Standing on a roller-coaster: the challenge of source water quality management in eutrophic reservoirs under recurrent drought conditions

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Structural water deficit is common to all Mediterranean regions. Demand concentrates in summer under dry-arid conditions, while precipitation mainly occurs in winter. Water availability also exhibits large inter-annual fluctuations. In the Guadalquivir River Basin in Southern Spain, for example, annual availability ranges from 400 to more than 20000 Mm^3/yr, while yearly water demand remains stable at 3500 Mm^3/yr. In such a context of extreme hydrological variability, man-made reservoirs used for drinking water supply and/or irrigation, are strategic infrastructures.

Spain alone has more than 1600 man-made reservoirs, satisfying nearly 80% of the water demand. Almost 90% of these reservoirs are reported at risk of eutrophication. Spain, though, is not unique in facing eutrophication. This is a pervasive and global environmental problem, exacerbated by urbanization, industrialization, and intensified agriculture. Nutrient enrichment, mainly nitrogen and phosphorus, evidenced by the increasing frequency of algal (including in some cases cyanobacteria) blooms, the development of near-bottom hypoxia during summer stratification, and the subsequent mobilization of reduced substances (Figure 1), they all have dramatic consequences for drinking water sources, fisheries, and recreational activities. Most efforts in water quality management have been aimed at reducing nutrient loading from contributing watersheds, initially through the construction or upgrading of wastewater treatment plants for point-source control (as instructed in the European Council

