REAL-TIME, ADAPTIVE, SELF-LEARNING MANAGEMENT OF LAKES

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ABSTRACT

Lakes and reservoirs are increasingly threatened by anthropogenic activities, with serious environmental and financial consequences. In particular, nutrient loadings are increasing due to expanding human populations and food demand, and thermal stratification is increasing due to global warming. For deep lakes, this is leading to an increase of the seasonal water column stability, extending the duration of seasonal deoxygenation of hypolimnetic waters, as well as increasing the nutrient inventory within the bottom sediments. The large volume of deoxygenated hypolimnetic water and nutrient-enriched bottom sediments increase nutrient releases. This overturn brings the deoxygenated, nutrient rich hypolimnetic water into the euphotic zone, leading to increased primary productivity, organic enrichment, and providing a feedback mechanism for further degradation of the fauna and flora living in the epilimnion, potentially culminating in total death of aerobic organisms by asphyxiation. Reservoirs and shallow lakes are increasingly subjected to toxic algal blooms in response to changing patterns of stratification in combination with the increasing nutrient loadings. We use two examples to illustrate the problems presently encountered, the range of control strategies available to manage the consequences and then show how adaptive, real-time, self-learning technologies may be used to dynamically optimize the ecosystem health, as both the impacts and the system change with time. The first example is deep Lake Iseo in Italy. The period between overturns has increased from around every ten years to twenty years in Lake Iseo over the last 50 years. We show that the water column stratification may be controlled with solar-powered impellers, allowing the frequency of overturning to be regulated so as to prevent the buildup of large volumes of low-oxygen hypolimnetic waters. The second is shallow Lake Ypacarai in Paraguay. It has undergone rapid eutrophication, resulting in severe toxic algal blooms that are having a devastating impact on the economy of Paraguay. Using the numerical simulations of the lake ecosystem, we carried out a sensitivity analysis of the available controls for the mitigation of the algal blooms. The simulations demonstrate how a decrease in the nutrient loadings, decrease in the water levels, flushing of the lake with bore or river water and increase in water opacity provide multiple potential bloom control mechanisms. The results for both lakes indicate that a real-time adaptive management system using model forecasts could optimize environmental controls on attributes (e.g. cyanobacteria and dissolved oxygen) that would otherwise seriously deteriorate and impact the ecological processes throughout the lake ecosystems.

Keywords: Lakes; global warming; nutrient loadings; algal blooms; adaptive management.

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1 INTRODUCTION

The traditional response to manage algal blooms in standing waters is to develop an environmental plan aimed at reducing external macronutrient loads (Paerl et al., 2016). Often, however, more often than not, the problem of increasing nutrient loads is ignored until, for example, a cyanobacterial bloom develops and/or fish kills occur (e.g. Kangur et al., 2016). At this point, the plans are taken off the shelf and a blame game is set into motion. Even when such plans are activated, they are often compromised by large inventories of macronutrients (legacy nutrients, Spears et al., 2014) stored in the bottom sediments, and reflecting historical excesses of catchment loads (Hamilton et al., 2016). This inventory is often mobilized unpredictably and rapidly in response to declining ecological condition in lakes (Zhu et al., 2014). Recent trends in environmental management have been to move away from management via fixed plans and abrupt, often politically driven responses, towards "adaptive, real-time, self-learning control and management". There are three main reasons for this change. First, it is extremely difficult to impose a strict "plan" over a lake basin, as both natural and anthropogenic loadings evolve in response to multiple factors (e.g. climate, human populations, changes in weathering) so rigid control, involving prohibition or restriction of land use activities, is very expensive and rarely works. Second, the scale of human actions and the reach of actions have become global in the last 20 years or so. The outcome is that local actions aimed at improved practices can be diluted by political imperatives usually driven by global trends and economic incentives. The result is changing ecological functioning of both the lake basin and the lake itself, as well as the changes in weather, invalidating the assumption of statistical stationarity upon which conventional management plans are predicated. Third, sensor, communications and modeling technologies have all recently greatly improved, allowing decisions to be made in real-time, based on the dynamic feedback from the environmental domain coupled with real-time numerical simulations (e.g. Marti and Imberger, 2015, Reis et al., 2015). This allows non-stationary behavior to be better quantified, understood and managed.

Adaptive management recognizes the non-stationary nature of a system and consists of five, complementary, components (Marti and Imberger, 2015, Gunderson, 2015):

1. *Process field work and experimental studies aimed at identifying and quantifying the sensitivity of the controls on the system*. The basis of this scientific investigation is to understand the underlying ecological processes at catchment scale, quantify and predict their responses to anthropogenic impacts, and provide data suitable for testing the relative sensitivity of possible ecological controls.
2. *Numerical models to mimic the ecological function of the domain.* Fundamental process understanding is used here to set up relevant numerical models that are suitably resolved in time and space to simulate the responses from expected anthropogenic developments. Such models will first, contain deficiencies in their initial process descriptions and will therefore require additional process descriptions to be added as the system characteristics are described more completely, as anthropogenic impacts change, and with changes in community expectations over time.
3. *Real-time monitoring hardware.* Installation of critical real-time monitoring sensors provides opportunity for feedback of the system response and may be used to evaluate the simulation model results, *i.e.* for validation purposes (Hamilton et al., 2014).
4. *A Real-time Online Management System (RMSO).* This system allows the simulation models to run both in real-time and forecast mode and real-time data to be connected and fully integrated into the decision making, thus allowing:
   a. Custodians of the lake basin to be alerted, in real-time, of model and data stream departures from normal operating and/or ecological conditions.
   b. The deviation between model and data streams as feedback to assess the need for new process knowledge. This facilitates new algorithm development and cutting-edge science.
   c. Connection of the simulation models to "cloud" derived boundary conditions data streams, such as meteorological forcing from WRF [Weather Research and Forecasting Model (Skamarock et al., 2008)], open ocean forcing from HYCOM [HYbrid Coordinate Ocean Model (Chassignet et al., 2007)] and surface tide and wave characteristics from Wavewatch III (Tolman, 2002). Such boundary condition data streams, coming from the cloud, are now available for up to 20 years in forecast mode, allowing long time predictions to be made of the impacts of proposed developments. Given the advances in models, even a Monte Carlo approach can be used to arrive at optimum designs for new developments.
   d. Adapting a neutral objective function, such as the ISF [Index of Sustainable Functionality (Imberger et al., 2007)], that provides a quantitative measure of whether actions lead to mounting unwanted externalities.
   e. Disseminating the objective function value to the community and all stakeholders via the internet, providing a learning base for an educated stakeholder response that can stand up to special interest pressures.
5. *Solicit Stakeholder Feedback.* Set up close links with educational institutions in the lake basin, through social media, to provide a real life, local and sound educational tool. Use social media to

facilitate active communications with management system in place in other countries, to provide for comparative studies and facilitate rapid learning and uptake of universally acknowledged best practices.

In this contribution we focus on assessing the feasibility of using an adaptive management approach (Figure 1) in order to improve the health and resilience of lakes across the globe, to mitigate toxic algal blooms in shallow water bodies, and more generally to conserve flora and fauna of inland waters, as more biota are at risk of extinction in freshwater ecosystems than for any other ecosystem across the globe. We provide process evidence that the periodicity of overturning in large lakes may be controlled by using submerged impellers to artificially mix the water column and that toxic algal blooms are best mitigated with a multiple control strategy approach.

