NUMERICAL MODELING OF THE TURBID TROPICAL COINTZIO RESERVOIR, MEXICO

Phuong T. K. Doan*

The University of Danang - University of Science and Technology, Vietnam

*Corresponding author: dtkphuong@dut.udn.vn

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Abstract - The Cointzio Reservoir in central Mexico faces significant degradation due to urban expansion and agricultural activities, leading to high turbidity and eutrophic conditions. Surface chlorophyll-a concentrations (~70 µg L^{-1}) indicate harmful algal blooms, and sedimentation has reduced storage capacity by 20-25%. A coupled numerical model combining a 1-D hydrodynamic module with the ecological model Aquasim was used to simulate seasonal stratification, mixing dynamics, sediment accumulation, and nutrient-phytoplankton interactions. Model results aligned with field observations, demonstrating its effectiveness in capturing the main mechanisms of water quality decline. This study highlights how integrated physical and ecological models can aid reservoir management in regions with heavy nutrient and sediment loading.

Key words - Turbid reservoir; Mexico; eutrophication; biogeochemical modelling; climate change

1. Introduction

Reservoirs constitute key elements of water supply systems, ensuring drinking water security, irrigation, hydropower production, and flood mitigation. However, these benefits are often compromised in tropical and subtropical settings where high temperatures and nutrient enrichment favor intense eutrophication. Excessive primary production can lower transparency, trigger harmful algal blooms, and ultimately reduce the quality of water available for human use. When reservoirs also experience accelerated siltation, their storage capacity and long-term service reliability decline simultaneously, creating a dual challenge for sustainable management.

The Cointzio Reservoir exemplifies these problems. Situated close to Morelia, the capital of Michoacán, the reservoir is exposed to continuous inflows of urban wastewater and runoff from intensively farmed land. High external loads of nitrogen, phosphorus, and suspended solids have transformed the system into a turbid, nutrient-rich water body. Measurements show summer chlorophyll-a concentrations of about 70 µg L^{-1}, which correspond to dense algal blooms. Furthermore, bathymetric surveys indicate that two to three decades of sedimentation have diminished storage by approximately 20–25% relative to the original capacity.

Given these pressures, reliable tools are required to understand and predict the combined effects of hydrodynamics, sedimentation, and nutrient cycling. Process-based models have become valuable in this context, as they can integrate physical transport with ecological interactions. By applying such models to Cointzio, this study aims to (i) reproduce the main water quality dynamics observed in the reservoir, (ii) evaluate the consequences of sediment and nutrient inputs, and (iii) provide a scientific basis for management interventions designed to curb eutrophication and prolong reservoir function.

2. Study Area

The Cointzio Reservoir (19.622°N, –101.256°W) is located at an elevation of about 1920 m within the Trans-Mexican Volcanic Belt. It serves as a critical multipurpose water body, meeting nearly 20% of the domestic water needs of Morelia, supplying irrigation to downstream agricultural lands, and providing flood regulation. The reservoir drains a watershed of 627 km^2 and, despite having a maximum depth of 29 m, it is classified as a deep aquatic system [1]. Inflows are heavily enriched with nutrients due to the absence of wastewater treatment in upstream areas and the continuous transport of fine clay sediments [2]. Between 2007 and 2010, with intensive surveys in 2009, field observations revealed persistently high turbidity (Secchi depth < 0.3 m) along with algal blooms reaching chlorophyll-a concentrations of up to 70 µg/L. Since its impoundment in 1940, the reservoir has lost about 20% of its original storage capacity due to siltation [1].

The climate of the region is temperate sub-humid, with precipitation concentrated in the rainy season from May to October, followed by a prolonged dry season [3]. The main tributary, the Rio Grande de Morelia, originates roughly 25 km upstream and is the principal supplier of water and sediments to the reservoir. In certain reaches, sediment deposits are so pronounced that the natural course of the river has disappeared. During the wet season, this tributary alone contributes approximately 77% of the water inflow and nearly 98% of the sediment load entering the reservoir [4]. Outflows are regulated through dam gates.

