Martín Monerris, M.; Hernández Crespo, C.; Andrés Doménech, I.; Benedito Durá, V. (2020). Fifty years of eutrophication in the Albufera lake (Valencia, Spain): causes, evolution and remediation strategies. Ecological Engineering. 155:1-12. https://doi.org/10.1016/j.ecoleng.2020.105932

Fifty years of eutrophication in the Albufera lake (Valencia, Spain): causes, evolution and remediation strategies.

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Abstract

The water quality deteriorated in the middle of the 1970s in the Albufera lake, a shallow Mediterranean coastal lagoon in the east coast of Spain. In few years, the water changed from an oligotrophic status to hypereutrophic as the lagoon received sewage and agrochemicals, lacking adequate sanitation facilities. For more than 40 years, the lake was used as a wastewater treatment plant given the urban development in the surrounding area. It was not until the early 1990s, 20 years after the hypereutrophic state was reached, when the first sanitation facility protecting the lake was implemented: a perimeter intercepting sewer carrying out the sewage to a waste water treatment plant. This paper describes the different engineering solutions and tools implemented to improve the water quality in the Albufera lagoon. We describe the measures and their effects on the water quality as well as their limits. Those are sanitation solutions as sewers, wastewaters treatment plants, stormwater detention tanks, and nature based solutions as constructed wetlands that have been used in these years. In addition, the role of agricultural activity in the water balance (quantity and quality), the importance of sediments management and the use of water quality models in environmental engineering have been assessed. Evidences of the improvement of environmental quality are the decrease of mean clorophyll *a* concentration from 800 μg Chl *a* l^{-1} in 1980s to less than 100 μg Chl *a* l^{-1} currently observed, the increase of water transparency and the recovery of macrophytes within the lake or the presence of winterbirds which disappeared years ago.

Keywords

Eutrophication; Sanitation facilities; Constructed wetlands; Green infrastructures; Flushing; Sediments

1. Introduction.

The Albufera (Valencia, Spain) is a typical Mediterranean shallow coastal lagoon located within the Natural Park of *l'Albufera de Valencia*. As many others in the Mediterranean Sea, it was long time ago separated from the sea by a shoal, but artificial canals maintain current connectivity. Over time, natural and, mainly, anthropogenic factors have shaped the lake to what is known today. The original brackish lagoon has changed to a fresh water ecosystem nowadays because the last five centuries of intensive irrigation farming in its catchment. The open water surface has been reduced from more than 30,000 ha estimated in the Roman period to currently 2,433 ha because the natural silting and human pressure: in the XIX-XX centuries, farmers created new rice paddies filling water plots as polders (*Tancats*) with soil and mud. The natural hydrological functioning, with free flows from the lake to the sea, has also been changed because the lake is used as a reservoir for irrigating rice paddies. The lake is also vulnerable to silting: accumulations of sediments around one meter deep have already been found, and sediment dredging is a recurring issue among stakeholders.

The ecological status of the lake has seriously deteriorated since the 1970s because of different processes that are described hereinafter. The lake remains at hypertrophic status, with high phytoplankton populations, current annual mean of 100 µg Chl *a* l^{-1}, with peaks around 300 µg Chl *a* l^{-1}; with the predominance of cyanobacteria. Very low transparency and intense daily oscillations in pH and dissolved oxygen (DO) concentrations give rise to a dramatic impact on biodiversity. The most frequent inflows (1990/91-2009/20 period) are between 210 and 300 hm^3 yr^{-1} (60% of the time) and the mean hydraulic residence time (HRT) is 0.08-0.11 year (CHJ, 2017).

Despite of this, the Natural Park has still enough environmental value to be included in the Ramsar List of Wetlands of International Importance (1989); it is also a Special Protection Area and Natura 2000 site. Nevertheless, beyond the need of environmental protection, the main challenge of the Albufera environment is the management of its unique water system, developed during centuries, and the set of agro-ecosystems according with the Sustainable Development Goals (Jégou and Sanchis-Ibor, 2019).

Engineered solutions used in the Albufera have evolved in line with the techniques and paradigms of their time, from grey hydraulic/sanitation infrastructures in the twentieth century to more nature based solutions nowadays (Figure 1).

Fig.2. Restoring measures implemented in the Albufera of Valencia.

2. Sanitation networks. The Albufera as a wastewater treatment plant

The Albufera receives surface and subsurface flows from a 738 km^2 catchment basin (Mondría, 2010). In this area, 17 municipalities are less than 10 km from the west side of the lake. At the beginning of the twentieth century, these small agriculture-based villages managed theirs urban wastewaters at household level using individual seeping cesspits or discharging them directly to irrigation channels. Since the middle of that century, disconnection of cesspits to sewage networks and the growth of industrial activity and population (from 93,691 in 1950 to 281,563 inhabitants in 1980), extensively increased the wastewater volume produced. Unfortunately, the end of pipe was not a wastewater treatment plant (WWTP), but the closest irrigation channels, most of them discharging into the lake (Mondría, 2010).

Since then and until the end of the century, from a sanitary engineering point of view, the Albufera has been working as a facultative waste stabilization pond (Kayombo el al. 2010), where organic matter from sewage is removed but new organic matter is produced as algae. The main design parameters and operation of facultative ponds (1-2 m deep, 2-3 weeks HRT, chlorophyll *a* concentrations between 500 and 2000 µg Chl *a* l^{-1}, aerobic and anaerobic layers, warm Mediterranean climate) were fully met by the Albufera. In this way, without being aware of the environmental impact, a solution to wastewater treatment was found. The positive collateral effect was the preservation of the shoreline water quality, an important economic and tourism asset in the Valencia Region.

Those years were a bad example of urban planning: installing sewage sewers did not guarantee the environmental protection if the wastewater treatment facility was not implemented at the same time. In rural areas where irrigation is predominant, there is a temptation to discharge the wastewaters into irrigation channels assuming an unconscious infinite self-purifying capacity. Therefore, the first lesson learnt from the Albufera case is evident for any with the slightest knowledge about sanitation: the sewage sewer system must always be installed with an adequate treatment.

3. Sanitation solutions (I). Perimeter intercepting sewer *vs*. wastewater treatment plants

The first solution designed in the 1980's and implemented in the 1990's was a conventional sanitary engineering infrastructure: a perimeter intercepting sewer receiving flows from a large number of branch sewers from 13 municipalities around the lake and conducting wastewater to the *Valencia-Pinedo* WWTP (852,799 p.e.). This intercepting sewer is a concrete 11 km long pipe ranging from 800 mm to 1800 mm inner diameter.

Its maximum hydraulic capacity is about 5 m^3 s^{-1}. The alternative solution based on several WWTPs distributed along the system was not considered at those times because the lack of and experience in designing and operating nutrient removal treatment systems in Spain.

The intercepting sewer system expected to have very positive effects on the Albufera water quality by reducing pollution from urban areas into the lake. Jucar River Basin Administration (CHJ), the competent authority in the catchment, quantifies the decrease of total phosphorus (TP) loads from 150-320 to 70-120 t P yr^{-1} in first half of the 1990's decade with the sewer system implementation (CHJ, 2003). This reduction has been confirmed by other researchers (Romo et al., 2005), showing that the perimeter intercepting sewer reduced 77% of TP (from 18 to 4 g P m^{-2} yr^{-1}) and 24% of total nitrogen discharged (from 324 to 247 g N m^{-2} yr^{-1}), mainly from urban and industrial sewage produced from the northern and western part of the lake.

