

# Floating photovoltaic plants: Ecological impacts versus hydropower operation flexibility



J. Haas<sup>a,e,\*</sup>, J. Khalighi<sup>a</sup>, A. de la Fuente<sup>c</sup>, S.U. Gerbersdorf<sup>d</sup>, W. Nowak<sup>a</sup>, Po-Jung Chen<sup>a,b</sup>

<sup>a</sup> Stochastic Simulation and Safety Research for Hydrosystems (IWS/SC SimTech), University of Stuttgart, Stuttgart, Germany

<sup>b</sup> Department of Mechatronics Engineering, University of Waterloo, Waterloo, Canada

<sup>c</sup> Department of Civil Engineering, University of Chile, Santiago, Chile

<sup>d</sup> Hydraulic Engineering and Water Resources Management (IWS), University of Stuttgart, Stuttgart, Germany

<sup>e</sup> Department Energy Systems Analysis, Institute of Networked Energy Systems, German Aerospace Center (DLR), Stuttgart, Germany

## ARTICLE INFO

### Keywords:

Solar energy  
Paris Agreement  
Eutrophication and algae reduction  
Water and ecology management  
Numerical modeling  
Energy and water nexus

## ABSTRACT

Floating photovoltaic power plants are a quickly growing technology in which the solar modules float on water bodies instead of being mounted on the ground. This provides an advantage, especially in regions with limited space. Floating modules have other benefits when compared to conventional solar power plants, such as reducing the evaporation losses of the water body and operating at a higher efficiency because the water reduces the temperature (of the modules). So far, the literature has focused on these aspects as well as the optimal design of such solar power plants. This study contributes to the body of knowledge by i) assessing the impact of floating solar photovoltaic modules on the water quality of a hydropower reservoir, more specifically on the development of algal blooms, and by ii) studying the impact that these modules have on the hydropower production. For the first part, a three-dimensional numerical-hydrodynamic water-quality model is used. The current case (without solar modules) is compared to scenarios in which the solar modules increasingly cover the lake, thus reducing the incident sunlight from 0% to finally 100%. The focus is on microalgal growth by monitoring total chlorophyll-a as a proxy for biomass. For the second part, as the massive installation of solar modules on a reservoir may constrain the minimum water level (to avoid the stranding of the structures), the impact on hydropower revenues is examined. Here, a tool for optimal hydropower scheduling is employed, considering both different water and power price scenarios. The Rapel reservoir in central Chile serves as a case study. The response of the system strongly depends on the percentage that the modules cover the lake: for fractions below 40%, the modules have little or no effect on both microalgal growth and hydropower revenue. For moderate covers (40–60%), algal blooms are avoided because of the reduction of light in the reservoir (which controls algal growth), without major economic hydropower losses. Finally, a large solar module cover can eradicate algal blooms entirely (which might have other impacts on the ecosystem health) and results in severe economic hydropower losses. Altogether, an optimum range of solar module covers is identified, presenting a convenient trade-off between ecology health and costs. However, a massive deployment of these floating modules may affect the development of touristic activities in the reservoir, which should be examined more closely. In general, the findings herein are relevant for decision-makers from both the energy sector and water management.

## 1. Introduction

Solar energy is renewable, quiet, widely available, and cost-effective, making it a very convenient power source. However, solar installations might compete with other land uses, which is especially critical in densely populated areas [1]. One emerging solution is locating the panels on water bodies, called floating solar photovoltaic (FPV). The deployment of FPV has been explosive in the last years,

growing from 0.01 GW in 2014 to 1.1 GW in 2018, with over 0.5 GW added only in that last year [2]. Still, this number is modest in the context of the total installed solar photovoltaic capacity of over 500 GW by the end of the same year [3].

FPV has distinct advantages over conventional solar photovoltaic installations. One is the lack of competing uses of the water surface (with the exception of recreational activities). Second, an easy site-preparation (leveling of the terrain is unnecessary) and modular

\* Corresponding author at: Pfaffenwaldring 5a, 70569 Stuttgart, Germany.

E-mail address: [jannik.haas@iws-uni.stuttgart.de](mailto:jannik.haas@iws-uni.stuttgart.de) (J. Haas).

<https://doi.org/10.1016/j.enconman.2019.112414>

Received 24 September 2019; Received in revised form 13 December 2019; Accepted 14 December 2019

Available online 14 January 2020

0196-8904/ © 2019 Elsevier Ltd. All rights reserved.

deployment lowers total costs [2]. Third, FPV can reduce the evaporation losses of the water body by as much as 90% [4]. Fourth, FPV may limit algal growth, thus improving water quality indirectly [2]. Fifth and final, the water cools down the panels, which results in 2% [5] to 7% [6] higher solar efficiencies, and water bodies are unshaded surfaces with high albedos (sunlight reflection), further improving the solar generation [7]. As challenges, when FPV is installed on large water bodies, they must be able to withstand storms (requiring a strong mooring and anchoring system), which may also imply deviations from the optimal orientation and tilt [8]. Maintenance of FPV might be more challenging than earth-mounted PV, and given their incipient deployment, some components are still more expensive but could benefit in the future from economies of scale. For further differences between floating PV and conventional PV, the reader may consult reference [9].

FPV can be installed on natural or artificial water bodies. Flooded mines and hydropower reservoirs are examples of the latter, and they might be particularly attractive for FPV given the existing infrastructure. This includes access to roads and transmission systems, which are a common barrier for solar deployment [10]. Hybridization with hydropower reservoirs is especially promising because i) such reservoirs are very widespread (installed power capacity over 700 GW worldwide, plus 170 GW of pumped hydro), ii) most electrical equipment (transformers, transmission lines) are in place, and iii) a combined operation can offer a steady power output (that a stand-alone solar photovoltaic would struggle to do [11]). However, studies on such hybrids are scarce. A recent (2018) conference publication from Breyer's team [7] determined the world's potential for such hybrids. They found that covering the existing hydropower reservoirs with 25% of FPV could at least double the hydropower generation (6300 TWh versus 2500 TWh). The study from Cazzaniga [12] goes in a similar direction, finding that covering 2.5% of the existing reservoirs could increase the energy production from such hybrids by around one third. Nevertheless, FPV might also constrain the operation of hydropower because a minimum water level needs to be held to avoid the stranding of FPV structures (this is similar, for example, to hydropower flow constraints which also impact the revenues [13]), but this has not been assessed so far.