3. Data and modeling approach

To investigate the biogeochemical dynamics of the Cointzio Reservoir, a series of hydrodynamic and water quality surveys were carried out over three years, with 2009 serving as the key reference year. At the onset of the project, two intensive field campaigns were performed in December 2005 and May 2006 under contrasting seasonal conditions. The objective was to determine whether lateral variability influenced reservoir hydrodynamics. During these campaigns, temperature, turbidity, and dissolved oxygen (DO) were measured at 47 vertical profiles distributed along the main longitudinal axis and across five transversal transects (Figure 1). Results indicated no significant lateral heterogeneity, justifying a subsequent focus on temporal variability along the main axis.

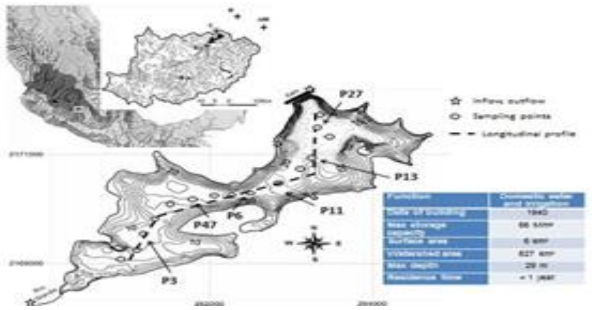

Figure 1. *Maps of the Cointzio reservoir, the reservoir watershed, and localization of sampling sites (geographical station in UTM). 15 vertical profiles were realized along the longitudinal axis (dashed line)*

From September 2007 to January 2010, hydrodynamic parameters (temperature, turbidity, and meteorological variables) were monitored at biweekly to monthly intervals along this axis. At two key sampling stations - P6 (located at the reservoir midpoint) and P27 (the deepest site) - additional vertical water sampling was conducted. At these sites, samples were collected at multiple depths (0, 1, 2, 5, 10, 15, 20 m, and near the bottom where feasible). Secchi disk transparency was also measured at each visit to assess light attenuation caused by suspended particles. A detailed account and interpretation of these monitoring data are provided in [5].

The collected field observations formed the basis of the modelling study. In the following sections, we first present the datasets used, followed by the description of the modelling framework.

3.1. Model Input Requirements

The reservoir modeling framework required four principal data groups. First, morphological and descriptive features of the reservoir were essential for system definition. Second, hydrodynamic drivers including meteorological forcing, inflows, and outflows, were incorporated to represent physical dynamics. Third, water quality indicators such as dissolved oxygen (DO), nutrient concentrations (NO_3^-, NH_4^+, PO_4^{3-}), chlorophyll-a, and suspended solids (turbidity) were provided. Fourth, the model initialization required baseline conditions for all simulated variables. Field surveys supplied inflow data and vertical chemical profiles, which were subsequently used for calibration. Outflow water quality was not prescribed but treated as a model output.

3.2. Model Output Variables

The simulations emphasized five key ecological indicators: dissolved oxygen, phosphate, ammonium, nitrate, and chlorophyll-a. These state variables provide insight into the reservoir's trophic status and overall ecological functioning.

3.3. Modeling Approach

A coupled modeling strategy was applied, combining hydrodynamic and biogeochemical components. Vertical mixing and thermal stratification were reproduced with a buoyancy-extended k-ε turbulence scheme [6]. Biogeochemical cycling was represented through an advection–diffusion–reaction module built on Aquasim [7] adapted from [8]. This integrated framework captures interactions between physical mixing, nutrient transformations, and biological activity.

3.3.1. Physical k-ε model

The k-ε turbulence formulation generated half-hourly vertical diffusivity profiles (Kz(z)) for the year 2009. Two calibration parameters were tuned against observed monthly temperature profiles using least squares fitting: the wind energy transfer coefficient for internal seiches ($\alpha = 0.0025$) and the wind drag coefficient ($C10 = 0.0001$). These diffusivity time series subsequently drove the Aquasim biogeochemical module. A limitation of Aquasim is its simplified handling of water balance, where inflow is automatically adjusted whenever outflow surpasses it. Nevertheless, the framework proved sufficiently robust for simulating coupled hydro-biogeochemical dynamics.