Nevertheless, this infrastructure was not efficient enough to improve by itself the trophic status of the lake. Chlorophyll *a* concentrations and turbidity remained high because other sources of nutrients were still active.

In addition, combined sewer overflows (CSO) during rainfall episodes were more frequent than expected. The system was designed to collect wastewater but after years and years, sewer networks became mainly combined. Under frequent rainfall episodes, the system capacity is exceeded and overflows occur also into the irrigation network and, finally, are conducted into the lake. Besides, the imperviousness ratio of the 1,700 ha tributary catchment of the sewer has significantly increased in the last decades: in the 1980's, more than 50% of the catchment was agricultural land; at the beginning of the 21st century, almost 70% of the catchment were urban and industrial areas (1,200 ha). Nowadays the area is mainly fully developed. Uncontrolled connexions between sewers and the irrigation network because to sometimes poor planned urban growth, worsen the problem.

The intercepting sewer system provided direct benefits to the lake. Nevertheless, the system became obsolete because of the rapid and massive urbanisation of the catchment. Thus, the sanitary system was not able to cope successfully with pollution reduction into the lake. New additional solutions were required to increase the system efficiency.

4. Sanitation solutions (II). Improving performance of the wastewater treatment plants

It is a basic concept in aquatic ecosystems that the change in any of the growth limiting factors (light, temperature and nutrients), modifies the growth pattern of phytoplankton, disturbing the food web. In the case of the Albufera, as many others, phosphorus is considered nutrient limiting, so phosphorus removal processes must be included in all the WWTPs discharging into to the Albufera basin. A question of greatest interest is about the TP concentration for the discharges from WWTPs. In the EU, nutrients load limits are established using concentrations as key parameters: according with Directive 91/271/CEE, 1.0 or 2.0 mg P l^{-1} (depending on population served) are the target outflow concentrations. Many experts consider this target concentration too high for an ecosystem like the Albufera (Typsa, 2004) and the future objective should be that all incoming waters have TP concentrations below 0.1 mg P l^{-1}. As a first step, the CHJ has set the standard value of 0.6 mg P l^{-1} for all WWTPs located in the Albufera area. In accordance with this, four WWTPs with 235,077 p.e. (EPSAR, 2018) improved theirs nitrogen and phosphorus removal systems, obtaining effluent TP concentrations between 0.30 and 0.49 mg P l^{-1} (2018 annual mean).

Additionally, in order to explore complementary solutions, the use of vertical flow constructed wetlands (VFCW) with active substrate was studied in 2010-2012. The VFCW is described in Martin et al. (2013). The inflow comes from *Valencia-Pinedo* WWTP, after a coagulation/flocculation and filtration treatment, leading to TP annual (2011/12) mean concentration of 0.635 mg P l^{-1}. With a surface of 2,530 m^2, the VFCW was able to treat 115,267 m^3 yr.$^{-1}$ in two daily cycles of 157.9 m^3 each (0.134 m^3 m^{-2} d^{-1}), obtaining an annual mean outflow concentration of 0.152 mg P l^{-1} (n=138). The sorbent used was 3% iron oxide in sand.

5. Urban runoff. Stormwater detention tanks

Stormwater detention tanks are useful conventional drainage infrastructures to avoid polluted overflows into the environment from densely urbanized areas, even under scenarios of climate variability (Andrés-Doménech et al., 2012). During the first decade of the XXI century, several studies were developed to complete the perimeter intercepting sewer system with stormwater tanks, in order to reduce CSOs frequency and pollution loads into the lake (TYPSA, 2004; Acuamed, 2007).

The first step consisted of characterizing pollutant loads and patterns from CSO occurring into the environment. Several automatic and manual sampling campaigns were developed during rainfall events in 2006 (Acuamed, 2007). As mentioned before, there is an historical problem of inter-connection between sewer networks and the irrigation system within the Albufera environment. The development of the intercepting sewer system led to improve disconnection between the sewer network and irrigation channels, promoting the construction of new sewer branches from urbanized areas into the main perimeter sewer. Irrigation channels are recovering their former irrigation purpose but, unfortunately, many of them are still receiving CSO. Identification of how much runoff is directed to irrigation channels or sewers is a hard task, because of the system complexity and the lack of data. Works aiming at a better understanding and characterization of the system are still ongoing nowadays, led by the regional government.

The analysis of sampling data led to the definition of four different water quality patterns: two for irrigation channels receiving runoff and two for CSO from the sewer network. For each one, the first pattern characterises the first flush period of the hydrograph and the second one the rest of the event. The first flush period depends on the catchment response to rainfall; in this specific case, it corresponds to the first three hours of the event. Table 1 shows concentrations of the main water quality variables used thereafter for pollution loads estimations.

Table 1

Water quality patterns calculated for every runoff type in the Albufera catchment.

Pollutant	**Irrigation channels**		**Combined sewer overflows**	
	First flush	**After the first flush**	**First flush**	**After the first flush**
BOD_5 (mg l^{-1})	66.0	10.0	160.0	140.0
COD (mg l^{-1})	135.0	24.0	340.0	290.0
TSS (mg l^{-1})	120.0	61.0	140.0	94.0
TKN (mg N l^{-1})	10.0	8.5	45.0	39.0
TP (mg P l^{-1})	2.5	0.9	5.7	5.0
NO_3^- (mg N l^{-1})	5.0	11.0	2.0	2.0

The optimum number of tanks was found to be seven, with detention volumes varying between 5,000 and 25,500 m^3. The total detention volume of the system was 121,000 m^3, which represents a detention ratio of 100.8 $m^3 ha^{-1}$. According to international standards, this ratio per impervious area is high, based on the high pollution hazard from the catchment and the high vulnerability of the receiving environment (Andrés-Doménech et al., 2010; Hermoso et al., 2018). This design ratio allows an average reduction of annual overflows into the lake from 16 (without tanks) to 4 (with tanks). In terms of average annual volume discharged, the reduction is from 1.85 $hm^3 yr^{-1}$ to 0.83 $hm^3 yr^{-1}$, i.e. a 55% reduction. These design parameters were obtained from the 1938-2002 rainfall series in Valencia and an estimated initial abstraction of 7.2 mm in the catchment.

Thereafter, the designed system response was modelled for an average year (1985 according to the total rainfall amount and its distribution throughout the year) to estimate the system efficiency in terms of CSO frequency reduction, CSO volume reduction and, especially, detention efficiency of pollutant loads (Mondría, 2010). During this year, 24 runoff events were recorded and only four would have produced overflow into the environment. The system efficiency was 83% in terms of detention frequency (Figure 2). As the most harmful pollutant concentrations correspond to the first flush and, thus, to small and frequent events, a complete detention of this episodes ensures a great benefit for the environment. In volumetric terms, the tanks detain 58% of the total annual runoff. Regarding water quality, simulations conclude that pollution loads spilled into the lake are reduced between 50% and 62%. The lowest reduction corresponds to NO_3^- whereas the highest is for TSS. Focusing on BOD_5 the reduction (58%) represents around 5,500 equivalent inhabitants. Other authors have reported similar reductions for this thank size ratio (de Paola and de Martino, 2013).

Fig. 2. Simulation of detained and spilled volumes (m^3) in the stormwater tanks during the average year 1985.

During the design of the stormwater tanks, the management of collected water was an issue. One of the first proposals was to empty the tanks into the lake after a coagulation/flocculation process into them. Authorities were reluctant with this solution mainly because of its performance and maintenance costs. Then, the system was designed to conduct the retained volumes to the *Valencia-Pinedo* WWTP, thus losing any opportunity for water reuse on site. The tank emptying operation rules are not still defined because it depends on both perimeter intercepting sewer and WWTP capacities.

