Monitoring lake hydraulics using remote sensing techniques in West Macedonia

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ABSTRACT: Traditional monitoring of lakes involves specialized instrumentation, personnel and both on site and laboratory analysis. Up to date information is not always available. A methodology is applied for providing complementary information essential to aspects of lake monitoring. It integrates remote sensing, GIS, simulation techniques for the study of lakes in West Macedonia with emphasis in Macro Prespa lake, which is shared by Albania, Greece, and the FYR of Macedonia in the Balkan Peninsula. An application of hydrodynamic simulation of Lake Vegoritis is also accomplished. The methodology provides information regarding: Surface water monitoring of lake by extracting the circulation patterns that prevail in the lakes. Decadal trends of Macro Prespa lake hydraulics, like internal distributions of temperatures, surface currents, circulation gyres, turbulence characteristics and transport phenomena are identified. The methodology proved to be cost effective and have the potential to significantly improve the understanding of hydraulic processes of lakes.

1 INTRODUCTION

Lakes are valuable natural resources for water supply, food, irrigation, transportation, recreation, and hydropower. They also provide a refuge for an enormous variety of flora and fauna. Variability in heat fluxes through the lake surface, in addition to chemical and biological properties (such as concentrations of salt, dissolved gases, particles, and algae), also affect the stratification and water movement. The resulting internal hydrodynamics is important in understanding the lake’s physical, chemical, and biological structure. The transport and distribution of dissolved and particulate substances have important management consequences for the wise use of lakes. Available measurements of water levels, discharge, suspended solids and water quality no longer satisfy new demands, as they are subject to change. It is now necessary to collect data faster, more frequently and more reliably.

About 65% of the surface waters of Greece are in its north-western part, in the periphery of West Macedonia. Some of the most valuable lakes of Europe in terms of biodiversity are located in this area, (Figure 1). In this work we focus on Macro Prespa lake which is a transboundary lake that it is shared between FYR of Macedonia, Greece and Albania. There are recommendations for priority data collection (meteorological data on higher elevations, snowfall data, flow gauges, sediment load, groundwater level and water quality). Traditional monitoring of water quality as well as other environmental parameters involves specialized personnel and both on site and laboratory analysis. Up to date information seems to be lacking or its access is difficult in this region.

Figure 1 Pilot project area: Lakes and reservoirs of Water District 9 in West Macedonia.

Water quality parameters of the lakes can be retrieved from remote sensing. ENVISAT MERIS satellite data have been used for the assessment of spatio-temporal variability of selected water quality parameters like turbidity, dispersion of suspended solids and algae or chlorophyll concentration. Although MERIS data has a fine temporal resolution (3 days) cloud cover and sensor's coarse resolution (300 m) has limited the application of this data for the monitoring the water quality parameters, (Stefouli et. al. 2007, 2008).

2 OBJECTIVE, DATA AND PROCESSING TECHNIQUES

The objective of this study is to identify selected hydraulic parameters of lakes like surface currents, circulation and temperature structure of lakes of West Macedonia in order to fill the existed lack of information. The status of lakes on long-term (decadal, annual) scales is analysed. For that purpose, we use multitemporal optical- VIS / thermal infrared-TIR satellite images of Landsat ETM+, ASTER systems, GIS techniques and hydrodynamic simulation techniques. This includes the analysis of data from the Landsat and ASTER satellite systems. Image processing techniques have been applied on the Landsat images in order to extract the regions of interest (i.e. Lake surface), to make the various colour combinations and to classify the images. Fuzzy C Means classification techniques proved effective in identifying the various categories of lake circulation patterns. Raster to vector techniques have been applied in order to update the GIS database. GIS techniques have been applied for the formulation of maps and the estimates of surface extents of the lakes, dimensions of gyres and the assessment of multi-temporal differences of circulation patterns, Figure 3.

3 GYRES RECOGNIZED IN THE VISIBLE RANGE OF SPECTRUM

The regional surface currents are mapped from Landsat satellite imagery for a sample of five cases, i.e. Landsat images acquired during August of 1988, 2000, 2008 and November 1972, 2009. The formation process of gyres in Lake Macro Prespa as observed using the August scenes (B,C,D in Figure 2) is interpreted in the VIS images. A gyre of the northern part of the lake is clearly identified in all three images. However turbulence is increased in the August 2008, D image scene and additional gyres with clockwise / counter clockwise movements are formed.