And there is another yet unexplored issue of FPV, which is its effect on the aquatic ecosystem. For example, FPV may impact the ecology because photosynthesis is controlled by light. Controlling sunlight to the right amount might reduce oxygen depletion as a consequence of eventually degrading algal biomass and might prevent the development of toxic algal blooms [14]. However, too much shading could kill all pelagic primary producers, such as microalgae, which could have detrimental impacts on the overall food chain. Some studies [2,7,15] comment that FPV *could* impact the water quality but do not perform the corresponding scientific experiment. Two recent literature reviews on FPV ([9] from 2019 and [16] from 2016), which in total looked at around 200 publications, revealed that most available studies focus primarily on technical and implementation aspects, as well as the techno-economic assessment of FPV. Both studies identified the need for *starting* to understand the ecological impact of FPV on the water body.

In the present study, the impact of FPV is examined in terms of controlling microalgal blooms, and potential limitations to hydropower operations. More specifically, the main contribution of the current work is answering the following questions:

- i. How does shading by FPV impact microalgal biomass development? Understanding this issue for assuring a healthy ecosystem is relevant, particularly in the context of such a fast-growing technology.
- ii. How does FPV interfere with hydropower operation? Assessing the impact on hydropower revenues is crucial, given the large potential that these reservoirs offer for new floating solar installations.
- iii. What FPV sizes are to be tolerated or ideal in regard to the previously raised issues? The interaction of impacts (to both algal

growth and hydropower operation) may lead to an optimal range of FPV.

To answer these questions, a simulation framework is proposed that will be illustrated in a case study. The Rapel hydropower reservoir in Chile [17] is selected because it is close to a densely populated area (i.e. valuable land) and it frequently suffers from toxic cyanobacterial blooms. Furthermore, Chile is expected to require strong investments in storage technologies [18] to integrate the vast solar potential the country offers [10]. Thus, better understanding FPV-hydropower hybrids, as virtual storage [7], helps in that mission.

The next section elaborates on the methods applied in this study, which includes the simulation framework and description of the case study. Results pertaining to algal growth and hydropower operation are discussed in Section 3. Finally, conclusions are drawn in Section 4.

## 2. Methods

A simulation framework composed of two models will answer the posed research questions. The first is a numerical model that simulates the hydrodynamics of a water body, allowing to examine how FPV, by reducing the incoming light, affects the development of microalgal biomass (presented in Section 2.1). The second model is an optimization tool for hydropower scheduling, used to assess the impact of FPV on the hydropower operation (Section 2.2). This framework is applied in a case study on a real hydropower reservoir in Chile (Section 2.3).

### 2.1. Ecology model

To assess the ecological health of water bodies, nowadays, numerical models are commonly used. Contrary to physical-ecological studies that excel when taking snapshots of current situations, numerical models are especially helpful to study future or extreme scenarios. Here, a three-dimensional hydrodynamic/ecology model, called ELCOM-CAEDYM (Estuary, Lake, and Coastal Ocean Model - Computational Aquatic Ecosystem Dynamics Model), is chosen [19]. ELCOM is a computational simulation tool that considers the hydrodynamic and thermodynamic behavior of stratified lakes and reservoirs. The transport and the interactions between biological and chemical processes are simulated by dynamically coupling the water quality module (CAEDYM) [19]. There is other software available for water quality simulation. For example, the open-source tool CE-QUAL-W2, a 2D model (laterally averaged) used for long and narrow reservoirs [20] or the commercial tool MIKE 3, a 3D model with a water quality module [21]. In general, any software that is able to couple the hydrodynamics of the reservoir with the water quality would be suitable for the here intended simulations. The selection of ELCOM-CAEDYM for the purposes of this study is based on previous knowledge of the Rapel Reservoir with this particular model [22–24].

Fig. 1 illustrates the conceptual scheme of the ELCOM-CAEDYM model and the full technical detail can be found in reference [19]. The main inputs refer to the bathymetry, meteorological data, inflows, biochemical loads of the tributaries, and outflows (than can be controlled by hydropower generation).

A direct effect of installing FPVs is reducing the incident short-wave solar radiation on the water surface. To explore this impact on the ecosystem, the full range of scenarios going from 0% to 100% of covered area is explored. The FPV systems are here assumed to be opaque and equally distributed over the water body; hence, each scenario reduces the incident short-wave solar radiation over the whole lake between 0% and 100%. CAEDYM uses the incident shortwave radiation as input to compute the surface thermodynamics. For simulating primary algal production, the short-wave intensity at the surface is converted into the photosynthetically active component (assuming that 75% of the incident spectrum is between 400 and 700 nm in CAEDYM). As this component penetrates into the water column, CAEDYM calculates, for

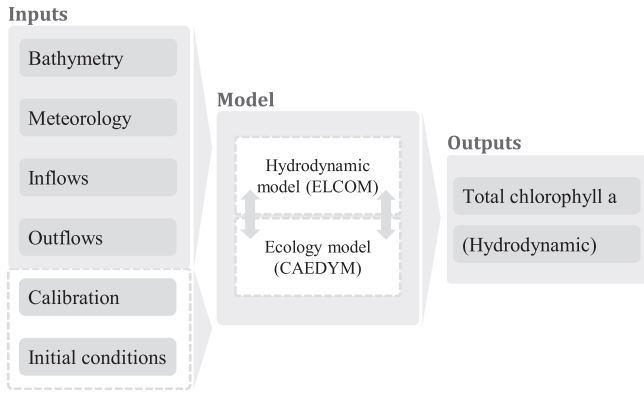


Fig. 1. Hydrodynamic/ecology model: ELCOM-CAEDYM.

each computational cell, the light extinction coefficient as a function of the concentrations of algae, inorganic, and detritus particles, and dissolved organic carbon contents. This way, the light that penetrates into deeper waters depends on the extinction coefficient (i.e. the components listed above) of the shallower waters. This is a commonly used approach that can be consulted in reference [25]. Out of scope is addressing the light attenuation of various wavelengths over depth (different algal species need varying ranges of wavelengths) because this is not influenced by FPV, rather by the characteristics of the water body itself.

In terms of output, the focus is on total chlorophyll-a, a common proxy for photosynthetic active biomass [26]. The total chlorophyll-a concentration is defined as the sum of three groups of freshwater algae species (chlorophytes, diatoms, and cyanobacteria) that are simulated by CAEDYM. The growth of each concentration  $C$  during the time  $t$  is simulated as a first-order kinetic reaction ( $\partial C/\partial t = \mu C$ ), where the net growth rate  $\mu$  depends on the water temperature, nutrient availability, water salinity, and light intensity [25].

