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# Assessing the link between environmental flow, hydropeaking operation and water quality of reservoirs

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ABSTRACT

Eutrophication is a common problem in lakes and reservoirs with high incoming loads of nutrients. The consequent algae bloom affects the water quality and causes incompatibility with tourist and recreational activities. This is the case of the Rapel reservoir, an old, dendritic and monomictic reservoir located in central Chile (34° S, 71.6° W, 105 m.a.s.l.), which has received high loads of nutrients, sediments and metals during its operation and has been known for its numerous algae bloom events. On the other hand, the reservoir outflow is mainly controlled by the electrical demand and the minimization of economic costs, independent of any ecological analysis in the reservoir. Thus, the aim of this study is to analyze the effects of the hydropower plant operation scheme on the reservoir water quality. Several scenarios are performed considering five hydrological conditions for the Rapel tributaries and the incorporation of an environmental flow (EF) constraint to the hydropower plant operation, which are represented by four minimum outflow scenarios. The hydrodynamic and water quality of the reservoir are modeled using ELCOM-CAEDYM, while the hydropower plant operation is obtained using an optimization model, which replicates the practices of Chilean system operator. The results of the simulations are analyzed through the comparison of time series for hydropower generation, water level variations, hydrological alteration and phytoplankton concentration. The results show that under a wet scenario there is no significant difference between any of the parameters during the simulation period. In contrast, for normal and dry hydrology, the inclusion of environmental constraint to the operation of the hydropower plant increased chlorophyll-a concentration in the reservoir. However, this proportional relationship is not valid for higher EF in dry scenario that showed important improvements in the water quality and hydrological alteration index. This study evidences the conflicting goals among environmental considerations, reservoir water quality and tourist interests, and at the same time, it expands the possibilities of using the operating schemes as a prevention and control tool for reservoir water quality problems.



## 1. Introduction

The construction of a dam implies the creation of a new and complex human-made ecosystem with non-natural regulation depending on the purpose of the reservoir. Reservoirs enable flood control, electricity generation, and water management for human consumption and agriculture. Other purposes, such as navigation and recreation, have been added over time. Regardless of these uses, the construction and operation of a reservoir lead to environmental problems affecting the riverine vegetation, aquatic species, water quality, and river morphology, as well as social impacts on the surrounding areas (Collier et al., 1996). In this context, the construction and operation of the reservoir require awareness of the effects on both the pre-existing environment and the new human-made reservoir.

Most previous studies have focused on the downstream river, where the operational scheme of the withdrawals alters the natural flow rate and the sediment load. Downstream of the dam, erosion near structures and modifications of the channel morphology are to be expected, among other effects (Carling, 1988; Brandt, 2000; Graf, 2006). Additionally, the presence of a dam affects the aquatic ecosystem downstream of the reservoir due to alterations of the flow rate itself, changes in water depth and velocity, variations in water temperature, destruction of fish nesting sites on banks, obstruction of fish migration due to the dam barrier and increases in the concentration of fine sediment (Baxter, 1977; Collier et al., 1996; García et al., 2011; Gray and Ward, 1982). Water quality

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problems, as well as the anomalous growth of biological species and changes in biodiversity, are common inside the reservoir itself (George and Edwards, 1976; Baxter, 1977; Chung et al., 2009a). With respect to the nutrients, catchment management and the control of point and non-point source emissions have been useful in the mitigation of these environmental problems (Cooke et al., 2005; Peng et al., 2014). In other cases, it has been necessary to implement in-lake engineering, which includes the use of mixers, barriers, oxygenators and selective withdrawals (Morillo et al., 2006; Chung et al., 2009b, 2014).

In the particular case of a reservoir built for hydropower purposes, the operation of the hydropower plant alters the thermal structure of the water column and the mixing processes in the reservoir, due to the number of outlets, the location of the outlets and the withdrawal scheme (Casamitjana et al., 2003; de la Fuente and Niño, 2008; Ibarra et al., 2015). Hydropeaking operation in the hourly scale characterizes the behavior of hydropower plants. This operation policy produces energy for only a few hours each day, when the energy demand is maxima, while the rest of the time the system produces minimal energy and stores the inflow volume. The environmental flow usually defines this minimum energy produced during the day. The impacts of hydropeaking operation on the downstream river are well-understood: changes in benthic communities, habitat degradation and fish mortality, among others (Saltveit et al., 2001; Young et al., 2011). However, the influence of the hydropower operating policy on the reservoir water quality is not clear. Changes in the outflow are external perturbations of the physical environment, which have ultimately consequences on plankton dynamics (Reynolds, 1984, 1993; Hoyer et al., 2009).

