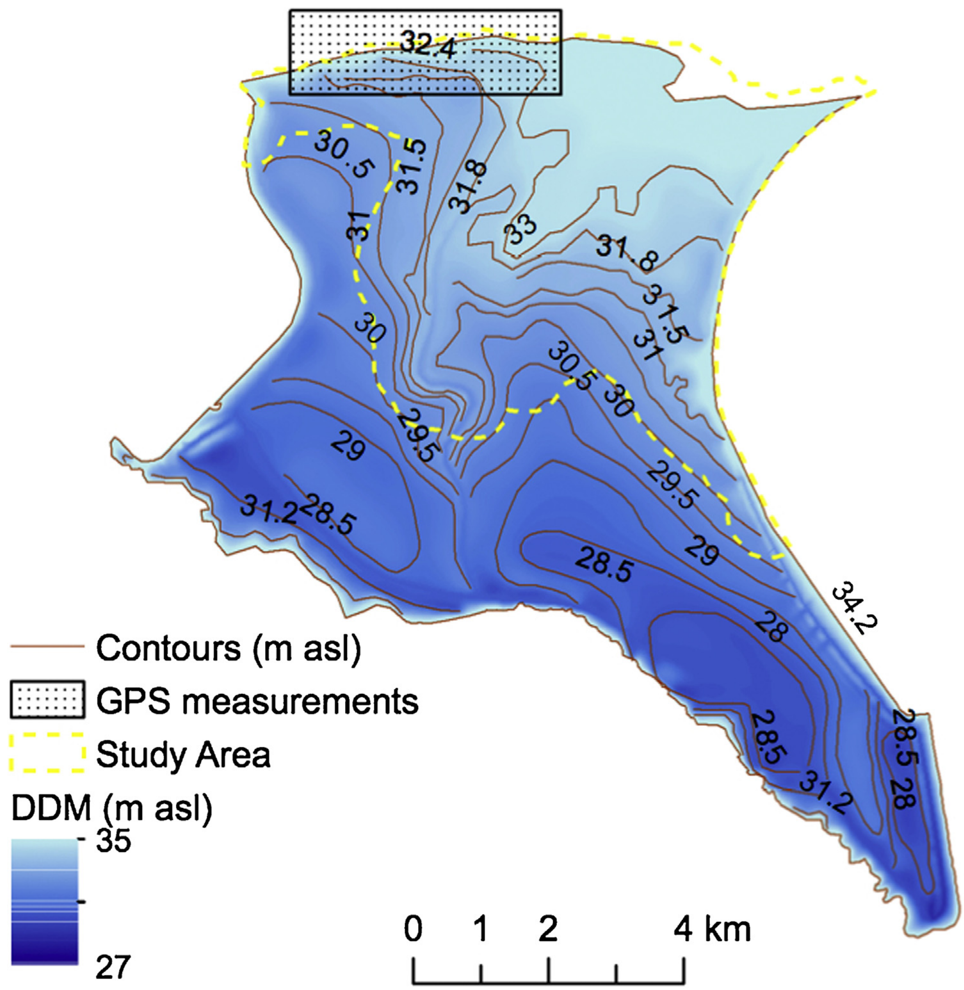

Fig. 4. Existing lake basin map of 1991 (Psilovikos and Margoni, 2010).

1989). It follows a progressive approach to the creation of a continuous surface, which begins with creation of a coarse raster, then the initial z values are averaged, and finally, successive finer resolution rasters are interpolated using the spline method. This interpolation process was selected because it performs well even with relatively small input datasets and uses a roughness penalty parameter that can be modified to allow the fitted surface to follow the smooth changes of the lake bottom (Alexandridis et al., 2007).

The case study focused on the nearshore shallow areas with a gentle slope (north and northeast part of Lake Kerkini) where the water level alteration could show some horizontal variation, and excluded the edges of the lake with high slopes (southwest part of the lake), embankments (east and west part) and the dam (Fig. 1).