At present, the seven tanks are built but still waiting to be operational because of technical and institutional issues, so their impact on the Albufera water quality improvement is still unknown. After almost 15 years from the system design, our present understanding of urban drainage would have led to other solutions, surely combined with nature-based infrastructures to improve the system efficiency and resilience.

6. Rice paddies: source or sink of nutrients?

Approximately, 12,408 ha of rice paddies are surrounding the lake by North, West and South (Mondría, 2010). Irrigation of paddies is the most significant element in the water balance of the Albufera. The traditional flood irrigation system produced both surface runoff and subsurface drainages, also known as return flows. They have been historically high; in fact, they were responsible of lake "sweetening" some centuries ago (Sanchis-Ibor et al., 2008). Since the 1980's the return flows towards the Albufera have suffered a growing decrease from 250-400 to less than 50 hm^3 $yr.^{-1}$ (CHJ, 2003). As they are responsible of 70% of inflows into the lake, this increases HRT thus contributing to eutrophication. Since 2001, 15000 ha of fruit trees and vegetable crops around the rice paddies are modernizing their irrigation system from flooding to trickle irrigation, so the returned flows are not currently as high as 30 years before, but they remain the main inflows.

There are two periods where paddies are flooded: between middle May to middle September to allow rice growing, and from November to February (winter flooding named *Perelloná*). Winter flooding is an old traditional agronomic management practice which still continues today, but mainly for environmental reasons (area for wintering birds, growing of zooplankton...) and hunting. In winter flooding, water surface is increased by three times and at least 20 hm^3 extra flow is needed, so it depends on water availability every year. At the end of winter flooding, approximately 18 hm^3 flow through the Albufera to the sea in two months. As can be seen from the previous sections, during many years, some paddies were irrigated with a mixture of river freshwaters and sewage in proportions depending of the development of sanitation infrastructures in each municipality. Since then, the idea that rice paddies functioning as a Land Wastewater Treatment System became popular, with some justification. Fortunately, civil works like the perimeter intercepting sewer and WWTPs have reduced the sewage loads and the role of paddies in water treatment is disappearing. Nowadays, paddies surrounding the lake, *Tancats*, are irrigated with water from it (eutrophic waters); closest paddies to Valencia city are irrigated with reclaimed treated effluents from *Valencia-Pinedo* WWTP; and the “highland” paddies, far from shores lake, are irrigated with natural freshwaters coming from Jucar river (Tous reservoir).

It is well known that exceeding P and N fertilizers can move, to some extent, from fields to waters producing diffuse pollution from agricultural areas, a worldwide problem. The Albufera is not an exception and diffuse loading from fields can be observed.

There are few studies about the direct effect of rice practices in water quality reaching the lake. According to a recent study (CEDEX, 2017), when reclaimed treated effluents are used in rice irrigation, some removal of N and P is observed: TN concentrations from 6.1 to 1.3 mg N l^{-1} and TP from 0.29 to 0.18 mg P l^{-1}. In growing period (middle May – middle September), the incoming nutrients are 6.12 kg P ha^{-1} and 110.73 kg N ha^{-1} while the outflow from paddies is 1.99 kg P ha^{-1} and 11.13 kg N ha^{-1}. These results have been confirmed by other studies (EPSAR, 2014), showing a decrease of TP from 1.62 to 0.45 mg P l^{-1} and from 38.8 to 4.82 mg N l^{-1} for total nitrogen.

However, when the irrigation water comes from natural freshwaters (Júcar river with TP concentrations around 0.05 mg P l^{-1}), input-output results change for TP: from 3.33 to 4.00 kg P ha^{-1}, showing that rice paddies are suppliers of TP to the lake. As with reclaimed waters, TN is reduced but to a lesser extent: from 78.41 to 64.38 kg N ha^{-1}. The conclusion is that during rice growth, TP is just reduced if the irrigation waters have high TP concentrations. Regarding TN, concentrations are always reduced but much less if the inflows are low concentrated.

Another evidence of nutrient fluxes from paddies is that nitrogen concentrations in incoming waters to the lake are quite variable depending on the rice farming stage. As an example of irrigation channel, Figure 3 represents TN concentration in *Acequia Puerto de Catarroja* since 2009 to 2020. Concentration ranges from 1.00 to 21.45 mg N l^{-1}, with a mean value of 4.81mg N l^{-1} (Std Dev 3.80, n= 169). The annual trend shows two major peaks in spring and winter, related to the water flows from paddies.

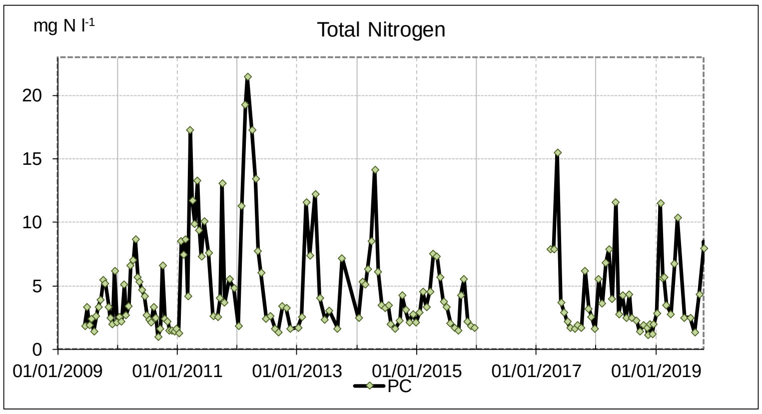

Fig.3. Total Nitrogen concentration in *Acequia Puerto de Catarroja* since 2009 to 2020.

Fertilising control is one of the solutions to reduce diffuse pollution but its implementation is fraught with difficulty due to socioeconomic aspects. Recently, small demonstrative projects introducing organic rice production have been successfully set in place (AVA-ASAJA, 2018). Switching from traditional intensive rice production to an organic modality would have a formidable positive impact over the Natural Park as a whole, giving rise to an agro-ecosystem rich in biodiversity.

The role of winter flooding in the water quality is starting to be studied. A recent monthly monitoring has been performed by the authors during the last winter (2019-2020) in one rice field fed with eutrophicated water from the lake. The results showed that TP was reduced from the inlet to the outlet on average by 17%, from 0.259 to 0.216 mg P l^{-1}. TN was reduced by 70% on average, from 3.97 to 1.18 mg N l^{-1}. Among nitrogen species, nitrite and nitrate were efficiently reduced, from 0.036 to 0.008 mg N l^{-1} (79%) and from 3.03 to 0.24 mg N l^{-1} (92%) respectively. Conversely, ammonium increased by 21%, from 0.104 to 0.126 mg N l^{-1}. These results indicated the occurrence of anoxic conditions, with a release of ammonium, and denitrification processes. The conclusion is that physicochemical variables in the paddies irrigated with lake waters are improved, mainly for nitrogen. There is a lack of information on the effect of paddies flooded with natural freshwaters from Júcar river in winter flooding.

