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INTEGRATED ECOSYSTEM ECOLOGY (CHLOROPHYLL-A) OF EYDAP'S RESERVOIRS PROFILES BY USING ROBOTIC BOATS

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Abstract. The Research and Development Department of EYDAP (R&D) is responsible for the operation of two autonomous robotic boats as a result of participation in the EU funded INTCATCH project. The autonomous boats operated in 2020 in all four Reservoirs of EYDAP (Yliki, Marathon, Mornos and Evinos) and with their integrated sensors (chl-a, dissolved oxygen, conductivity, pH, temperature, total nitrogen and phosphorus) collected more than 290,000 data along the perimeter of the Reservoirs, covering more than 90 kilometers. The data appeared in real time in the field and in the headquarters office via tablet, mobile and PC through appropriate applications, providing at the same time a safer working environment against COVID-19. The aim of the present study is to investigate the trophic state of EYDAP's reservoirs assessing chlorophyll-a concentrations. The robotic boats scanned a far greater area of all catchments and the results proved the oligotrophic state of Mornos and Evinos reservoirs while the state of Yliki and Marathon ranges between oligotrophic to mesotrophic. By using the continuous monitoring system, potential sources and pathways of nutrients inputs could be identified and the results provided EYDAP the opportunity to have a more comprehensive picture of the trophic state and the water quality of the catchments in real time and take immediate countermeasures if necessary.
Keywords: Robotic boats, Greek Catchments, Monitoring Strategy, Real-time, Trophic State, Chlorophyll-a.

1. INTRODUCTION

The European Water Framework Directive (WFD, 2000/60/EC) has been in force since December 2000. The Directive sets out the principles and proposes measures for the conservation and protection of all waters - rivers, lakes, transitional, coastal and groundwater - introducing for the first time the concept of "ecological importance" of water in parallel and regardless of any other use. Therefore, main aim of WFD is to achieve a good status for all water bodies within specific deadlines. This comprises the objectives of good chemical and ecological status by the year of 2027 (European Commission 2000). In order to achieve these objectives, the Member States are obliged to carry out Surveillance, Operational and Investigative monitoring programs. The WFD has established, for the first time, the framework for the protection of all waters in a holistic approach at the level of the River Basin Management Plans (RBMPs).

Current monitoring strategies are highly susceptible to discontinuous and/or unpredictable precipitation and hazardous events, such as direct discharge of sewage, combined sewer overflows or surface run-off from agricultural areas into drinking water resources or water bodies used for recreational purposes. Such events occur occasionally and are usually not reflected by fixed date measurements and the results of those investigations are often rather poor in terms of data density, predictive power, and, thus, for deriving effective countermeasures (Moustaka-Gouni et al., 2019). This points out the great importance of an improved monitoring strategy leading to more reliable datasets and, hence, allowing the prediction of water quality on catchment scale as well as paving the way to water quality improvements (Vlachopoulou et al. 2014; Voulvoulis et al., 2017; Mantzouki et al., 2018; Warner et al., 2018).

Reservoirs are protected water bodies that are used for the abstraction of water intended for human consumption. In Greece, Athens Water Supply and Sewerage Company S.A (EYDAP SA), serves approximately 4.5 million customers with drinking water and is responsible for the monitoring and water quality control of four reservoirs (Yliki, Marathon, Mornos and Evinos) in accordance to the provisions of the WFD (Fig. 1). The raw water resources are of excellent quality with an average safe annual yield of 440-570 million m^3.

The current monitoring programs are carried out by EYDAP S.A. and by the Ministry of Environment. Monitoring is carried out on a monthly basis at specific sampling locations (mainly inputs and outputs). According to EU Directive 75/440/EEC, as well as in the framework of the National Monitoring Program, in accordance to the Joint Ministerial Decree 140384/2011 surface water is classified in three categories A1, A2 and A3 depending on the quality associated with specific physical, chemical and microbiological parameters. These parameters are classified furthermore into three Groups (I, II, III) depending on their required minimum measurement frequency and analyzed at EYDAP laboratories, where approximately 8,000 tests taking place annually. One of the main concerns for water reservoirs is eutrophication that could lead to occasional algae blooms and could degrade water quality (Gelis et al., 2017; Ho et al., 2019). A more detailed investigation is necessary in order to correlate pressures with the impacts to water quality and therefore, it is very important to afford early warning systems that can measure real-time physicochemical parameters which can be associated with possible pollution (Hitz et al., 2012; Katsouras et al., 2020).