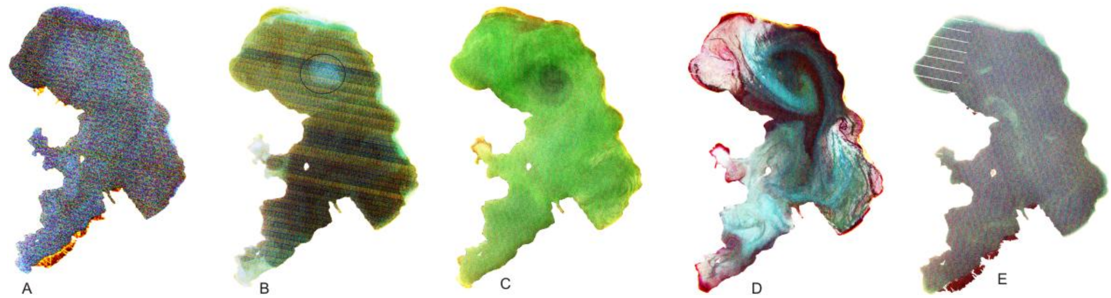


Figure 2. R/G/B 3/2/1 color composites of Landsat images of Macro Prespa lake A: November 1972, B: August 1988, C: August 2000, D: August 2008, E: November 2009

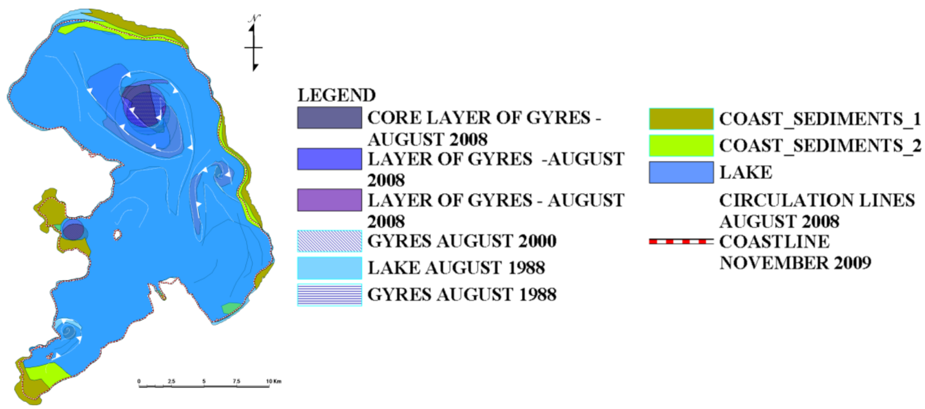


Figure 3. Decadal trends of Macro Prespa lake hydraulics, circulation patterns as detected in the multi temporal VIS Landsat images.

These current patterns are interpreted from the configuration of sediment tendrils observed on enhanced and classified images using the visible part of the spectrum. The current trajectories are viewed as potential effluent pathways. Evidence of a "coastal jet" is found along the lower part of the western shore of Prespa lake. A counterclockwise flow is observed in all cases of summer scenes in the Northern part of the lake. The geometric characteristics of the gyres can be measured. The North circular gyre of the August 1988 image has a diameter of about 3 km. A similar circular gyre is also formed in the 2000 scene with a diameter of about 4.7 km. The 2008 scene shows an elongated clearly defined gyre with a major axis of about 8 km and a minor axis of about 5 km. This appears to be part of a gyre within the lake and it is related to a second clockwise gyre that it formed in the eastern part of the lake. It is possible that sediments released from the rivers into the lake would become part of a closed circulation. As in many elongated lakes internal waves propagate along its main axis. However, not only the geometry of the lake but also that of the wind pattern in relation to the lake topography seems to be important in the Prespa lake (Monino-Ferrando et al. 2006). The basin of Prespa Lake is consisted of a specific regime of local winds. These special characteristics have been developed by the lake because of the heating of the wind layers above the ground and the lake surface. The prevailing winds are mostly north and northeast and less south and southwest, because of the north opening of the Big Prespa. The north and northeast winds are generally colder, especially in the winter. The mean velocity of the winds is 2,5 - 5 m/sec.

The transport and settling of inorganic particles from the rivers is expected to be governed by wind driven water currents and the momentum generated by stream discharge. It seems that the large scale counterclockwise gyre acts as a barrier of transporting the sediments of Golema river that enter in the lake in its northern part. This pattern seems to be related to summer season as the mapped circulation pattern is not evident in the November scenes. According to Kumagai et al., (2002) and Yamashiki et al., (2003), the peristrophic gyres have seasonal occurrence mainly in the spring and they disappear in the autumn.The implications for the sensitive marshes in the northern region must be considered.

4 GYRES IN THE THERMAL PART OF THE SPECTRUM

Thermal infrared (TIR) satellite images can be used to study transport processes in lakes, such as wind-driven upwelling and surface circulation, providing a measure of spatial variability and horizontal distribution of water temperature that conventional field-based measurements cannot provide. High-spatial-resolution TIR images provide a detailed view of fine-scale processes, such as surface jets, that cannot be clearly resolved in moderate-resolution images, and they enable the accurate measurement of surface transport and circulation patterns.

