



A coupled hydrodynamic biological model for cyanobacteria dynamics in reservoirs

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Abstract

The potentially harmful phytoplankton bloom is a world wide problem that became frequent in the last decade. *Microcystis aeruginosa* is a toxic cyanobacterium that proliferates frequently in reservoirs deteriorating their water quality. Hence, a monitoring and warning system to forecast the risk of cyanobacteria proliferation became essential for lake managing. For that purpose, a one dimensional hydrodynamic (DYRESM) model coupled to an ecological model (CAEDYM) has been applied to simulate the growth of cyanobacteria colonies found in a French reservoir. As primary results the model was able to follow the trend of the cyanobacteria dynamics in the reservoir.

Keywords

Cyanobacteria; management; modelling

INTRODUCTION

Lakes and reservoirs are used for many purposes to complete human needs such as: drinking, agricultural irrigation, industrial and cooling water supply, sports or commercial fisheries, recreation and navigation. Reservoirs are often constructed for the specific purposes of flood control, power generation, agricultural irrigation, industrial and cooling water supply, sports or commercial fisheries, recreation, navigation and mostly for drinking purpose when the underground water are unsuitable or insufficient.

Phytoplankton is microscopic, single-celled photosynthetic plants that use chlorophylls and carotenoids to absorb light for photosynthesis. The name "phytoplankton" consists of two Greek words meaning "plant" (phyto) and "wanderer" (plankton) meaning a collective of organisms that are adapted to spend part or all of their lives in apparent suspension in the open water of the sea, lakes, ponds and rivers . Cyanobacteria are an important component of the pico-phytoplankton in both marine and freshwater systems. They could be unicellular or colonial, lacking membrane bound plastids . Pigmentation of cyanobacteria includes chlorophyll a, blue and red phycobilins (phycoerythrin, phycocyanin, allophycocyanin, and phycoerythrocyanin), and carotenoids (Barasanti and Gualtieri 2006; Reynolds 2006).

Protection of freshwater resources is of great importance. Reservoir water problems are either quantitative or qualitative. Karaoun reservoir (Lebanon) and Grangent reservoir (France) are important reservoirs that suffer from qualitative problem caused by harmful cyanobacteria in spring and summer period.

Microcystis aeruginosa is the toxic cyanobacteria species that are frequent in these reservoirs, this cyanobacteria perturbs the drinking water supply, agriculture, swimming and energy production. They are colonial species that are common in nutrient enriched fresh water with low salinity.

Microcystis aeruginosa is characterized by spherical cells grouped in colonies with uniform mucilage. The colonies have many different forms: they can be spherical, cylindrical, entire or lobed and sometimes perforated (Bourrelly 1985). Colony size can reach several centimetres, while the size of a cell is between 0.8 and 10 microns (Leitão and Couté avril 2005).

In Lake Grangent, the local authority needs simple tools for early warning of phytoplankton proliferations. Hence, the Proliphyc research project was created, consisting of high frequency measurements by an autonomous wireless buoy, used as inputs for a model performing automatic forecasts of phytoplankton dynamics.

Water quality models became a beneficial and essentially needed after the spread of eutrophication problem in many world reservoirs (Forsberg 1987; Canfield and Hoyer 1988). These models range from zero dimensional models to three dimensional models. DYRESM-CAEDYM (DYCD) is a one dimensional model that is suitable for numerical modelling of small and medium sized reservoirs, as in the case of Grangent and Karaoun reservoirs where the horizontal variation are less important than the vertical variation in the water body.

The objective of the thesis is to understand the physical determinants of phytoplankton blooms in the Karaoun reservoir, that represents a typical example of water storage in Lebanon and Mediterranean countries. For achieving this objective the following tasks will be performed: (1) to verify the ability of DYCD to simulate cyanobacteria dynamics; (2) to build a reliable database, gathering the existing data and performing field surveys for completing the data set; (3) to model Karaoun's thermal and biogeochemical functioning and (4) to provide recommendations for water management of the dam.

The predictive capabilities of an ecological model depend greatly on the accuracy and availability of data for input to the model. In order to validate the model, experimental measurements had to be performed regularly to provide all the input data needed for DYRESM-CAEDYM functioning.