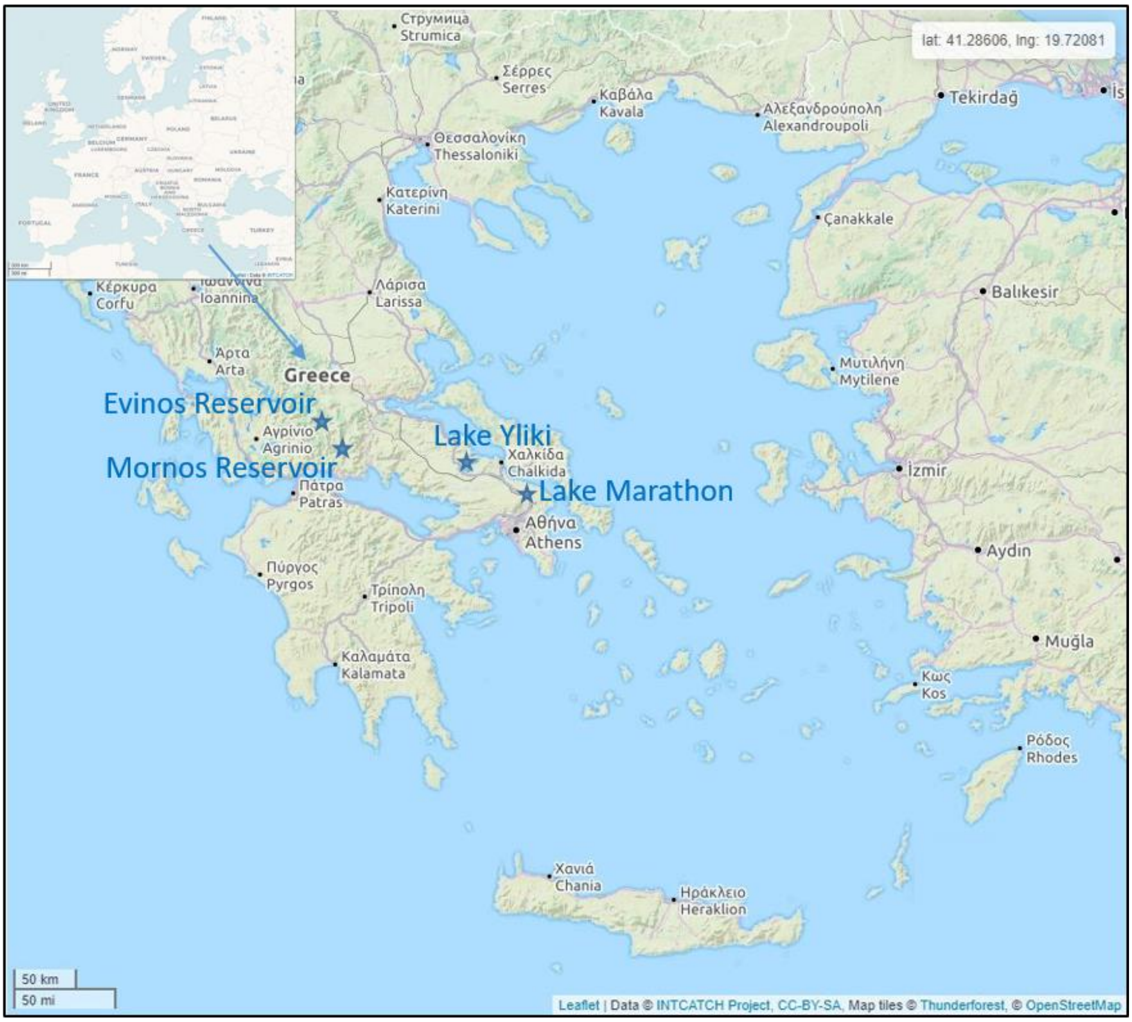

Figure 1. Study sites of EYDAP's four reservoirs (Yliki, Marathon, Mornos and Evinos)