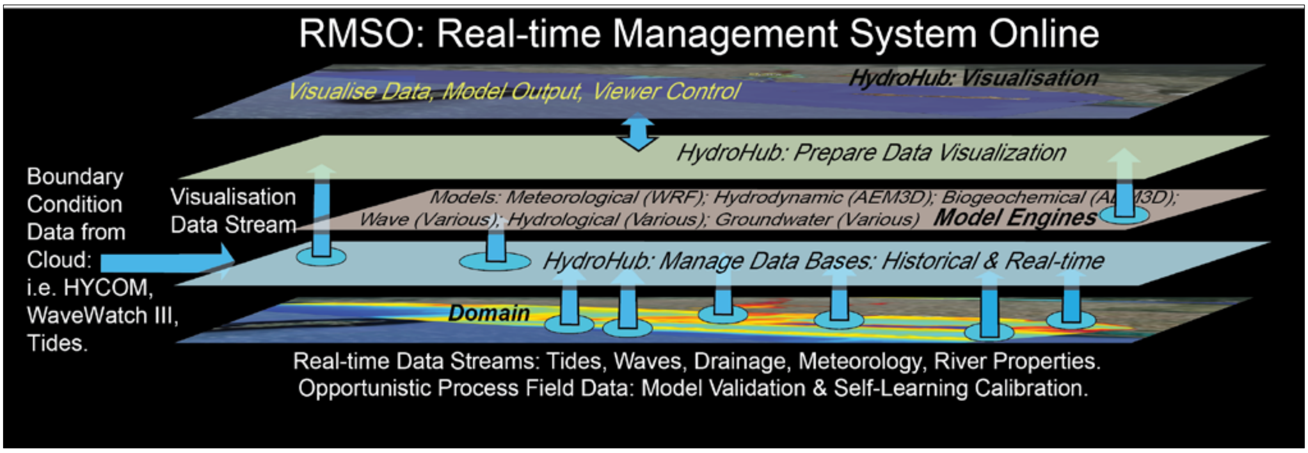

Figure 1. Schematic of a real-time adaptive management component structure and connectivity.

2 METHODS

2.1 Numerical Model

In this study, numerical simulations were conducted with the 3-dimensional coupled Hydrodynamic-Aquatic Ecosystem Model (AEM3D, Hodges and Dallimore, 2016) that was developed from the ELCOM-CAEDYM (Hodges et al., 2000, Romero et al., 2004) source code. The hydrodynamic solver uses the unsteady, viscous Navier-Stokes equations for incompressible flow with or without the hydrostatic assumption for pressure (Hodges et al., 2000). Calculated processes include baroclinic and barotropic responses, rotational effects, tidal forcing, wind stresses, surface thermal forcing, inflows, outflows, transport of salt, heat and passive scalars and mixing of all the state variable with either a mixed fraction algorithm or a Richardson Number dependent eddy diffusion coefficient. The hydrodynamic algorithms are based on the Euler-Lagrange method for advection of momentum with a conjugate-gradient solution for the free-surface height. Passive and active scalars (*i.e.* biogeochemical state variables, salinity and temperature) are advected using a conservative ULTIMATE QUICKEST discretization. The biogeochemical model includes a library of algorithms that represent the key biogeochemical processes (Romero et al., 2004) influencing water quality under the simulated physical conditions. Mixing and transport are solved separately to the rate of change due to the biogeochemical processes. The biogeochemical processes include primary production, secondary production, nutrient, carbon and metal cycling, oxygen dynamics and the transport and deposition of suspended solids. AEM3D can be run either in standalone hydrodynamic mode or as a fully coupled hydrodynamic biogeochemical model. The reader is referred to Marti et al. (2016) for similar application of the AEM3D model to Lake Iseo and for Lake Ypacarai, the default configuration was used for the hydrodynamics, but given that the focus was to understand the triggers for the toxic algal bloom observed in 2012, the configuration of the biogeochemical model component was adapted to include two phytoplankton state variables, but no higher levels of the food web.

2.2 Focus sites

2.2.1 Lake Iseo

The period between deep overturns is a decisive factor for the evolution of water quality and biocenosis in deep lakes, because the deep circulation oxygenates the hypolimnion (Boehrer and Schultze, 2008). Global warming is intensifying the thermal stratification of deep, mid-latitude lakes, leading to longer stratified periods, stronger thermal gradients across the thermocline and altered mixing conditions in the metalimnion (Peeters et al., 2002, Danis et al., 2004). Recent observations suggest that the time between complete water column overturn in deep lakes in general has increased by more than twofold in mid-latitude lakes, close to urban centres (Garibaldi et al., 2003). This is the result of three factors. First, increased phytoplankton growth in the surface layer increases the turbidity of the surface layer waters, causing the short wave radiation to be absorbed closer to the lake surface. Second, increasing greenhouse gases leads to an almost insignificant increase in incoming long wave radiation, but this amplified by the resulting increased humidity heat, resulting in a net increase of incoming long wave radiation, ΔQ_{LWI}, of approximately:

$$\Delta Q_{LWI} = 4\,\mathrm{Wm}^{-2}. \quad [1]$$

Third, the increasing water column stability progressively shuts down the dissolved oxygen fluxes derived from surface aeration and production, while at the same time the increased phytoplankton biomass leads to an increase in oxygen demand, which in turn, fosters an enhanced dissolution of redox sensitive chemicals from the sediments into the lower part of the water column. In the extreme case, this initiates a transition for the lake to become meromictic. The water column potential energy is therefore a major factor influencing ecosystem health in a deep lake.

Lake Iseo is the fourth largest Italian lake in terms of volume, with a volume of 7.9 km^3, a surface area of 60.9 km^2 and a maximum depth of 256 m. The major inflows into Lake Iseo are the Oglio River and the Industrial Canal, entering the lake at the northern end, while the major outflow, the Oglio River, leaves the lake at the southwestern end (see Figure 2a). The lake is L-shaped with steep sides and with a 4.5 km^2 island in the central part of the basin. The wind field over the lake varies greatly spatially being strongly influenced by the island and the surrounding mountainous topography. This spatial variability is important as it determines which internal modes are excited by the wind forcing, which in turn, determines the mixing regimes in the lake (Valerio et al., 2012, Marti et al., 2016).

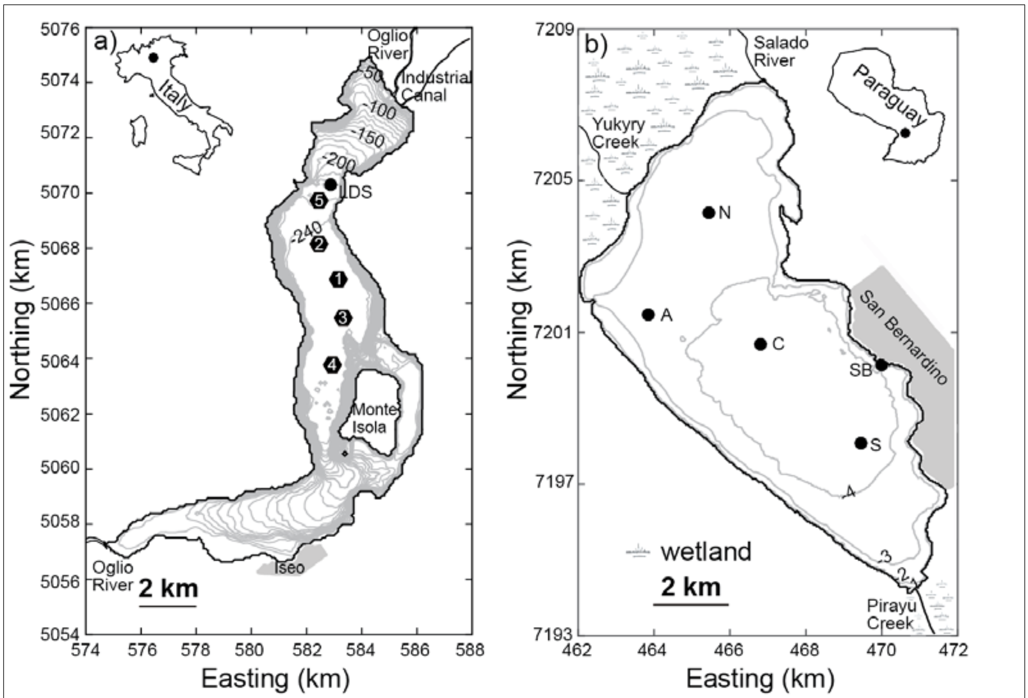

Figure 2. Location and bathymetry of (a) Lake Iseo and (b) Lake Ypacarai. Circles indicate the locations of the field data sampling stations. Hexagons in a) indicate the locations of the impellers. Contour values (in metres) are expressed relative to mean water level.