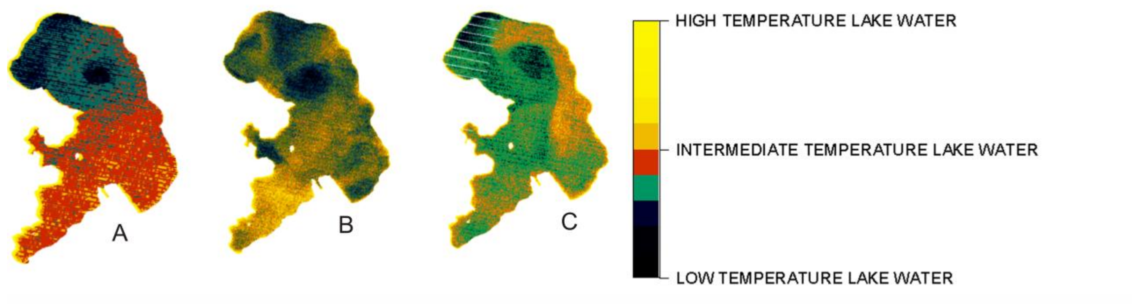


Figure 4. Surface distribution of temperatures of Macro Prespa lake as it is shown on the TIR Landsat Images with different acquisition dates, A: August 1988, B: August 2000, C: August 2008.

The images show that probably wind-driven partial upwelling events occur at summer stratified period, transporting water from intermediate depths to the surface. These are important events that contribute to the patchiness and heterogeneity (Monino-Ferrando et al. 2006) that characterize natural aquatic systems. The surface temperature maps derived from high-resolution thermal infrared Landsat ETM+ images enabled the characterization of wind-driven upwelling and the measurement of surface currents and circulation at Macro Prespa Lake, Figure 4.

Convergence and divergence zones and inflows can also be clearly resolved in the thermal patterns of the high-resolution TIR satellite images. The driving force of gyre formation is assumed to be differential heating due to heat volume differences between mid-lake and shoreline areas (Schwab 1992) along with the direction of the wind. The significant patterns of gyre formation are identified on both visible VIS and thermal TIR images. It is concluded that the surface heat transfer process is one of the major driving forces for gyre formation.

The spatial variability evident in the images of Figure 3 and 4 illustrates the advantages of satellite measurements over in situ point measurements alone to characterize upwelling since, depending on location, in situ sensors might not even capture an upwelling event.

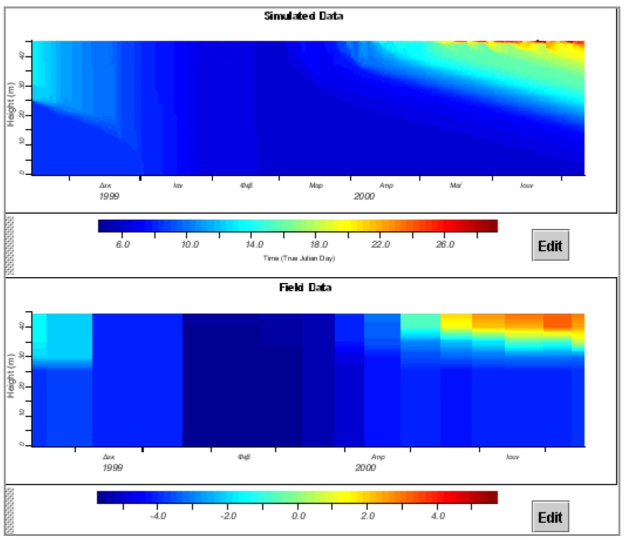
5 HYDRODYNAMIC SIMULATION

Remote sensing techniques, such as those mentioned before, provide information which is limited to the surface of a lake. For a more complete water management it is necessary to have information of the state of the lake in depth. A hydrodynamic simulation has been performed in order to gather that kind of information for one of the lakes of Western Macedonia mentioned above, Lake Vegoritis, and was combined with information gathered by satellite images and “in situ” observations.

During the simulation period (1999-2000) Lake Vegoritis had the following characteristic dimensions: maximum depth of 45 m, maximum volume of $600x10^6$ m^3, surface area of about 3 km^2 and maximum length and width of 12 km and 5.5 km respectively. For many years Lake Vegoritis has been a recipient of wastewater generated by municipal, industrial, mining and agricultural activities which caused severe problems to the lake. These facts, along with a rainfall height decrease during the corresponding period, an illegal use of lake’s water for irrigation purposes, and the disposal of municipal wastes and of mining lignite tails into the lake, led to a deterioration of its water quality. Therefore detailed information was needed on the processes affecting the quality of water in the lake.

