THE EFFECT OF WATER HYACINTH ON PHYTOPLANKTON BIOMASS IN A HYDROPOWER RESERVOIR: A 3D MODELLING APPROACH

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Abstract. Eutrophication is a water quality issue around the world. However, its impacts in tropical developing countries are even stronger because of the temperature-dependent process rates and the lack of funding for efficient catchment measures. Alternative in-situ strategies need to be implemented to mitigate the most extreme effects of eutrophication such as toxic algal blooms, oxygen depletion and fish mortality. This paper investigates the use of water hyacinth (*Eichornia crassipes*) as a biofilter to reduce phytoplankton biomass in a hypereutrophic deep reservoir in Colombia. The effect was tested using a coupled hydrodynamic-ecological model in short term simulations. The results show that the model reproduces the hydrodynamic and ecological variables in selected sections of the system. The scenario for biofilter implementation suggests that an area of 100 ha covered with water hyacinth is required to decrease the level of health risk of cyanobacteria blooms in the reservoir. The use of such approaches can help decision makers to accurately assess the risks and costs of operating and maintaining a large biofilter.

Key words: Hydrodynamic modelling, reservoir water quality, water hyacinth, adaptation measures, Porce II reservoir, Colombia

1. INTRODUCTION

Eutrophication as a result of the excessive loading of phosphorus and nitrogen onto surface waters caused by human activities is one of the most pressing and wide-spread water quality issues around the world (Wetzel, 1992; Elliott *et al.*, 2000; Jonoski *et al.*, 2013). Among the common characteristics of eutrophication in water bodies are the development and persistence of harmful algal blooms (HABs) (Chung *et al.*, 2014) and the high growth rate and associated impacts of invasive aquatic macrophytes (Reddy *et al.*, 1989). The spatial-temporal dynamics of HABs and macrophyte infestations depend on the complex interactions among the hydrodynamic, meteorological, morphodynamic, chemical, and biological processes in the ecosystem (Garnier *et al.*, 2005). In tropical systems, algal bloom events and the invasion of aquatic plants are even more critical because of the high rates of the temperature-dependent processes, the strong anthropogenic pressures on natural resources that provide favorable conditions for plant proliferation, and the lack of planning and resources for long-term catchment strategies.

While major efforts to address point sources of nutrient pollution in the catchment remain critical, innovative in-situ remediation measures and adequate evaluation of their effectiveness are also needed (Arhonditsis and Brett, 2005; Søndergaard *et al.*, 2003). One such innovation is the use of water hyacinth (*Eichornia crassipes*) as a bioremediation agent in tertiary treatment facilities (Reddy *et al.*, 1989). However, little is known about the effects of water hyacinth mats on environmental variables in large-scale systems such as reservoirs or lakes (Rommens *et al.*, 2003). Some studies have found antagonist effects between *E. crassipes* and phytoplankton due to nutrient competition (Mangas-Ramírez and Elías-Gutiérrez, 2004) and shading (Villamagna and Murphy, 2010). Despite the known benefits of water hyacinth in bioremediation, its impact on phytoplankton dynamics in large reservoirs remains understudied. This study aims to address this gap using a 3D hydrodynamic-ecological model.

Porce II, a reservoir located on the Porce River in Antioquia Department, Colombia, is used primarily for hydropower and is classified as one of the most eutrophic reservoirs of the country. The resulting water hyacinth invasion reached a peak coverage of around 40% of the total surface water in 2008 and 2010. This was reduced by mechanical control (using six excavators, five dump trucks and two boats), which successfully achieved the total removal of water hyacinth in 2012. A questionable success, when considering that the algal blooms reappeared in the same year together with complaints of the surrounding communities about the green coloration of the water (RPR, 2016).

As a response to these issues the operator company of Porce II reservoir, Empresas Públicas de Medellín (EPM), started in 2012 a program called "Phytoremediation in reservoirs" with the aim of determining the best practices in reducing the eutrophication of the reservoir. The initiative was also motivated by an interest in using the water hyacinth's capacity to remove pollutants as part of a tertiary treatment of eutrophication. The program started with a pilot area of two hectares in the middle part of the reservoir, as an attempt to improve the water quality (Arteaga, 2009; Castro and Saladarriaga, 2013). However, the effect that the water hyacinth cover had on the reservoir phytoplankton communities could not be determined quantitatively, and the effectiveness of this *in situ* management strategy for improving the water quality of the system remained to be demonstrated.

Since then, several studies were conducted to understand the processes occurring in the Porce II ecosystem (ESP Medellín, 2009; RRP, 2016). One of the studies, conducted from 2009 to 2015, aimed to characterize the ecological functioning of the reservoir and develop an integrated hydrodynamic and water quality model using ELCOM-CAEDYM software (RRP, 2016). The work focused on the effect of operational conditions on reservoir water quality, but did not address the macrophytes-phytoplankton interactions or evaluate any bioremediation strategies.

Ecological modelling is a useful tool to capture the dynamic ecological phenomena and forecast the outcomes of different management strategies (Cabecinha *et al.*, 2009; Lindim *et al.*, 2011; Romero *et al.*, 2004). A dynamic, quantitative approach that considers the complex physical, chemical and biological interactions is needed to evaluate the effects of water hyacinth on phytoplankton communities and its potential to mitigate algal blooms. This can be achieved with coupled hydrodynamic-ecological models which can then also be applied as decision support systems for long term planning (Jung *et al.*, 2010, 2011). Such an approach was used previously for modelling water quality in several reservoirs around the world (Yue *et al.*, 2013; Popescu *et al.*, 2015) but has not been attempted so far to address the eutrophication of the Porce II reservoir.

This paper aims to presents the research carried out to investigate if nutrient removal by water hyacinth influences the spatial variability of chlorophyll-a as a phytoplankton biomass indicator. The research was carried out using the Delft3D-flow suite of tools for hydrodynamic modelling, and Delft-ECO for reproducing water quality in the top surface layers of the reservoir.

The numerical model helped to increase understanding of the possible impact of a biofilter on algal blooms in freshwater ecosystems and provides a framework for modelling work in the future. The specific objectives were to: (1) Set up a 3D hydrodynamic model coupled with a water quality model; (2) Run the model with different scenarios; (3) Calculate the area required to have effect on phytoplankton dynamics and (4) Provide a tool that allows decision-makers to balance the risks and benefits of implementing a water hyacinth biofilter as a strategy for bioremediation.