Lake Iseo shows a strong seasonally succession of phytoplankton consisting of cyanobacteria (mostly *Planktothrix rubescens*), green algae (mainly *Sphaerocystis schroeteri* and *Mougeotia spp.*) and diatoms (mainly *Fragilaria sp.* and *Diatoma elongatum*) (Garibaldi et al., 2003, Marti et al. 2016). Since the end of the 1980s, the deep layers of the lake have become more severely deoxygenated (see Figure 3) and the frequency of full overturn has changed from about once less than about 12 years before 1980 to 25 years in the period between 1980 and 2005. Also noticeable from Figure 3 is the increase in the rate of oxygen depletion of the hypolimnetic waters from an average of about 1 mg $L^{-1} y^{-1}$ in the 1990s to about 3 mg $L^{-1} y^{-1}$ in between 2006 and 2011.

These observed changes may be explained as follows. The reduction of the Secchi depth (Figure 3) from around 6 to 4 m over 20 years implies an increase of the extinction coefficient from about 0.28 to 0.42 m^{-1}. Assuming the increase in light absorption is predominantly due to higher concentrations of phytoplankton, then using the correlations established by Behrenfeld and Boss (2006), this implies a threefold increase of phytoplankton concentration in the surface layer. Assuming that the mass of organic matter falling into the hypolimnion, as dead algal cells, is associated with uptake of oxygen in this layer and that phytoplankton biomass in the surface layer is linearly related to the dissolved oxygen concentration, then the hypolimnetic oxygen uptake rate would have increased from 1 mg L-1 y^{-1} in the 1980s to 3 mg L-1 y^{-1} around 2010 (Figure 3). These biological changes combine with the small changes in the surface heat and momentum fluxes due to global warming. However, as shown by Tanentzap et al. (2008) and O'Reilly et al. (2015), each lake must be viewed on its own merits, as global warming is also known to force strong local weather changes. Thus, the small consistent increase in incoming long wave radiation due the greenhouse effect, may be overwhelmed by local variations in air temperature, wind speed and humidity that are changing on a global warming time scale, but at different rates and signs depending on the geographic regional location, all impacting on the heat budget of the surface layer. Thus, to gain a quantitative overview of how a particular lake responds to global warming and increased nutrient loadings, it is necessary to use local meteorological and stream flow data.

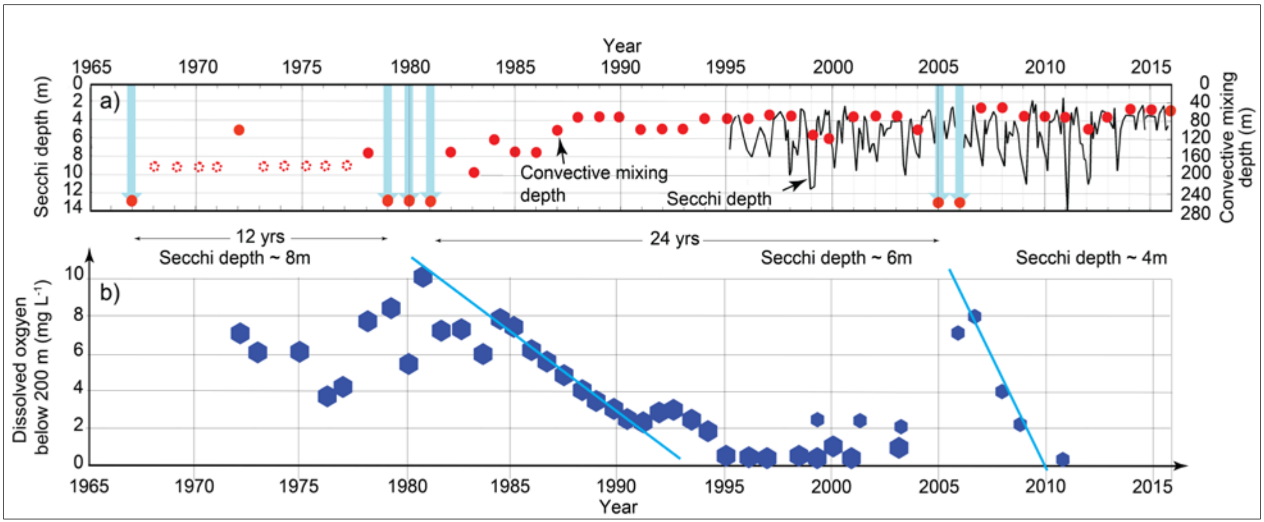

Figure 3. The time evolution, between 1965 and 2015 of the water column characteristics of Lake Iseo: (a) Secchi depth and convective mixing depth and (b) dissolved oxygen concentration at 200 m depth. Arrows in (a) indicate the full overturn of the lake. Lines in (b) represent the best fit during the period of oxygen depletion. (Data source: Bonomi and Gerletti, 1967; Cordella, 1976; Ambrosetti and Barbanti, 2005; Salmaso et al., 2007; Pilotti et al., 2013).

The objective of the present contribution is to show, by examining the response of a particular lake, Lake Iseo, with numerical simulations using AEM3D, that the increasing potential energy, due to heating from global warming heating, increasing extinction coefficient and increased solute in the hypolimnion, is small enough, at about 12 kW, to be countered with simply solar powered underwater impellers, described by Morillo et al. (2009) that individually were shown to have a mixing energy capacity of about 3 kW per impeller.

2.2.2 Lake Ypacarai

Lake Ypacarai, located in Paraguay, is approximately 30 km to the east of the capital Asunción (Figure 2b). The lake has a volume of 115 x 10^6 m^3, a surface area of 59.6 km^2, a maximum depth of 4 m and a mean depth of 2 m. The lake is located 62.7 m above sea level, and the associated river basin has an area of ~ 1100 km^2. The major inflows are the Yukyry Creek from the north and the Pirayú Creek from the south. The lake has only one outflowing river, the Salado River, which flows into the Rio de la Plata River via the Paraguay River to reach the Atlantic Ocean. It is important to note, as seen in Figure 2b, that there are extensive wetlands at the delta of Pirayú and Yukyry creeks. Under normal conditions, when the wetlands are not flooded, they intercept and abate the nutrient and sediment loads coming from the basin, before they reach the lake proper and add humic acids to the water (Imai et al., 1999) that will be shown below to influence active algal growth.