### 2.2. Hydropower operation model

In the present work, the impact of FPV on hydropower operation is studied, in the task of better understanding the collateral effects of FPV. The operation (and revenues) from the FPV power plant itself, topics a classical FPV project developer would be interested in, are per experiment-design out of scope. The area of installed FPVs sets a minimum water level and a corresponding minimum volume that the reservoir needs to maintain. If the water level dropped further, and the surface became smaller than this minimum surface, the solar panels would strand (see Fig. 2). This poses a volume constraint for hydropower operation. To evaluate the effects of the different levels of FPV covers on a reservoir hydropower plant, an optimization model for reservoir operation is developed and used. This model is implemented in GAMS [27], a commercial software to formulate optimization problems. Once the problem is set up, it is solved with a commercial solver: CPLEX [28].

The model is based on maximizing the revenue  $Z$ , which is the product between the generated power  $G_t$  and the selling electricity price  $P_t$ , summed over time (see Eq. (1)). To account for seasonalities inherent to hydropower operation, the model considers a time horizon  $T$  equal to one full year, i.e. 8760 sequential hourly time steps.

$$Z = \sum_{t=1}^{T=8760} G_t \cdot P_t^{scenarios} \quad (1)$$

The hourly power generation  $G_t$  is calculated as the product between the water release  $Q_t^{turbine}$  and its hydropower yield  $Y$  (see Eq. (2)). This yield is the product of the efficiency of the hydropower plant, acceleration of gravity, water density, and the hydraulic head. Here, a constant yield is assumed, implying a constant head, which is a necessary simplification for preserving the linearity of the model for the sake of

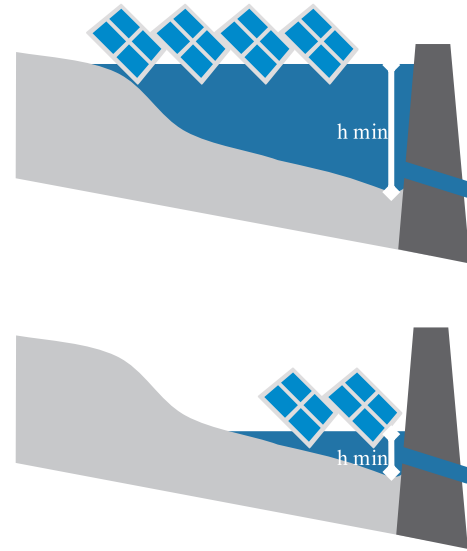


Fig. 2. FPV and its impact on the minimum water level for hydropower.

solving speed. Note that for high-head reservoirs (such as it is the case of the case study), this approximation-error is limited.

$$G_t = Y \cdot Q_t^{turbine} \quad (2)$$

The hydropower operation is constrained by its water balance (Eq. (3)). The reservoir volume of the next time step  $V_{t+1}$  is calculated as the difference between inflow  $Q_t^{in}$  and the water released to the turbines  $Q_t^{turbine}$  (multiplied by the duration of the time step, i.e. one hour), plus the previously-stored volume  $V_t$ .

$$V_{t+1} = (Q_t^{in_{scenarios}} - Q_t^{turbine}) \cdot dt + V_t \quad (3)$$

The maximum and minimum volumes of the reservoir limit the hydropower operation (Eq. (4)). The maximum volume  $V^{max}$  is defined by the physical capacity of the reservoir, while the minimum volume  $V_{scenarios}^{min}$  corresponds to either the minimum technical volume (due to the water intakes) or to the minimum level imposed by FPV. The ending condition of the stored volume is a decision set to be equal to the starting volume. This avoids undesired emptying of the reservoir.

$$V_{scenarios}^{min} \leq V_t \leq V^{max} \quad (4)$$

### 2.3. Field of study

This section will describe the field of study. First, a general description is provided, followed by the defined scenarios for the ecology model, and the defined scenarios for the hydropower operation model.

#### 2.3.1. Description

The above-proposed framework is applied to the Rapel reservoir, a hydropower plant in central Chile. This reservoir is selected because of three reasons. 1) it is close to a densely populated region; hence, the land is expensive making it a classical candidate for FPV power plants. 2) it is downstream of strong agricultural activities; thus, wastewater and run-off of nutrients have impaired the water quality of the lake severely. Most significantly, it has accelerated the growth of micro-algae, in particular, the taxon cyanobacteria that are well-known to produce harmful and deadly toxins. Moreover, their mass occurrence and impact on the food chain poses a threat to the overall biodiversity of the ecosystem [22]. And 3), the reservoir shows strong fluctuations in its water level conditioned by the operation of its hydropower plant. In this sense, installing FPV here is very different from a lake with more constant water levels. Care must be put on avoiding the stranding of FPV, which in turn impacts the hydropower revenues.

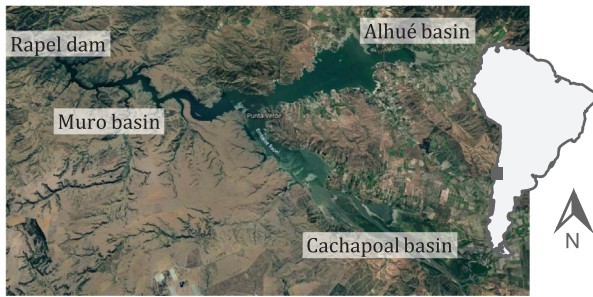


Fig. 3. The Rapel hydropower reservoir and its basins. (Satellite image from Google Maps.)

The Rapel reservoir (34°S, 71.6°W, 105 m.a.s.l.) was constructed in 1968 for power generation (380 MW, about 75 m of head) but has since also become an important recreational area. It is a dendritic and temperate monomictic reservoir with a storage capacity of 400 Mm<sup>3</sup>, composed of three sub-basins (Fig. 3). The southern part of the reservoir contains the Cachapoal basin, which receives water from the Cachapoal and Tinguiririca Rivers. In the eastern zone, the Alhué basin receives waters from Alhué Creek. The Muro basin receives contributions from the other two basins and is located in the northwestern zone of the reservoir. The reader may consult reference [29] for further details.

2.3.2. Inputs and scenarios for the ecology model

In terms of inputs for the ecology model (recalling the left side of Fig. 1), these are taken from reference [23]. The initial condition of the lake was obtained from field observations [22]. This setup for the Rapel reservoir was previously calibrated and validated in 2014 for a regular mesh grid of rectangular elements 50 m×50 m in the horizontal dimensions, and 2 m in the vertical [22]. More details on the model for this specific reservoir can be found in reference [22]. In short, a model that was calibrated in earlier studies is here used to answer new questions, now related to the impact of FPV on the reservoir.

In total, a time horizon of 2.5 years is simulated, starting in January of 2011 (austral summer). This time horizon is chosen because of data availability: for these years, there are several publications available that serve as a baseline against which the results from the current work can be compared. Much longer time horizons are challenging in both computational and memory terms. For the analysis, the first months (before the winter-overturn of the reservoir) are excluded because these are strongly influenced by the initial conditions (vertical water temperature profile). Thus, the resulting time frame applies from October 2011 to May 2013.