The structure of this paper is organized mainly in three sections as follows: a short overview of the location and environmental/technical aspects of the freshwater reservoir and its catchment, followed by the description and set up of both the hydrodynamic and the ecological models. The main results from testing the bioremediation strategy on bloom density is provided in the results sections and finally, the concluding section shows the potential future works and learning lessons derived from this research project.

2. STUDY AREA

The research was carried out in the Porce II reservoir located northwest of Antioquia Department, in Colombia (Fig. 1). The reservoir has a surface area of approximately 10 km^2 at fully operation level, with a maximum elevation level at 924.5 m above the sea level. The reservoir has a maximum depth of 96.5 m close to the dam, where the intake water tower is located, and an average depth of 30 m. Its maximum active volume is 142.7 Mm^3.

There are three major rivers supplying water into the reservoir: Porce II (mean flow rate: 124.6 m^3/s), Guaduas Creek (mean flow rate: 0.6 m^3/s), and Cancana Creek (mean flow rate: 3 m^3/s), while the discharge through the turbines ranges from 0 to 135.8 m^3/s. A mean surface residence time of 10 days for the reservoir was determined by Reservoir Research Project (RRP 2016). Porce II is part of a cascade of hydropower reservoirs. Water is withdrawn in the east part of the reservoir and released to the next reservoir called Porce III. Secondary uses of Porce II water are recreation and fishing, which have increased in the last years transforming the reservoir into one of the most productive reservoirs for fishing in the country. There are more than 100 artisanal fisherman and tourists, who are in direct contact with the water of the reservoir on a regular basis (EPM Humedales, 2014).

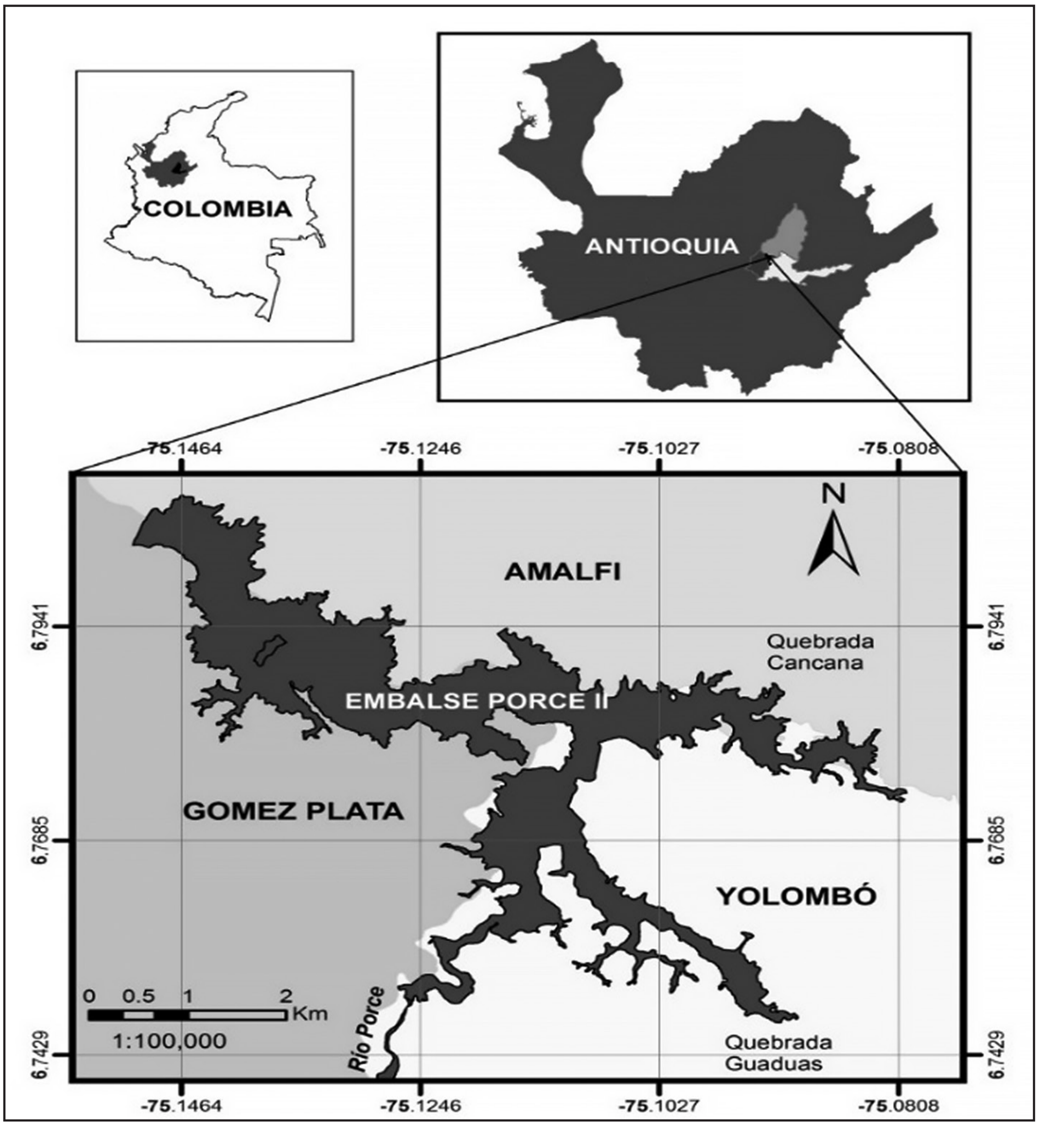

Fig. 1. Porce II reservoir.

With 98% of total inflows, the main river contributing to the reservoir is the Porce River. This river has a catchment area of 5,248 km^2 and receives industrial and domestic discharges from 10 municipalities, including Medellin City, with a population of more than three million inhabitants. To date only 30% of the effluents into Porce River are treated in the San Fernando waste water treatment plant. The remaining effluents are discharged directly into the river. In addition, there are agricultural and mining activities in the catchment, as well as landfills, which together with the point sources deteriorate the water quality of the reservoir.