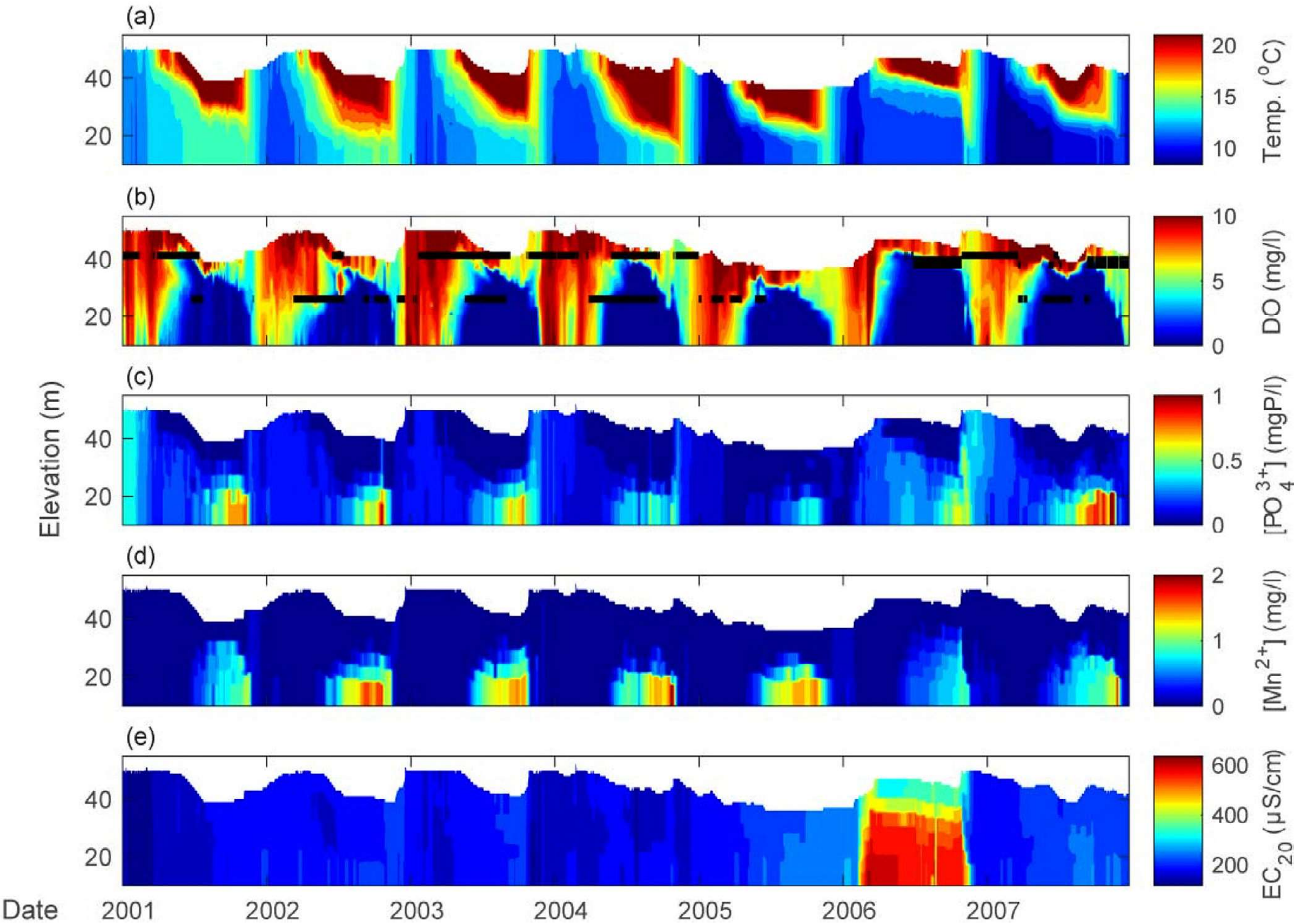

Figure 1 | Time series of (a) temperature, (b) dissolved oxygen, (c) phosphate, (d) dissolved manganese and (e) conductivity profiles from El Gergal reservoir long-term monitoring program, from 2001 to 2007 (both inclusive). Outtake levels are shown in subplot (b) as black dots. El Gergal is part of the drinking water supply system of Seville. During the 2004-2006 drought, high-conductivity water from the Guadalquivir River was pumped into the reservoir (note the high values of conductivity in e) to boost water levels (Source: Carmelo Escot, EMASESA).

Directive 91/271/EEC concerning urban waste-water treatment), and more recently through the adoption of best management practices aimed at controlling non-point source pollution from agricultural lands. While reducing nutrient loads from contributing watersheds is deemed the most efficient measure for lake restoration projects, this approach can take decades to be effective due to near-saturation levels of nutrients in the agricultural soils and/or the internal P loadings.

In-lake/reservoir methods, even if they fail to address the root cause of eutrophication, need to be implemented in the short term to mitigate water quality problems arising from nutrient oversupply. One of the most widely used approaches in man-made reservoirs consists of selecting the withdrawal level, and thus, selecting the water quality of a particular layer of the lake. The benefits of outtake selection to reduce the cost of chemicals required for water treatment are widely recognized among water utilities, but those benefits are rarely quantified and optimized. Selective withdrawal programs require that multi-level intakes are available and maintained. They also require a well-designed monitoring program that provides high-frequency uninterrupted time series data for decision-making and strategy evaluation. Nowadays, there is a growing number of selective-withdrawal programs being developed (Figure 2). Unfortunately, without in-depth cost/benefit analysis, the list of real-time data acquisition programs that are discontinued due to budget limitations grows. In fact, not many long-term monitoring programs exist in Spain. The few that exist primarily focus on the water supply systems of large urban areas and are operated by public or semi-private corporations. These are multiple-source systems, which may include two or more man-made surface water reservoirs with several outtake levels, and, even groundwater aquifers. In general, operational management for drinking water supply in eutrophic systems focuses on trying to avoid withdrawals from anoxic layers. As the number of reservoirs and outtake levels increases, so does the range of options available for source water quality control, and, the resilience of the system to eutrophication-related pressures. However, selecting a withdrawal level can significantly change stratification and redox conditions in the water column. Decisions concerning intake selection which are solely based on information from the current state of the reservoir could reduce treatment costs at present, but, they could also increase those costs later. Therefore, decision-making processes in selective withdrawal programs should incorporate cyber infrastructure based on real-time monitoring and the use of digital twins (data- or process-based eco-hydraulic models) capable of predicting the likely short-term evolution of reservoir water quality in response to any given perturbation (withdrawals) under a range of weather forecasts (an example of hydrodynamic forecasts for several alpine lakes in Switzerland can be found at https://www.alplakes.eawag.ch/).