An innovative quality monitoring strategy by using robotic boats could increase available water quality data without requiring labor-intensive and costly monitoring schemes. This novel strategy was introduced for the ***first time in Greece by EYDAP*** and the present study aims to highlight the benefits that are derived by the application of the ***robotic boats in water monitoring***. This highly promising and target-oriented approach into investigative water quality monitoring leading into long-term uses appropriate sensors so as to attain real-time water quality monitoring. The first full application of the robotic boats that took place in 2020 in all four reservoirs of EYDAP is presented. An autonomous boat equipped with a chlorophyll-a sensor allowed monitoring of ecological status more accurately with emphasis on phytoplankton growth. Trophic status of a water body is of great importance (Katsiapi et al. 2016; Sinha et al., 2017; Bresciani et al., 2018) and can roughly be assessed by using information about the concentration of chlorophyll (an indicator of phytoplankton biomass), with the most widely accepted limits being those suggested by the Organization for Economic Cooperation and Development (OECD). According them, a water body classified as oligotrophic with a mean chl-a value of < 2.0 μg/l (max < 8.0 μg/l), as mesotrophic with a mean chl-a value of < 8.0 μg/l (max 8.0-25 μg/l) and as eutrophic with a mean chl-a value of > 8.0 μg/l (max > 25 μg/l) (Istvánovics, 2009). The trophic state and the current monitoring programs classified Yliki and Marathon as oligotrophic to mesotrophic (mean chl-a < 8.0 μg/l) while Mornos and Evinos as oligotrophic (mean chl-a < 2.0 μg/l).

2. THE INTCATCH SYSTEM ARCHITECTURE AND TECHNOLOGICAL FLOW

The INTCATCH system architecture consists of the boat, the electronic parts (Bluebox, circuit boards, raspberry) and the sensors (Fig. 2 and Fig. 3).

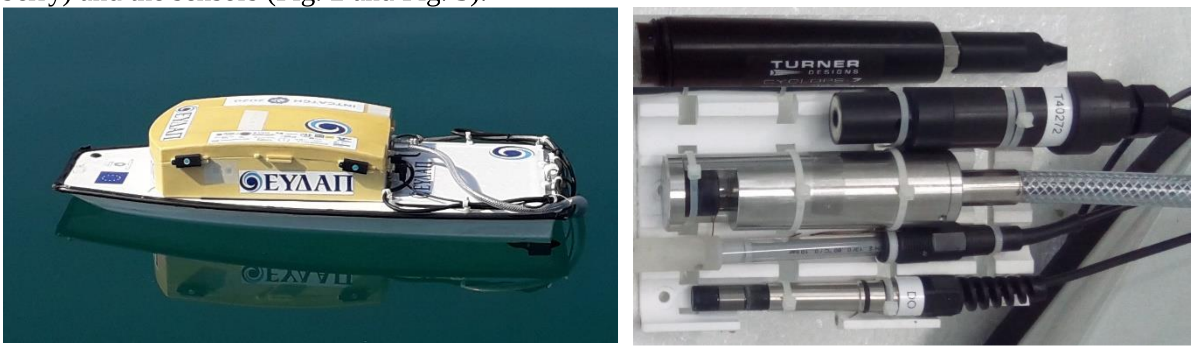

Figure 2. Autonomous Boat equipped with sensors DO, pH, ISA, EC and Chl-a (bottom to top)

The boat has low profile to minimize wind resistance. It can be deployed in as little as 25 cm of water and has two in-water propellers with differential drive system for its navigation (Bloisi, 2018; Calisi, 2018). The electronic parts are mounted inside the boat (Fig. 3). The main board of the circuit is GO-Systemelektronic's Bluebox which manages the sensors and the supporting boards (Knutz, 2020), stores locally in a flash memory the data coming from the sensors and sent them via serial connection to the Raspberry. They are also sent via the built-in modem UMTS (3G) to the BlueGate storage database and thus into the INTCATCH Water Information System (WAIS), where it can be used by the visualization applications (WAQUIN). The raspberry is used to handle the receiver inputs, control the motors and implement the autonomous navigation. One of the GPS modules is used for this purpose and the other one is plugged directly to the bluebox and is used for the data collection (Tsalas et al., 2020). The user, via a tablet, can interact with the boat using a GUI (graphical user interface) android application, to show the sensor values in real time and to receive commands from the operator (Steccanella et al., 2019), while at the same time controls all the autonomous behaviours of the platform and displays the state of the boat (e.g. position on the map).