The reservoir has been classified by various limnologic studies as eutrophic-hypereutrophic with an annual range concentration of orthophosphates (PO_4) of 0.1 mg/L and total nitrogen (TN) of 2.40 mg/L. The chlorophyll-a concentration levels reached up to 300µg/L and the cyanobacteria density has been recorded at 339,000 cells/mL (ESP Medellín, 2009; RRP, 2016).

3. METHODOLOGY

3.1. General approach

A 3D hydrodynamic model coupled with a water quality module was developed using DELFT 3Dsoftware of Deltares in the Netherlands (https://oss.deltares.nl/web/delft3d/about). Within DELFT 3D, DELFT-FLOW is a two (depth-averaged) or three-dimensional hydrodynamic module which solves (2D+1D) shallow water equations with the hydrostatic and Boussineq approximations derived from the Reynolds averaged Navier-Stokes equations for incompressible fluid boundary-fitted grids. Friction is calculated with the Manning approach and eddy viscosity coefficients are used to define turbulent behavior (Deltares, 2014a). DELFT–ECO was developed to carry out eutrophication studies considering the carbon, nitrogen, phosphorus and silica cycles. The substances, rate constant and parameters can be defined by the user (Deltares, 2014b). Another module in DELFT 3D is DELFT-ECO, which is based on BLOOM II as developed and presented by Van der Molen *et al.* (1994). This model is a multispecies algal model based on linear optimization technique and a strict Liebig's Law approach.

The effect of the water hyacinth on phytoplankton was investigated in two steps: first, the macrophytes module of DELFT-ECO was used to model plant growth using the growth parameters of water hyacinth in Porce II as obtained by Arteaga (2009); second, nutrient load boundary conditions were set based on the water hyacinth removal capacity, taking into account the daily nutrient uptake of water hyacinth for a given area, and comparing it with the nutrient inputs of river Porce. Hence, the removal capacity was configured as a percentage reduction of the daily nutrient loads as a result of the biofilter implementation.

3.2. Hydrodynamic model

The Delft 3D model of the Porce reservoir used a horizontal varying rectangular grid with 104 cells on the x direction and 77 cells on the y direction. Overall, the number of active cells in grid was 8008, varying in a horizontal resolution with sizes between 33 to 85 meters. In depth of the reservoir a vertical sigma model schematization was used with 20 layers of variable thickness (Fig. 2).

The hydrodynamic model requires meteorological data such us: solar radiation, cloud coverage, air temperature and air humidity. These data were available from an automatic station located close to the dam site and provided by Empresas Públicas de Medellín, EPM. The wind speed and direction were assumed to be constant in space but variable in time, with a resolution of 30 minutes. The input flows (inlets and outlets) were obtained from the RRP (2016) report and from the hydrological stations located at the dam and along the Porce II River, which have been collecting data since 1994. Input boundary data for the hydrodynamic model were available every 30 minutes for inflows and outflows (intake and spillway). The reservoir outflow data were based on the established operation rules.

Water level records were taken from Mango station near the dam and compared with simulated data from station 12, located adjacent to the dam. Additionally, water temperature profiles in the reservoir and tributaries were established based on monitoring campaigns conducted by RRP (2016) using a CTD probe model SBE 25, SeaBird Electronics (Fig. 3).

3.3. Water quality model

The water quality module of the Delft3D model of Porce II used the same grid as the hydrodynamic model in the horizontal direction and one single layer in the vertical direction, representing the surface layer. The model was set up for 35 substances, for which the following basic processes were activated: nitrification, denitrification, algal blooms, oxygen reaeration, mineralization of carbon-nitrogen and phosphorus detritus, decomposition, macrophytes production, adsorption of orthophosphates onto inorganic sediment, and mineralization of organic carbon, nitrogen and phosphorus in the sediment.

Initial and boundary conditions were defined as constant for the entire computational domain, based on data collected by RRP (2016) during a dry period between February 1st and 10th 2012. Different kinetic coefficients and parameters were tested in a step-by-step sensitivity process for analyzing the factors that influence the water quality of the reservoir. The state variables assessed in this research were nitrate, ammonium, orthophosphates and chlorophyll-a.

Three phytoplankton groups (blue-green, green algae and diatoms) were represented by Chl-a concentration. The phytoplankton data collected by RRP (2016) were measured using a Moldaenke FluoroProbe flow cytometer.

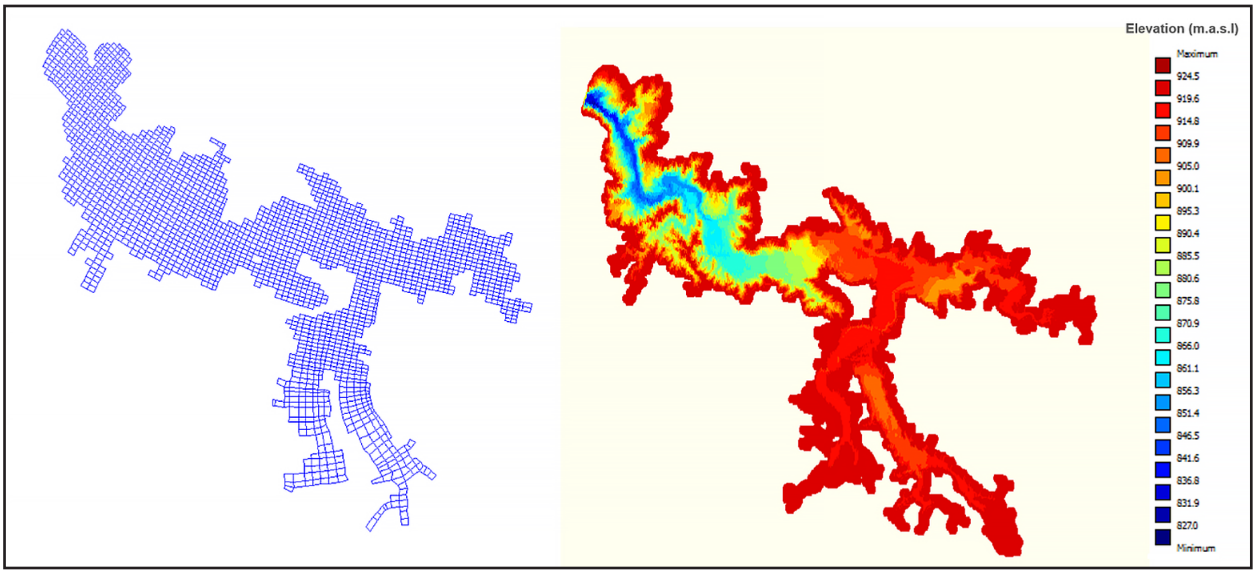

Fig. 2. Grid (left) and elevation (right) of Porce II reservoir.