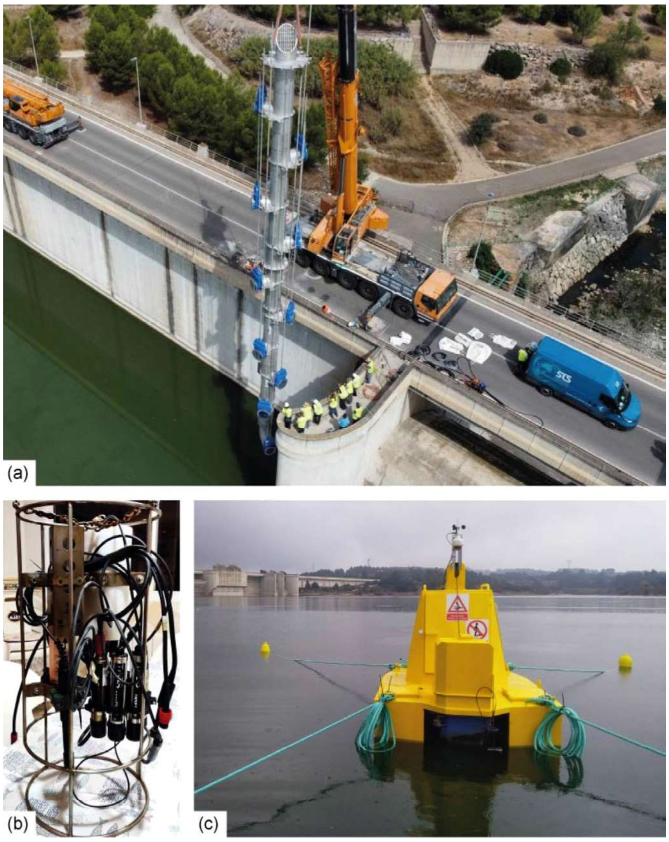

Figure 2 | Selective withdrawal project in Bellus reservoir in Valencia, Spain. (a) Deployment operation of the multiple-outtake structure (Source: Jucar River Water Management Agency). (b) Water quality sondes and (c) profiling system deployed near the dam (source, Agustín Monteoliva, ECOHYDROS, SL).

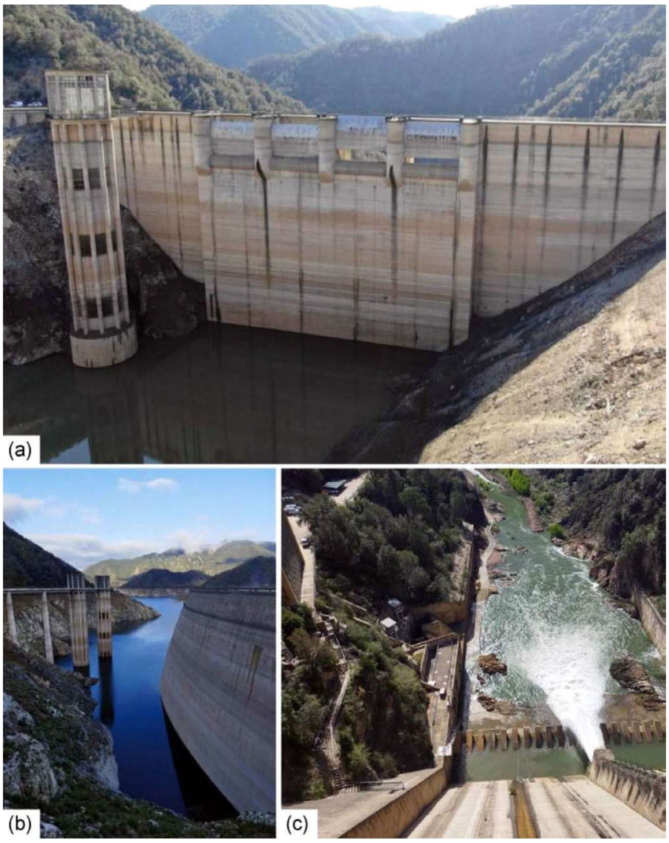

Figure 3 | Outtake structures in Sau reservoir (a) and Susqueda (b) in Catalonia, Spain, on 6 March 2024 and 19 April 2024, respectively. All outtakes in Sau are above the lake level, and the only discharge structure available is the bottom outlet. Only one of the four outtakes in Susqueda remains submerged. (c) Bottom outlet discharging from Sau reservoir to Susqueda reservoir on 12 April 2024. Discharges through hollow jet valves in the bottom outlets can be used to re-oxygenate deep water. Source: Juan Carlos García and Jose Javier Rodríguez-Subiza (ATLL).

Figure 4 | After three years of drought in northeastern Spain, the stored volume in Sau reservoir was only 16% of its capacity (150 hm3) in March 2024. This is one of the three reservoirs in Catalonia, Spain (Sau, Susqueda and El Pasteral) built in the Ter River which are part of the water supply system for the metropolitan area of Barcelona. Source: NASA.

Coping with eutrophication in drinking water supply reservoirs is, in general, a difficult task when trying to optimize source water quality and reduce treatment costs. But it becomes a serious challenge, under drought conditions, with the subsequent level drawdowns. Extreme hydrological variability in general, and recurrent droughts, in particular, are probably one of the most overriding stressors of water supply systems in Spain. Recent analyses of precipitation and evaporation records in the Iberian Peninsula over the past century have revealed the recurrent nature of drought episodes, characterized by varying intensity and duration, with the most severe episodes affecting vast areas of the Iberian Peninsula[1]. Under drought conditions, the occurrence of cyanobacterial blooms increases, oxygen levels decrease, and the range of options for source-water quality control shrinks. For instance, the outtake tower may sit above the lake level, so that only the bottom outlets/valves are available for discharge (Figure 3). Under those conditions, water utilities will attempt to maximize the number of outtakes in the system positioned away from the near-bottom anoxic layers. Upstream reservoirs can be drained in the winter, when the water column is well oxygenated, through bottom outlets to boost water levels downstream (Figure 4). Alternatively, if the necessary infrastructure is in place, water can be diverted or pumped into the reservoirs of nearby water systems (Figure 1e).