Lake Ypacarai and its basin ecosystems are the holiday destination and principal place of leisure for the population of Asuncion, so they have a major economic and tourism value. Lake Ypacarai is also the water source for the city of San Bernardino (Figure 2b), which has a population that can exceed 50,000 in the summer tourist season. In the last 50 years, the expansion of the urban areas of Asuncion towards the lake and the associated changes in land use, in most of the lake basin, have resulted in a marked deterioration of the water quality in the tributary streams increasing the nutrient, heavy metals and sediment loadings to the lake, adversely impacting the ecological health of both the lake and the wetlands (Stanley, 2009). Furthermore, most of the population does not have access to a sewage network and effluents are simply discharged directly into the ground by cesspools and septic tanks. The total annual loads of nutrients reaching the wetlands were estimated to be in the order of 5,450 t of total nitrogen (TN) and 1,180 t of total phosphorus (TP). Over 60% of the loads are generated in the Yukyry creek basin and about 55% are produced by the population through the disposal of sanitary wastewater, while the animal farming activities are responsible for 35% of the total. The remaining 10% is from other sources. The annual organic load was estimated to be in the order of 24,000 t of BOD5, 70% of which is produced by the disposal of sanitary wastewater and 20% by urban runoff. The rest is from other sources (Consorcio BETA Studio - Thetis, 2015). These loads do not all reach the lake, but undergo some reduction during their journey to the lake due to the natural remediation capacities of the wetlands. Such reduction depends on the time the pollutants stay in the wetlands. It is estimated that the wetlands of the Yukyry creek, when the inundation is optimum, capture somewhat more than 70% of the total loads coming from the basin, before the water reaches the lake (Consorcio BETA Studio - Thetis, 2015). In addition, the data collected since the intense cyanobacteria bloom in 2012, show that the concentration of dissolved organic carbon (DOC) is a function of the extent of inundation of the wetland, as quantified by the surface water level. The lake is characterized by low transparency (0.10 - 0.20 m), high suspended solids concentration (70 - 80 mg L^{-1}) and high concentrations of DOC coloring the water when it is most strongly influenced by wetland inputs. The lake is a eutrophic to hypertrophic water body (Consorcio BETA Studio - Thetis, 2015) characterized by high nutrient concentrations (TP ranges from 0.005 to 0.55 mg L^{-1} and TN from 0.5 to 3 mg L^{-1}) and in the last 15 years, high concentrations of cyanobacteria (e.g. *Microcystis, Anabaena*). During the period September 2012 to December 2012, high numbers of the cyanobacterium *Cylindrospermopsis raciborskii* were observed (~ 1,000,000 cells mL^{-1}) (OPS, 2012). This period corresponded to a time when a bridge construction in the Salado River outflow caused high water levels in the lake. In the following months of 2013, the abundance of this species remained high, with values of about 100,000 cells mL^{-1} (Benitez et. al., 2015).

Traditional management strategies for the alleviation of toxic algal blooms, are based on reduction of the various form of P and or N, but as mentioned above, with respect to Lake Iseo, reducing the macronutrient loadings is made difficult by perception in developed countries that pollution is a right, and also, when it is successfully implemented, it is very expensive (Hammerl and Gattenhoehner, 2003). Analogous to Lake Iseo, the question here in Lake Ypacarai is whether the real-time adaptive management methodologies can be used in form of water level control, maximizing the export of color from wetland and possibly flushing the lake with nutrient free groundwater. Here, we explore the sensitivity of the water quality in the lake to the above controls.

3 RESULTS

3.1 Lake Iseo

The objectives of the Lake Iseo simulations were first, to quantify the effect of a small increase in incoming long wave radiation the result of global warming and a small increase in the extinction coefficient, the result of increasing primary production, on the water column stability of the lake. Second, to show, by the example of Lake Iseo, that the above two increases of potential energy may be kept in check, or even reversed by mixing the water column with submerged impellers, of the type described by Morillo et al. (2009). To achieve this objective only the hydrodynamic code was applied to the Lake Iseo bathymetry (Figure 2a), using the dataset by Pilotti et al. (2013). The model was run on an 80 m x 80 m horizontal grid with a vertical resolution ranging from 0.5 m in the diurnal surface layer to 25 m at the bottom. Three cases were simulated. First, a 2012 base simulation was run using measured forcing data (Figure 2a) and a measured extinction coefficient of k = 0.40 m^{-1}. The year 2012 was chosen as good field validation data were available for that year. Second, a simulation mimicking the lake behaviour in the 1990s, referred to as the 1990 case, was run by using the same meteorological forcing data but reducing the incoming long wave radiation by 4 W m^{-2} and changing the extinction coefficient to k = 0.28 m^{-1}. Third, a mixing impeller simulation, based on the 2012 base case was run with five mixers located at the thermocline (see Figure 2a) pushing water down with a thrust of 4600 N each (Morillo et al., 2009). The metric used to quantify the difference between the three cases was the amount of energy required to fully mix the lake to its average temperature at any point in time; the energies were then normalised to the 1990 case as shown in Figure 4. As expected, the increased radiation and extinction coefficient of the 2012 case leads to a significant increase in the stability of the water column during the warming period. As seen from Figure 4b, the five impellers are able to negate the increase in the water column stability and return the water column potential energy back to the 1990 case in a period of four months. Work is currently in progress to derive a dynamic control algorithm for the location of the impellers that would minimize the impeller energy input.

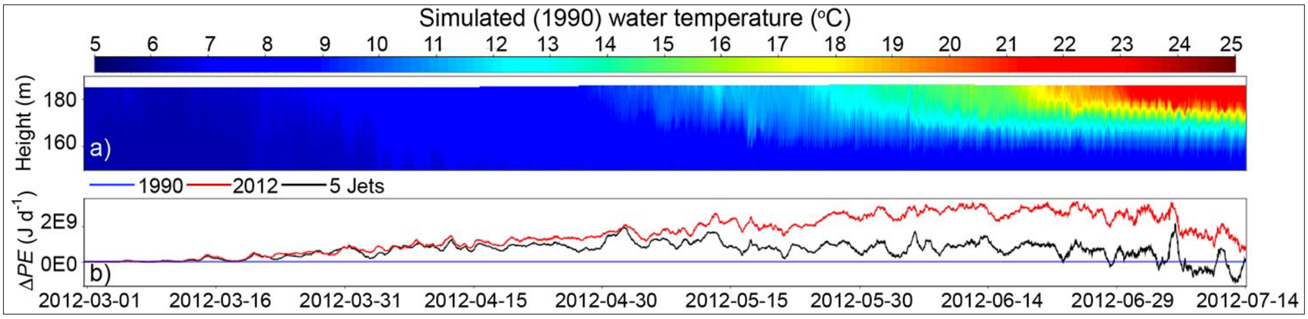

Figure 4. (a) Thermal structure of the top 40 m for the one year simulation with k = 0.27 m^{-1} and no extra heating: 1990 case. (b) The energy required to fully mix the water column relative to the 1990 case for the 2012 case and the 2012 case with 5 impellers pointing down located dynamically at the middle of the thermocline. .2 Lake Ypacarai

The domain of Lake Ypacarai was discretized with a uniform horizontal grid spacing of 80 m, with a vertical resolution of 0.10 m in the upper 0.50 m, and expanding gradually to 0.25 m at depth. Grid resolution studies at finer scale showed no significant difference in model results. The appropriate algorithms in the hydrodynamic model were activated to include atmospheric exchange, inflow and outflow dynamics, turbulent mixing dynamics and Coriolis forcing. The flow was assumed hydrostatic. The biogeochemical model was configured to simulate two groups of phytoplankton (cyanobacteria and diatoms) and the dynamics of phosphorus, nitrogen, dissolved oxygen (DO), silicon, organic matter and one group of suspended solids. Algal biomass was modeled as carbon (C) converted to chlorophyll a (Chl a), with a constant C: Chl a ratio. Phytoplankton dynamics was based on simple growth limitation functions (Hodges and Dallimore, 2016) being constrained to temperature, nutrients, and light, as well as silica in the case of diatoms, mortality, excretion, respiration, settling, and resuspension. Cyanobacteria (*Microcystis aeruginosa*) and diatoms (*Aulacoseira* sp.) were assigned to have constant buoyant and sinking velocities, respectively. The calibration/validation simulations were conducted for a one-week period, starting on 16 September 2015 for which period in-lake field data were available (Figure 2b, INYMA CONSULT SRL, 2015). The model time step was set to 120 seconds. During the period of simulation, the inflows from the Yukyry and Pirayú creeks were negligible and the outflow was assumed to balance the inflows so the lake was assumed closed, with only meteorological forcing acting on the surface. The simulation was driven with 15-minute air temperature, relative humidity, shortwave radiation and 3-hour cloud cover data from a meteorological station located in Asuncion, ~ 30 km northwest of the lake, and 10-minute wind speed and direction data from a meteorological station located in San Bernardino, at the eastern side of the lake. The simulation was initialized with horizontally and vertically homogenous temperature, DO, nutrients (NH_4, NO_3, PO_4 and SiO_2), suspended solids and Chl a (nominally *Microcystis aeruginos*a and *Aulacoseira* sp.) constructed from measured data on 17 September 2015 by averaging data from the five stations shown in Figure 2b. For the validation period the water depth was 2.98 m. The ecological parameters values were derived from the literature (Romero et al., 2004, Reynolds, 2006). The hydrodynamic model did not require calibration, as the physical aspects of water movements in reservoirs are fairly well understood. The water quality model was calibrated by adjusting the Secchi depth through the suspended solids attenuation coefficient. The simulation results achieved are shown in Figure 5, together with field data from the Central station (C in Figure 2b). Horizontal variability was small during the simulation period.