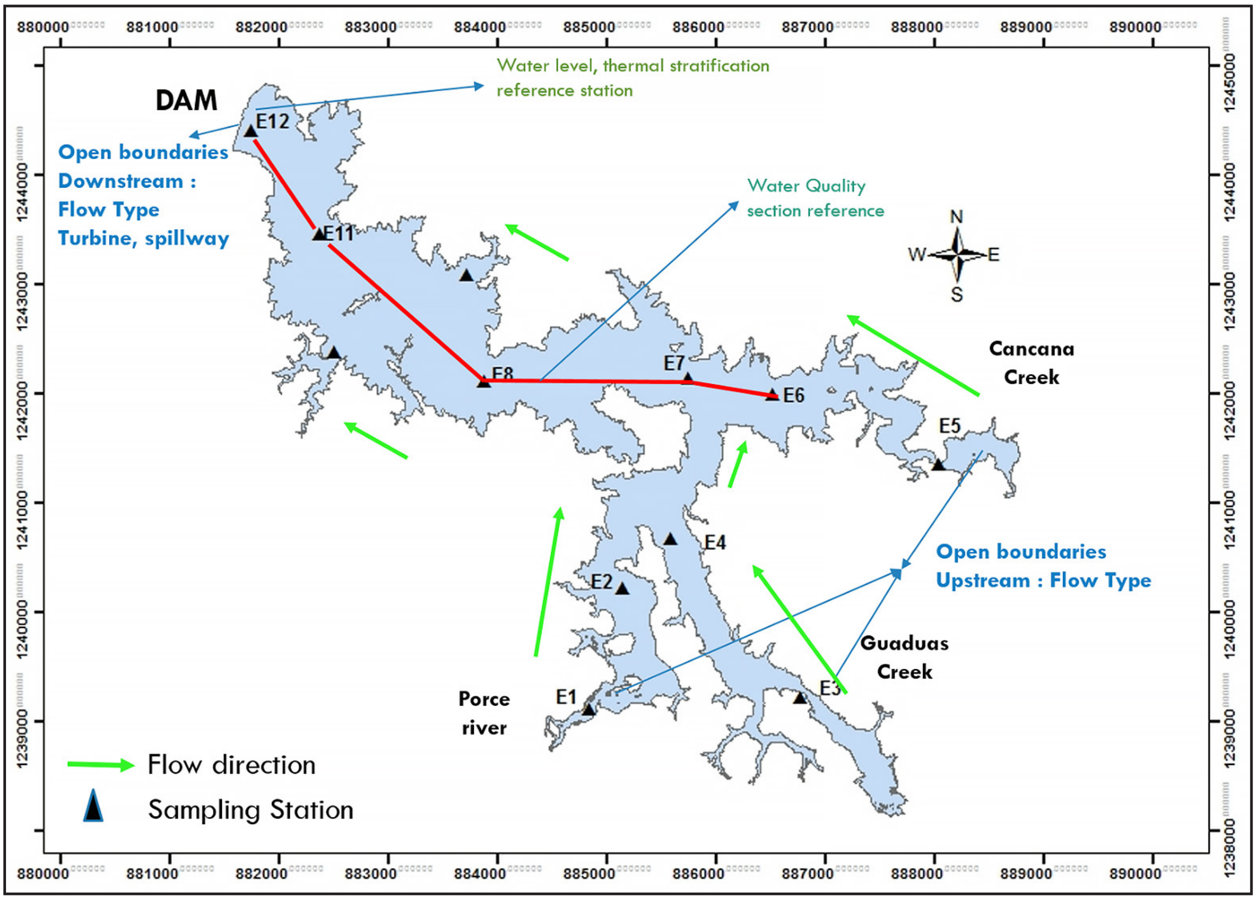

Fig. 3. Porce II model extent and water quality sampling stations location.

Phytoplankton parameters were set according to those defined by Troost *et al.* (2014) for tropical ecosystems. The three phytoplankton groups differ in their maximum growth rates, nitrogen and phosphorus kinetics, and settling velocities. Even though the model can differentiate phytoplankton concentrations by species, in this research the total phytoplankton biomass was assessed during modelling.

3.3. Scenarios for the effect of water hyacinth on phytoplankton

Two alternatives were tested to evaluate the effect of a biofilter using water hyacinth on phytoplankton biomass. The first option used the dynamic macrophytes module of DELFT3D-ECO, which is generic, and does not have predefined macrophyte species. The coefficients and parameters for water hyacinth were based on values obtained from experiments and field measurements in Porce II reservoir (Arteaga, 2009; ESP Medellin, 2009), and the ones defined by Troost *et al.* (2014). The model was set with a habitat suitability index of 1 or 0, depending on the region where water hyacinth was allowed to grow. Two size areas were tested (i.e., biofilter sections in the reservoir): the current biofilter of 2 ha, and an expanded biofilter of 100 ha.

The simulation results showed that macrophyte growth was not significant compared to the designated area for their growth. It was concluded that the water hyacinth growth rate was insufficient to cover the required area within the 10-day simulation period. The model does not allow setting an initial coverage percentage or area for macrophytes, which likely would solve the problem. On the other hand, it is possible to modify the growth rate, potential biomass and initial biomass, but the nutrient uptake results were not consistent with the real situation of the reservoir. Hence it was not possible to test such a biofilter scenario with Delft 3D.

The second option considered the nutrient removal capacity of water hyacinth in the reservoir, based on the following assumptions:

- The removal capacity of the water hyacinth when it covers 100 ha (11% of the total surface of the reservoir) is estimated to reduce the daily P and N load inputs by 6.9% and 8.4%, respectively;
- Average TP/PO_4 and TN/NH_4 ratios at sampling station E1 (Porce II river entrance) were computed based on the data available for 2010-2016 (n=50);
- The PO_4 and NH_4 concentrations were modified with the possible reduction effect of the water hyacinth removal capacity.

These input concentrations were set as new boundary conditions in the model (i.e., changes in orthophosphates, ammonium, and nitrate boundary conditions).