3.3.2. Aquasim Biogeochemical Model

Internal nutrient cycling was represented using BELAMO [8] and its tropical adaptation RES1 [9]. The state variables included temperature (T), dissolved phosphate ($SHPO_4^{3-}$), nitrate (SNO_3^-), ammonium (SNH_4^+), dissolved oxygen (SDO), algal biomass (XALG), zooplankton biomass (XZOO), and detrital organic matter (X). Ten key processes were simulated: algal growth, respiration, and mortality; zooplankton growth, respiration, and mortality; phosphate uptake and release; nitrification; aerobic, anaerobic, and anoxic mineralization (including denitrification); and background oxidation of reduced substances.

Model calibration followed a stepwise approach. Thermal stratification was first constrained with the k-ε module, then DO, phosphate, ammonium, and nitrate concentrations were fitted to observed profiles. Finally, chlorophyll-a dynamics were adjusted to match algal biomass patterns. Parameter values were cross-checked against literature to ensure plausibility. For instance, maximum algal growth rates (k_gro_ALG_20, k_gro_ALG_N2_20) and mortality (k_death_ALG_20) were tuned against chlorophyll-a. Nitrification constants (k_nitri_wat_20) were aligned with NH_4^+ and NO_3^- trends, while phosphate uptake affinity (K_HPO4_ALG) was optimized using PO_4^{3-} data. Aerobic, anoxic, and anaerobic k_miner_anox_20, k_miner_anaero_20), together with background mineralization (k_miner_bg), were constrained using DO observations.

3.4. Modelling scenarios

To explore potential long-term changes in the Cointzio Reservoir, several simulation scenarios were designed, with emphasis on hydrological variability and projected climate change. The baseline reference corresponds to the calibrated 2009 simulation, hereafter termed the "Present" scenario. Alternative scenarios were then constructed to represent different future conditions, allowing for comparative assessment of water quality responses. A summary of these prospective scenarios is presented in Table 1.

Table 1. *Summary of scenarios for water and ecological quality assessment of the Cointzio reservoir*

Scenarios	Description	Parameters used
Present	Target year 2009	Water level H=26 m
P1	Dry year 1990, nutrient inputs 2009	low water level H = 21 m
P2	Wet year 1996, nutrient inputs 2009	high water level H= 29 m
P3	P1 with an increase in air temperature (T_{air}) of 2.5°C	H=21 m and +2.5°C in T_{air}
P4	P1 with an increase in T_{air} of 4.4°C	H=21 m and +4.4°C in T_{air}
P5	P1 with a long term reduction of 50% of nutrient inputs (N,P)	H=21 m, & -50% (N,P)
P6	P1 with a long term reduction of 90% of (N,P) inputs	H=21 m, & -90% (N,P)
P7	P1 with a long term reduction of 100% of (N,P) inputs	H=21 m, & -100% (N,P)
P8	P4 with a long term reduction of 50% of (N,P) inputs	H=21 m, +4.4°C in T_{air} & -50% (N,P)
P9	P4 with a long term reduction of 90% of (N,P) inputs	H=21 m, +4.4°C in T_{air} & -90% (N,P)
P10	P4 with a long term reduction of 100% of (N,P) inputs	H=21 m, +4.4°C in T_{air} & -100% (N,P)

3.4.1. Effect of hydrology

After model calibration, additional simulations were carried out to assess how variations in hydrological conditions influence phytoplankton dynamics. A 20-year record of reservoir water levels was analyzed to identify representative dry and wet years (Figure 2). For this purpose, the storage level on January 1st was adopted as a key indicator of hydrological status.