7. Constructed wetlands

As previously explained, the current hydro-morphology of the Albufera is the result of human silting to gain paddies. Nowadays, the interface land-water is a sharp slope where depth goes quickly to 0.8-1.5 meters. Excluding the mouths of some gullies, there is no soft shores, so the establishment of vegetation and the spontaneous creation of new wetland habitats is rather difficult. The transformation of rice fields located on the shores to wetlands is in mind of many stakeholders for many years. From 2004, simultaneously to enhancements on WWTPs and stormwater detention tanks projects, the idea of a “green belt” arose. Promoted by Public Administration, 90 ha of rice fields were transformed into three medium size constructed wetlands (CW) between 2009 and 2011. CWs design and performance have been extensively described in Martin et al (2013), Hernández-Crespo et al (2017) and Rodrigo and Segura (2020).

The three CWs (*Tancat de la Pipa, TPCW, Tancat de Milia, TMCW, and Tancat de L'Illa, TLICW*) have different combinations of both Free Water Flow Constructed Wetlands (FWFCW) and Horizontal Subsurface Flow Constructed Wetlands (HSSFCW). All of them have a shallow lagoon located at the end of the system. The incoming water is eutrophic water from the Albufera and after flowing through the *Tancats*, water is returned to the lake. As wetlands are described as "the kidneys of the landscape" (Mitsch and Gosselink, 2007), *TancatsCWs* could be "the kidneys of the Albufera lake".

Results of the effectiveness of the *TancatsCWs* can be found in Hernández-Crespo et al (2017). In summary, mass removal efficiencies for water constituents are significantly dependent on hydraulic loading rates, vegetation cover and surface or subsurface flow CW type. Maximum efficiencies can be found in subsurface CWs at the highest HLR tested (18.25-54.75 m^3 m^{-2} yr^{-1}); 80%, 55%, 50% and 80% for TSS, TN, TP and Chl *a*, respectively. Except when both vegetation cover and HLR are low, the efficiency is always positive in surface flow CWs. However, the contribution of *TancatsCWs* to the improvement of the lake goes beyond the physico-chemical improvement. Results demonstrate that they are "nurseries" for zooplankton (Rodrigo et al, 2020) that can help to rebuild the food web interactions reducing the hypertrophic status. Additional ecosystem services as refuge of endangered species or educational/scientific issues increase the added value of these green infrastructures in natural environments.

One of the most interesting results is the role of constructed wetlands as buffer systems to reduce pollutants peaks incoming to the lake. In Fig 4 a), inflows from channel named "PC" to *TPCW* and outflows from *TPCW* are represented. The input peaks of TN in winter and spring are effectively reduced in the CW: 35% of the inputs are higher than 5 mg N l^{-1} but just 1.5% of the outputs. In addition, the peaks from urban runoff are reduced. In Figure 4 b) the TP concentration in inflows from channel "BP" to *TPCW* and outflows from this CW is represented. All the input concentrations higher than 0.4 mg P l^{-1} are related with rain events and the incapacity of the urban sewage network to carry out these waters far from the Albufera. Maximum output concentration in the period (2009-2013) is 0.35 mg P l^{-1} (mean output value is 0.17 mg P l^{-1}) thus demonstrating the effectiveness of CWs in pollution control.

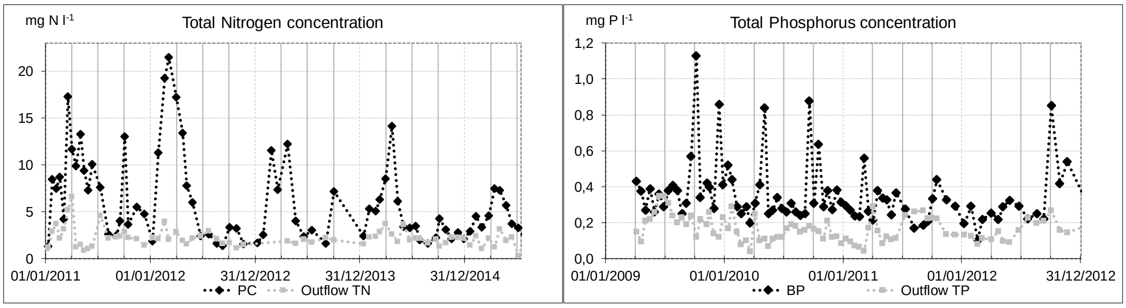

Fig 4. Total Nitrogen inflow concentrations from PC channel (left) and total Phosphorus from BP channel (right) and outflows from the *TPCW* showing the decrease of peak concentrations.

In many meetings with local population and stakeholders, two questions usually arise: first, what is the life span of *Tancats* and, second, how many would be needed to "clean" the lake.

A first look about life span can be obtained from historical data in *TPCW*, the oldest CW, for the past 10 years. If the evaluation of removal efficiencies in this period would show a steep decline, it could be an evidence of ageing and it would be necessary to "reboot" it. After the start up in April 2009, TN and TP efficiencies were quite satisfactory in spring, around 60%, but not in summer, less than 10% (Figure 5). Both efficiencies show a downward trend throughout the forthcoming years because the maturation of the new wetland ecosystem: more vegetation, more organic sediments, fishes, birds…In summary, more biodiversity than in rice fields. Maintenance works were limited owing to the interest to allow the ecosystem develops itself. The result in terms of biodiversity was quite good, but not regarding nutrients removal. In 2014-15, some actions of a specific EU-LIFE Project (LIFE12 ENV/ES/000685, ALBUFERA) were developed over 30% of total *TPCW* area. Vegetation and soil management was intensified, and the results were improved in spring, but not in summer. Learning from this, in summer 2019, 60% of the *TPCW* wetlands, including canals, were completely renewed.

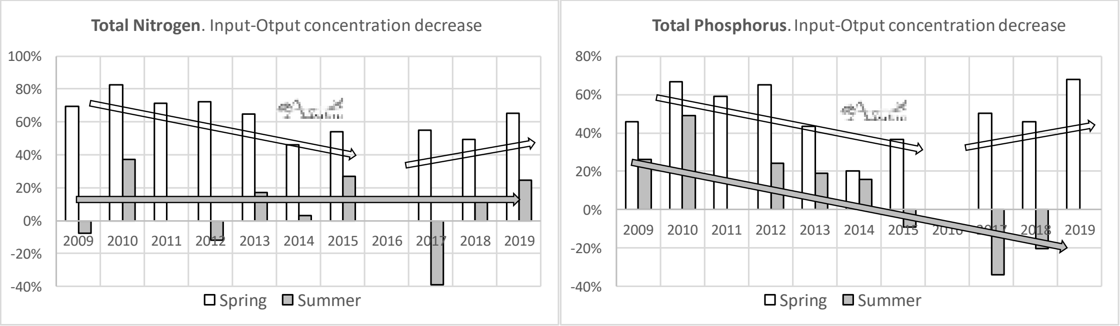

Fig. 5. Percentage reduction of Total Nitrogen (a) and Total Phosphorus (b) concentrations between inputs and outputs of *TPCW* in spring, best season, and summer, worst season, (n= 167).

The second question is much more difficult to respond. Firstly, it is important to explain the current impact of *TancatsCWs* over the lake. Figure 6 represents an annual general TP balance.