The model was calibrated using data collected by the Reservoir Program Research in the monitoring campaign between February 1st and 10th, 2012. Temperature and water level measurements at station 12 (E12) were compared with the simulated values. The computational time step was 60 minutes for the hydrodynamic module and 30 min for Delft-ECO. Simulations of the model were carried out for the period 1 - 10 January, 2012.

The nitrate, nitrite, orthophosphates, and chlorophyll-a concentrations simulated by the water quality model in five stations (E6 and E7 – transition stations; E8 – central area; E11 – bay area; and E12 – dam area) located between the river mouth and the dam (Fig. 3) were compared with field data for these substances that were obtained using different instruments and methods. Daily average water temperature profiles were collected using a CTD probe. Concentrations of NH_4, NO_3 and PO_4 at 0.1 meters below the surface were measured following EPA methods, and chlorophyll concentrations were determined using a flow cytometer.

A set of calibration statistics was used to assess the performance of the model. The determination coefficient between the model predictions and observational data was computed, as well as mean absolute error (MAE) and mean root square error (RMSE). In addition, visual techniques were applied to evaluate the model fit.

4. RESULTS AND DISCUSSION

4.1. Hydrodynamic Model

Comparison of the observed and simulated water level (Fig. 4) showed that water level was slightly underestimated by the model. The average difference between the observed and simulated data was only 16 cm and the Coefficient of Efficiency (COE) and the root mean square error R^2 were close to 1. This demonstrated the capacity of the model to accurately simulate water level changes, making it suitable for further use in water quality analysis.

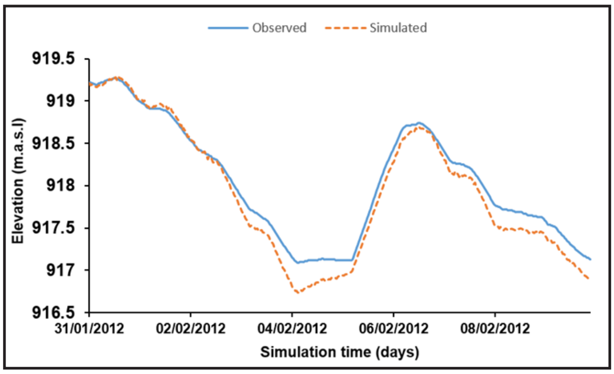

Fig. 4. Water level Porce II reservoir.

4.1.1. Water temperature

RRP (2016) identified Porce II as a permanently stratified reservoir. Given that the biochemical reactions driving phytoplankton and macrophyte dynamics are temperature-dependent, predicting the time and space variability of the thermocline accurately is essential. A sensitivity analysis was conducted for water temperature to changes in one of the following parameters:

- background horizontal and vertical eddy viscosity;
- background horizontal and vertical horizontal diffusivity;
- ozmidov length, which were tested within literature ranges for two depths (surface and bottom) (Table 1).

The parameter with major effect on water column temperature was the eddy horizontal diffusivity, with a value of 1 x 10^{-5} m/s. Figure 5 presents system behavior before the calibration of the model. After calibration, the surface layer had a simulated temperature of approximately 24–24.5°C, while the bottom reached 21-22°C, showing a difference of about 2.5°C between upper and bottom layers.

Errors between modeled and observed temperatures were highest in the bottom layer, with a temperature difference of approximately 0.7°C, while in the surface the RMSE obtained was only 0.26°C which represents a good agreement between the observed and simulated data in the epilimnion zone (Table 2).

4.2. Water quality

The model results for chlorophyll, ammonium, nitrate and phosphorus were compared with the field measurements conducted on February 8th, 2012 (Fig. 6). The results of the chlorophyll-a concentration indicate that the model accurately reproduced the phytoplankton concentrations at most stations, except for sampling point E12, the station located near the dam. There, the observed chlorophyll-a concentration was nearly three times higher than the average concentration in the central part of the reservoir, with a value of 54 µg/L. These differences may arise due to the fact that the wind direction in the morning is from the river mouth to the dam, causing an accumulation of the phytoplankton in that location. The model is unable to reproduce this phenomenon because, unlike Delft-Flow, the WAQ module uses daily wind speed settings without incorporating wind direction. The nutrient concentrations at station E12 were lower than those in the main body of the reservoir based on RRP report (2016). For that reason, it is unlikely that nutrient concentrations were the cause of the high chlorophyll-a concentration. However, it is important to investigate in detail the underlying processes, because high Chl-a levels (200µg/L) were also found during the monitoring campaigns of July 2010-2011 in that station.

The ammonium simulation showed the capacity of the model to capture the decreasing trend of this variable along the reservoir, with maximum values near the tributaries (1.8 mg/L) and a minimum value of 0.4 mg/L close to the dam.

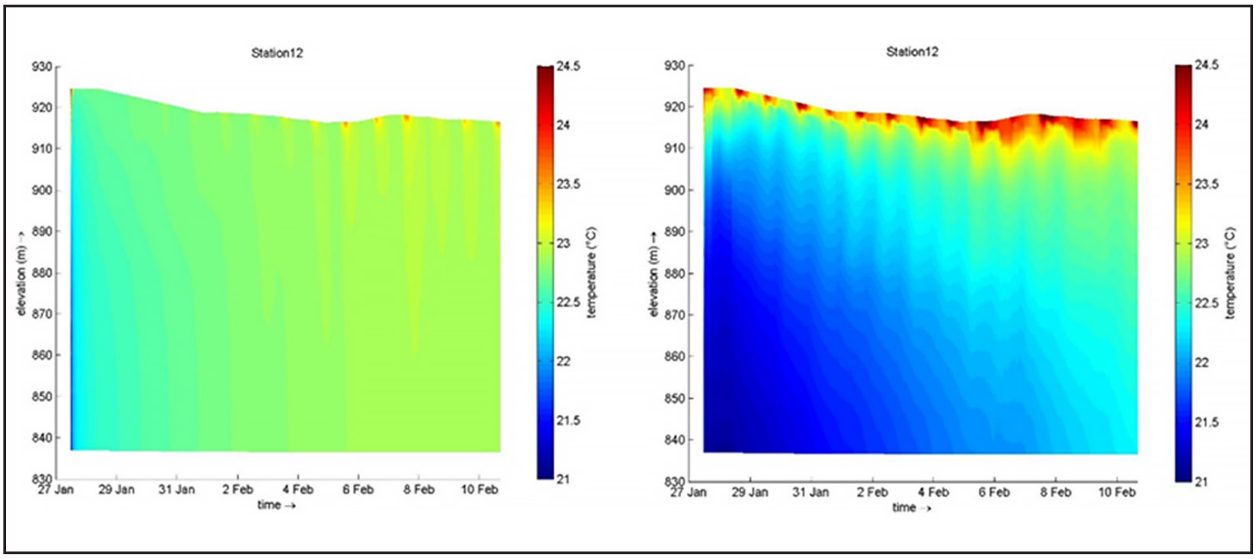

Fig. 5. Temperature profile in station 12 before and after the calibration process.