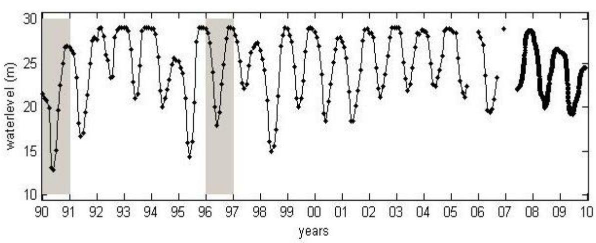

Figure 2. *Time series of the water levels in the Cointzio reservoir*

Three contrasting conditions were selected for simulation: the reference year 2009, a dry year, and a wet year drawn from the two-decade dataset (Figure 2). The year 1990, with a minimum water level of 21 m on January 1st, was chosen as the dry year, while 1996, characterized by a maximum level of 29 m on the same date, was considered the wet year. To enable direct comparison across scenarios, inflow volumes and water quality characteristics for 1990 and 1996 were set equal to those observed in 2009 during the modelling exercises.

3.4.2. Effect of climatic conditions and global warming

Climatic warming is anticipated to strongly influence reservoir functioning, particularly in tropical systems where annual evaporation typically exceeds precipitation; [10]. For the Cointzio watershed, regional projections indicate a mean annual air temperature rise of about 2.5°C by the 2060s and up to 4.4°C by the 2090s [11].

To isolate the impact of air temperature, simulations were carried out assuming inflow volumes and nutrient inputs remained identical to those observed in 2009. Given the need to explore realistic but less optimistic trajectories, model runs were performed under dry-year hydrological conditions combined with incremental temperature increases of +2.5°C and +4.4°C, representing mid- and late-century scenarios.

4. Results

This section first presents the outcomes of the hydrodynamic simulations, which provide the framework for the subsequent biogeochemical modelling. The performance of the calibrated model under present-day conditions is then assessed before analyzing alternative scenarios.

4.1. Physical k-ε model

Calibration of the hydrodynamic model was conducted using field observations from 2009, while validation relied on independent datasets collected in 2008 at the reservoir's deepest site (P27). Figure 3 illustrates the temporal dynamics of observed and simulated water temperature, together with the deviations between measured and modelled values, for both the calibration year (2009) and the validation year (2008).

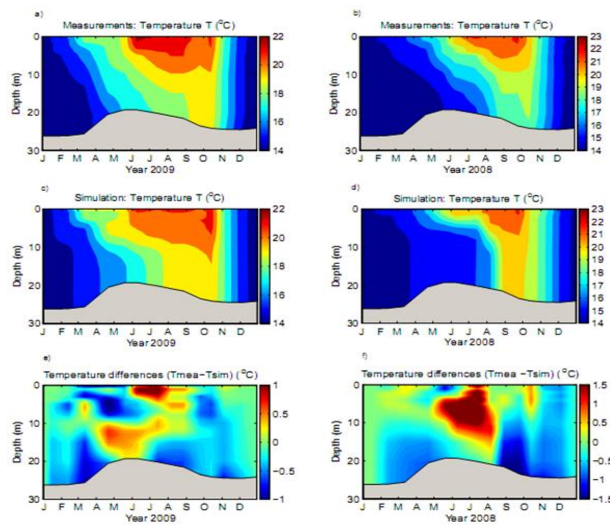

Figure 3. *Time evolution of the temperature in 2009 (left panels) and 2008 (right panels). The top map is obtained with the measured temperature, the middle one with the simulated one. The bottom one depicts the residues Tmea-Tsim*

4.1.1. Model calibration

The top left panels illustrate temperature fluctuations in the reservoir, with a minimum of 14°C in January and a peak of 22°C in June. Stratification persisted for nine months, from February to October, while vertical mixing occurred from late October to January due to surface cooling and wind. Surface temperatures remained high between June and October, while deeper layers stayed cooler. The model effectively reproduced both mixing and stratification periods, though neither field data nor simulations revealed a distinct thermocline - i.e., a sharp temperature gradient over short vertical distances.