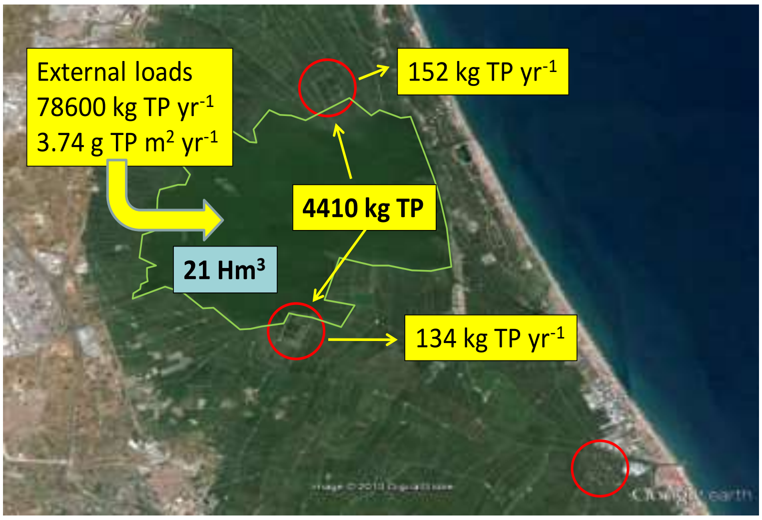

Fig. 6. Estimated TP flows among external loads, contained into the lake and taken by constructed wetlands.

The 24 hm^3 volume of the lake contains approximately 4,410 kg of TP. *TPCW* and *TMCW* take water from the Albufera and are able to remove 286 kg P per year, 6.5% of the total content inside the lake, but just 0.36% when comparing with the external inputs from irrigation channels and natural gullies.

Water quality models are useful tools to help answering this question, as discussed in the next section.

8. Flushing and Water Quality Modelling in the Albufera

The use of water quality models (WQM) is widespread in environmental engineering. WQM are useful tools that help understanding the functioning of water bodies. Nevertheless, in the area of water resources management, the main difficulty is to develop the most suitable model to give answers to the question raised by the decision maker.

In the case of the Albufera, up to five different WQM have been developed in the last 20 years (Martin, 1998; Typsa, 2004; Del Barrio et al., 2012; Onandia et al., 2015; and Aquatool/Gescal, 1996-2018). The first was the basis to further developments, while the last is being used by CHJ for water resource planning in the Albufera watershed. Aquatool (Andreu et al., 1996) is a robust, long-life, and internationally recognised support decision software. The Gescal module of Aquatool is the responsible for assessing water quality in the different watershed elements (river sections, reservoirs, lakes, etc.). After the Water Framework Directive came into force, Aquatool/Gescal have been used in the development of the Jucar River Basin Plans (JRBP) to evaluate the impact of some programme measures in the recovering of the Albufera. An example is the assessment of the Albufera flushing.

Flushing of eutrophic water bodies to change the nutrient dynamics and phytoplankton composition is a physical technique with one hundred years of history (Cooke et al., 2013; Jagtman et al., 1992). In this case study, flushing volumes to reduce significantly the hydraulic residence time during enough time to produce quick and permanent changes are not available. However, with lower water resources, it can be hypothesised that flushing in specific moments could be enough to produce the aforementioned changes. The management strategy of the available freshwaters resources is not to provide them at low constant rate over long term, but high flows in short time. For instance, it is known that phytoplankton peaks occurs in spring and early autumn; if a flow flush could be done just before, the expected results over phytoplankton biomass might be enough to increase transparency and thus facilitate the spread of macrophytes.

In such complex irrigation network as the Albufera, the first task is to identify the best water paths capable to preserve the freshwater quality from the river towards the lake. Secondly, it is necessary condition to store in a reservoir the waters to be used to flushing. In the early autumn of 2008, this condition was achieved because 20 hm^3 were available in the Tous reservoir, Júcar river, upstream the Albufera (Figure 1). The flushing lasted for one month, from 18/10/2008 to 12/11/2008; but the direct inflow into the lake ended on the 3/11/2008. Since this day, the flow was used for rice paddies winter flooding. Four different water paths, selected from a previous study, were used to discharge the freshwater to the Albufera. Samples for water quality analysis were taken in Tous reservoir, in every channel just in their mouth to the lake, and in 10-100 m from the mouth, inside the lake. An additional sampling point was in the main outflow channel connecting the lake to the sea (Gola de Pujol, GP). Monitoring was done three times: 18/10 (1), 4/11 (2) and 20/11/2008 (3). Table 2 shows the water quality changes observed in Barranco Beniparrell path (BB), a 45 km open channel path between Tous reservoir and the lake.

The concentrations of TP and TN are doubled during the journey because the increase of dissolved species as nitrates and phosphates, but both remain lower than the Albufera. Organic matter, turbidiy and phytoplankton (Chlorophyll *a*) remain unchanged, demonstrating that BB is a good path to be used in flushing.

Table 2

Changes in water quality during the water travel and change produced on the lake during flushing.

		Bco. Beniparrell	**ALBUFERA**	
Pollutant	**Tous reservoir**	**Inflow to the lake**	**Change in BB mouth (from 18/10 → to 20/11)**	**Change in GP (from 18/10 → to 20/11))**
COD (mg l^{-1})	5.9	6.7	58.0 → 29.0	74.5 → 46
DO (m g l^{-1})	8.6			
TSS (mg l^{-1})	2.4	3.3	38.0 → 25.0	45.33 → 24.5
Turbidity (NTU)	< 1	1.7	69 →39	73 →36
Total N (mg N l^{-1})	1.17	3.85	2.00 → 3.80	3.70 → 2.55
N-NH_4^+ (mg N l^{-1})	0.05	0.11	0.08 → 0.05	0.12 → 0.12
NO_3^- (mg N l^{-1})	1.50	3.71	0.10 →2.1	1.50 →0.29
Total P (mg P l^{-1})	0.065	0.155	0.63 → 0. 25	0.25 → 0.26
P-PO_4^{3-} (mg P l^{-1})	0.027	0.110	0.005 → 0.05	0.005 → 0.005
Conductivity (µS cm^{-1})	962	1027	1245 →1353	1595 →1400

pH	7.90	7.95	7.66 → 8.05	8.77 → 8.52
Chlorophyll *a* (μg l^{-1})	< 5	< 5	130 → 87	294 → 143

Figure 7 shows the concentrations of TP and Chl *a* in the five points sampled and three times (1, 2 and 3). The sharper fall in the concentrations happened during the two first weeks, with percentages between 24-50% for TP and 65-93% for Chl *a*. After this “first flush”, phytoplankton reaches a mean value of 112.5 μg l^{-1}. Knowing that in November months in the period 2005-2011 (excluding 2008) the mean Chlorophyll a concentrations ranges between 91.87 and 154.22 μg l^{-1} (GVA-Wetlands water quality database), it can be assumed that “normality” was reached.

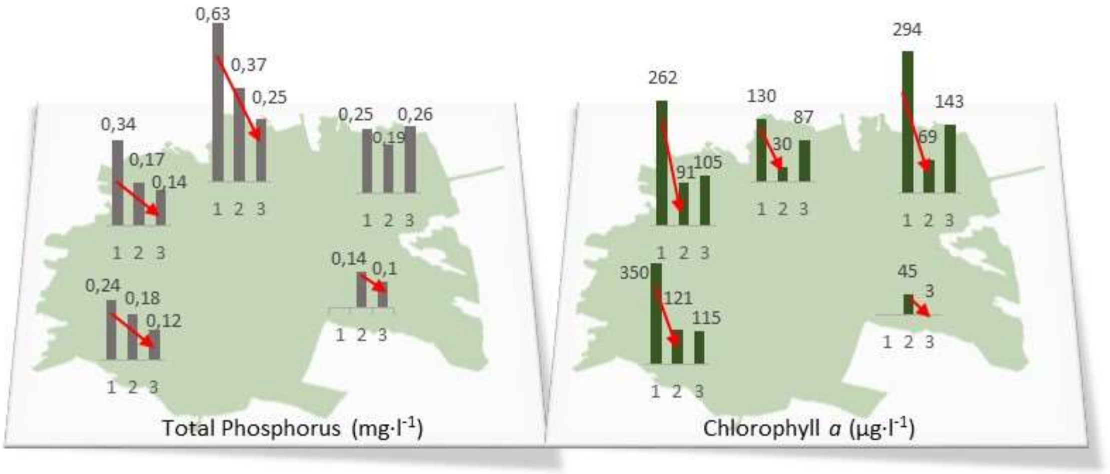

Fig 7. Concentrations of total phosphorus and Chlorophyll *a* during the flushing measure inside the Albufera. X-axis represents the sampling: 1 (18/10/2008), 2 (04/11/2008), 3 (20/11/2008).