The error of producing the MODIS shorelines was estimated using two different methods that estimated the mean horizontal deviation from the ETM+ shorelines, which were considered as references due to their higher spatial resolution. Digitized shorelines derived from the two sources of satellite images were compared only in cases of either simultaneous or within one day acquisitions. The first method involved estimating the mean horizontal distance between the MODIS and ETM+ shorelines, sampled every 500 m on average. The second method involved calculation of the area of the longitudinal polygon formed between the two sources of shorelines, then divided by its length (Fig. 5).

Considering the two distinctive periods of the annual water level fluctuation, it was decided to analyze them separately. The first was the period with an increasing water level trend (denoted as "increasing") from winter to spring because of extensive inflows from the upstream part of the basin, and the second, the period with a declining water level trend (denoted as "declining") during summer and autumn because of extensive water abstractions for agricultural purposes. This approach provided a mechanism to evaluate the impact of both rising and falling water on the placement of contours.

3. Results

3.1. Assessment of the digital depth model

The digitized shorelines representing the contours of the lake bed of the study area are presented in Fig. 6. These covered a wide range of elevation contours, ranging from 30.9 m in January to 35.9 m a.s.l. in late May. From the available contours, those with overlapping elevation within each period (increasing or declining) were excluded. These were contours that appeared during consecutive satellite observations without notable water level change, such as DOY 270-300 in Fig. 2. Thus 20 contours were used, selected to cover the above mentioned maximum vertical range at approximately 0.5 m contour interval.

The error of producing the contours from the MODIS images was estimated using concurrent Landsat images. Matching dates for images of MODIS and Landsat were only available from January to August, thus the error assessment was limited to these months. The mean horizontal deviation of MODIS contours from the equiva-

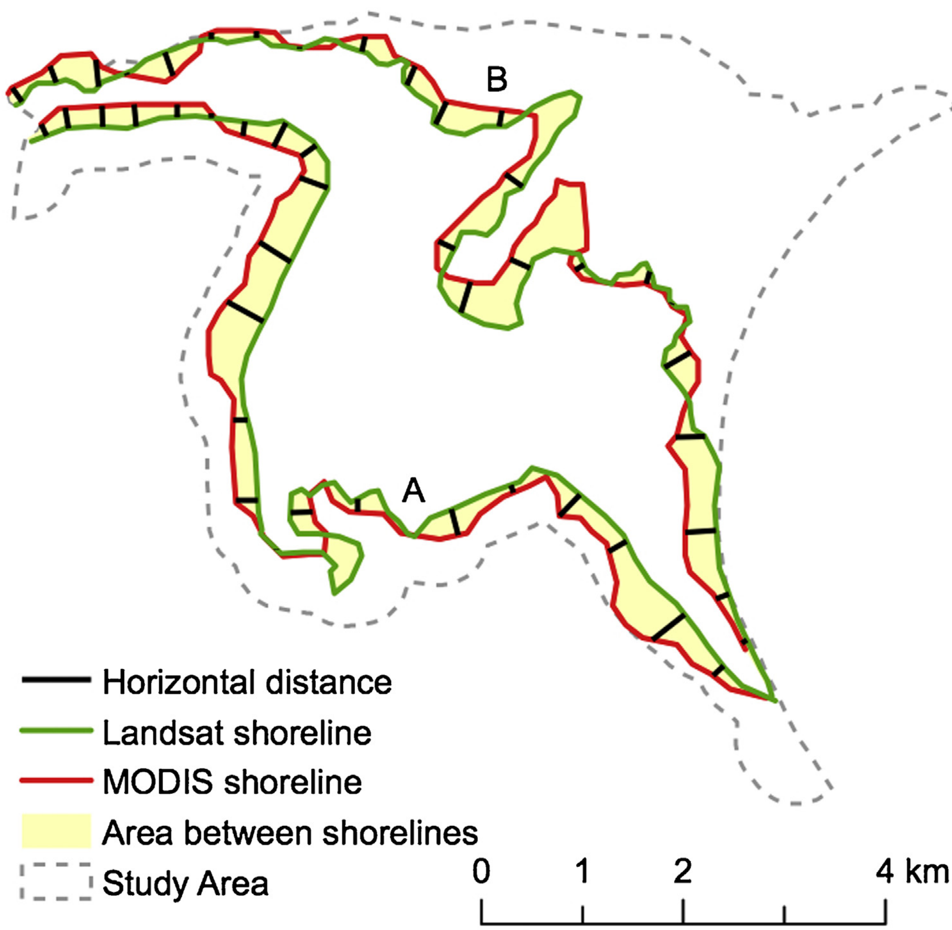

Fig. 5. The two methods used in error assessment: horizontal deviations between Terra MODIS and Landsat ETM+ shorelines, and longitudinal polygons between them. Two examples are displayed, for 07/01/07 (A) and 02/07/07 (B).