The first objective of the thesis, presented in this paper, is to verify if the one-dimensional deterministic DYCD model has the ability to perform short-term simulations of cyanobacteria dynamics. For that purpose, we applied DYCD to the Grangent reservoir where the PROLIPHYC monitoring and warning system was implemented. The Proliphyc system is an autonomous buoy that performs meteorological measurements and includes profilers with underwater sensors. Measured data are transmitted daily by GPRS to the onshore laboratory to be treated and used by DYRESM-CAEDYM to perform the simulations. Based only on buoy measurements, the cyanobacterial biomass has been simulated for the year 2010 after it has been validated for the year 2009. Achieving this work will provide a deep understanding of the modelling process.

MATERIAL & METHODS

Study sites

Grangent reservoir

Grangent reservoir (45.27°N; 4.15°E) located in Massif Central (France), in the upper part of Loire River, is a eutrophic reservoir that was created in 1957. Grangent is kept full in summer (Briand, Escoffier et al. 2009). It is used mainly for energy production, drinking and irrigation, in addition to bathing and nautical activities in summer (Latour, Salençon et al. 2007). The reservoir has a surface area of 365 ha with a length of 21 km, a maximum depth of 50m and a capacity of 57.4 MCM.

The average residence time for water varies from 16 to 32 days (Salençon 2004).

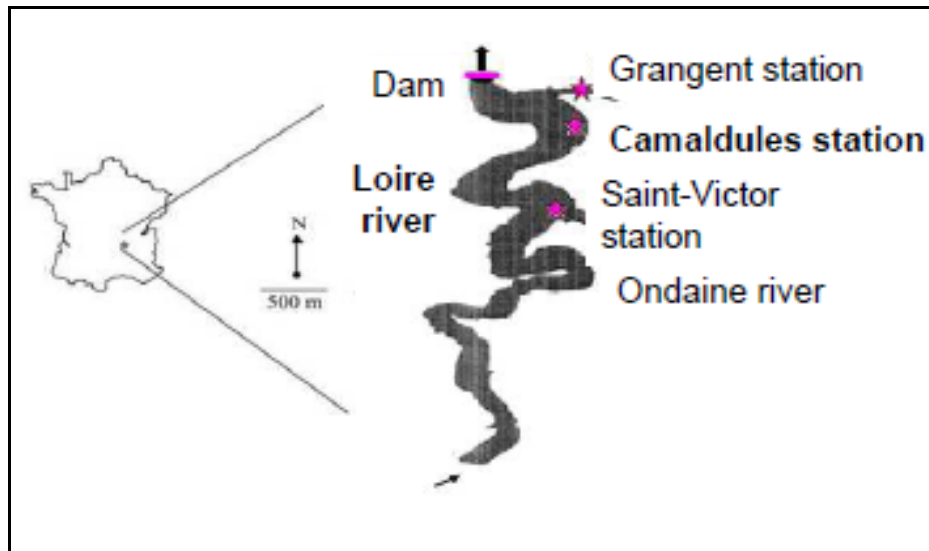


Figure 1 Grangent reservoir location in France

Karaoun reservoir

The Karaoun reservoir (33.34° N, 35.41° E) is the largest reservoir in Lebanon. It is located in Bekaa valley lying between the two Lebanese mountains ranges. It was constructed in 1965 (Shaban and Nassif 2007) to hold back the Litani River (170 km length), the longest and largest river in Lebanon (Saad, Kazpard et al. 2006). The reservoir is a touristic site with fishing and sport activities. It has a surface area of 12.3 Km² with a maximum depth of about 45 m and 860 meters elevation.

The dam is 60 m high and 1350 m long. It stores up to 220 million m³ (Catafago), of which 160 million m³ are used annually (for irrigation of 310 km² of farmland in South Lebanon and another 80 km² in the Bekaa valley, industry and hydropower) and 60 million m³ remain in storage over the dry seasons (Jurdi, Ibrahim Korfali et al. 2002).