The sensors are located beneath the boat (Fig. 3) with the basic set consist of Dissolved Oxygen (DO) and Temperature (T), pH and Electrical Conductivity (EC), while in addition it has two specialized sensors, adapted to the needs of the Service (Fig. 2). The first is the Chlorophyll α (Chl - a) sensor, model cyclops 7, whose principle of operation is through an optical system that emits light at a specific wavelength and determines the chlorophyll from the fluorescent radiation of longer wavelengths. It is also equipped with the Intelligent Spectral Analyzer (ISA) sensor (Knutz, 2020), a spectrophotometer that, with proper calibration (Allabashi, 2019), can determine parameters of interest for reservoir water such as total nitrogen (TN), orthophosphate (o-PO_4) and nitrate (NO_3) and depending on the aquatic system under consideration, biochemically required oxygen (BOD), chemically required oxygen (COD), ammonia, soluble organic carbon (DOC), total organic carbon (TOC), total suspended solids (TSS) and turbidity, Color/Hazen, UV254.

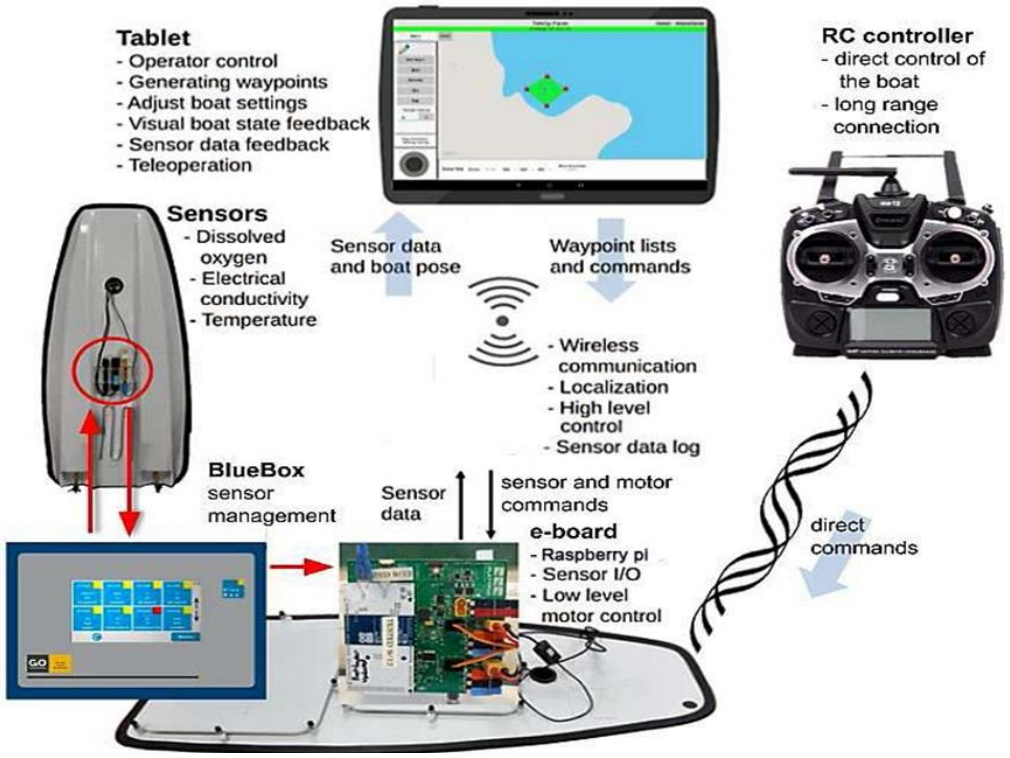

Figure 3. Architecture of the boat control system showing options for manual RC control and autonomous operation through the Control App running on the tablet

3. RESULTS AND DISCUSSION

EYDAP uses raw water mainly from surface water resources (Marathonas, Yliki, Mornos, Evinos). From these four reservoirs, only Yliki is natural, while the others have been created by the construction of dams in the appropriate places in Evinos, Mornos and Haradros (Marathon Dam) river beds respectively (Source: EYDAP S.A.).