The base case (no FPV) is compared to scenarios in which the FPV covers increase in steps of 10% (of covered area) until fully covering the lake. These 10 scenarios, in addition to the base case, should provide a fair resolution in the context of this exploratory study. These scenarios will be abbreviated, such that, for example, FPV10 refers to a covered lake area of 10% (which at the same time reduces the short-wave radiation by 10%).

2.3.3. Inputs and scenarios for the hydropower operation model

To assess the impact of FPV on the hydropower operation, three dimensions were subject to scenario analysis: Water inflows, electricity prices, and minimum reservoir volumes. The two former are known drivers for hydropower operation, while the latter is defined to test the hypothesis of the current study. The details are as follows:

- Inflow scenarios are based on historical flow provided by Chile’s National Power System Coordinator [30]. This data showed to have better availability than the inputs for the ecology model, which allowed to simulate 55 years (data between the years 1961 and 2015). Note that only the inflows are varied, while the meteorological

forcings (wind speed, air humidity and temperature, and cloud cover) are not modified (i.e. they correspond to the time horizon mentioned in Section 2.3.2).

- The electricity price data were obtained from Chile’s National Power System Coordinator for the years 2014 through 2017 (four years) [31]. These are hourly time series for the node closest to Rapel.
- Each FPV scenario has a surface value (FPV area), which translates into a corresponding minimum volume. As the most extreme scenarios are likely to have a significantly higher impact on results, those are given a higher resolution (instead of defining only 10 scenarios as in the ecology model, here 14 are run).

Combining all three dimensions (55 hydrological years × 4 electricity price years × 14 minimum volumes) is the resulting scenario setup for studying the hydropower operation under different levels of FPV.

3. Results and discussion

Recall that the focus of the present study is on two unexplored aspects of FPV. One is its impact on lake ecology and the other on hydropower operations. But it should not be omitted that FPV also offers other advantages as explored in earlier studies, including a reduction in evaporation and a displacement of carbon emissions (CO<sub>2</sub>). For example, the water saved (due to lower evaporation) in FPV100, the most extreme scenario of this study, would be close to 15% of the reservoir’s total volume per year. By displacing conventional coal generators, FPV100 would also reduce the CO<sub>2</sub> emissions by over one million tons per year (for more details, see Table 1 in the appendix).

The remainder of this section first discusses the findings of the water quality simulations (Section 3.1), followed by the hydropower optimization (Section 3.2). The final section (Section 3.3) focuses on describing the optimal range of FPV sizes by combining the results from Section 3.1 and Section 3.2.

3.1. Microalgal biomass development as a proxy for water quality

This subsection has two parts. The first focuses on the spatial distribution of chlorophyll-*a* for the different FPV scenarios and the second on the temporal evolution.

The spatial concentration of chlorophyll-*a* in the Rapel reservoir is shown in Fig. 4. This plot shows the top view of the reservoir and displays depth-averaged chlorophyll-*a* values (with red standing for high values of chlorophyll-*a*) for the end of the simulation horizon. The

Table 1  
General aspects of FPV scenarios.

Scenarios	PV covered area (km <sup>2</sup> )	Installed power capacity (MW) <sup>1</sup>	Reduction in CO <sub>2</sub> emissions (kt CO <sub>2</sub> /year) <sup>2</sup>	Annual evaporation reduction (%) <sup>3</sup>
FPV0	0	0	0	0%
FPV10	4	195	130	2%
FPV20	8	390	260	3%
FPV30	12	585	390	5%
FPV40	16	780	520	7%
FPV50	20	975	640	8%
FPV60	23	1170	770	10%
FPV70	27	1365	900	12%
FPV80	31	1560	1030	13%
FPV90	35	1755	1160	15%
FPV100	39	1950	1290	16%

<sup>1</sup> Assuming 0.5 MWp per hectare.

<sup>2</sup> Using 1500 yearly full load hours [38,39] and a greenhouse gas emission factor for Chile of 0.44 tCO<sub>2</sub>/MWh [40].

<sup>3</sup> Using the simplified Penman equation, based on radiation and wind speed [41]. Expressed relative to the reservoirs maximum volume.

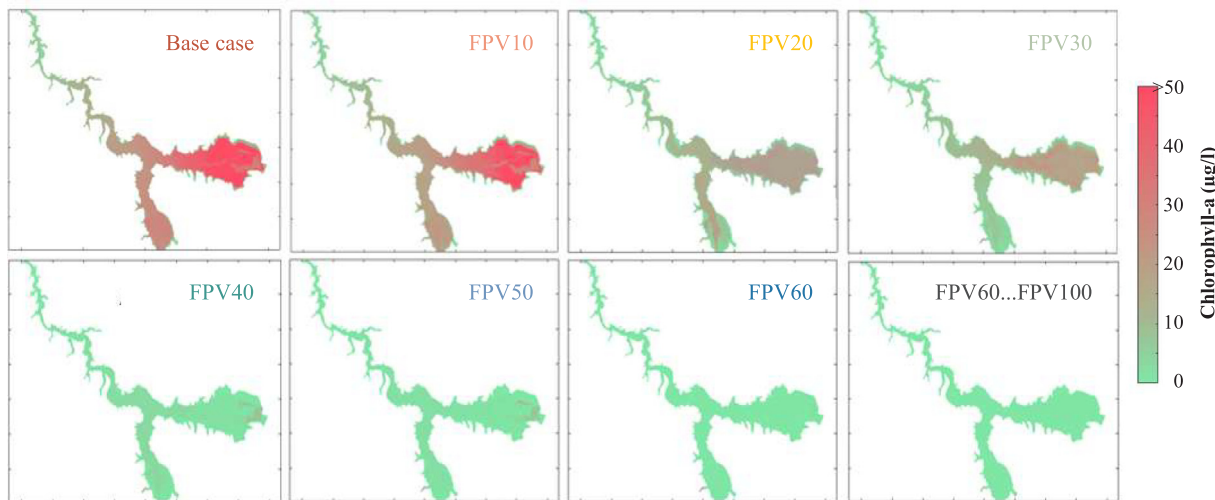


Fig. 4. Concentration of chlorophyll-a in Rapel after the simulation period for the different FPV scenarios. (The color-code of these FPV scenarios will also be used in the upcoming plots.)

first subplot shows the base case, that is without FPV. From here, it can be observed that most of the cases exhibit concentrations between 20 and 50  $\mu\text{g/l}$ . These are extremely high values in the context of the World Health Organization’s guidelines for safe recreational water environments (10  $\mu\text{g/l}$  chlorophyll-a) [32]. Especially, the Alhué creek basin suffers from strong algal blooms due to its longer retention times [33]. Conversely, the Muro basin experiences lower concentrations of microalgae, possibly influenced by a stronger hydrodynamic regime due to turbine action (higher flow velocities and mixing rates). More on the behavior of the base case can be read in Refs. [22,23].