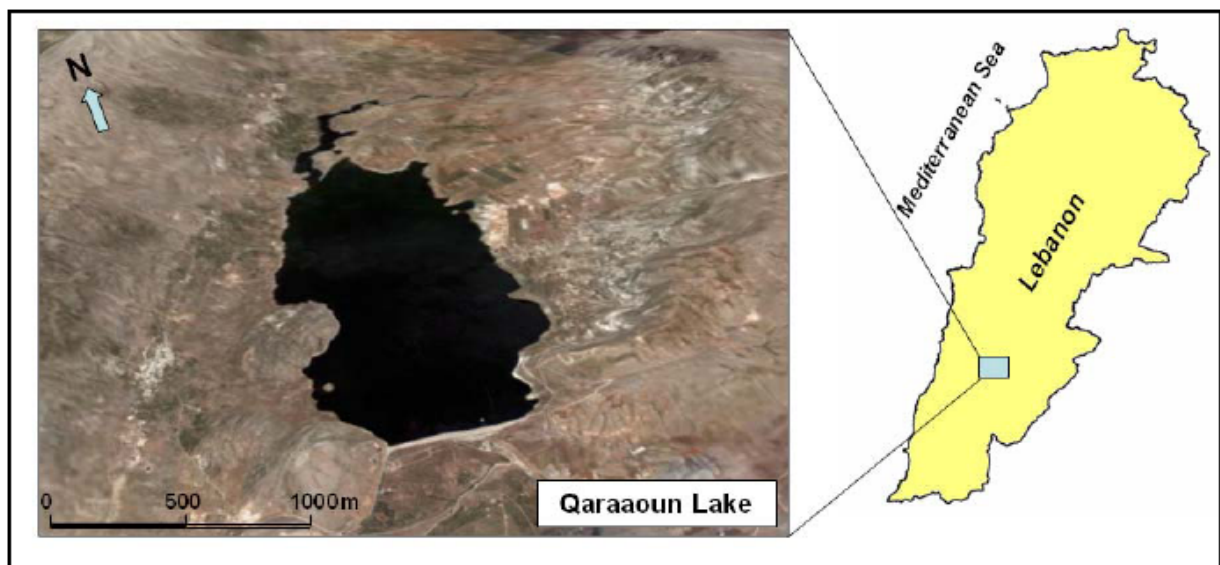


Figure 2 Karaoun reservoir location in lebanon (Shaban and Nassif 2007)

Measurement methods for Grangent

The predictive capabilities of an ecological model depend greatly on the accuracy and availability of data for input to the model. In order to validate the model, experimental measurements had to be performed regularly to provide all the input data needed for DYRESM-CAEDYM functioning. For that purpose the PROLIPHYC monitoring and warning system was created. It is an autonomous system that performs meteorological measurements and includes profilers with underwater sensors. Measured data are transmitted daily by GPRS to the onshore laboratory to be treated and used by DYRESM-CAEDYM to perform the simulation (Le Vu, Vinçon-Leite et al., 2010)

Table 1 PROLIPHYC monitoring and warning system

Variables	Time interval	Depth	Sensor name
Temperature Conductivity Pressure Dissolved oxygen Chlorophyll-a fluorescence	30 min	1 and 15 m in 2009; 1 and 5 m in 2010; 1 to 4 metric profiles a Day	Nke MPx multiprobe Aanderaa 3835 optode BBE-Moldaenke FluoroProbe100
Air temperature Pressure Humidity Wind speed Rain Solar radiation	30 min	1.5 m above water surface	Vaisala WXT520 Kipp&Zonen CMP11

Models

DYRESM-CAEDYM is the coupled temperature and water quality model that was used to model the thermal and biological processes occurring on Grangent. It was designed by the Centre for Water Research (CWR), Australia (Hamilton and Schladow 1997). This model will also be used for Karaoun reservoir.

DYRESM stands for Dynamic Reservoir Simulation Model. Its first application was on Wellington reservoir in Australia (Imberger 1978; Imberger 1981). Based on an assumption of one dimensionality (i.e. the variations in the vertical play a more important role than those in the horizontal direction), it simulates the vertical distribution of temperature, salinity and density in lakes and reservoirs (Yeates and Imberger 2003). The first application of this model was on Wellington reservoir in Australia.