Table 1
Mean horizontal deviation of MODIS contours from the equivalent Landsat contours (m) per date, using two different methods.

Date	Method 1	Method 2
08/01/2007	210.8	186.2
13/03/2007	156.6	165.8
14/04/2007	151.2	161.9
30/04/2007	147.5	165.6
16/05/2007	178.9	180.9
03/07/2007	174.1	170.2
19/07/2007	172.3	167.6
04/08/2007	159.3	170.5
Average	168.8	171.1

lent Landsat contours was assessed using the two different methods is presented in Table 1. Both methods show similar temporal patterns with a high correlation ($r = 0.9$, $p = 0.0022$). Although the first method slightly underestimated the error, their mean difference was negligible ($d = 2.25$m). Thus, the second method was used thereafter, being the most stringent and easiest to implement. The horizontal error ranged from 161 m to 186 m without any obvious temporal pattern during the examined months. The overall deviation was 171.1m. In all cases, the error was acceptable as it never exceeded the MODIS pixel size.

Using the produced contours, the DDM of the lake basin was created with spatial interpolation (Fig. 7) and covers approximately 40% of the lake extents at maximum water level. Two versions of the DDM were created after dividing the year into two periods; the DDM constructed during the increasing water level (hereafter DDM_{incr}) using 11 contours (Fig. 7a) and the DDM constructed during the declining water level (hereafter DDM_{decl}) using 9 contours (Fig. 7b). Due to the fact that in the declining period the water never reaches the lowest level of the increasing period, the extent of the DDM_{decl} is smaller. Both produced DDMs follow a similar pattern, with few visible differences around the river's outflow into the lake.

To assess differences between the two DDMs, the DDM_{decl} values were subtracted from the equivalent DDM_{incr} values (Fig. 8). Elevational differences between DDMs for the periods of increasing and declining water level did not exceed an absolute value of 0.5 m for most of the study area, which is within the accuracy of the proposed method. Notable positive differences were evident on both sides of the river internal delta. These are cases of underestimation of elevation by the DDM_{decl}, which could be due to the appearance of temporary water ponds as the water was declining. These are evident in the different shape of the increasing and declining shorelines (Fig. 6).

The accuracy of the developed DDMs was evaluated by comparing with available elevation data from the in-situ measurements with the GPS. Average slope in the area of the GPS measurements was 0.24%, giving a vertical error of 0.41 m for the estimated digitizing error (171.1 m from Table 1), which is the maximum possible accuracy provided by the proposed methodology. Comparison of the DDM_{incr} against the GPS measurements gave a 0.52 m vertical RMSE, which is acceptable provided the maximum accuracy given above. The RMSE for the DDM_{decl} was 0.64 m, slightly higher. Thus, the DDM_{incr} was used in additional analyses.