In order to evaluate the water quality of Lake Vegoritis a multilevel integrated management approach was used. This approach included: a) hydrodynamic and water quality simulations, b) analysis of the lake's surface by applying remote sensing techniques in respect of water quality and temporal changes of the lake (shape, size) over several decades, and c) field measurements of several water quality parameters in characteristic points of the lake throughout the water column. For the case of Lake Vegoritis the 1-D (vertical) model DYREM-CAEDYM has been chosen for conducting the hydrodynamic simulation, as well as the water quality parameters estimation. The physical and biochemical parameters examined include the water temperature and density, the water pH, and the concentrations of DO, NO3, NH4, PO4, Chl-a, TN (total nitrogen) and TP (total phosphorus).

Simulation results are shown in the following figures. Figure 5 shows the comparison of simulated and field data for the seasonal variation of temperature over the lake's depth, with a satisfactory agreement. Figure 6 shows a seasonal plot of Chl-a, where an increase of values during summer can be noted when the temperature rises. The figures presented here show satisfactory the seasonal changes over the depth of Lake Vegoritis in respect of water quality parameters such as Chl-a.



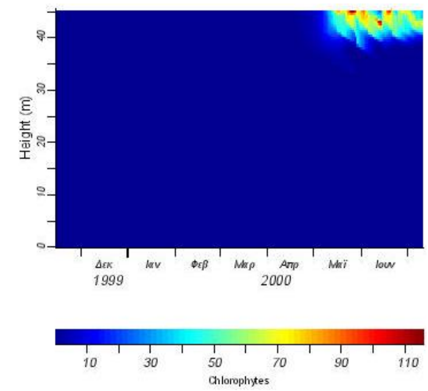


Figure 6. Chl-a distribution.

Figure 5. Seasonal variation of temperature profiles (comparison of simulation and field data).

The combination of the other two components of this analysis (the remote sensing techniques and the field measurements) provided information of the lake's surface in respect of temporal size changes as well as water quality parameters, such as water clarity, Chl-a concentration etc. In this example multi-spectral satellite data obtained from LANDSAT-ETM (Enhanced Thematic Mapper) and ASTER images of a lake's surface were used and combined by field measurements of the lake and its inflows over the same period.

Figure 7 shows various images of the surface of the lake. The data from band 2 of Landsat images (A, B) and from band 1 of the ASTER image (C) have been used in the analysis of surface water quality (and temperature) of the lake, since they correspond to the same spectral region of 0.52-0.60 μm. The same colour palette has been used for displaying the characteristics of multi-temporal images. Blue-green colours indicate relatively low sediment content, while red-yellow colours indicate high sediment content. The lake bathymetry map is also displayed in Figure 2 (D) to facilitate interpretations of the images.

In order to compare the DYRESM-CAEDYM model simulation results with "in situ" data, the field observations collected by (Antonopoulos&Papamichail, 1991), during the period between November of 1999 and July of 2000, were used. The meteorological forcing (wind velocity and direction, air temperature and pressure, precipitation, cloud-cover, etc) needed, to drive the model over the corresponding period, was obtained from the Kozani meteorological station, a local branch of Greek National Weather Service.

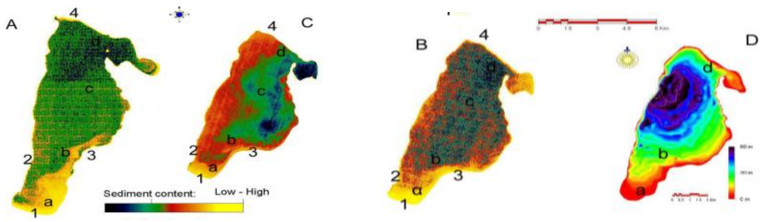


Figure 7. Band 2 of the Landsat image (A: October 1986, B: November 1999) and band 1 of ASTER images (C: October 2001). The right image (D) shows the bathymetry map of the area.

6 DISCUSSION

We were able to identify the dynamics of the horizontal structure of currents and water temperature regime of peristrofic gyres in Macro Prespa lake. Peristrophic movements (gyres) were clearly identified in the time series images, both in the optical and thermal bands of the Landsat satellite system for the Macro Prespa lake. Understanding naturally occurring mixing processes in the lake aids in determining the ultimate fate of pollutants, and supports good management strategies and practice. The high spatial resolution of the satellite images allow the surface currents and general circulation in lakes to be accurately identified using the multi-temporal imagery. High-resolution TIR imagery used in conjunction with in situ lake measurements and hydrologic models can provide spatial context for the in-lake data, describing the spatial extent and variability of lake processes, which can help improve monitoring of the clarity and general water quality of Macro Prespa Lake and other lakes.

Finally the combination of different data sources (hydrodynamic simulation, remote sensing and field data) lead to a complete description of the state of a lake, as described above. This example shows that a complete water recourses management is feasible with the combination of different methods.

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