Within the context of the innovative monitoring program, online measurements by autonomous robotic boats took place during the period from May 2020 until October 2020 in order to cover seasonal variability and more than 290,000 data collected along the perimeter of the Reservoirs, covering more than 90 kilometers. The results were used in order to define differences that indicate their limnological category and anthropogenic impact and evaluate the quality of EYDAP's reservoirs. In this study we present the values of chl-a concentration and their fluctuations that are shown spatially on the map of every Reservoir. For the best visualization of the results, a specific color pattern is followed, which includes the colors Blue, Green, Yellow, Orange and Red (indicating increasing values).

The natural Lake Yliki (9th largest in Greece) is located in Eastern Central Greece (Fig. 4 and Fig. 5). It was joined in water supply system of Athens in 1959 in order to meet the increasing water consumption due to urbanization. Yliki lake is situated on a lower altitude compared to Athens. For that reason, the lake water intake structures depend on the operation of various pump units of significant power capacity (both submerged and on - land). Its central pumping station is one of the largest in Europe. Nowadays Yliki Reservoir works as an auxiliary water source for emergencies. The concentration of Chl-a in Lake Yliki ranged from 0.5 to 10 μg/l, with most of the values fluctuating from 2.5 to 5.0 μg/l. There was a small increase (5.0 - 10 μg/l) offshore along the channel (Fig. 4), while at the mouth of the Kanavaris and Kalamitis (Fig. 4) as well Voiotikos Kifisos rivers (Fig. 5), the values were less than 5.0 μg/l. Close to the pumping station (water abstraction) in the artificial part of the lake the concentration of Chl-a was found to be less than the value of 5.0 μg/l (Fig. 4).

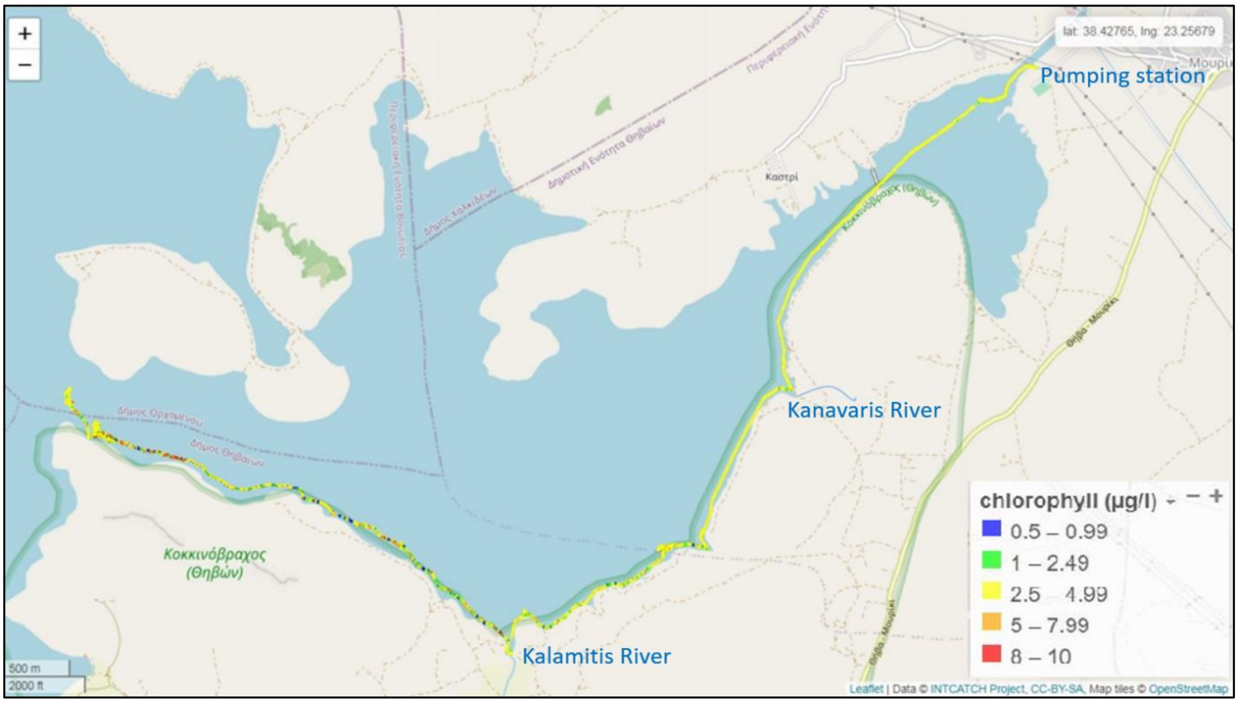

Figure 4. Spatial distribution of chl-a in the east part of Lake Yliki, 28/05 and 24/09/2020