The Aquatool/Gescal Albufera model was used to simulate this flushing experience. Figure 8 shows the Chl *a* and TP simulated concentrations in the Albufera without and with flushing.

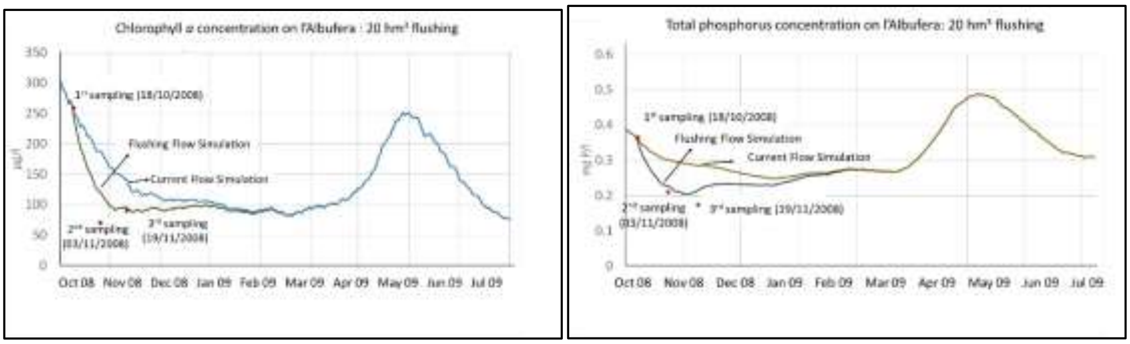

Fig. 8. Measured (red points) and simulated Chl *a* and TP concentrations in the flushing of 2008.

Once validated, the model can be used in the assessment of flushing strategies, for example, discharging a fixed volume in a short period according to a Chl *a* concentration inside the lake. The result of such simulation is showed in Figure 9: 20 hm^3 in 20 days when Chl *a* concentration reaches 200 µg l^{-1}. In addition to reducing the peaks of phytoplankton more than 30%, mean concentration is reduced by 21%, demonstrating that in a context of low water resources, planned flushing is a strategy to be considered.

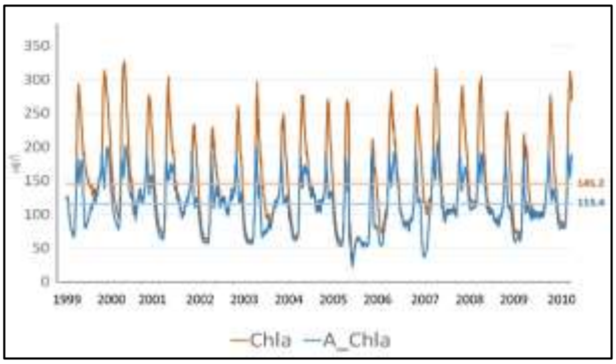

Fig. 9. Chlorophyll *a* concentrations (µg l^{-1}) simulated between 1999 and 2000. Chl *a* series is current flow while A_Chl *a* series is with flushing.

Flushing is repeated only when Tous reservoir has an excess of stored water in early autumn, according with their operation rules, as for example in October 2015. Unfortunately, it does not happen every year because the highly variable rainfall, typical of semiarid Mediterranean climates.

Water quality models can also be used in an attempt to respond to the question about the positive impact of CWs on the lake. In the framework of EU-LIFE ALBUFERA project, a wetland-WQM developed from Aquatool/Gescal support system, named HUMEDAL, allowed us an approximation to this question. After calibration and validation using two years data from *TPCW*, *TMCW* and *TLICW*, different scenarios were assessed (LIFE_ALBUFERA_Informes, 2016). For example, the decrease of Chl *a* concentrations when increasing subsurface wetlands was evaluated (Figure 10). In the case showed, mean decreases between 22 and 40% could be achieved with 400 – 1200 ha of new wetlands working at 25 m^3 m^{-2} yr^{-1} HLR.

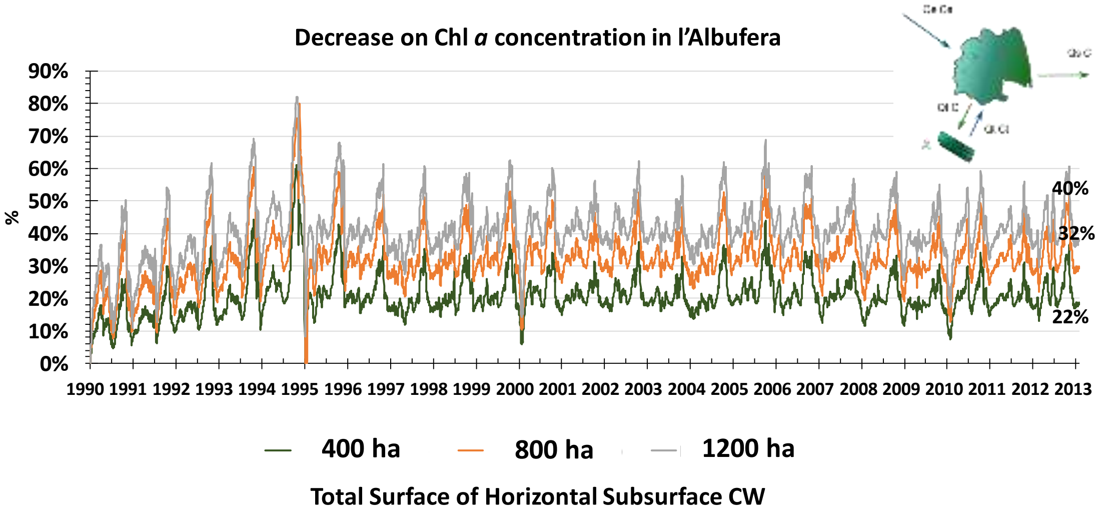

Fig. 10. Simulation results from HUMEDAL model considering different HSSFCWs areas. Y axis represent the percentage reduction of Chl *a* concentration compared with the Chl *a* concentration without CWs.

9. Fluxes from sediments

Another threat to which the Albufera is exposed is the accelerated accumulation of sediments. The acceleration of the erosion process in the watershed, consequence of deforestation and extreme rainfalls, has given rise to the disappearance of different habitats (uniformized bottom) and ultimately, can lead to the silting up of the lake. Additionally, sediments act first as a sink of pollutants, however, later there is a risk of pollutant remobilisation into the water column, for instance when resuspension occurs, thus acting as a ‘‘time bomb’’ (Charriau et al. 2011). The mean sediment depth is 0.9 m (Typsa, 2004) so the total estimated volume in the lake is around 21.9 hm^3.