The model showed strong agreement with observed temperature profiles, with a mean square error of just

0.24°C, indicating that the calculated diffusivities in the epilimnion, metalimnion, and hypolimnion were well estimated. Minor discrepancies, with a maximum deviation of ±1°C from May to September, were attributed to missing surface temperature data during that period, which were interpolated using correlations with air temperature [12].

4.1.2. Model validation

Model validation involves evaluating its performance under different meteorological and hydrological conditions. The right panels in Figure 3 show both observed and simulated temperature profiles for the year 2008. Despite the varying hydrological conditions compared to the calibration year, the model demonstrated a strong fit to the observed data, confirming its reliability.

4.2. Biogeochemical model

4.2.1. Present scenario - Target year 2009

Using the calibrated parameter set (Table 2), simulations of water quality for the reference year 2009 were carried out. The outcomes, presented in Figure 4, serve as the baseline against which alternative scenarios are evaluated.

***Table 2.** Literature values and main parameters of the biogeochemical model compared to other published applications of the same model*

Parameters	Units	Cointzio reservoir (This study)	Lake Zürich [8]	Lakes Walensee/ Zürich/ Greifensee [8]	Itezhi – Tezhi reservoir [9]	Lake Ohrid [10]	Other literature values and ranges
k_gro_ALG_20[a]	d^{-1}	1.2	1.1	1.6	1.1[c]	1.88	0.58-3
k_gro_ALG_N2_20[a]	d^{-1}	0.85	-	-	0.25	-	
k_gro_ZOO_20[a]	$gDM^{-1} m^3 d^{-1}$	0.001	0.3	0.4	0.25[c]	3.47	0.15-0.25
k_death_ALG_20[a]	d^{-1}	0.03	0.03	0.03	0.01[d]	0.03	0.03
k_death_ZOO_20[a]	d^{-1}	0.1	0.029	0.01/0.035/0.11	0.1[d]	0.029	0.003-0.155
k_resp_ALG_20	d^{-1}	0.05	0.05	0.05	0.05[c]	0.05	0.05-0.15
k_resp_ZOO_20	d^{-1}	0.003	0.003	0.003	0.003[c]	0.003	0.001-0.11
k_nitri_wat_20[a]	$gN^{-1} m^3 d^{-1}$	0.05	0.1	0.1	0.1	-	0.03-0.25
k_miner_aero_20[a]	d^{-1}	0.1	0.01	0.005	0.1	0.008	
k_miner_anox_20[a]	d^{-1}	0.01	0.01	0.005	0.01	-	
k_miner_anaero_20[a]	d^{-1}	0.001	-	0.0005	0.001	-	
k_miner_bg[a]	d^{-1}	0.1	-	-	0.1	-	
K_HPO4_ALG	gPm^{-3}	0.0007	0.0019	0.0005	0.002	0.0019	
K_I_ALG	Wm^{-2}	34.32	34.32	10[b]	34.32	-	
S_HPO4_crit	gPm^{-3}	0.0042	0.0042	0.004	0.004	0.004	
DeltaS_HPO4	gPm^{-3}	0.0013	0.0013	0.0013	0.0013	0.0013	
k_upt	$m^4 gDM^{-1} d^{-1}$	1200	1200	30[b]	1200	1200	

Cointzio reservoir: Turbid tropical eutrophic reservoir
Lake Zürich: Mesotrophic temperate lake
Lakes Walensee/ Zürich/ Greifensee: Temperate lakes (Walensee is oligotrophic, Greifensee is eutrophic)
Itezhi –Tezhi reservoir: Tropical eutrophic reservoir
[a]Parameters fitted during the calibration of the Cointzio reservoir.
[b]Large change in meaning due to modification of the formulations.
[c][9] adapted from [8].[d][9] adapted from [8].

The model reproduced dissolved oxygen (DO) dynamics in 2009 with high accuracy (Figure 4), correctly simulating both the onset and extent of anoxic conditions. Deviations between measured and simulated concentrations were within ±1 mg/L, except in April (Figure 5). From April to October, bottom waters (<10 m) experienced persistent anoxia (<1.0 mg/L), while surface layers maintained DO levels above 6.0 mg/L, largely supported by photosynthetic production and atmospheric exchange. A detailed analysis of vertical distributions for DO, chlorophyll a, phosphate, ammonium, and nitrate are available in [5].