CAEDYM stands for (Computational Aquatic Ecosystem DYnamics Model). It is a multivariable aquatic ecological model that was designed to be linked to a hydrodynamic model like DYRESM.. It includes comprehensive process representation of the C, N, P, Si and DO cycles, several size classes of inorganic suspended solids, and phytoplankton dynamics. However, in our case we focused only on the cyanobacteria simulation (Hipsey 2007).

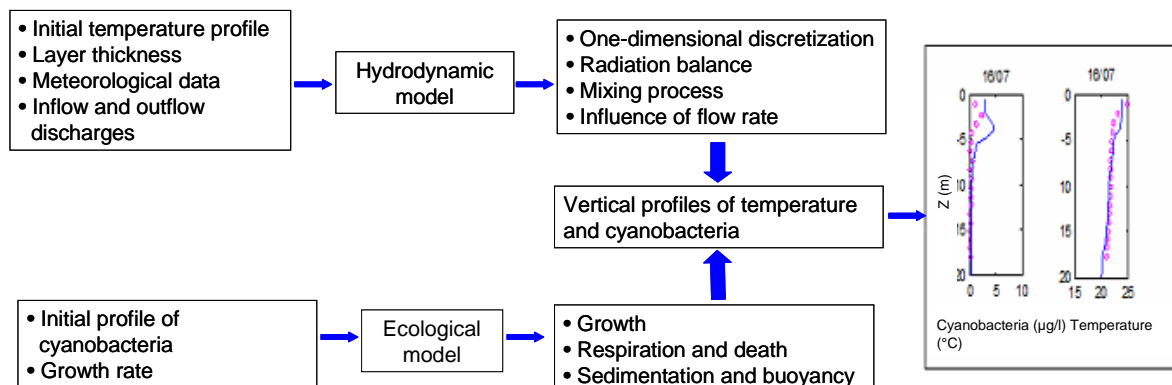


Figure 3: Representative schema of DYCD model run

RESULTS AND DISCUSSION

Field observations

Analyzing meteorological conditions is essential to notice the variables that affect the phytoplankton group we are intending to model. Water temperature and wind speed have been found to be the main environmental factors controlling the initiation of cyanobacteria growth in Grangent (see Figure 4). The cyanobacterial biomass started in 26/06 while phytoplankton bloom started earlier in 22/06. *Microcystis aeruginosa* is the cyanobacteria species that are frequent in Grangent, its growth is known to be weak below 15 °C and optimal above 25°C (Yamamoto; Okino 1973; Chu, Jin et al. 2007) this explains their absence before 26/06 where the temperature ranged between 15 and 20 °C.

Phytoplankton biomass was more affected by the wind speed that was high (above 5 m/s) before 22/06. Their biomass was enhanced later by the increase of water temperature (after 22/06).

Mixing and stratification affect the vertical distribution of cyanobacteria and phytoplankton in Grangent. Mixing was produced by the wind speed and the decrease in temperature at night causing a night mixing; this process can be observed by comparing the phytoplankton and cyanobacteria concentration at both 1m and 5m depths, where phytoplankton concentration at 1m decreases with a simultaneous increase of phytoplankton at 5m depth

The surface layer was mixed to 5m depth between 20/6 and 22/6 as a result of strong wind speed, this can be observed from the water temperature that was the same at both depths, suppressing the phytoplankton growth in that period, then stratification process became more established after 27/06, although it was interrupted by high wind speed in 01/07.