Now, as the FPV cover increases, the concentration of chlorophyll-a declines resulting from a reduction in photosynthesis at lower irradiances. FPV20 and FPV30 achieve significant reductions but still exceed the recommended level (by the World Health Organization). In scenarios FPV40 and beyond, the blooms are effectively prevented. From scenario FPV70 onwards no measurable differences in algal concentration are observed (for the time chosen in the figure). An apparent exception is FPV10, which, compared to the base case, shows no (or only minimal) changes. This may relate to the fact that the solar radiation of the base case is close to or beyond the photosynthesis saturation point (i.e. it is not a limiting factor).

In terms of temporal evolution, Fig. 5 shows the lake-averaged

chlorophyll-a concentration for the simulation horizon. Starting with the base case (no FPV), it can be observed how the concentration evolves from low values at the starting point in October 2011, to a first bloom in summer 2012 (January-March), followed by a decay in winter, and yet another bloom in summer 2013. In general, larger installations of FPV result in gradually lower peak concentrations of chlorophyll-a, especially those summer peaks. Scenarios FPV10 to FPV30, while following that trend, still result in blooms. High chlorophyll-a concentrations are only avoided from scenario FPV40 and onwards. Now, some of these scenarios have another issue: persistently low concentrations of these primary producers. This is critical because microalgae are an important part of the lake’s food chain. The literature shows minimum (average) concentrations of 0.4  $\mu\text{g/l}$  chlorophyll-a for similar but healthy oligotrophic lakes in Chile [34]. Especially scenarios FPV70 to FPV100 are consistently below that minimum threshold, potentially threatening the ecosystem (although some reservoirs for drinking water might benefit from the total absence of algae). If such extreme covers are intended, a potential solution is acting on the transparency of the FPV installations, which can be done by varying the design of the floats (pontoons) and the panels.

Summarizing the ideas above, FPV shows to reduce concentrations of chlorophyll-a effectively. In order to avoid the algal blooms from

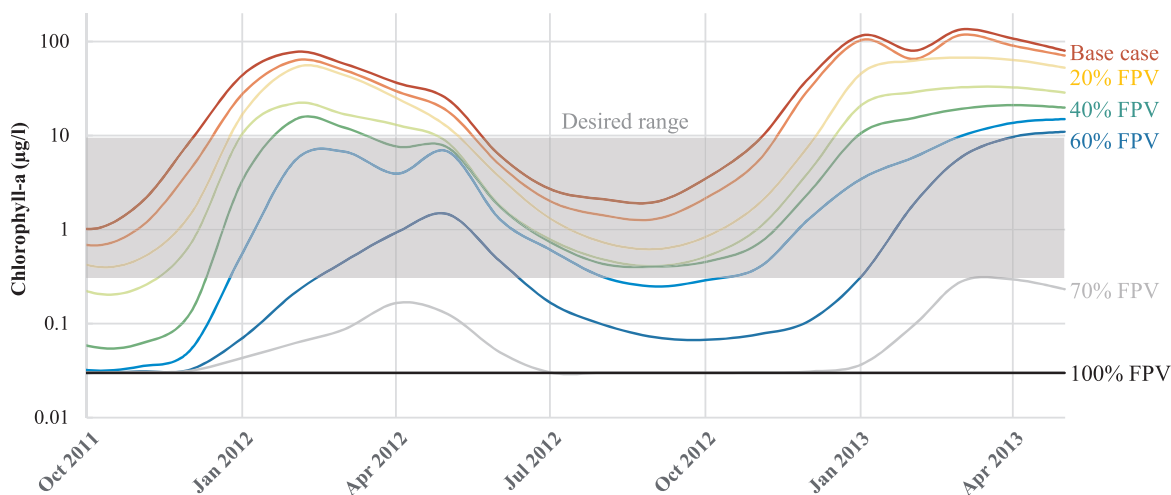


Fig. 5. Chlorophyll-a concentrations (lake-averaged) for the different FPV scenarios over the modeling horizon.

which Rapel is suffering, scenarios FPV40 to FPV100 are candidate solutions. However, scenarios FPV60 to FPV100 might limit algal growth too severely, resulting in persistently low concentrations that might restrict the carbon transfer into higher food levels and thus hamper the lake ecology. The thresholds are specific to each ecosystem, which is why it is recommended conducting studies at the sites of interest for new FPV installations. Acknowledging and understanding allowable ranges of FPV cover is relevant for all future FPV projects, as well as stakeholders interested in preserving the lake's ecology.

As a final note for this subsection, microalgal growth is a consequence of CO<sub>2</sub>, light, and nutrient availability. Hence, by reducing irradiance with FPV, a possibly high nutrient regime (called eutrophication) remains unaltered. Here, simply the algal growth is restricted. This still has some advantages: (a) lower biomass leads to eventually less dead organic material, less bacterial degradation activities, and less oxygen consumption; and (b) lower algal biomass significantly reduces the likelihood of developing toxic species and the release of their toxins. In other words, in this study, severe effects of water pollution are attenuated by reducing algal growth.

### 3.2. Hydropower operation

The impacts of FPV on the revenues of the hydropower plant will be assessed next. Recall that each FPV scenario requires a minimum water level in order to avoid the stranding of the structures, which limits the operational range of the hydropower plant.

Fig. 6 shows the yearly incomes of the hydropower plant over the different FPV scenarios. The different data points, for a given cover of FPV, correspond to the diverse hydrologic and electricity-price conditions (as explained in Section 2.3). Each revenue is normalized by the values from the corresponding base case (FPV0, under the same hydrological and price conditions).

Fig. 6 shows that up to FPV30, there is no change in revenue (all data points are at 100%). This is to be expected as 30% of the lake area corresponds to the minimum volume (given the turbines' intakes). Hence, such FPV sizes would not alter the hydropower operation. From FPV40 to FPV80, revenues start decreasing. The behavior seems linear in this range, and the forgone-revenue in FPV80 reaches 10% on average. The spread between the different scenarios (hydrology, electricity prices) grows up to 20%, adding uncertainty to the hydropower operation. For FPV90 and FPV100, the revenues drop dramatically by, on average, 15 and 30%, respectively. In the extreme, FPV100 displays a maximum of 90% of (the base case's) revenues and a minimum of

45% of revenues. Here, all operational flexibility is lost; the hydropower system operates as a run-of-river power plant (i.e. a full-reservoir, in which all inflows are immediately released to the turbines).