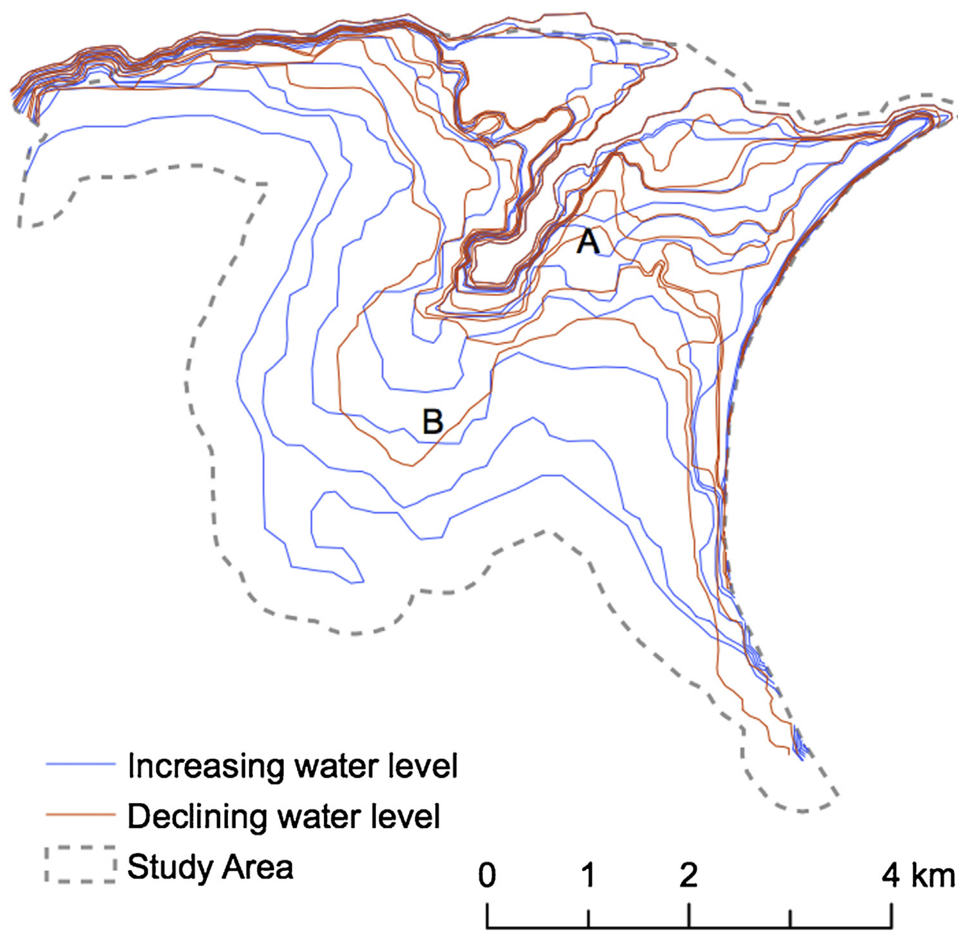

Fig. 6. Total digitized shorelines.

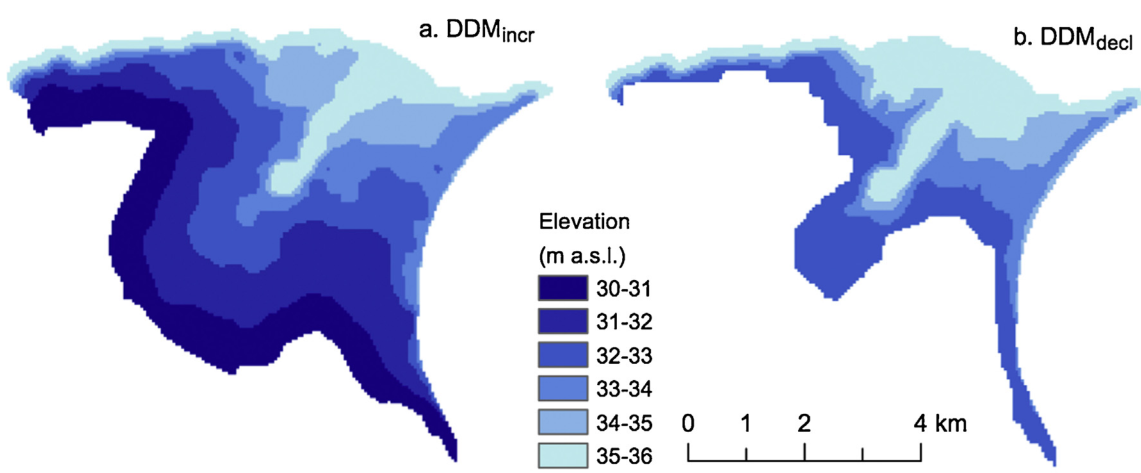

Fig. 7. DDMs created from increasing water level (a) and declining water level (b).

3.2. Assessment of sedimentation in Lake Kerkini

The suggested methodology was used to assess sedimentation patterns in Lake Kerkini. The latest available DDM of the lake (1991) was compared with the constructed DDM based on imagery of 2007 using raster subtraction. Mapped differences provided changes in lake sedimentation from 1991 to 2007 (Fig. 9). Most of the study area (65%) showed a difference not exceeding an absolute value of 0.5 m, with absolute values of 0.5–1 m covering 20% of the study area. Higher differences appeared along the perimeter of the study area to the northwest and southeast sides, which could be due to engineering activities to reinforce the embankments around the lake.