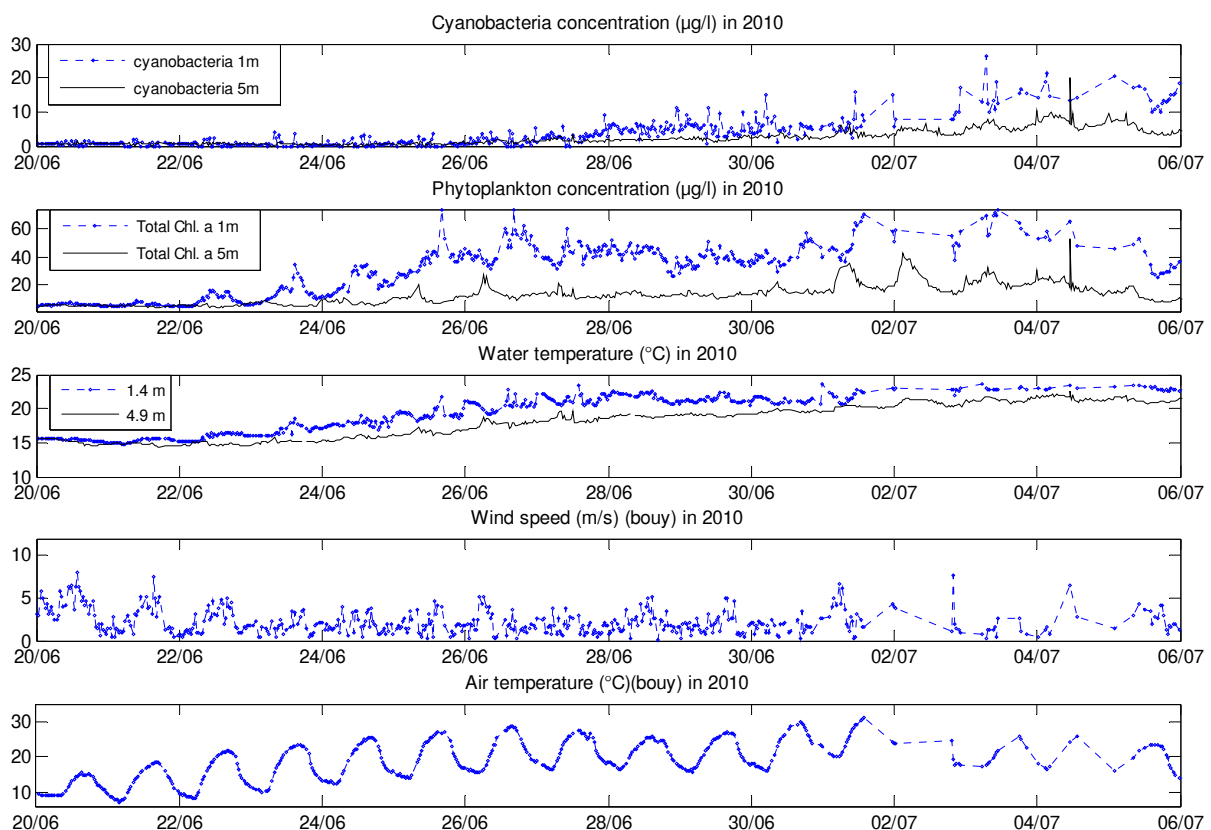


Figure 4 : Four variables: cyanobacteria concentration, phytoplankton concentration, water temperature, wind speed, air temperature.

Simulation

Simulations were performed over a period of 2 months ranging from 28th of June till 28th of August of the year 2010.

The inflow and outflow were neglected because we lacked these data. But since only the 1m-depth results are considered, it will not have a great effect since the river discharges at an average depth of 22 m thereby affecting the temperatures between 15 and 30m depth (Sellamie, 2010)

For temperature modelling, the layer thickness and the incident light attenuation were calibrated, where a value of 45% of light attenuation coefficient had fit the best for the 2010 simulation.

For biological simulation, the most important parameters were calibrated: maximum potential growth rate of cyanobacteria (1.5/day), light extinction coefficient (0.25), average ratio of carbon to chlorophyll a (180), optimal temperature (20 °C), and rate of light dependant migration velocity (0.3 m/hr). It is assumed that there is no variation in nutrient levels.

Result interpretation

The surface temperature varied between 20 and 24 °C, comparison between field and simulated temperature data are shown in figure 5. It is clear that the model has reproduced the variation in water temperature at 1 m depth showing a good model performance with an average mean squared error less than 1 °C.

In terms of cyanobacteria dynamics, although the field and simulated data show some discrepancy, the model was able to detect and follow both the increase and decrease of the cyanobacterial biomass.

Between the 8th and 18th of July, a breakdown of the buoy data transmission occurred and we lacked data at that duration. Therefore, a comparison between field data and model results cannot be performed for this period.