Such an extreme scenario, as FPV100, seems unattractive to all involved stakeholders. More in detail, FPV100 consists of a power capacity of 2 GW, a massive size for floating solar power plants (the world's added FPV capacity during 2018 was 0.5 GW [2]), which might be unrealistic to be deployed on a single water body. The economically most attractive FPV size is likely to be one that matches the hydropower plant's capacity to utilize its existing electricity installations (transformers, transmission lines). In the assessed case, this size is around FPV10 to FPV30 (depending on the power capacity density, MW/ha, resulting from the floats used), which is in line with the sizes assumed in reference [7]. Nevertheless, exploring the full range of FPV is valuable as it allows for identifying overall trends.

As summary of this subsection, only large installations (FPV40 and beyond) might interfere with hydropower operations. Until FPV90, the forgone revenues are below 10% (relative to the base case). These grow significantly in the extreme case (FPV100) with a large variance depending on price and inflow scenarios. Understanding how FPV interferes with hydropower is highly relevant for companies who are projecting FPV on hydropower reservoirs. For example, with these results, maximum FPV covers can be identified, or compensation payments from the FPV to the hydropower plant could be designed.

### 3.3. Finding the optimal range

In this last subsection of results and discussion, the findings from the two aspects analyzed earlier will be combined, and some limitations of the present study will be addressed.

The two subsections above looked at how FPV could impact algal growth and hydropower revenues. These two aspects are plotted in Fig. 7 (on the primary and secondary y-axis, respectively) versus the FPV scenarios (x-axis). From here three distinct ranges of FPV scenarios can be identified, depicted by the light-blue vertical:

- 1) FPV0 to FPV40: these configurations have virtually no impact on hydropower revenues and only a small impact on algae growth. Although all FPV scenarios in this range decrease the algae growth, as commented earlier (Section 3.1), it is not sufficient to prevent future blooms.
- 2) FPV40 to FPV60: these sizes start to affect hydropower revenue, but the losses are limited to 5%. In terms of algae, there is a significant

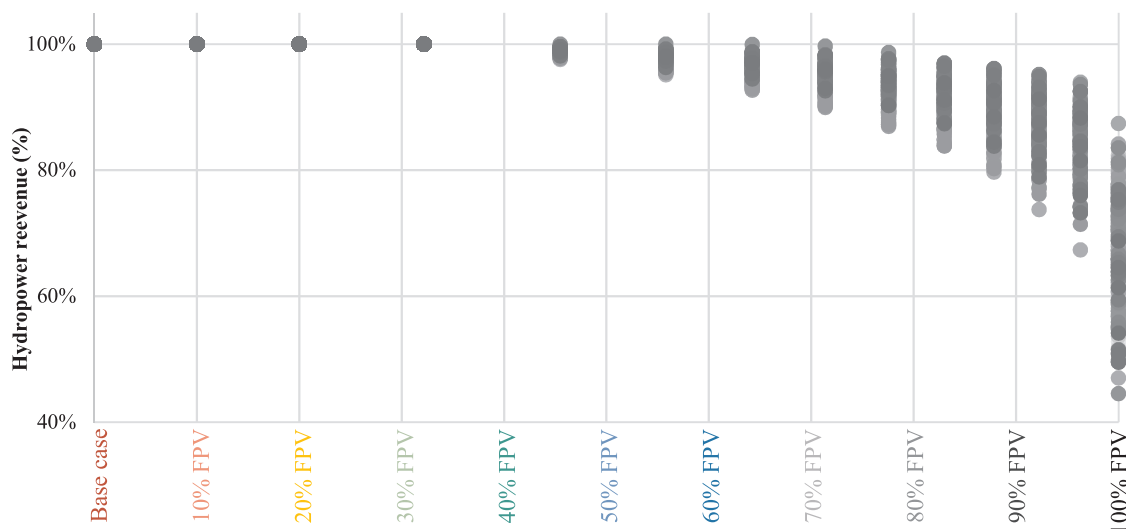


Fig. 6. Annual revenues for the FPV scenarios under different hydrologic and electricity-price conditions. Revenues are normalized by the corresponding base case (FPV0).

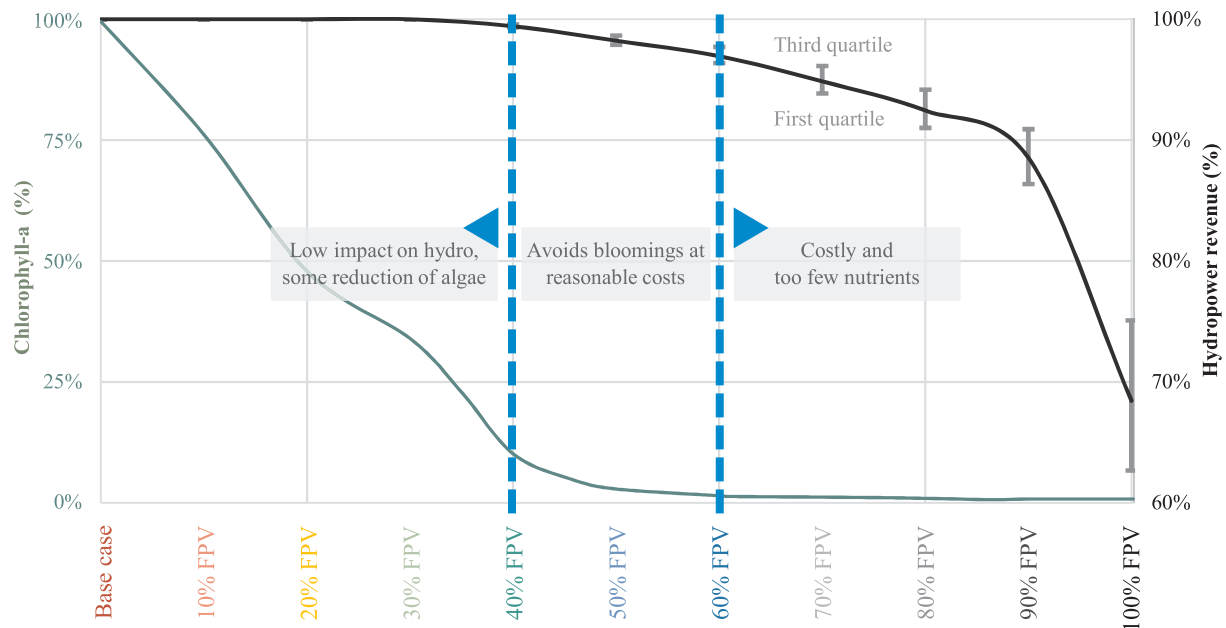


Fig. 7. Chlorophyll-a concentration (lake-averaged) and hydropower revenues for different FPV scenarios.

improvement. Both maximum and minimum concentrations are met over the whole simulation horizon.