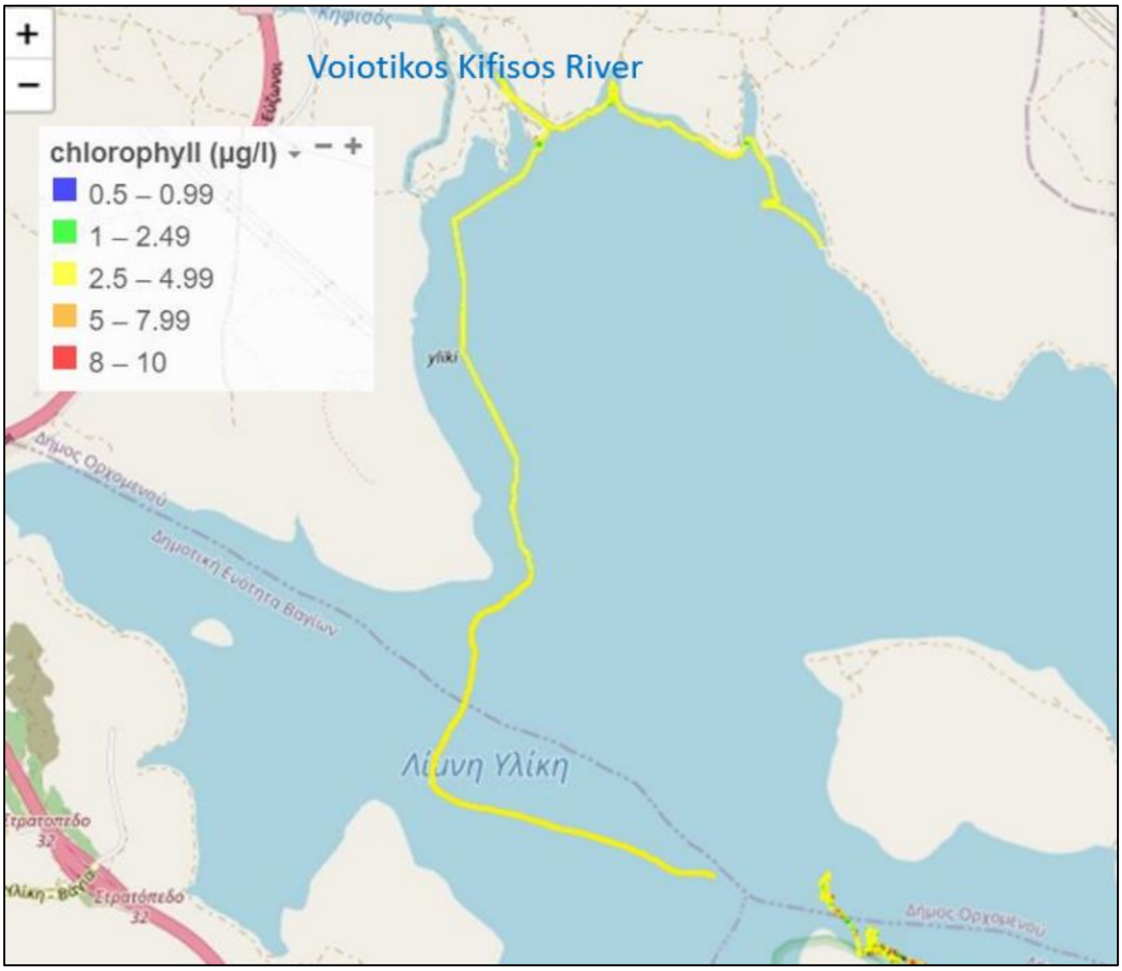

Figure 5. Spatial distribution of chl-a in the west part of Lake Yliki, 05/08/2020