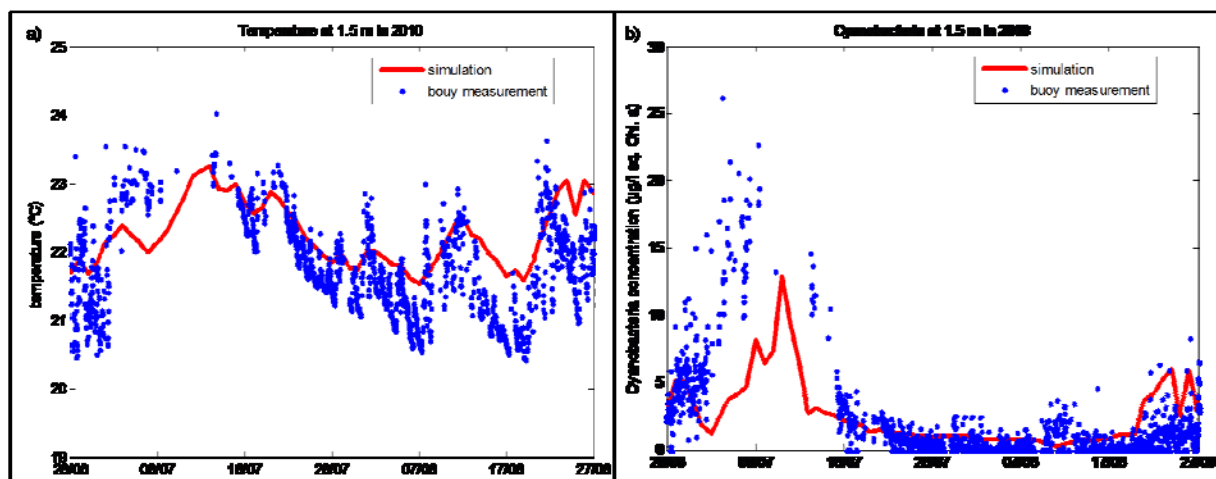


Figure 5 Results of the hydrodynamic model for 2010, a) temperature b) cyanobacteria

CONCLUSIONS AND PERSPECTIVES

The DYCD model has shown its capability to simulate cyanobacteria dynamics after it was applied successfully to Lake Grangent for 2 years (2009 and 2010). Until starting with field campaign and modelling of Karaoun reservoir we have a period of 2 months in which we are expecting to improve the simulation Grangent reservoir for the year 2010 by simulating two or more phytoplankton classes, modelling outside the summer period, testing the effect of management scenarios and modelling with the phosphorus cycle, to understand algal succession in the reservoir.

Grangent reservoir was a good practicing tool for DYCD, all the input data that were used for DYCD were of high precision and with high frequency measurements. This is not the case for Karaoun reservoir, where we have low frequency measurements and there are many input variables to be measured. The hydrological data will be supplied by the Litani River Authority (LRA). But, there is no data base about the cyanobacteria biomass and temperature profiles for Karaoun Lake and this should be created carefully and with high precision. Our next target will be planning for an organized field campaign that would be from the mid of August till the mid of October.

We have to propose and analyze management scenarios to limit the proliferation of cyanobacteria starting from the model. The treatment of meteorological, hydrological and physiochemical data with the analysis of management procedures of Karaoun reservoir will allow us to reach a deterministic model of phytoplankton growth. This will be achieved by studying:

- The influence of water withdrawal (for power production, irrigation...) on the dynamics of the phytoplankton in the reservoir.
- The role of winter rains on recolonization of sediment cyanobacteria on the water column.
- Influence of drought on the risk of algal blooms in Karaoun reservoir.