- 3) FPV60 to FPV100: hydropower revenues decrease further, in the most extreme case showing losses around 30%. Algal blooms are avoided, but (recalling the results from Section 3.1) the average concentrations are below the minimum threshold necessary to sustain the ecosystem.

Altogether, FPV40 to FPV60 offers a good trade-off between lake ecology and hydropower losses in the studied reservoir. Economic losses are well below 5%, while algal blooms are controlled.

At this point, the reader is reminded that lake ecology is very individual to each lake, as it depends on numerous factors, such as meteorology, the concentration of nutrients in the inflows and sediments, etc. Therefore, the specific ranges found above are only valid only for this study site. Still, the inhere proposed methodology, as such, is transferable. The authors argue that in any reservoir, it would be possible to observe that more extensive FPV covers reduce the chlorophyll-a concentrations, as well as the hydropower flexibility (which in turn would decrease the revenues). How sensible the response is to changes on the FPV cover depends on the reservoir geometry and the trophic state of the reservoir. Particularly, in reservoirs where the surface area does not change significantly with the height, the optimal range defined in Fig. 7 may widen to the right, whereas in a reservoir with good water quality that range might move to the left.

In terms of limitations of this study, and steps proposed as future work, there are other factors, beyond the considered algal growth and hydropower revenue that may impact the feasibility and success of FPV. For example, FPVs could interfere with recreational activities, as well as the water value of hydropower [35]. Moreover, there are synergies that remain unstudied, such as a hybrid operation between FPV and hydropower, which could offer valuable services (such as steady power output) to the power system. For such systems, the environmental conditions (such as wind speed, evaporation, temperature) could be important since they act on the FPV plants. All of that could help to assess a more detailed performance. Also, the shadowing of FPV on the lake could be simulated in more detail. For example, the spatial distribution and detailed attenuation of radiation might be relevant (here only a uniform shading was assumed) since they support different taxa of microalgae with various accessory pigments absorbing at different wavelength regions. Studying the different microalgal taxa could reveal

insights on the food chain impacts (some might be inedible and, hence, impact the carbon transfer into higher trophic levels) or other ecological functions (carbon storage by photosynthesis, self-purification by reducing nutrient levels, etc.). And finally, water quality is far more complex than only algal concentrations; many other biological, chemical, and physical factors could be looked at [36].

As a general comment, when a lake suffers from algal blooms, the most sustainable solution is to avoid high nutrient availability (which is a driver for algae growth). Nutrients can be controlled in the inputs to the ecosystem (inflows and sediments) or by applying *in-situ* techniques, such as sediment removal or media-filtering [37]. In this case study, nutrients come from agriculture activity and urban areas within the catchment. Here, FPV showed to be either neutral or positive for improving the situation of algal blooms (in the range identified) but should not be considered as a stand-alone solution.

#### 4. Conclusions

This paper studies how floating photovoltaic systems (FPV), if installed on a hydropower reservoir, would impact i) the development of algal blooms (as proxy for water quality) with possibly positive consequences for the overall oxygen budget and in avoiding toxin-producing species, and ii) the hydropower revenue by considering a minimum height as to which the FPV is not stranding. For the first objective, a numerical-hydrodynamic model (ELCOM-CAEDYM) is applied to simulate the concentrations of chlorophyll-a as a proxy for algae. The current condition of a lake (no FPV installed) is compared to scenarios of increasing (in increments of 10%) levels of FPV cover (in terms of total area as well as incident short-wave solar radiation). For the second objective, a hydropower scheduling tool is used. These issues are illustrated in a case study on the Rapel reservoir of Chile.

Small FPV installations show to have little success in preventing algal blooms. Moderate sizes of FPV can effectively avoid blooms while supporting algal concentrations that are recommended for *healthy* lakes. Very large FPV covers eliminate algae altogether, which might threaten the lake's ecology.

In terms of hydropower revenues, small and moderate installations of FPV provoke only minor revenue-losses. These losses quickly increase (up to 30%) for large installations because of the more stringent minimum volumes that imply losing valuable hydropower flexibility.

When combining both aspects, the case study gave evidence that

FPV should ideally be sized to about 40 to 60% of the lake's surface. In that range, the algal concentrations are kept within recommended concentrations without incurring in revenue losses. These numbers are specific to the shape and conditions of the water body.

As future steps, exploring with more detail the operation and synergies from a combined solar-hydropower plant is proposed. Furthermore, the spatial modeling of FPV (and their cast shadows) could be improved, that together with more attention on different algal taxa, could reveal more details on foodchain impacts. Overall, the approach used in this work is relevant for decision-makers from the energy sector and ecology that are looking to develop an effective design concept for the deployment of floating solar modules.

#### CRedit authorship contribution statement

**J. Haas:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Project administration. **J. Khalighi:** Data curation, Formal analysis, Investigation, Writing - original draft. **A. de la Fuente:** Conceptualization, Methodology, Supervision, Writing - review & editing. **S.U. Gerbersdorf:** Formal analysis, Writing - review & editing, Supervision. **W. Nowak:** Conceptualization, Writing - review & editing, Funding acquisition. **Po-Jung Chen:** Software, Data curation.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgments

The authors thank the support of the German Academic Exchange Service (DAAD), the German Research Foundation through the grant DFG-NO 805/11-1, and the Chilean Council of Scientific and Technological Research (CONICYT/FONDAP/15110019).