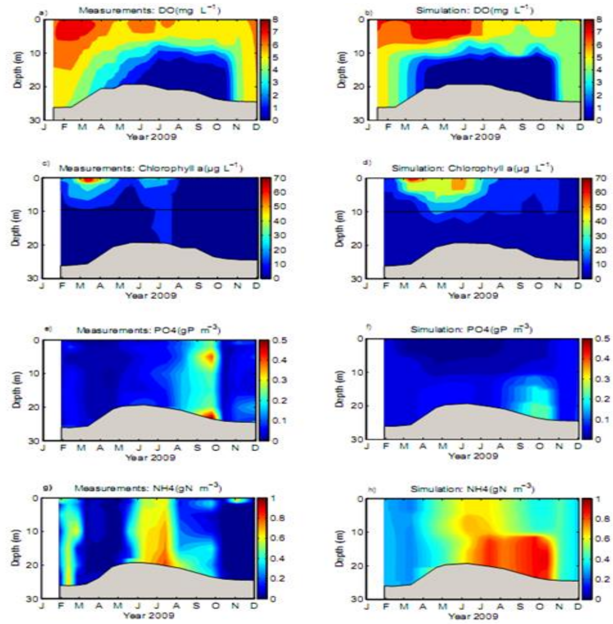

***Figure 4.** Vertical profiles of measured (left panels) and simulated (right panels) DO, chlorophyll a, PO43-, NH4+ at P27 of the Cointzio reservoir in 2009*

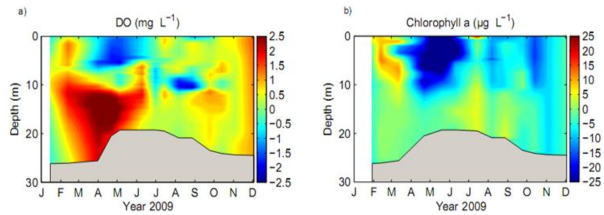

***Figure 5.** The residues between measurement and simulation of DO and chlorophyll a in 2009*

4.2.2. Application to Historical Conditions

P1 Scenario – Dry Year 1990

During the dry year of 1990, chlorophyll *concentrations* were elevated, and the anoxic phase was slightly prolonged relative to 2009. In the early stratification period, chlorophyll a in the upper 10 m reached 22.9 µg/L, compared to 18.9 µg/L in the baseline year. Surface maxima rose to 86 µg/L (Figure 6), exceeding the 70 µg/L observed in 2009. Despite these differences, surface DO remains above 6.0 mg/L, whereas bottom waters stayed anoxic from April to October, with the oxycline stabilizing near 8 m depth.

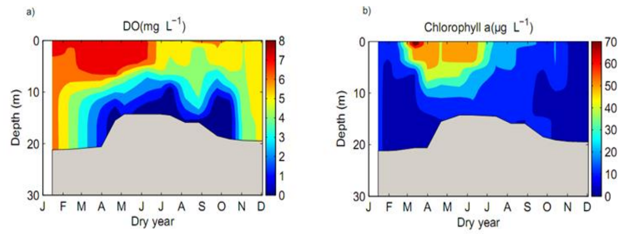

***Figure 6.** Simulation of DO and chlorophyll a under the dry year conditions (P1 scenario)*

P2 scenario – Wet year 1995

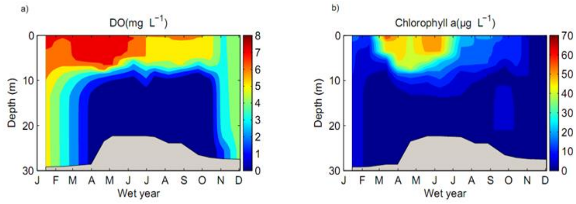

Figure 7. *Simulation of DO and chlorophyll a under the wet year conditions (P2 scenario)*

Simulation results for 1995 indicated reduced phytoplankton biomass compared to the baseline and dry year conditions. The summer chlorophyll peak reached 58 µg/L, substantially lower than the 70 µg/L observed in 2009 (Figure 7). Dissolved oxygen declined below 1.0 mg/L at the bottom and remained depleted throughout the hypolimnion down to 10 m between April and October.