REFERENCES

- Barasanti, L. and P. Gualtieri (2006). General Overview. *Algae: Anatomy, Biochemistry, and Biotechnology*, Taylor & Francis Group: 15-27.
- Bourrelly, P. (1985). *Les algues d'eau douce: algues bleues et algues rouges*, N.Boubée.
- Briand, E., N. Escoffier, et al. (2009). "Spatiotemporal changes in the genetic diversity of a bloom-forming *Microcystis aeruginosa* (cyanobacteria) population." *Isme Journal* 3(4): 419-429.
- Canfield, J. D. E. and M. V. Hoyer (1988). "The eutrophication of Lake Okeechobee." In: G. Redfield (Editor), *Lake Reservoir Manage* (4: 91-100.).
- Catafago, s. *Restructing water in Lebanon: Litani River Authority facing the challenges of good water governance*. Lebanon, Faculty of engineering.
- Chu, Z. S., X. C. Jin, et al. (2007). "The effect of temperature on growth characteristics and competitions of *Microcystis aeruginosa* and *Oscillatoria mougeotii* in a shallow, eutrophic lake simulator system." *Hydrobiologia* 581: 217-223.
- Forsberg, C. (1987). "Evaluation of lake restoration in Sweden." *Scheiz. Z. Hydrol.* (49: 260-274).
- Hamilton, D. P. and S. G. Schladow (1997). "Prediction of water quality in lakes and reservoirs. Part I -- Model description." *Ecological Modelling* 96(1-3): 91-110.
- Hipsey, M. R. (2007). *Water quality modelling of west Seti hydropower reservoir using DYRESM-CAEDYM*. Australia, the University of Western Australia.
- Imberger, J., Patterson, J. C., Hebbert, B. & Loh, I. (1978). "Dynamics of reservoir of medium size." *Journal of Hydraulics Division ASCE* 104: 725-743.
- Imberger, J. P., J. C. (1981). «A dynamic reservoir simulation model DYRESM: 5. In *Transport Models for Inland and Coastal Waters* (ed. H. Fischer)." Academic Press, New York: 310-361.
- Jurdi, M., S. Ibrahim Korfali, et al. (2002). "Evaluation of Water Quality of the Qaraaoun Reservoir, Lebanon: Suitability for Multipurpose Usage." *Environmental Monitoring and Assessment* 77(1): 11-30.

- Latour, D., M. J. Salençon, et al. (2007). "Sedimentary imprint of *Microcystis aeruginosa* (Cyanobacteria) blooms in Grangent reservoir (Loire, France)." *Journal of Phycology* 43(3): 417-425.
- Le Vu, B., B. Vinçon-Leite, et al. (2010) High-frequency monitoring of phytoplankton dynamics within the European Water Framework Directive: Application to metalimnetic cyanobacteria *Biogeochemistry* 28.
- Leitão, M. and A. Couté (avril 2005). Guide pratique des cyanobactéries planctoniques du Grand Ouest de la France. Honfleur, Agence de l'eau Seine-Normandie.
- McDonald, C. P. and N. R. Urban "Using a model selection criterion to identify appropriate complexity in aquatic biogeochemical models." *Ecological Modelling* 221(3): 428-432.
- Okino, T. (1973). "Studies on the blooming of *Microcystis aeruginosa*. II. Rapid accumulation of phosphate by *Microcystis aeruginosa*." *FAC. SCI.* 8: 135-145.
- Reynolds, C. S. (2006). *Phytoplankton. Ecology of Phytoplankton*. M. Usher, D. Saunders, R. Peet and A. Dobson, Cambridge University Press.
- Saad, Z., V. Kazpard, et al. (2006). "Use of hydrochemistry and environmental isotopes to evaluate water quality, Litani River, Lebanon." *Journal of Environmental Hydrology* 14.
- Salençon, M. J. (2004). *Ecosystème de la retenue de Grangent, Présentation générale*, EDF R&D, Laboratoire Nationale d'hydraulique et environnement, Projet E3-98-03 I, rapport interne. Chatou: 18.
- Shaban, A. and N. Nassif (2007). "Pollution in Qaraaoun Lake, Central Lebanon." *Journal of Environmental Hydrology* 15.
- Yamamoto, Y. "Contribution of bioturbation by the red swamp crayfish *Procambarus clarkii* to the recruitment of bloom-forming cyanobacteria from sediment." *Journal of Limnology* 69(1): 102-111.
- Yeates, P. S. and J. Imberger (2003). «Pseudo two-dimensional simulations of internal and boundary fluxes in stratified lakes and reservoirs." *Intl. J. River Basin Management*: 297-319.

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