A series of simulations of the hydrodynamics and phytoplankton biomass were conducted in order to explore strategies to mitigate the severity of high biomass algal blooms (cyanobacteria *C. raciborskii)* as observed in 2012 in Lake Ypacarai. These simulations were aimed at testing mitigation strategies to minimize the impact of the phytoplankton bloom and were conducted for a period of 30 days starting on 9 September 2012. The simulations were driven with air temperature, relative humidity, shortwave radiation, wind speed and direction data recorded at 15-minute intervals and cloud cover data recorded at 3-hour intervals from the same meteorological station located in Asuncion, ~ 30 km northwest of the lake. Constant inflow and outflow rates were assumed for the Pirayú and Yukyry creeks and Salado River (2m^3 s^{-1}, 7m^3 s^{-1} and 6m^3 s^{-1}, respectively). For the 2012 period, the water depth was 3.98 m. Due to the lack of inflow temperature data, the two inflows temperatures were estimated as three-day running averages of the air temperature data. Constant values of DO, nutrients (NH_4, NO_3, PO_4 and SiO_2), suspended solids and Chl a (as *C. raciborskii,* the dominant species in the lake, no diatoms were counted) obtained from unpublished data were used for the inflows. The simulations were initialized with horizontally and vertically homogenous values of water temperature, DO, nutrients, suspended solids and Chl a compiled from different sources (Benitez et al., 2015, Consorcio Beta Studio-Thetis, 2015).

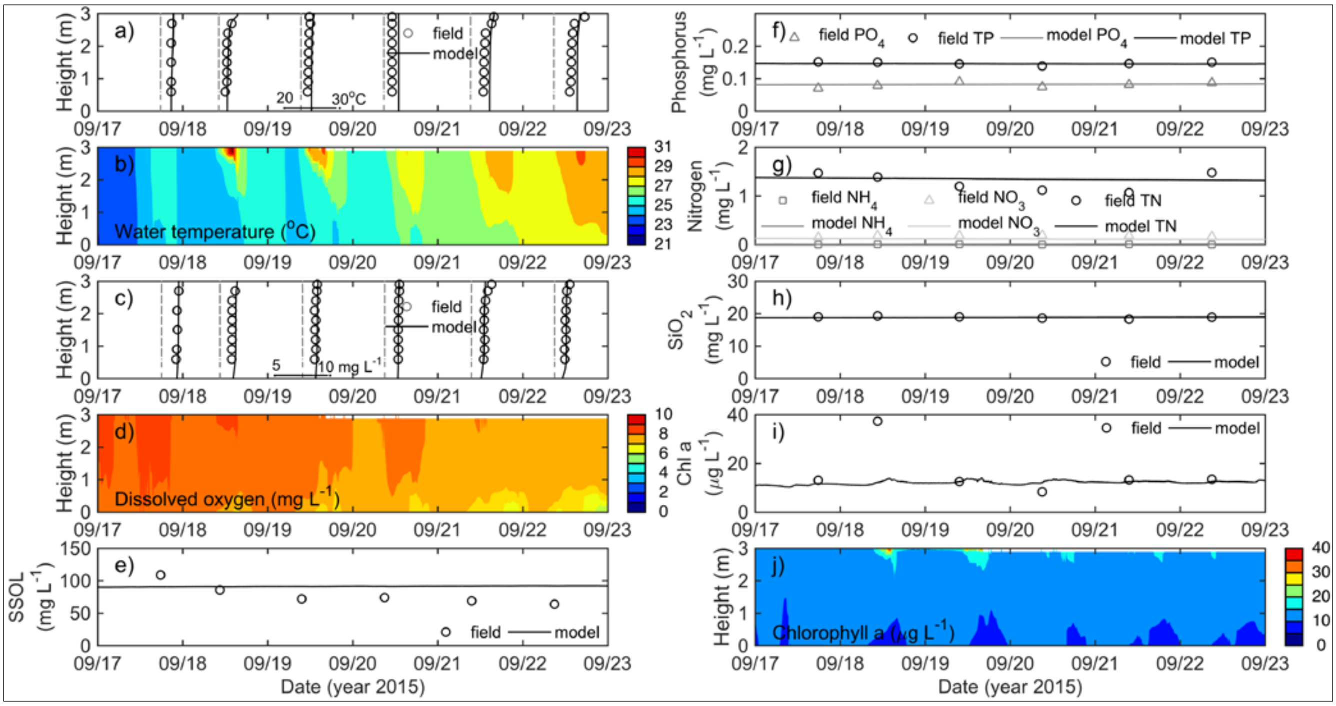

Figure 5. Measured in-lake field data and simulated results at the Central station for the validation period in 2015: (a) measured and simulated water temperature profiles, (b) simulated water temperature contours, (c) measured and simulated dissolved oxygen profiles, (d) simulated dissolved oxygen contours, (e) measured and simulated depth-averaged suspended solids (SSOL) concentrations, (f) measured and simulated depth-averaged PO_4 and TP, (g) measured and simulated depth-averaged NH_4, NO_3 and TN, (h) measured and simulated depth-averaged SiO_2, (i) measured and simulated depth-averaged Chl a, and (j) simulated Chl a contours.

The validated model configuration for 2015 was applied to the one-month period in September and October 2012, the time of the major cyanobacteria bloom. The simulation results for the base case, which we shall refer to as the "mockup", shown in Figure 6a-h, uses the best estimate for the forcing and initial conditions. The objective was to determine the conditions responsible for the 2012 bloom. Given the paucity of good initial conditions and inflow data, and the absence of any in-lake data during the bloom, such comparisons could not be made, but it will be instructive to see whether the validated model configuration, with realistic forcing and initial conditions, would produce a bloom or bloom tendencies in October. As shown in Figure 6h, the assumed initial cyanobacteria concentration of 30 µg L^{-1} grew to a little under 40 µg L^{-1} in the period from 09/09 to 09/23, then reached a maximum concentration of around 65 µg L^{-1} by 10/09 or about 500,000 cells mL^{-1} with the most rapid growth occurring in the last week of the simulation period. The rate of growth was completely determined by the combination of light limitation and temperature expressed quantitatively by the product of the maximum rate of growth, μ_{max}, times the availability of light, f(I), times the temperature function, f(T), *i.e.* μ_{max} x f(I) x f(T) = 0.7 x 0.2 x 1.4 = 0.2 d^{-1}, implying a doubling time of the concentration field of between three and four days, which conforms to what is seen in Figure 6h; neither P nor N limited growth at any time of the simulation. The results, from this mockup simulation, show that during a bloom, the phytoplankton grow in the diurnal surface layer, whenever there is sufficient light, the water temperature is near that required for optimum growth and the wind is weak enough so as not to mix the blooming phytoplankton more than approximately one meter below the photic depth (Figure 6c,h from 09/20 to 10/09); the one meter is because the assumed rise rate is 1 m d^{-1}. In summary, the mockup simulation suggests that the conditions conducive for the occurrence of a bloom in Lake Ypacarai are that the diurnal mixed layer is comparable, in depth, to the photic depth plus the rise distance per day. Nutrients are more than plentiful, but the growth seems to almost completely be controlled by the availability of light. To test the above light limitation hypothesis a number of scenarios were run. First, the water level was reduced by 1.20 m with same water quality as the mockup case. As seen in Figure 6i, the reduced depth prevented the cyanobacteria from being mixed out of the light zone plus 1 m (> 2) and this caused, as expected, an enhanced phytoplankton growth, the concentration reaching nearly 90 µg L^{-1} by the end of the simulation period. The second way to influence the light climate in the water column was to activate the action of the wetlands and increase the background extinction coefficient and DOC in both the inflows and the initial conditions of the simulations. A scan of the available data of Secchi, the depths revealed an extreme condition where the Secchi depth was only about 15 cm. Figure 6j shows that the cyanobacteria could not grow under these conditions. A second simulation with this extinction coefficient adjustment and reducing the water level again by 1.20 m is shown in Figure 6k. Both scenarios conformed to the assumed hypothesis. The deeper water case (Figure 6j) showed a dramatic growth reduction that was mitigated by reducing the water depth (Figure 6k), as discussed above.