The aim of this article was to investigate the link between hydropower plant operation, environmental flow constraints and water quality at a reservoir. The Rapel reservoir (34° S, 71.6° W) was chosen for this purpose: an old, dendritic and monomictic reservoir, located in central Chile (Vila et al., 1987, 2000; de la Fuente and Niño, 2008). The Rapel hydropower plant operates in the context of the Central Interconnected System (SIC), which provides energy to most of the Chilean population (CDEC-SIC, 2013). An Independent System Operator (ISO) minimizes the system's economic costs and defines which power plants will supply the energy demand. Since the construction of the Rapel Dam in 1968, no environmental restrictions have been imposed on its operation, and therefore the ISO has established a hydropeaking operation scheme. During its operation, the reservoir has received discharges of domestic, agro-industrial and mining wastewaters, which contain high rates of sediments and nutrients as well as metal compounds (Vila et al., 2000). The first eutrophication-related problems were observed in the 1970s: unnatural fish deaths and algae bloom events started to occur (Cabrera et al., 1977; Vila et al., 1987, 2000). Previous research has shown that hydropower operation affects the hydrodynamics of the reservoir, forces deeper stratification (de la Fuente and Niño, 2008), enhances vertical mixing and decreases horizontal dispersion (Ibarra, 2013; Ibarra et al., 2015), and alters the effluent temperature (Guzmán, 2013).

For this study, the three-dimensional ELCOM-CAEDYM model (Hipsey et al., 2010) was implemented to simulate the hydrodynamic and water quality of the reservoir, together with the interactions among sediments, nutrients and algae species. Operation of the ISO was simulated using a model called MIPUC that reproduces the economical operation of the entire SIC and consequently defines the required water volume to be released for hydropower generation. This outflow information is used as input data in ELCOM-CAEDYM simulations, which output the water quality of the reservoir, specifically, the variations in phytoplankton concentrations. The next section describes the models implemented in this study, the indicators used for analysis and comparison of the results, and the simulation scenarios proposed. The results section presents the validation of the models. Finally, the results of a total of 20 simulation scenarios are compared in terms of the indicators, as well as in terms of the factors that enhance or limit phytoplankton growth.

## 2. Methods

### 2.1. Study site

The Rapel reservoir is a dendritic and monomictic reservoir with a storage capacity of 400 $Hm^3$, composed of 3 sub-basins with different retention times (Fig. 1a). The southern part of the system contains the Cachapoal basin, which receives inflows from the Cachapoal and Tinguiririca Rivers. In the eastern zone, the Alhué basin receives waters from Alhué Creek. Finally, the Muro basin receives contributions from the other two basins, and it is located in the northwestern zone of the reservoir.

Cachapoal River is characterized by a nivo-pluvial regime and an average flow rate of 172 $m^3/s$ during winter and 98 $m^3/s$ during summer, whereas the Tinguirica River has a mostly pluvial regime with average flow rates of 125 $m^3/s$ during winter and 46 $m^3/s$ during summer. The third affluent corresponds to Alhué creek, with a minor contribution of 2.0 $m^3/s$ on an annual average. The shape of the basins and the asymmetry in the tributary flow rates force a preferential flow path along the Cachapoal-Muro direction (de la Fuente and Niño, 2008). The Alhué basin is isolated from the rest of the reservoir and has larger retention times, between two and three months (de la Fuente and Niño, 2008). Originally, the reservoir had a maximum depth of 85 m in the zone closer to the dam. However, the transport and accumulation of sediments have reduced the maximum depth to approximately 55 m today (de la Fuente et al., 2010). In the Cachapoal basin, the maximum water depth is 25 m, with average retention time of approximately 13 days.

The Rapel hydropower plant has a production capacity of 378 MW with five Francis units, which allow operating at a total maximum flow rate of 587 $m^3/s$. The maximum normal water level is 105 m.a.s.l., and the minimum normal water level is 97 m.a.s.l., corresponding to water depths of 55 m and 47 m, respectively. The water level in the past ten years has remained above 100.5 m.a.s.l.

### 2.2. Field data

Field data for this research are available between November 2009 and March 2010. During that period of time, one standard meteorological station was located on the shore of the reservoir (34° 8′ 58.94″ south latitude and 71° 27′ 16.14″ west longitude, black star in Fig. 1a). Furthermore, a thermistor chain was located near the dam at the point in Fig. 1a marked with a black square. The thermistor chain registered information at every 5 m depth with hourly frequency. Regarding the water quality data, local measurements of nitrogen (organic and inorganic), phosphorus (organic and inorganic) and chlorophyll-a concentrations were taken at the white points indicated in Fig. 1a (EULA-Chile, 2011). Furthermore, some water quality samples were taken in the tributaries of the Rapel reservoir, including observations of nutrients (nitrogen and phosphorus) and suspended solids concentrations. Finally, the temporal distribution of all of these measurements is detailed in Fig. 1b, which indicates that the available data limit the period of simulation from the last week of November 2009 until the end of March 2010.

The bathymetry was obtained from a bathymetric survey conducted by the Chilean Hydrographic and Oceanographic Service of the Navy. This data allowed for obtaining the cumulative volume and surface are as function of the water level. The historic record of hourly energy production and water level of CDEC-SIC (2013) were