Across the three modeled years (Figures 5–7), the dry year (1990) exhibited the most eutrophic conditions, with the highest chlorophyll a peak (86 µg/L) and the greatest mean concentration at 10 m (22.9 µg/L). By contrast, the wet year (1995) displayed the lowest productivity, while the 2009 baseline fell between these two extremes. These results highlight the strong influence of hydrological variability on nutrient dynamics and oxygen depletion patterns in the reservoir.

4.2.3. Scenarios under global warming conditions

P3 scenario - Increasing air temperature of 2.5°C in 2060

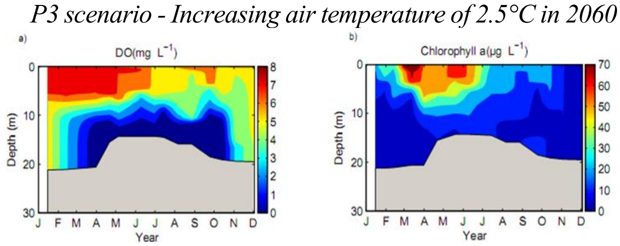

Figure 8. *DO and chlorophyll a in increasing air temperature of 2.5°C (P3 scenario)*

Figure 8 illustrates the model results for dissolved oxygen (DO) and chlorophyll a under a projected air temperature increase of 2.5°C. Elevated air temperatures directly raise surface water temperatures, which in turn enhance biological activity such as algal growth and organic matter decomposition. However, this warming also reduces DO solubility. As a result, chlorophyll a concentrations peaked at 93 µg/L, and anoxic conditions in the hypolimnion became more prolonged.

P4 scenario - Increasing air temperature of 4.4°C in 2090

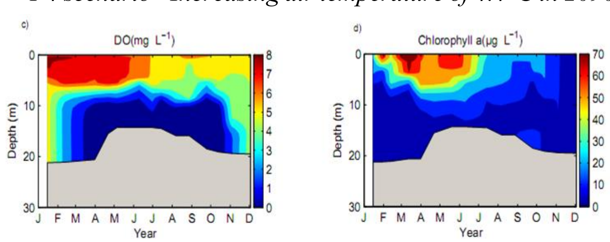

Figure 9. *DO and chlorophyll a in increasing air temperature of 4.4°C (P4 scenario)*

The P4 scenario, which combines a 4.4 °C increase in air temperature with minimal water levels, represents the most critical case. As shown in Figure 9, chlorophyll *a* concentrations rose markedly compared with 2009. The mean concentration within the upper 10 m reached 25 µg/L, higher than the 18.9 µg/L recorded in the reference year. The peak value increased to 94 µg/L, while the thickness of the anoxic layer expanded, with complete oxygen depletion extending to 7 m - slightly shallower than the 8 m depth observed in the P1 (dry year) scenario.

4.3. Discussions

4.3.1. Application of 1D modelling to reservoirs

Numerical modelling provides a powerful framework for analyzing complex aquatic systems by integrating multiple interacting processes. Numerous lake models have been developed for this purpose, with thermal structure and hydrodynamics often forming the essential starting point. Stratification plays a key role in controlling vertical exchanges and the distribution of dissolved and particulate matter [13].

The suitability of one-dimensional models depends largely on research objectives and temporal scale. Although 2D or 3D models can resolve spatial variability, their use is often constrained by the limited availability of high-resolution datasets. For most operational applications, a 1D approach is adequate, especially when reservoirs are neither highly elongated nor shallow [14]. In such systems, horizontal gradients are generally minor compared with vertical ones and are rapidly equilibrated by gravitational forces.