Underneath Lake Ypacarai lies a deep unchartered confined groundwater aquifer, 160 km to the east of the Lake is a further very large confined aquifer and the Paraguay River is also reasonably close by all suggesting a scenario where, when the RMSO unit predicts a pending bloom, additional water is used to partially flush the lake. Figure 6l shows the result for the case of an additional flow of 22 $m^3 s^{-1}$ that would be sufficient to flush the complete lake in 60 days. The impact is noticeable, but not dramatic at the Central station. With a focused design perimeter beaches could, however, be protected in this way.

The past scenario was verifying the obvious, if nutrients are reduced sufficiently, the algal blooms will be prevented (Figure 6m). To avoid the cyanobacteria concentrations from rising above 40 µg L^{-1}, the initial nutrient concentrations and loading had to be reduced to around 1% of the mockup case. In practice, this change would, however, not take effect, until all nutrients in the sediments were also used up.

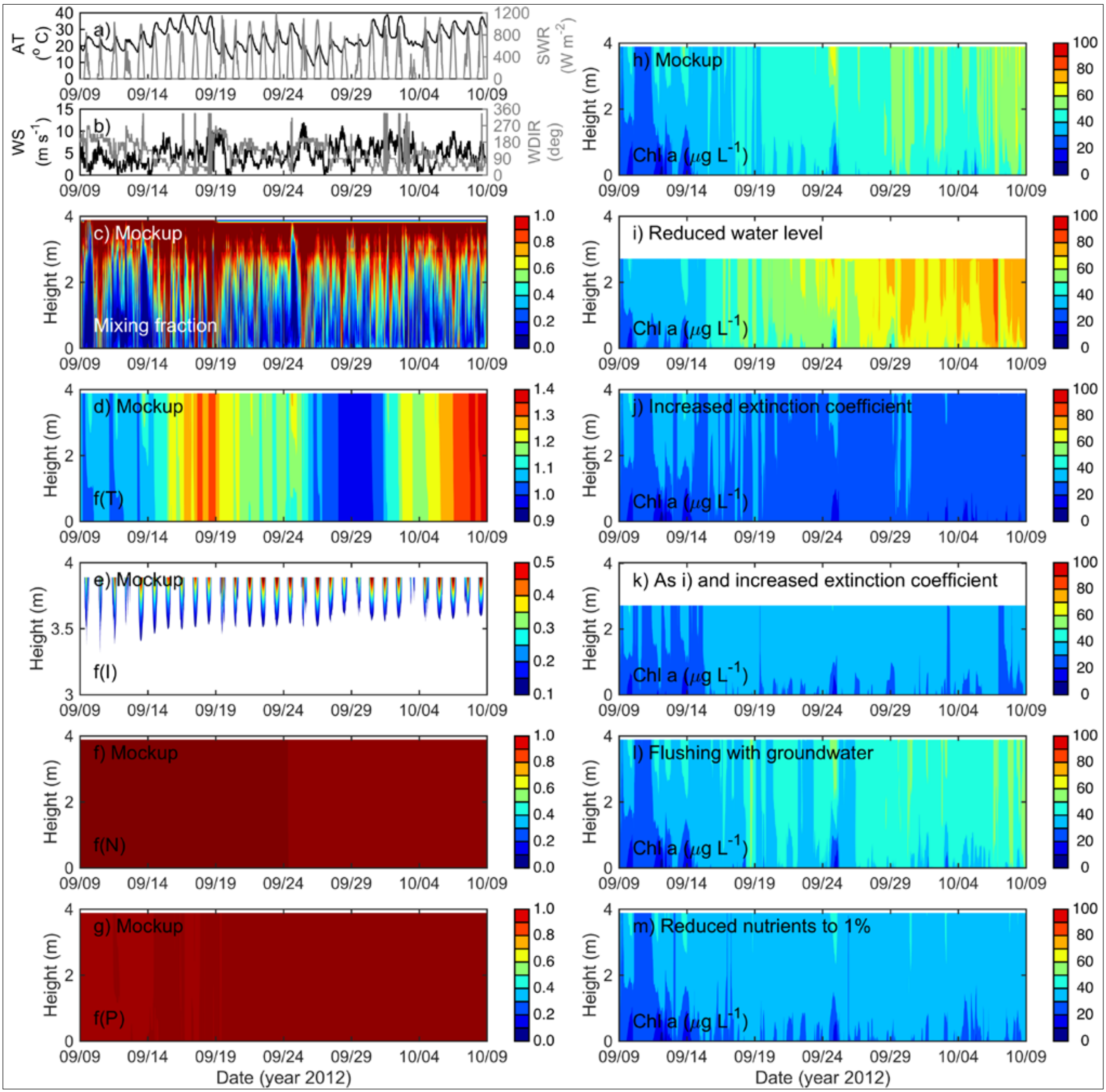

Figure 6. Times series of meteorological data and simulated results at the Central station for 2012: (a) Air temperature and short wave incoming radiation, (b) wind speed and direction, (c) mockup: simulated mixing fraction, (d) mockup: simulated rate of growth temperature dependence f(T), (e) mockup: simulated light limitation function f(I), (f) mockup: simulated nitrogen limitation function f(N), (g) mockup: simulated phosphorous limitation function f(P), (h) mockup: simulated Chl a concentration, (i) water level reduced with no other controls: simulated Chl a concentration, (j) increased extinction coefficient only to mimic possible

wetland restructuring with vegetation rich in tannins: simulated Chl a concentration, (k) water level reduced by 1.20 m, and extinction coefficient increased to mimic the action of the wetlands, in increasing yellow substances, at lower water level: simulated Chl a concentration, (l) adding 22 $m^3 s^{-1}$ of clean water to Pirayú inflow, designed to mimic flushing of the lake: simulated Chl a concentration, and (m) TP and TN inflow and initial concentrations reduced to 1% of those estimated for mockup: simulated Chl a concentration.

4 DISCUSSION

4.1 Lake Iseo

The Lake Iseo simulations clearly demonstrated that submerged impellers may be installed to control the water column stratification even in large deep lakes. A simple magnitude estimate analysis demonstrates the nature of the impeller action. The increase in incoming long wave radiation, is absorbed in the first few millimeters of the lake water column and is then distributed over the diurnal surface layer by the wind and night cooling, as shown schematically in Figure 7. Over a 24 hour cycle, from say 06:00 to 06:00 of the next day, we may assume that estimates of the temperature, θ', and the resulting relative potential energy increase due to global warming (GW), $\Delta PE|_{GW}$, of the diurnal surface layer are given by:

$$\theta' = \frac{\Delta Q_{LW}\Delta t}{\rho_0 C_P h_m} \sim 0.004^{o}\mathrm{C\,yr^{-1}} \quad [2]; \text{ and } \quad \Delta PE|_{GW} = A_0 g\alpha\theta'\rho_0 h_m\left(\frac{H}{2}-\frac{h_m}{2}\right) \sim 6.42\mathrm{x}10^{8}\,\mathrm{Jd^{-1}} \quad [3]$$

where $h_m = (h_1 + h_2)/2 = 20$ m, ρ_0 is a reference density, $H = 124$ m is the mean water depth, and C_P is the specific heat, $A_0 = 60.9 \times 10^6$ m^2 is the lake surface area, g is the acceleration due to gravity and α□is the coefficient of expansion due to heat.