The highest area of sediment deposition was just beyond the entry of the river into the lake and associated with the delta formed from loss of water velocity and deposition of heaviest sediment (Fig. 9) (SASSA, 2007) as noted also by Psilovikos and Margoni (2010). Additional areas of sediment deposition were noted lake-

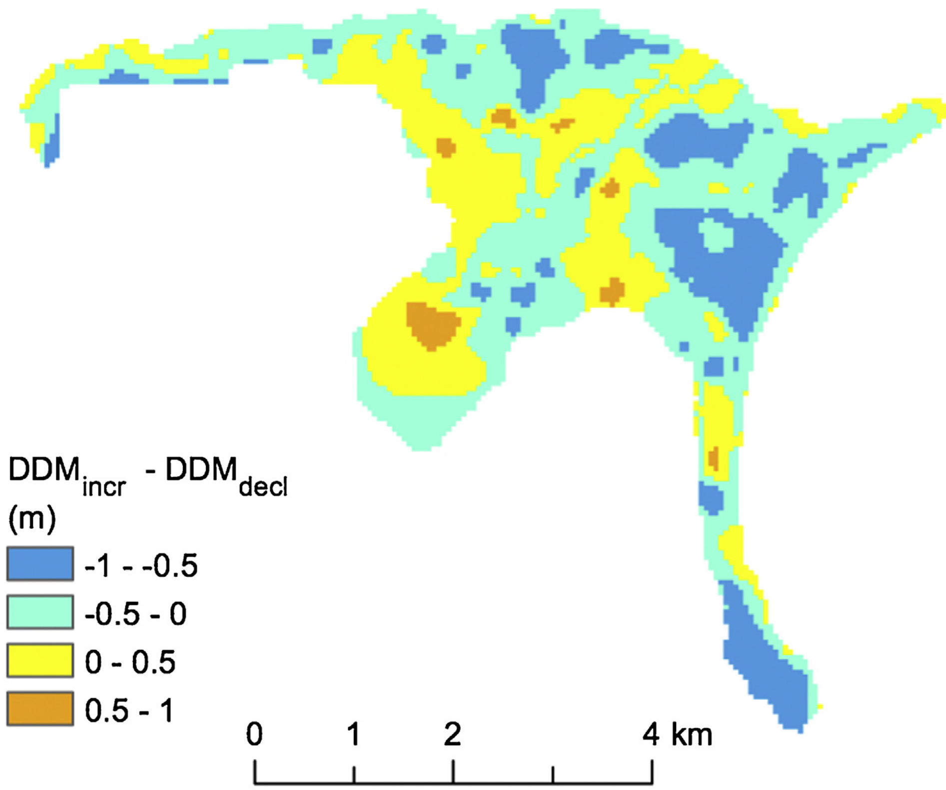

Fig. 8. Difference between DDMs for periods of increasing and decreasing water level.