In the Cointzio Reservoir, extensive three-dimensional measurement campaigns carried out in December 2005 and May 2006 - comprising 46 vertical profiles of temperature, turbidity, and dissolved oxygen - indicated no significant lateral heterogeneity. This finding justified shifting long-term monitoring efforts to temporal changes along the longitudinal axis. Routine vertical profiling at two representative sites (P27 and P6) further confirmed that horizontal variability was negligible for long-term simulations, except during short flood events of 3–5 days [1](Susperregui et al., 2009). Moreover, the lack of sufficient data to initialize and constrain a multi-dimensional model would have introduced considerable uncertainty, particularly in setting boundary conditions and quantifying spatial fluxes. For these reasons, a one-dimensional framework was identified as the most robust and practical modelling option.

4.3.2. Biogeochemical analysis of the models for the Cointzio reservoir

The simulation of dissolved oxygen (DO) in Aquasim integrates both sources - surface aeration and photosynthesis - and sinks, such as sediment oxygen demand, respiration, and nitrification. This makes DO a central indicator, reflecting nearly all biogeochemical processes in the reservoir. A mismatch observed in April between simulated and measured DO was attributed to hydrological imbalance, coinciding with the highest recorded discharge at the dam (Figure 5).

Oxygen depletion in bottom waters was primarily driven by sediment mineralization and background organic matter degradation. Two major organic inputs supported this process: (i) phytoplankton production and sedimentation early in the year (Figure 4), and (ii) hyperpycnal sediment inflows during the wet season (June–October; [5]. These mechanisms released phosphorus and ammonium, amplifying eutrophication. Following the March chlorophyll a maximum, algal biomass declined due to zooplankton grazing but later recovered. However, the limited temporal resolution of field data (monthly to triweekly) constrained model calibration, as chlorophyll a varied rapidly. The absence of zooplankton monitoring further limited accurate representation of secondary algal blooms.

Model assumptions also introduced uncertainty. Aquasim's use of a constant water level neglects real fluctuations that alter trophic interactions [15]. In addition, estimating light extinction in a turbid system is challenging, and inaccuracies affect the timing and intensity of phytoplankton peaks [16]. Despite these limitations, the model reproduced chlorophyll a dynamics sufficiently to inform reservoir management.

Nutrient dynamics followed expected seasonal patterns. Phosphate fluxes from sediment mineralization were prominent during high-flow periods, raising water-column concentrations (Figure 4). During the dry season, uptake in the epilimnion and particle settling reduced phosphate to low levels in both surface and mid-depth waters. While simulations captured these trends well, underestimation of wet-season mixing in the deep hypolimnion was apparent. Including phosphorus adsorption–desorption in future versions may improve accuracy.

Ammonium remained scarce in the epilimnion due to algal uptake but accumulated in the hypolimnion under stratification, reflecting mineralization and sediment inflow, especially during high discharge (Figure 4). These increases coincided with anoxic conditions. For nitrate, the model predicted decreasing concentrations with depth due to denitrification under anoxia; however, this was not supported by observations, highlighting the need to refine nitrate dynamics.

4.4. Conclusion

A coupled k-ε mixing model and Aquasim biogeochemical model were applied to the turbid Cointzio Reservoir in Michoacán, Mexico - the first such study in the Trans-Mexican Volcanic Belt. The k-ε scheme effectively reproduced thermal stratification, while Aquasim simulated major water quality variables for 2009, including DO, phosphate, ammonium, nitrate, and chlorophyll a. Calibration produced parameter values consistent with those reported in the literature.

This work demonstrates the usefulness of coupled models for guiding aquatic restoration strategies under variable hydrological and climate conditions. Using chlorophyll a and DO as core management indicators, the study explored multiple scenarios, including warming and flow variability. Results showed that a dry-year scenario combined with a 4.4°C air temperature increase produced the strongest eutrophication response, with chlorophyll a peaking at 94 μg/L and hypolimnetic anoxia intensifying.

These findings emphasize the importance of integrated modeling to anticipate ecosystem responses and support evidence-based reservoir management in the context of climate change.

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