The low oxygen condition in the hypolimnion is known to be causing a small increase of hypolimnetic salinity of around 0.002 psu per year. In terms of the water density, this corresponds to a temperature change of around 0.001 ºC yr^{-1} implying that potential energy increase associated with the salinity increase is smaller than that due to the change of potential energy due to global warming and can easily be overcome with impellers placed in the hypolimnion.

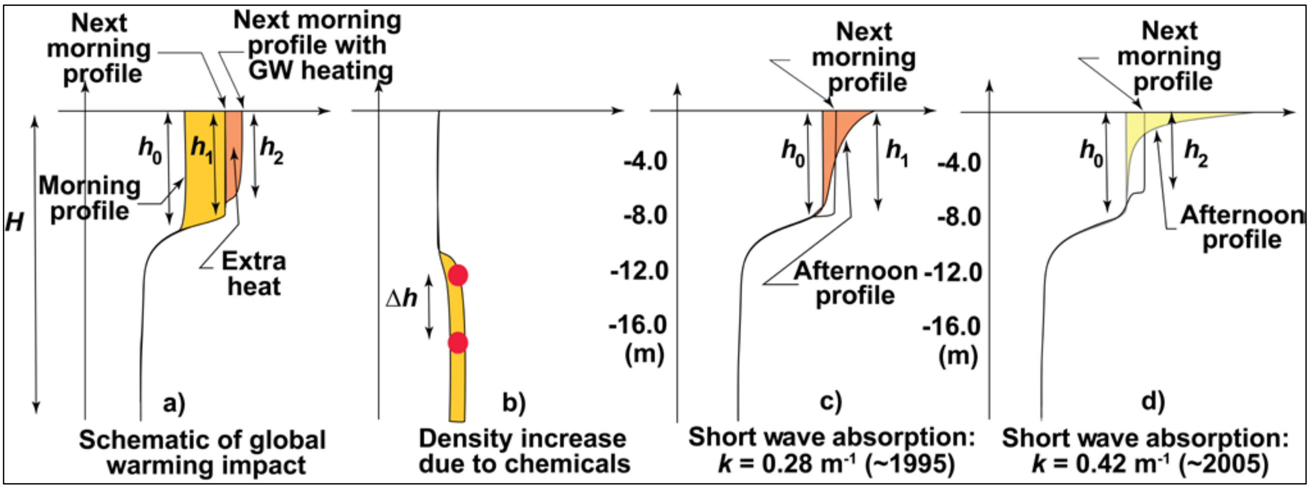

Figure 7. Schematic of the effect of global warming and increased primary production: (a) effect of increase in incoming long wave radiation, (b) density increase of the hypolimnetic waters due to dissolved chemicals, Δh = distance needed to raise extra mass for mixing, (c) short wave radiative heating with deep penetration, (d) short wave radiative heating with shallow penetration.

The effect of an increasing extinction coefficient (Figures 7c-d) is twofold. First, the larger the extinction coefficient, the closer to the water surface the incoming short wave radiation is absorbed and the larger the associated *PE* introduced to the water column and second, as shown in Figure 4d, a larger extinction coefficient, for the same incoming short wave radiation leads to slightly raised water surface temperature and thus a slightly increased long wave outgoing radiation, offsetting the increased long wave incoming radiation (Eq. [1]).

As shown in Figure 4, Lake Iseo experienced a threefold increase in the surface layer phytoplankton concentration over 20 years, which led to a 50% increase in the extinction coefficient. Suppose the short wave heat is distributed through the water column as described by Beer's law:

$$Q_{SW} = Q_{SWO} e^{kx_3} \quad -H < x_3 < 0 \qquad [4]$$

Where Q_{SW} is the short wave radiation at depth x_3, Q_{SWO}, is the short wave radiation entering at the water surface and k is the extinction coefficient. By way of illustration, consider the case where morning convective mixing has homogenized the diurnal surface layer to a depth a little greater than the Secchi depth establishing a uniform temperature, θ_0 over the depth of the surface layer. Carrying out a heat budget over the surface layer, using the absorption relationship (Eq. [4]) leads to a temperature profile $\theta'(x_3,t)$ given by:

$$\theta'(x_3,t) = \left(\frac{k\overline{Q_{swo}}}{C_P\rho_0}\right)e^{kx_3} + \theta_0 \qquad [5], \text{ implying } \Delta PE_{sw} = \frac{\alpha\overline{Q_{swo}} g A_0 t}{2C_P}\left(H - \frac{1}{k}\right) \qquad [6]$$

Where $\overline{Q_{swo}}$ is the time average incoming short wave radiation and $\rho'(x_3) = \alpha\rho_0\theta'$. Substituting values in Eq. [5] for a time average incoming radiation value of $\overline{Q_{swo}} = 500\,\mathrm{Wm^{-2}}$, suggests a surface temperature differential of 1.5 ºC for k_1 = 0.283 m^{-1} and 2.2 ºC for k_2 = 0.42 m^{-1}, respectively. The associated *PE* change, given by Eq. [6] using the above values leads to a value $\Delta PE'_{SW} = 4.578\mathrm{x}10^8\ \mathrm{Jd^{-1}}$.

The change in the outgoing long wave radiation emitted from the water's surface is given by the emission relationship:

$$\Delta Q_{LWO} = \varepsilon_w \sigma\left[(273+2.2)^4 - (273+1.5)^4\right] \qquad [7]$$

where $\varepsilon_w = 0.96$ is the emissivity coefficient of the water and $\sigma = 5.7\mathrm{x}10^{-8}$ is the Stefan-Boltzmann coefficient. Substituting the values in Eq. [7] implies that the outgoing long wave radiation would increase by about 3.2 W m^{-2}, which approximately equals the extra short wave coming towards the earth, due to greenhouse gases back radiation (Eq. [1]). Thus to first approximation, in Lake Iseo, in terms of heating, the anthropogenic impact of global warming (Eq. [1]) approximately balances extra back radiation, (Eq. [7]) induced by increased phytoplankton biomass, the result of increased nutrient loadings in contributing streams. By contrast, the changes to the potential energy are additive so that implying that bulk estimates of $\Delta PE' = (\Delta PE'_{SW} + \Delta PE'_{GW}) \sim 10^9\ \mathrm{Jd^{-1}}$, comparable to the simulation result as seen in Figure 4b.

The above estimates are clearly dependent on the daily cycle of heating cooling, which is accounted in the numerical simulations (Figure 4). Further insight may be gained by examining two extreme diurnal cycles. First, consider a day when the lake is exposed to a steady wind, strong enough to maintain a well-mixed surface layer preventing the buildup of the surface temperature (Eq. [5]). For such a day, the changes to outgoing long wave back radiation would be minimal, but the potential energy contributions (Eq. [3] and [6]) would be additive. By contrast, for a day with little wind during the sunshine hours, a clear sky and strong solar radiation, the near surface waters would stratify, so that the two radiation inputs would cancel, but again the *PE*'s would add. The above scale estimates suggest that the anthropogenic effects of global warming and increased nutrient loadings add approximately 10^9 J d^{-1} of potential energy to the lakes water column, explaining the simulation results shown in Figure 4. This additional potential energy must be overcome by the meteorological forcing if the historical pattern of complete overturn is to be maintained. For lakes, such as Lake Iseo, where the water column stability is in a delicate balance with meteorological forcing, this increasing potential energy, coupled with increased nutrient loadings, is leading to the period between overturns to progressively increase and if nothing is done three consequences are likely. First, the endemic fauna and flora will most likely be eliminated at the next complete overturn that will sweep low oxygen water into the surface layer. Second, in lakes that contribute to carbon sequestration, such as Lake Iseo, the increase in macronutrient loadings supports increased carbon sequestration in combination with increasing the water column stability. The sledgehammer approach of reducing the nutrient loadings targets both the stability and the sequestration rate, by comparison, mixing with impellers selectively targets only the increasing water column stability (Schindler, 2012). Third, in the long term, these lakes will become meromictic with a continually increasing concentration of dissolved chemicals.