Table 1. Sensitivity analysis of the calibration parameters for Porce II Reservoir. The values correspond to the maximum difference between temperatures observed on February 8th. The reference temperature is indicated in brackets. **S**: Surface; **M**: middle, and **B**: Bottom.

Parameter and unit of measure	Default Value	Studied range*	Impact Temperature (°C) S (22.9)	Impact Temperature (°C) M (22.8)	Impact Temperature (°C) B (22.8)	Final selected value
Horizontal eddy viscosity (m^2/s)	1	10^{-7} to 4	$5x10^{-7}$ decreased	0.009 increased	0.0017 increased	1
Horizontal eddy diffusivity (m^2/s)	10	1 to 10^{-7}	1.05 increased	0.1 decreased	0.86 Decreased	10^{-5}
Vertical eddy viscosity (m^2/s)	0	0 to 10^{-7}	9.3×10^{-3} increased	4.7×10^{-2} increased	5.2×10^{-2} increased	0
Vertical eddy diffusivity (m^2/s)	0	0 to 10^{-7}	2.7×10^{-3} decreased	6.4×10^{-3} increased	5.9×10^{-3} Increased	0
Ozmidov length (m)	0	0 to 0.05	9.1×10^{-3} increased	0.047 increased	0.052 increased	0

* Note: Interval ranges are set such that it will show if parameter was increased or decreased during sensitivity analysis

Table 2. Performance evaluation of temperature model for Porce II reservoir

Station	Layer	COE	R^2
Station 12	Upper	0.37	0.65
	Middle	0.87	0.94
	Bottom	0.89	0.64

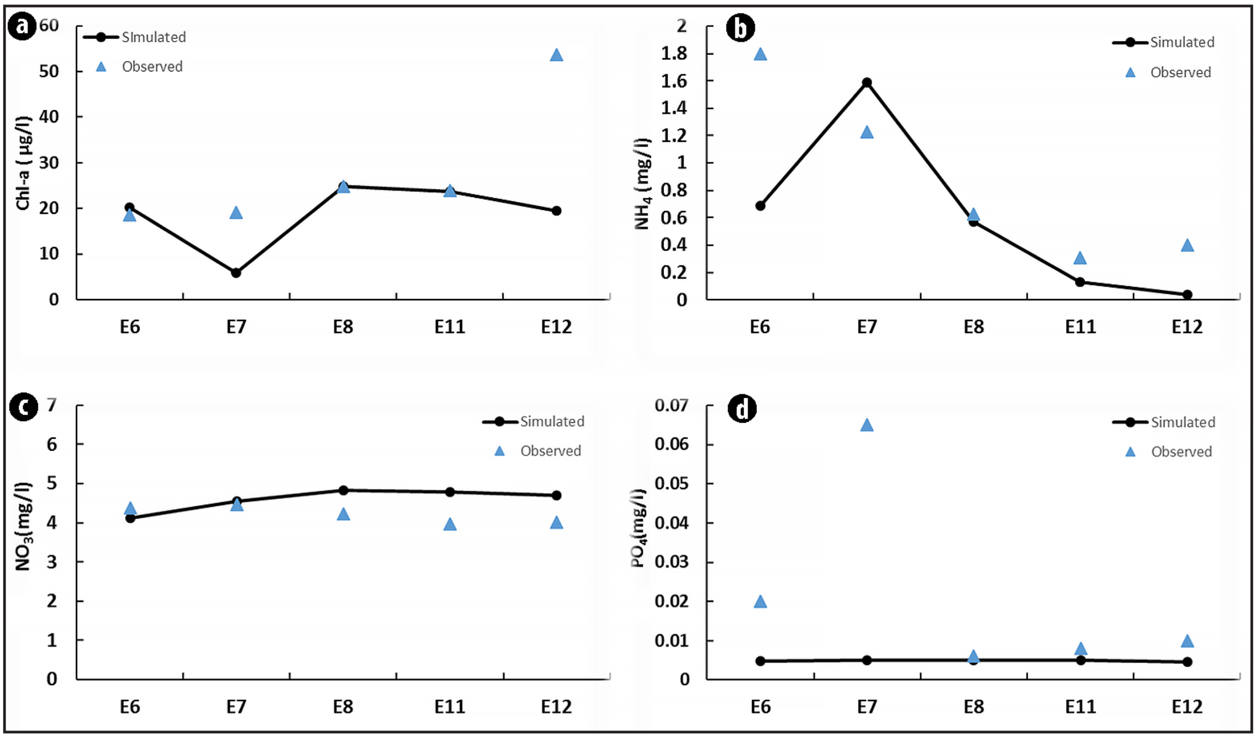

Fig. 6. Observed and simulated (**a**) chlorophyll-a, (**b**) ammonium, (**c**) nitrate and (**d**) phosphorus concentrations in a transect Porce II reservoir model. E6 and E7 are stations close to the mouth and E12 is the dam.

The nitrates and orthophosphates in this simulation period did not show large variations along the length of the reservoir (Fig. 6). Both the simulated nitrate and phosphate concentrations were in good agreement with field measurements, with the exception of the phosphate value reported in the Station E7. To ensure that these high values are not anomalies caused by field data collection protocols, they were analyzed to determine whether they could be attributed to the transport-hydrodynamic processes.

Overall, the model predictions of eutrophication in the Porce II reservoir are good, with a mean absolute error ranging from 0.005 to 0.5 mg/L and a root mean square error (RMSE) ranging from 0.007 to 0.56 mg/L in the nutrient assessment. For chlorophyll-a, the RMSE was 16 µg/L for the whole reservoir, and 6 µg/L when the dam station was excluded from the analysis. These results align with the performance criteria reported by research projects with coupled-ecological models (Chao *et al.*, 2007; Gal *et al.*, 2009), as highlighted in Table 3.