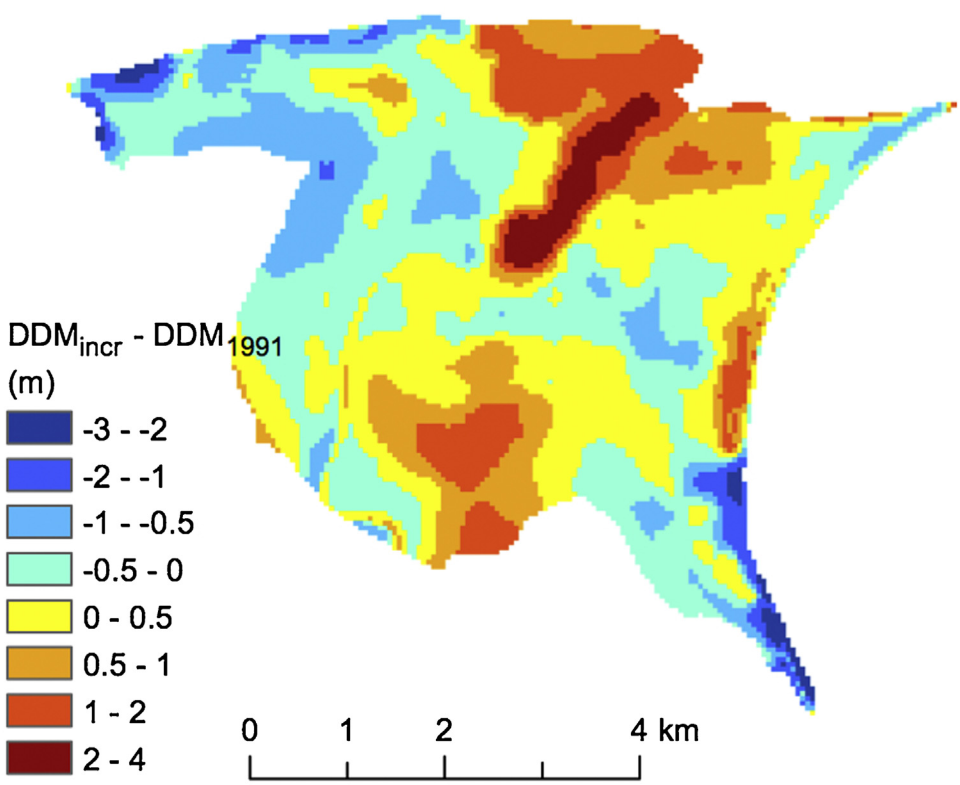

Fig. 9. Differences of updated DDMincr from earlier bathymetric survey of 1991 indicate areas of sediment deposition (red hues) and sediment removal (blue hues). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ward from the delta and likely associated with flood events or erosion of lake shoreline during receding water levels. Using 3D GIS analysis of the differences, the overall volumetric loss of the lake via sedimentation was estimated at 4.17 Mm^3.

According to reservoir classification based on the sediment distribution, Lake Kerkini is a floodplain – foot hill reservoir (Type II) (Psilovikos, 1994), systems characterized by an internal delta and overall sediment accumulation in the upper reservoir (Honningsvag et al., 2001). The estimated annual sediment infilling of 0.26 Mm^3 was supported by an empirical model derived from bathymetric surveys from 1933 to 1991, as it follows the temporal trend of decreasing sedimentation during this period (Psilovikos and Margoni, 2010). However, a change in sedimentation trend is expected after 1991 due to the change of the political regime and consequently shift to land ownership in Bulgaria, which dominates the Kerkini catchment with 73% of the area. Similar trends have been noted in eastern European and Mediterranean countries due to drastic changes in land cover (Cebecauer and Hofierka, 2008; Alkharabsheh et al., 2013; Szilassi et al., 2006).

4. Discussion

The proposed methodology is based on the assumption that water level of a lake fluctuates sufficiently to produce multiple shoreline stages throughout the year. However, configuration results for a lake bed can only be made available for the exposed area. Many lakes worldwide display wide water level fluctuation (Perlman, 2015), especially reservoirs for irrigation, power generation, river regulation and flood control (Cooke et al., 2005; Thornton et al., 1996). For these lakes, the frequent update of the active volume is of major interest.

Advantages of the proposed methodology include use of freely available time series of MODIS data, which spans 15 years. Also, use of composited 8-day satellite images helps avoid data gaps during periods of persistent cloud cover, which is a common hindrance of optical satellite images. However, the 8-day step may miss some shorelines where there are high rates of water level change, which usually coincide with the rainy season in the tropics and winter in temperate climates. In such cases of continuous cloud cover, SAR (Synthetic Aperture Radar) data can be used as an all-weather alternative (Billa and Pradhan, 2011). For the case of Lake Kerkini, the maximum mean vertical water level change within 8 days is 0.48 m (Fig. 2), which is within the limits of accuracy of the method.

The proposed methodology can be applied to medium or large sized lakes, as mentioned by Ordoyne and Friedl (2008), who concluded that MODIS imagery is not suitable for studying inundation in wetlands smaller than 26 km^2. Nevertheless, Wang et al. (2014) used MODIS satellite images to map water extents in lakes as small as 20 km^2. For smaller sized lakes, Landsat, Sentinel-2 or other continuously imaging satellites could be used.