4.2 Lake Ypacarai

We may inspect the phytoplankton growth simulation in Lake Ypacarai and write the phytoplankton growth equation in non-dimensional form:

$$\frac{\partial C'(x_i,t)}{\partial t'}+N_A v_i'\frac{\partial C'(x_i,t)}{\partial x_i'}-N_M\frac{\partial C'(x_i,t)}{\partial x_3'}=\varepsilon_j'(x_i,t)\frac{\partial^2 C'(x_i,t)}{\partial x_j'^2}+N_G\mu'(x_i,t)C'(x_i,t)$$

$$C'=\frac{C}{C_0},\ x_i'=\frac{x_i}{h},\ v_i'=\frac{v_i}{U},\ \varepsilon_i'=\frac{\varepsilon_i}{\varepsilon_i^{(0)}},\mu'=\frac{1}{\mu^{(0)}}\left\{\mu_{max}\left[Min(f(N),f(P),f(I),)f(T)\right]-Rf(S)-M\right\}$$

$$\text{and}\quad N_A=\left(\frac{Uh}{\varepsilon^{(0)}}\right);\ N_M=\left(\frac{Vh}{\varepsilon^{(0)}}\right)\ N_G=\left(\frac{\mu^{(0)}h}{\varepsilon^{(0)}}\right) \qquad [8]$$

Where C is the algae concentration and μ_{max} is the maximum rate of growth. This maximum growth is constrained by the availability of nitrogen, f(N), availability of phosphorous, f(P), and light, f(I). Furthermore, these constraints are modulated by a temperature function f(T); the growth is small if the water temperature is too cold, occurs at a maximum rate at an optimum temperature and death occurs when the water temperature becomes warmer than a critical temperature. R is the respiration and excretion loss term, f(S) is a salinity modifier for this term and is set to 1 for freshwater. M is the removal of phytoplankton due to grazing by zooplankton and bivalves. Given that here, we are illustrating the control of phytoplankton biomass through changing the physical regime of the water column we may assume that M = 0. The function, R:

$$R(T)=k_r\vartheta^{(T-20)} \qquad [9]$$

Where k_r is the respiration rate coefficient, T is the water temperature and ϑ is the temperature multiplier.

An understanding may be gained of the relative importance of each term in Eq. [8]. The vertical diffusion coefficient ε_3 is related to the mixing fraction, $\eta_{(i)}$ in AEM3D as follows:

$$\varepsilon_3=\frac{\eta_{(i)}\Delta_3^{(i)}}{\Delta t} \qquad [10]$$

Where $\eta_{(i)}$ designates the ith interface and $\Delta_3^{(i)}$ is the vertical grid spacing at the ith interface. The non-dimensional ratios in Eq. [11] indicate the relative importance of advection relative to mixing, N_A, phytoplankton vertical migration relative to mixing, N_M, and phytoplankton growth relative to mixing, N_G, respectively. The main offending phytoplankton species, cyanobacteria, have a rise velocity, V = 1 m d^{-1}, the scale for the rate of growth $\mu^{(0)}$ = 10^{-5} s^{-1}, the mean depth h = 3 m, and the vertical diffusion coefficient may be estimated from Eq. [10]. When the non-dimensional ratios are equal to 1, then the particular processes change the phytoplankton concentration at the same rate as the concentration is changed by mixing. If we assume h = 1 m, U = 0.1 m s^{-1}, V = 1 m d^{-1} = 1.16 x 10^{-5} m s^{-1} and $\mu^{(0)}$ = 1 d^{-1} = 1.16 x 10^{-5} s^{-1}, then a balance occurs as follows:

$$N_A=1\Rightarrow\varepsilon^{(0)}=Uh\sim10^{-1}\text{m}^2\text{s}^{-1}\Rightarrow\eta_{(i)}\sim0.08 \qquad [11]$$

$$N_M=1\Rightarrow\varepsilon^{(0)}=Vh\sim1.2\text{x}10^{-5}\text{m}^2\text{s}^{-1}\Rightarrow\eta_{(i)}\sim0.14 \qquad [12]$$

$$N_G=1\Rightarrow\varepsilon^{(0)}=\mu^{(0)}h\sim8.1\text{x}10^{-6}\text{m}^2\text{s}^{-1}\Rightarrow\eta_{(i)}\sim0.1 \qquad [13]$$

This analysis may be used to put the various scenarios simulated (Figure 6) into context. The diffusion coefficient (mixing fraction) will, in practice, be a function of the water depth and the meteorological surface fluxes. In extreme bloom situations, it is most likely that the concentration of phytoplankton will also affect the vertical mixing coefficient, especially when the mixing fraction is small, but little seems to be known about the possibility that the water may become non-Newtonian. In Lake Ypacarai, the water depth is controlled by an adjustable gate and so offers a possibility of using the water level as a control. However, for the effect of the water level to be properly quantified, a surface wave model must be included, this is beyond the scope of the present contribution. Also, the lake is too large for the meteorological fluxes to be influenced by the height of fringing vegetation. However, the water depth in the lake also appears to have a strong influence on the background extinction coefficient and through the light limitation function the effective rate of growth, $\mu^{(0)}$.

Thus, apart from flushing the whole lake with groundwater, controlling the light climate, through manipulating the wetland participation by adjusting the lake level to maximize the leaching of tannins from the wetland vegetation offers the most effective, practical and cost efficient management strategy.

4.3 Global relevance

By considering in detail, the globally relevant issues facing deep and shallow lakes, in Lake Iseo and in Lake Ypacarai, it has been possible to identify strategies for avoiding the anthropogenic disasters awaiting many inland standing water bodies. Combining the identified control strategies with an adaptive real-time, self-learning methodology, will provide solutions on a global scale that will yield positive results with a much higher probability than catchment cleanup programs and at a fraction of the cost. European governments are currently spending billions of Euros to remove P and N from contributing rivers. By way of example the Bodensee cleanup program (Hammerl and Gattenhoehner, 2003) reduced the PO_4 concentration from 90 µg L^{-1} in the 1980s to 6 µg L^{-1} in 2016 at a cost of over 20 EU Billion. However, even if this astronomical cost is ignored the side effect or in legal jargon, the “externality” of the cleanup action were, first, the fisheries in the lake crashed and secondly the desired reduction of phytoplankton biomass would have resulted in a reduction of greenhouse gas sequestration. Given that the world’s lakes and reservoirs sequester approximately three times more carbon than all the world’s oceans, returning the world’s lakes to their original trophic level will necessitate that a similar reduction in global anthropogenic emissions of greenhouse gases (Tranvik et al., 2009).

The priority for the management of shallow lakes, such as Lake Ypacarai, is clearly to gain a quantitative understanding of possible controls on the light climate together with a quantitative cost benefit of reducing the nutrient loading to a particular lake.

5 CONCLUSIONS

The potential energy in the water column stratification of deep lakes is relatively small and is therefore amenable to modification with a very small number of submerged impellers. By coupling the depth of the impellers and the impeller speed to a real-time adaptive management system with an appropriate ISF, it will be possible to control the lake aquatic ecology in order to optimize the lake’s function, conservation, water supply, hydropower, flood control and or carbon sequestration. On the other hand, for shallow lakes it was shown that the main, realistic, control of the aquatic ecosystem health lies in the control of the light climate. Again, using a real-time adaptive management system coupled with real-time data streams, running in forecast mode, would allow real-time Monte Carlo searches for the least risk action to prevent algal blooms.

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