Technical dredging is often used in the Albufera to maintain hydraulic capacity in irrigation channels and to increase water depth in small fluvial ports. Environmental dredging with the aim to reduce sediment oxygen demand, trace metals, pesticides, emerging pollutants or phosphorus fluxes from sediments have never been carried out. Previously to any dredging action, the first step is always the sediment impact assessment by means of sediment monitoring.

Hernandez-Crespo and Martin (2015) studied the sediment column and found that the highest trace metal content is in the first 25-30 cm of sediments. The results indicated a moderate pollution for Cu and Zn and minor enrichment for Cd, Ni and Pb, according to the enrichment factor. The sampling sites located in the perimetral area of the lake were the most polluted, whereas the metal concentrations of the site in the middle of the lake were at background levels. At that moment, the studied metals were not bioavailable according to the indicator based on acid volatile sulphide (AVS) and simultaneously extracted metals, nevertheless an AVS decreasing trend over time was found (Hernández-Crespo and Martin, 2013). This indicated that the potential bioavailability of metals was increasing over time. Peris et al. (2000) found concentrations of Cr up to 700 $mg \cdot kg^{-1}$ in front of ditches that acted as sewage network in the past.

Regarding organic matter and sediment oxygen demand (SOD), the top 15 cm has between 10 and 31.9 mg g^{-1} measured by manometric respirometry method in 40 days

(Hernández-Crespo, 2013). Demand from sulphide oxidation is about 3% and nitrification requires 15% of SOD; ammonium concentrations up to 100 mg $N\cdot l^{-1}$ were found in the pore water (Hernández-Crespo and Martin, 2015). Although the aerobic biodegradability is low, first-order rate constants 0.027-0.052 d^{-1}, the resuspension of sediments by wind, boats and dredging works can produce a sharp decrease of dissolved oxygen.

In 2004, a mesocosm scale experiment involving sediment dredging was done (Figure 11, left). Two methacrylate cells, 2 m^3 (1x1x2 m), C1 and C2, were embedded in the Albufera sediments and isolated from lake waters. Submerged probes recorded every 10 minutes the DO concentrations (Figure 11, right)

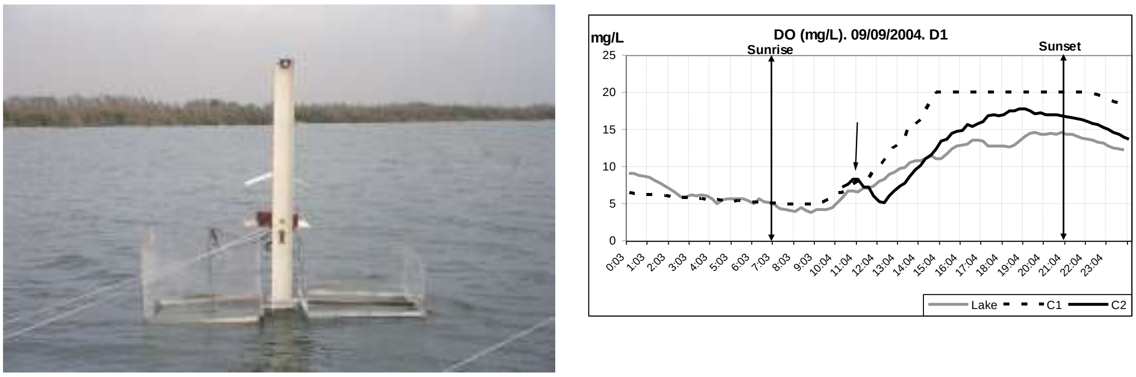

Fig 11. Dredging mesocosm experiment in the Albuera (left) and DO concentrations during the first dredging (right).

After half an hour extracting sediments with a 0.5 l Van Veen grab sampler, total suspended sediments increased from 46.0 to 873.0 mg l^{-1} and DO decreased from 8.0 mg l^{-1} to 5.0 mg l^{-1} in 1.5 hours. Phytoplankton oxygen production was calculated from the slope [DO] *vs* time in 2.16 mg l^{-1} h^{-1} in line with a concentration of 136.8 mg Chl *a* l^{-1}. The photosynthesis compensated the drop of dissolved oxygen and once the dredging finished, the DO quickly increased to oversaturation. Beyond the evidence of dredging impact on DO, the lesson learned is that in hypertrophic waters dredging works should be done intermittently during sunny days and finished three/four hours before sunset.

Other sources of sediment information can be obtained using WQM. From the WQM developed in the Albufera, some information about P fluxes can be extracted. For example, Del Barrio et al. (2012) performed a specific sampling to measure Soluble Reactive Phosphorus (SRP) fluxes at 17 stations in July 2009. The SRP fluxes from sediments to water ranged between 0.49 and 46.38 mg P m^{-2} d^{-1}, with a mean value of 20.72 mg P m^{-2} d^{-1}. Unfortunately, just one-day sampling is not representative because P fluxes are highly dependent on sediment redox conditions and temperature and July in Valencia is a hot month with low oxygen water/sediment interface concentrations. Onandia et al. (2015), estimated from model calibration the P fluxes in 6.2 10^3 kg yr^{-1} (aprox.0.71 mg P m^{-2} d^{-1}), a value in the lower range of Del Barrio et al. (2012).

These results are not sufficiently conclusive to recommend a complete dredging of sediments in the entire lake. If dredging is to be performed, removal of 25-30 cm top layer sediments from the most polluted zones (perimeter) would be enough to reduce significantly trace metals, SOD and nutrients. About the dredging technique, hydraulic dredges are recommended as well as curtains to prevent the increase of turbidity and nutrients in the action surroundings. Peris et al. (2000) proposed management solutions of the dredged sediments in civil engineering applications. However, it is of maximum importance to think about the mid-long term collateral effects. In such shallow lake, increasing 30 cm of water depth is increasing 30% its volume, and consequently increasing the HRT: just for maintain the same HRT it would necessary to increase the flow rate a 30%, around 70-90 hm^3 yr^{-1}. Also light penetration and DO in the water column would be altered with consequences over the macrophytes and nutrient fluxes not easy to predict.

Considering the abovementioned risks, complete dredging in specific sites inside the lake could be of interest in some cases. The existence of natural freshwater sources in the bottom of the lake is well known (named *Ullals*), but they have been silted and no more water flows currently. Removing sediment layer could restore natural flows and contribute to the improvement of the lake.

Bioaugmentation is a bioremediation technology based on the addition of an exogenous microbial community to sediments (Wessels Perelo, 2010). According to target pollutants studied, employed bacteria strains can be more or less diverse. There are some commercial products available to reduce organic matter in sediments (Fabiano et. al, 2003). In 1998, a company proposed the application of this technology to the Albufera sediments, but the proposal was quickly dismissed by technical and budgetary reasons. The first technical reason is related with organic matter content in sediments. The higher organic matter, the greater effectiveness of bioaugmentation; but the organic matter in the Albufera sediments, measured as lost on ignition (LOI), is lower than 10% (Hernández-Crespo, 2013). Secondly, accelerating organic matter biodegradation implies a faster supply of nutrients to water column increasing the eutrophication risk, that can only be balanced by an extra water supply. The third technical reason is that there is not experience in such large lake areas: about 2800 ha including irrigation channels. Finally, the cost of implementing this measure was budgeted in 1998 in 131.9 M€ (aprox. 196.0 M€ currently) without sediment dredging costs.