Marathon Reservoir was created 90 years ago by the construction of a concrete gravity dam on the east side of the intersection of the Charadros and Varnavas Torrents (Fig. 6). It is the oldest dam of Greece and the reservoir operates as a backup source for the water supply system of the greater Attica region and as a primary regulating reservoir. Marathon Reservoir supplies water from the reservoirs of Mornos and Yliki, via Yliki

Aqueduct and Mornos-Yliki Connecting Aqueduct. In Marathon Lake the concentration of Chl-a ranged between 0.1 to 10 μg/l, with most of the values being lower than 5.0 μg/l (Fig. 6). There is a small increase (2.5 - 5.0 μg / l) in the western part of the Reservoir, in the water inflow area of the Mornos - Yliki Aqueduct, probably due to the movement of water in this direction and the very low depth (< 3m). Around the dam and the Aqueduct, the Chl-a concentration was found to be less than 2.5 μg/l, as in the northern part at the mouth of the Varnavas river. Minutes variations greater than 8.0 μg/l were found at points, very close to shores with rich vegetation and reeds.

Figure 6. Spatial distribution of chl-a in Lake Marathon, 21/05 and 10/06/2020

Mornos dam with 126 meters high, is one of the largest earthen dams in Europe and operates since 1981 as the main water source for Athens. The dam is located at the riverbed of Mornos River, and supplies Athens with raw water through a 191 km canal. In Mornos Reservoir the concentration of Chl-a ranged from 0.1 to 8.0 μg/l, although most of the values varied less than 2.5 μg/l (Fig. 7). There is a small increase (2.5 – 5.0 μg/l) in the northern (western and eastern) part of the Reservoir, at the mouth of the rivers Kokkinos and Mornos. Around the dam and the Abstraction Tower, the concentration of Chl-a was found to be less than 2.5 μg/l, as in the southeastern part near Lidoriki. Few high values, greater than 5.0 μg/l were found locally, very close to shores with rich vegetation, such as the spring of Kallio (Fig. 7).