Streamflows in southern Spain have exhibited significant decreasing trends in the last 50 years, likely as a result of climate change, and droughts are expected to become longer, more severe and frequent. As drought-driven pressures on water systems increase, drinking water quality management will become a formidable challenge, and reservoir managers will have to resort to alternative approaches (do 'whatever it takes') to satisfy the drinking water demand. There is a large number of in-lake techniques, alternative to outtake selection, each with its own set of advantages and drawbacks in terms of cost, effectiveness and environmental impacts, that can be used for source water quality control, but remain largely unexplored in drinking supply reservoirs in Spain. Mechanical approaches[2], like hypolimnetic oxygenation or artificial mixing/destratification, which rely on altering mixing and thermal stratification, will require the expertise of hydraulic/environmental engineers and physical limnologists. They have been proved to be useful, but they can be expensive to implement and operate, and, hence, need to be carefully designed, closely monitored and evaluated. In particular cases, they may prove ineffective or even yield unexpected effects. These cases in particular (and not only the successful projects) should be well-documented and studied since they provide extremely important lessons for future endeavors. Furthermore, they should even be reanalyzed in light of new tools and concepts as they emerge. An example of such a revision exercise re-evaluates the field-scale performance of a bubble-plume oxygenation system installed in Amisk Lake, Canada, a two basin system, in 1990. This is a long, relatively narrow lake with two distinct basins. Oxygen diffusers were positioned at the deepest site of the north (N) basin and were operational from 1990 to 1993. Initial assumptions suggested that oxygen transfer into the south (S) basin would be hindered by the channel between the two basins; however, hypolimnetic oxygen injection increased DO concentrations both in the N and S-basins. Previous analysis, based on the interpretation of a spatially sparse experimental data set from 1991, using scaling arguments and simplified models of relevant processes, concluded that plume-induced circulation predominantly drove inter-basin transport, a concept even cited in textbooks. By contrast, more recent work based on the analysis and visualization of computer simulations conducted with a coupled plume-3D hydrodynamic lake model, and substantiated through an uncertainty analysis, suggested that inter-basin oxygen transport was largely driven by internal seiching[3]. Uncertainty analysis was considered a key component in the reanalysis exercise. While stakeholders typically seek quantitative and precise answers, as modelers, we are aware that our understanding of reservoir physics and biogeochemistry remains incomplete. Despite leveraging sophisticated approaches such as three-dimensional eco-hydraulic process-based modeling tools and/or artificial intelligence, uncertainty pervades our model predictions due to the stochastic nature of forcing and state variable data, but also because of the very own structure of the models in which complex processes are necessarily parameterized. Therefore, uncertainty must be explicitly included and quantified in the design, implementation, and, evaluation of water quality strategies, with its implications clearly communicated in project reports and forecasts. Such practices will definitely help stakeholders remain engaged in restoration projects, alleviating the sense of failure if the outcome differs from the expectations, and increasing the chances of success[4].

With increasing drought-related pressures on reservoirs, it is crucial to promote strategic thinking among water scientists, engineers, managers and stakeholders with a long-term vision, and foster the adoption of preventive rather than short-term reactive strategies for source water quality management. The current 'avoidance' strategy, based on epilimnetic/metalimnetic withdrawals, can be successful in reducing water treatment costs in the short term. For long-term management, however, there is an urgent need to further explore and analyze the applicability of existing restoration methods case-by-case with the aid of available modeling tools, to reduce the expenses associated with those methods, and, to incorporate and evaluate innovative and sustainable approaches. Few of the existing restoration strategies are aimed at reducing the legacy of P supply in the sediments, which otherwise perpetuates internal loadings and bottom hypoxia over the long term. The use of these strategies, based on sediment management[5] or hypolimnetic releases, aimed at flushing the legacy of nutrients existing in the reservoir sediments, should be further explored and considered so that the volume fraction of oxygenated water (usable for drinking purposes) stored in water supply systems increases.

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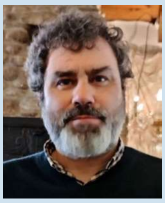

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