4.3. Macrophytes effect on phytoplankton

As the macrophytes module of Delft-ECO does not allow evaluation of the interactions between floating surface macrophytes and phytoplankton, this section shows the results achieved with the scenario in which initial conditions of river Porce are set based on the water hyacinth nutrient removal capacity.

Table 3. Statistics of Porce II modelling results in comparison with other similar studies.

Variable	Unit	Porce II Delft3D-Ecomodel		Literature				
				Arhondithis and Brett (2004)	Gal *et al.* (2009)		Trolle *et al.* (2008)	
		R^2	MAE	Percentile	R^2	NMAE	R^2	RMSE
Chlorophyll-a average	µg/L	0.03	9.85	10th	-	-	1	-
Chlorophyll -a at station 12	µg/L	0.48	3.76	50th	-	-	-	-
NH_4	mg/L	0.4	0.41	50th	0.5	0.6	0.03	0.068
NO_3	mg/L	0.4	0.46	20th	0.78	0.42	0.8	0.42
PO_4	mg/L	0.55	0	60th	0.02	0.97	-	-

Note: A "-" in Literature shows that the value was not computed, hence not available.

A biofilter covering an area of 100 hectares had a positive effect on the water quality of the reservoir, significantly reducing phytoplankton chlorophyll-a concentrations to approximately 7 µg/L at Station E6 and around 2 µg/L at Station E7. Simulation results shows that from the middle part of the reservoir up to the dam, the decrease of Chl-a concentrations is not high compared to scenarios without macrophytes. The spatial comparison of chlorophyll-a concentration distribution, with and without the presence of the biofilter, is shown in figure 7.

Chlorophyll-a concentrations with macrophytes were lower than without macrophytes in all the areas influenced by the Porce River (Fig. 7). Phytoplankton communities tend to grow in limnetic zones with reduced flow velocities and low suspended solid concentrations. This suggests that Porce II model is unable to fully represent phytoplankton growth, despite the high nutrient concentrations in this region of the reservoir. The changes in chlorophyll gradients between simulations, with and without the presence of the 100 ha biofilter, are evident.

Nevertheless, the question remains: What does the reduction in chlorophyll concentrations mean? Colombia does not have a policy or environmental regulations defining acceptable levels of chlorophyll-a for different water uses (recreation, water supply, and fishing, hydropower production) to mitigate health risk. So far however, EPM has adopted the guidelines for freshwater established by the World Health Organization (2003), which recognizes the importance to assess the cyanobacteria biomass because of the potential toxic effect of their cyanotoxins. Three levels of risk are distinguished:

- Low risk level = 10 µg/L or 20,000 cells/mL. Short-term adverse health outcomes, *e.g.*, skin irritations, gastrointestinal illness. At this Chl-a concentration, 2-4 µg microcystin /Liter may be expected when cyanobacteria are dominant;
- Moderate risk level = 50µg/L or 100,000 cells/mL. There is possibly 20 µg/L of microcystin in the top 4 meter of water body. Potential for long-term illness;
- High risk level = Cyanobacterial scums formation. Possibly 2000 µg/L of microcystin. When scums are presented, cell density may increase by a factor of 1000.

Based on these risk levels, figure 8 illustrates the low and moderate risk Chl-a levels simulated for the scenario without biofilter, and for the scenario with an area of 100 ha water hyacinth in the reservoir at station E6. For the transitional and main body regions (E7, E8 – see these station positions on Fig. 3), the decrease in the risk level risk (as a result of the biofilter) for people who conduct activities there can be observed. On the other hand, the level reached in station E12 (Fig. 9) was above the moderate risk level (50 µg/L), showing that although the biofilter was able to reduce the concentration, it is unlikely that the risk level could be minimized in that sector of the reservoir.

Overall, the biofilter with 100 hectares could reduce the phytoplankton biomass in some regions of the reservoir. The presence of microcystin produced by *Microcystis* sp. within the reservoir (RRP, 2016) suggests that the biofilter could also potentially minimize the health risk for the main and secondary users of the reservoir. However, long term simulations are needed to evaluate the phytoplankton performance under different hydrodynamic and environmental conditions. Moreover, additional monitoring campaigns and field data are needed for model calibration and validation.

The findings of the present research agree with different surveys which show an antagonist relationship between water hyacinth and phytoplankton (Rommens *et al.*, 2003; Villamagna, 2009; Villamagna and Murphy, 2010). The second alternative approach does not include the effect of coverage. Hence, the reduction of chlorophyll-a could be higher than what was estimated with this research. Outcomes of this research suggest that an integrated strategy has to be implemented in order to minimize the health risks associated with algae bloom events. Catchment measures together with in-situ restoration options are key for tropical ecosystems with eutrophication issues.

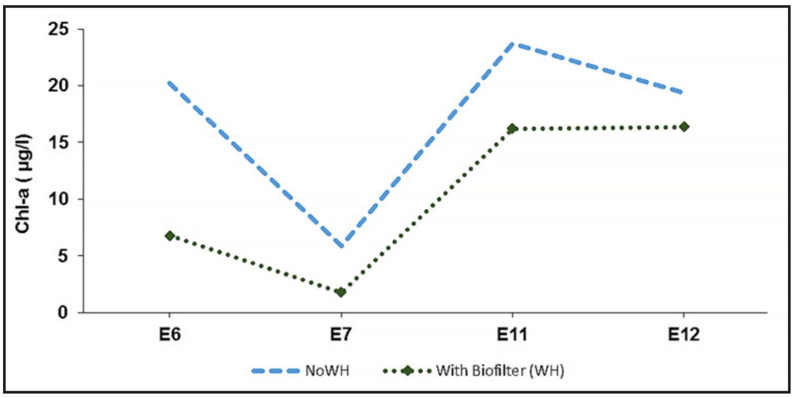

Fig. 7. Simulated chlorophyll-a concentration in a transect of Porce II reservoir with and without presence of Water Hyacinth (WH).