The estimated error of digitizing was acceptable and within the visual accuracy of the satellite's resolution. This can be projected into vertical accuracy of water level estimation depending on the slope of the lake, with milder slopes producing higher accuracies. Although automated methods of shoreline creation have been proposed using image bands (NIR and SWIR) and indices (NDVI and NDWI), computer-assisted photo-interpretation was preferred to avoid reported problems of automated methods: errors inserted by cliff and cloud shadows mistaken for water, low solar angles, emergent and floating vegetation, and variable water turbidity (Abileah et al., 2011; Heine et al., 2015; Wang et al., 2014). The error assessment for the produced DDM included comparison against the surveyed elevations, again providing errors within the equivalent visual accuracy of the satellite's resolution. Higher accuracies have been reported (<20 cm vertical), which were achieved using very high resolution satellite images and favoured by the absence of vegetation on the water-land fringes (Arsen et al., 2014; Heine et al., 2015).

Two versions of the same DDM were created: using shorelines while water level was ascending during the rainy season, and using shorelines while water level was declining during the dry irrigation season. The DDM during the declining water level had lower accuracy and slightly underestimated the elevation. This could be due to the appearance of temporary water ponds while water level was declining. Water trapped in these shallow ponds for a few days may appear similar to open water in higher elevation than the remaining water body. On the other hand, during the ascending period, low vegetation that grew on the exposed sediment may enhance the contrast with open water in near-infrared, thus increasing the accuracy. An effect similar to the water trapped in ponds has been explained by the inconsistent water level due to strong winds (Goerner et al., 2009; Zolá and Bengtsson, 2007). Another reason for the differences between the two versions of the DDMs could be due to the continuous natural sedimentation and scouring processes, influenced by the management policy of Lake Kerkini and the seasonal changes of upstream soil erosion (Alexandridis et al., 2015b; Panagos et al., 2011).

The proposed methodology is a low cost and efficient approach to update lake bed morphology, which can thereafter be used for validation and configuration of the mechanisms beyond the sediment distribution problematic that is directly or indirectly influenced by numerous climatologic, hydrologic, and morphological factors (Håkanson, 1977). The methodology can be complementary to surveys using an echo-scanner on a boat to cover parts of the lake that are too shallow to survey by boat. Considering the environmental status of Lake Kerkini, limited accessibility may also derive from restrictions to prevent habitat deterioration through annoyance of nesting birds.

Another important advantage of the proposed methodology is that it can be implemented on an annual basis to assess variation in lake morphology caused by extreme hydrometereological conditions. Thus, it can be used to update a reservoir's capacity for water storage, flood control, irrigation and power production. In cases such as Kerkini, with large catchments providing large volumes of sediment, life expectancy of the system is affected by the infilling rate. The proposed methodology can provide short interval assessments for studying the process and predict the life expectancy of reservoirs. In ecohydrological applications, the suggested methodology can provide information to define lake hydroperiod, and in conjunction with other spatial environmental information such as habitats distribution, it can identify the timing, duration and depth of habitats inundation (Crisman et al., 2014). Furthermore, it can be used as a source of validation for the volume of sediment deposition estimated by models (Psilovikos and Margoni, 2010) and for erosion processes in the upstream catchment (Alexandridis et al., 2015a).

5. Conclusions

This paper presented a methodology for easy updating the bathymetry of a lake with large water level fluctuations using high temporal resolution satellite images. It was possible to produce the lake DDM, using a time series of shorelines digitized on the near-infrared band of MODIS satellite images.

Validation of the produced DDM using in-situ GNSS measurements produced differences within the accuracy of the methodology. In order to assess the influence of seasonal water fluctuation, two versions of the DDM were produced. Their elevational differences were small and were attributed to seasonal water ponds and vegetation, as well as the natural sedimentation process.

The proposed methodology was applied to assess sedimentation patterns in Lake Kerkini 16 years after the last available bottom survey, revealing sediment deposition mainly along the entrance of the river. Although its application is limited to the exposed part of lake bottom, the methodology can be useful to cover the parts of the lake that are too shallow to survey by boat.

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