#### References

- Trapani K, Millar DL. Proposing offshore photovoltaic (PV) technology to the energy mix of the Maltese islands. *Energy Convers Manage* 2013;67:18–26.
- World Bank Group, ESMAP, and SERIS, “Where sun meets water - floating solar market report,” Washington D.C., 2018.
- REN21, *Renewables 2019 - Global Status Report*. Paris: REN21 Secretariat; 2019.
- Taboada MEE, Cáceres L, Graber TAA, Galleguillos HRR, Cabeza LFF, Rojas R. Solar water heating system and photovoltaic floating cover to reduce evaporation: experimental results and modeling. *Renew Energy* 2017;105:601–15.
- Ho CJ, Chou W-L, Lai C-M. Thermal and electrical performance of a water-surface floating PV integrated with a water-saturated MEPCM layer. *Energy Convers Manage Jan.* 2015;89:862–72.
- Kougias I, et al. The potential of water infrastructure to accommodate solar PV systems in Mediterranean islands. *Sol Energy* 2016;136(2016):174–82.
- Farfan J, Breyer C. Combining floating solar photovoltaic power plants and hydropower reservoirs: a virtual battery of great global potential. *Energy Procedia* 2018;155:403–11.
- Choi Y, Lee N, Lee A, Kim K. A study on major design elements of tracking-type floating photovoltaic systems. *Int J Smart Grid Clean Energy* 2013;3:70–4.
- Ranjbaran P, Yousefi H, Gharehpetian GB, Astaraei FR. A review on floating photovoltaic (FPV) power generation units. *Renew Sustain Energy Rev* 2019;110(April):332–47.
- Haas J, et al. Sunset or sunrise? Understanding the barriers and options for the massive deployment of solar technologies in Chile. *Energy Policy* 2018;112:399–414.
- Rahmann C, Mayol C, Haas J. Dynamic control strategy in partially-shaded photovoltaic power plants for improving the frequency of the electricity system. *J Clean Prod* 2018;202:109–19.
- Cazzaniga R, Rosa-Clot M, Rosa-Clot P, Tina GM. Integration of PV floating with hydroelectric power plants. *Heliyon* 2019;5(6):e01918.
- Anindito Y, Haas J, Olivares M, Nowak W, Kern J. A new solution to mitigate hydropeaking? Batteries versus re-regulation reservoirs. *J Clean Prod* 2018;210:477–89.
- Li W, Guo Y, Fu K. Enclosure experiment for influence on algae growth by shading light. *Procedia Environ Sci* 2011;10(PART B):1823–8.
- Redón Santafé M, Torregrosa Soler JB, Sánchez Romero FJ, Ferrer Gisbert PS, Ferrán Gozálviz JJ, Ferrer Gisbert CM. Theoretical and experimental analysis of a floating photovoltaic cover for water irrigation reservoirs. *Energy* 2014;67:246–55.
- Sahu A, Yadav N, Sudhakar K. Floating photovoltaic power plant: a review. *Renew Sustain Energy Rev* 2016;66:815–24.
- Vila I, Contreras M, Montecino V, Pizarro J, Adams DD. I/, “Rapel: A 30 years temperate reservoir. Eutrophication or contamination?”. *Spec Issues Adv Limnol* 2000;55:31–44.
- Haas J, Cebulla F, Nowak W, Rahmann C, Palma-Behnke R. A multi-service approach for planning the optimal mix of energy storage technologies in a fully-renewable power supply. *Energy Convers Manage* 2018;178:355–68.
- Hodges B, Dallimore C. “Estuary, Lake and Coastal Ocean Model: ELCOM v2. 2 User Manual,” 2010.
- Cole T, Wells S. CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.1. Department of Civil and Environmental Engineering. Portland State University., 2003.
- Edelvang K, Kaas H, Erichsen AC, Alvarez-Berastegui D, Bundgaard K, Jørgensen PV. Numerical modelling of phytoplankton biomass in coastal waters. *J Mar Syst* 2005;57(1–2):13–29.
- Rossel V, de la Fuente A. Assessing the link between environmental flow, hydropeaking operation and water quality of reservoirs. *Ecol Eng* 2015;85:26–38.
- Carpentier D, Haas J, Olivares MA, de la Fuente A. Modeling the multi-seasonal link between the hydrodynamics of a reservoir and its hydropower plant operation. *Water* 2017;9(6):367.
- Ibarra G, de la Fuente A, Contreras M. Effects of hydropeaking on the hydrodynamics of a stratified reservoir: the Rapel Reservoir case study. *J Hydraul Res* 2015;53(6):760–72.
- Hodges B, Dallimore C. “Estuary, lake and coastal ocean model: ELCOM v2.2 science manual.” Centre for Water Research, University of Western Australia, 2006.
- Shamshirband S, Jafari Nodoushan E, Adolf JE, Abdul Manaf A, Mosavi A, Chau K. Ensemble models with uncertainty analysis for multi-day ahead forecasting of chlorophyll a concentration in coastal waters. *Eng Appl Comput Fluid Mech* 2019;13(1):91–101.
- GAMS Software GmbH, “GAMS.” 2017.
- IBM, “IBM ILOG CPLEX Optimization Studio.” 2018.
- Muñoz-Ramírez CP, Victoriano PF, Habit E. Inter-basin dispersal through irrigation canals explains low genetic structure in *Diplomystes cf. chilensis*, an endangered freshwater catfish from Central Chile. *Limnologia* 2015;53:10–6.
- Chile's Independent System Operators (CDEC-SING and CDEC-SIC), “Statistics of inflows,” 2016. [Online]. Available: <https://sic.coordinadorelectrico.cl/informes-y-documentos/fichas/estadistica-de-caudales-afuentes/>. [Accessed: 10-Oct-2016].
- Coordinador Eléctrico Nacional (Chile's Power System Operator), “Public information system,” 2017. [Online]. Available: <https://www.coordinadorelectrico.cl/sistema-informacion-publica/>. [Accessed: 08-May-2017].
- World Health Organization, “Guidelines for safe recreational water,” *Environments*, vol. 2, pp. 3505–3518, 2006.
- de la Fuente A, Niño Y. Pseudo 2D ecosystem model for a dendritic reservoir. *Ecol Modell* 2008;213(3–4):389–401.
- Pizarro J, Vergara PM, Cerda S, Briones D. Cooling and eutrophication of southern Chilean lakes. *Sci Total Environ* 2016;541:683–91.
- Guisández I, Pérez-Díaz JI, Nowak W, Haas J. Should environmental constraints be considered in linear programming based water value calculators? *Int J Electr Power Energy Syst* 2020;117:105662.
- Alizadeh MJ, Kavianpour MR, Danesh M, Adolf J, Shamshirband S, Chau K-W. Effect of river flow on the quality of estuarine and coastal waters using machine learning models. *Eng Appl Comput Fluid Mech* 2018;12(1):810–23.
- Chang N-B, Wanielist M, Daranpob A. Filter Media for nutrient removal in natural systems and built environments: II—design and application challenges. *Environ Eng Sci* 2010;27(9):707–20.
- Departamento de Geofísica Universidad de Chile, “Explorador Solar,” 2017.
- Cordero RR, et al. The solar spectrum in the Atacama desert. *Sci Rep* 2016;6:22457.
- International Energy Agency, *Energy Policies Beyond IEA Countries: Chile* 2018. IEA Publications, 2018.
- Linacre ET. Data-sparse estimation of lake evaporation, using a simplified Penman equation. *Agric For Meteorol* 1993;64(3–4):237–56.