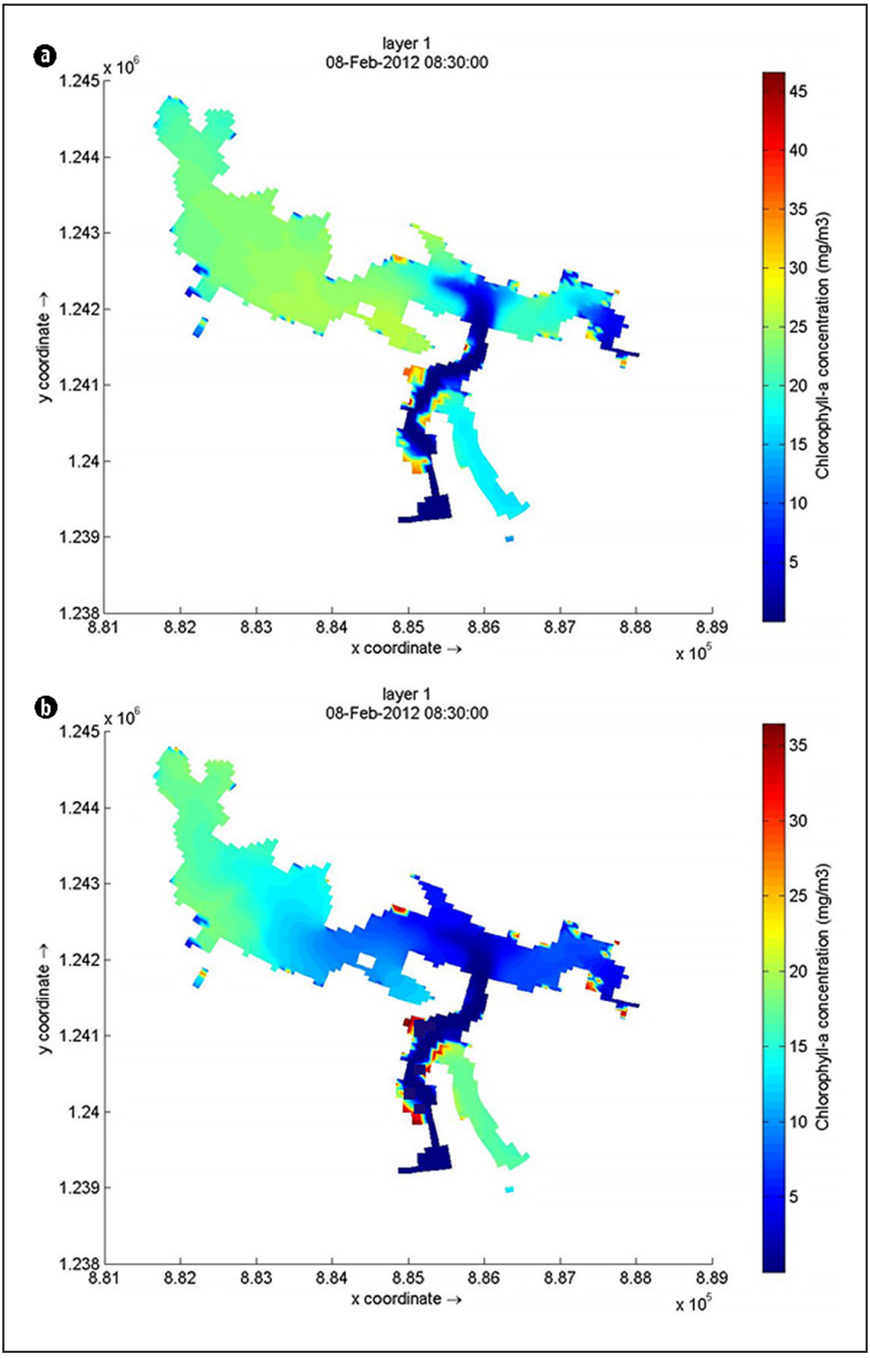

Fig. 8. Effect on chlorophyll-a with biofilter using Water Hyacinth (**a**) without macrophytes (**b**) biofilter of an area of 100 hectares.

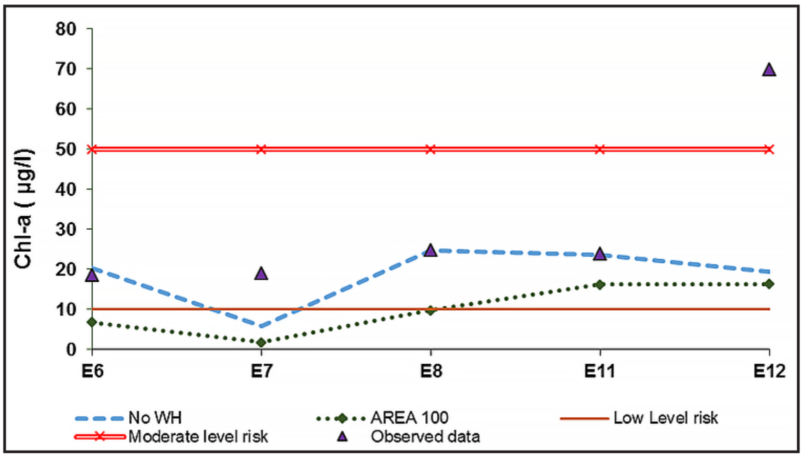

Fig. 9. Critical chlorophyll-a concentration for health risk in Porce II reservoir.

5. CONCLUSIONS

A coupled hydrodynamic-ecological model set up for Porce II reservoir was used to test the effect of water hyacinth on phytoplankton biomass, using total chlorophyll-a as an indicator. The hydrodynamic model was able to reproduce the water level and thermal performance with a good agreement showing that horizontal eddy viscosity was the primary factor influencing the stratification processes. The water quality model successfully captured the space variability of the state variables when the biofilter was represented as a water hyacinth. However, further calibration both at the species group level and across different temporal scales could increase the overall accuracy of the model. Current findings suggest that water hyacinth has a negative relationship with cyanobacteria, reducing its biomass down to the lowest health risk levels proposed by World Health Organization guidelines. These results give insights into the area of biofilter needed to establish area restrictions for the safe use of the water by communities surrounding the reservoir. It is advisable to increase the frequency in water quality input parameters and applied non uniform values in the horizontal scheme for wind, Secchi depth, and initial conditions. The results of this study show the potential of coupling macrophyte models to hydrodynamic-ecological models to evaluate in-situ restoration strategies for eutrophic reservoirs under variable operating conditions.

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