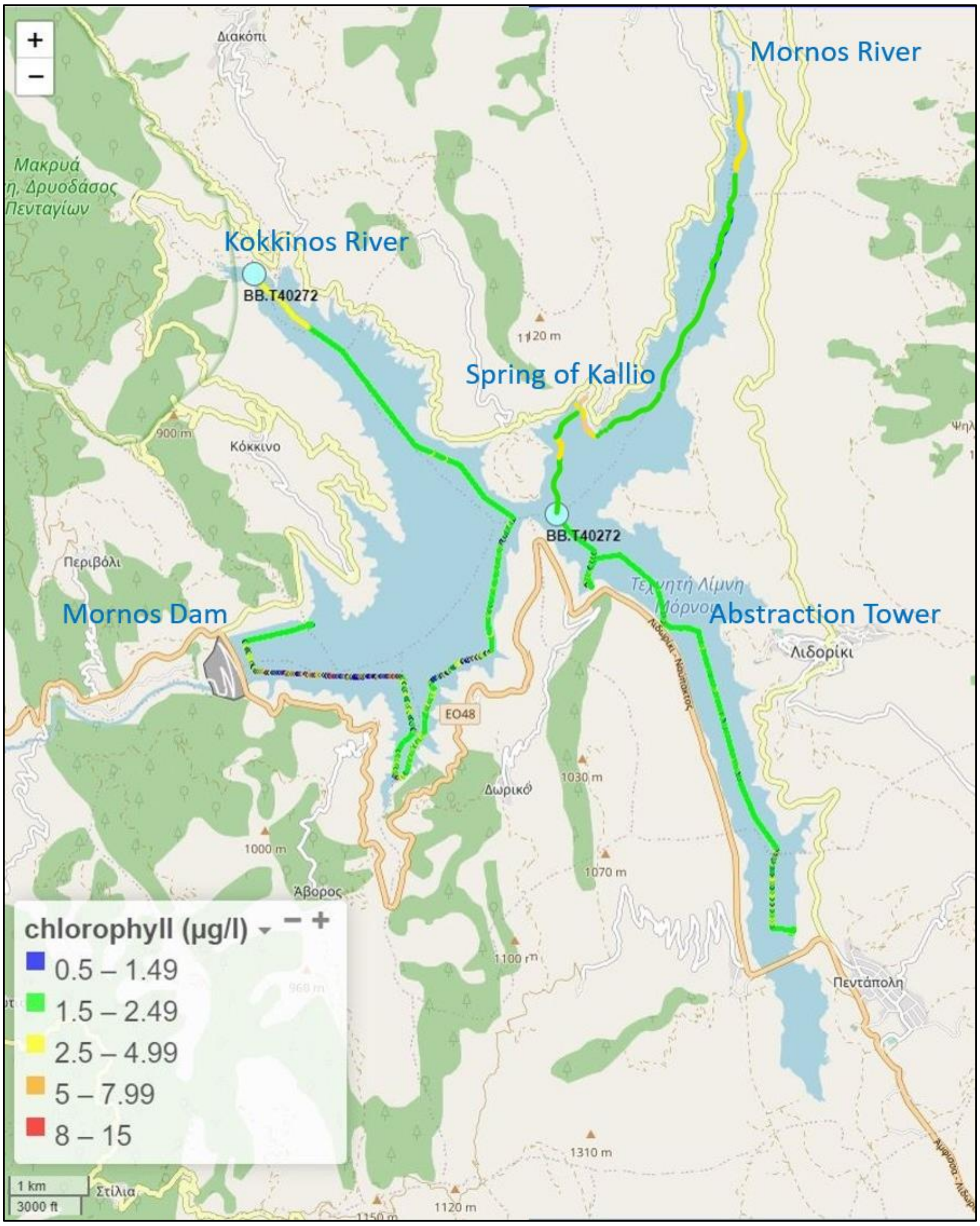

Figure 7. Spatial distribution of chl-a in Mornos Reservoir, 1-2/07/2020

Evinos Reservoir was created in 2001 by the construction of an earthen dam in the River Evinos, at the Perfecture of Aitoloakarnania (Mountainous Nafpaktia), and included as well as the construction of Evinos-Mornos tunnel. In Evinos Reservoir the concentration of Chl-a ranged from 0.1 to 3.0 μg/l, confirming the oligotrophic state of the Reservoir (Fig. 8). Constantly low concentrations (< 2.5 μg/l) were recorded around the perimeter of the dam and the Abstraction Tower. Minimum values, greater than 2.5 μg/l were found at points, very close to the mouth of Evinos river and Skotinorema.

Figure 8. Spatial distribution of chl-a in Evinos Reservoir, 1/10/2020

4. CONCLUSIONS

According to the River Basin Management Plans developed by the Greek Ministry of Environment, it is of great importance to preserve the reservoir's current water quality conditions and if possible, upgrade the ecological and chemical status. The key water quality challenges for Water Reservoirs are water abstraction and anthropogenic activities (urban, agricultural, industrial etc.) in the catchment area. As reflected by the results of the current monitoring programs, a more detailed investigation will improve the correlation of environmental pressures with the impacts to lake water quality. To enhance this process, an ***innovative monitoring strategy*** with high resolution in space and time was conducted for the ***first time in Greece***.

The use of robotic boats achieves ***a thorough monitoring coverage both in space and time*** and provides significantly higher amount of water quality data without requiring labour-intensive and costly monitoring schemes. It allows monitoring of ecological status more accurately with emphasis on phytoplankton growth and proved the oligotrophic state of Mornos and Evinos reservoirs while the state of Yliki and Marathon ranges between oligotrophic to mesotrophic. Additionally, the application of robotic boats providing EYDAP with valuable insights into the distribution and the responses of several physicochemical parameters to environmental pressures.

The innovative water quality monitoring strategy achieved the collection of data even from unaccessible sampling areas covering broader spatial extents in a shorter time enhanced that way ***a more representative coverage of the whole catchment***. Another important key element is that robotic boats provide a safer working environment, improving management of the site sampling plan and subsequently ***raising alerts in time*** to take action to protect end users.

The use of EYDAP autonomous boats has shown that it can contribute to the most complete and best quality control of the Reservoirs, detecting in time, if necessary, possible pollution from anthropogenic activities or natural processes. Additionally, the systematic, full scale application of autonomous boats ***could support the investigative monitoring programs of the WFD in the future*** and represent a valid rapid tool/approach ***in case of emergencies thus assisting in more effective crisis management*** (e.g. in relation to climate changes events such as floodings). The Vision is that EYDAP will provide a service to authorities and organizations interested in assessing water quality in relation to catchment management and the traditional spot sampling protocols.

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