10. Is the status of l'Albufera improving over time?

Since the implementation of sanitation measures (Figure 12), there has been a significant and progressive decrease of Chlrophyll *a* concentration over time ($r_{\_Pearson} = -0.42$; $p<0.001$) and a significant increase of Secchi depth over time ($r_{\_Pearson} = 0.31$; $p<0.001$). Therefore, the monitoring data demonstrate the efficacy of the implemented measures. It also shows the importance of continuous monitoring to check the improvement in the water quality status.

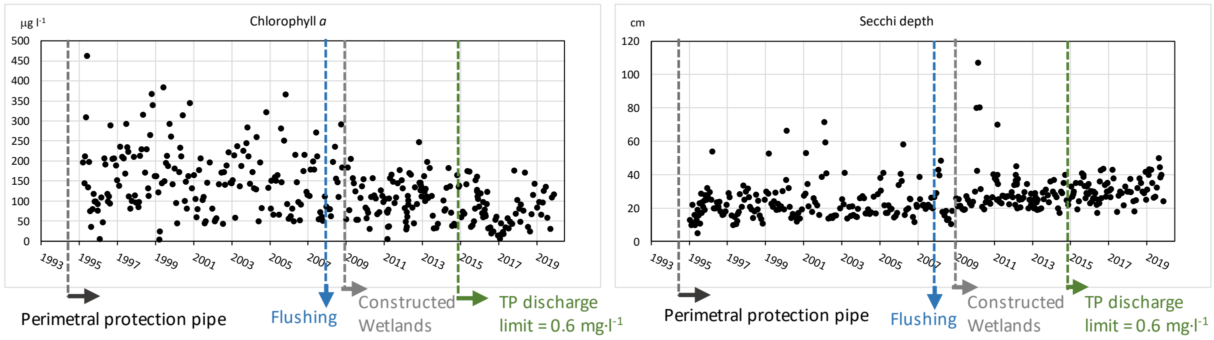

Fig 12. Mean values of Chlorophyll *a* and Secchi disk in the Albufera. Values are the average of 4-7 sampling points taken monthly (GVA-Wetlands water quality database, 2020). The arrows indicate some important milestones of measures undertaken for the lake restoration.

The annual mean concentration of Chlorophyll *a* for the last five years is 78 µg·l^{-1}, which is below the target set in the JRBP by 2021 (90 µg·l^{-1}).

The response of closest aquatic ecosystems to improvements in WWTPs is very quick. Fig 13 shows the spread of a typical wetland macrophyte (*Potamogeton nodosus*) in *Alqueresía* channel, formerly one of the most polluted irrigation channels, in 2015, two years after the implementation of *Albufera Sur* WWTP. Macrophytes disappeared in the Albufera environment in 1970's but are slowly recovering since 2015. Figure 13 (right) shows the increase of macrophytes area on the lake (CHJ, 2016; GVA, 2018) since their reappearing in 2015.

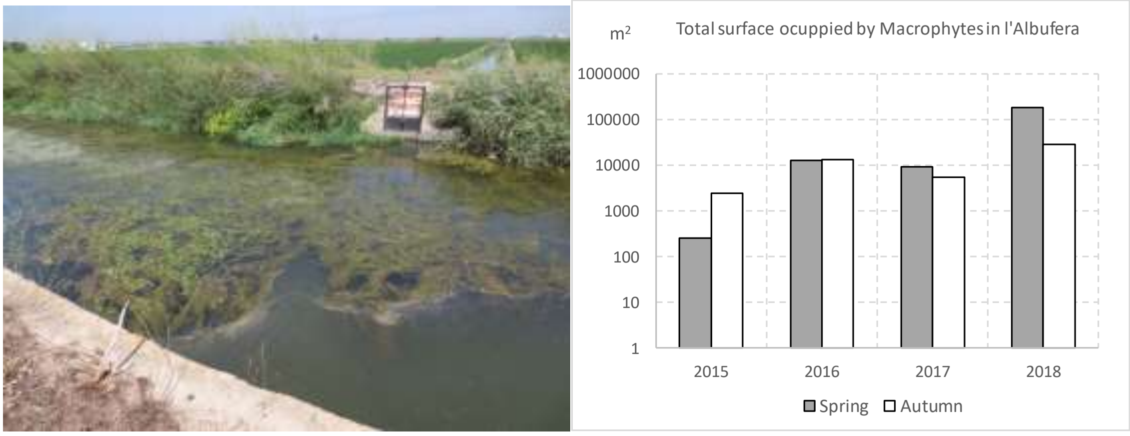

Fig 13. Left: Potamogeton nodosus in Alqueresía ditch in September 2015; right: shifts on macrophytes surface (mainly *Miriophyllum spicatum, Potamogeton pectinatus and P. nodosus*) since its reappearing in 2015 (GVA, 2018).

Other evidences of the improvement of the lake, and consequently the improvement of the whole Natural Park, is the presence of certain species of wintering waterbirds or breeding pairs, showing an enhancement of biodiversity. For instance, the overwintering population of Glossy Ibis (*Plegadis falcinellus*) has increased steeply since 2011 (Vera et al. 2019). Another important finding is that a large part of the couples of several bird species chose the CW to breed. Therefore, the CW acted as a nursery, hosting above 70% of the total breeding population in the Albufera for *Anas Strepera*, *Netta rufina* or *Fulica atra* (Vera et al. 2016).

11. Conclusions, recommendations and the future.

Environmental engineers focusing on restoring aquatic ecosystems have many tools on their hand. Because of the complexity of ecological interactions, it is very difficult to attribute any type of improvement to a single measure. The strongest proof of environmental recovering of the Albufera is the macrophytes return, with an upward trend since 2015 strongly associated, but not only, to an increase on Secchi depth.

Nowadays, a sanitation solution based solely on large perimeter interception sewer would be unthinkable. Additional and complementary solutions would be necessary, for example, managing the urban runoff after first flush. Wastewater treatment technologies are capable to obtain the most stringent water quality standards, so the option to treat sewage should be the first to be implemented. Additional advantages are the reuse opportunities for reclaimed waters.

Efficiency of CWs on water pollution control and as “nurseries” of filter-feeding zooplankton has been proved, but their effectiveness depends on how much area can be developed to this end. The currently available surface of CWs (90 ha) is not enough to produce a quick change within the lake but the additional ecosystem services provided make them key elements of the lake restoration. Additionally, CWs are proving to host waterbird species of high conservation value. Therefore, they play a key role for the water quality improvement and biodiversity enhancement.

The environmental dredging is recommendable for hot spot areas in order to remove these highly polluted sediments, but it is unaffordable for the whole lake. Once all the discharges into lake will be removed, including CSO, the dredging should start in the surrounding irrigation channels and gullies.

The environmental improvement observed demonstrate that measures undertaken have had positive effects. Nevertheless, the lake remains in a hypereutrophic status, according to the OECD classification (1982), and further measures are needed to achieve the 2027 target (30 $\mu g \cdot l^{-1}$).

Future measures proposed by public administrations combine grey and green infrastructures taking the best of each and thus optimising their efficiencies. Improving sanitation with a new WWTPs, enhancing the hydraulic capacity of the perimeter interceptor sewer, complementing stormwater detention tanks with stormwater wetlands or basins, increasing 100 ha the surface of CWs around the lake and spreading sustainable urban drainage systems (SUDS) within the municipalities are the new measures to be considered for the 2027 horizon.

Nevertheless, the future of the agro-ecosystem of the Albufera is closely linked to the challenge of climate change. In coastal lakes like this, the sea level rising associated to higher temperatures will increase its salinity. The extent of this process will depend on future temperature changes, but managers and stakeholders of this area need to be aware of such possibility and thus adapting the restoration measures according with this.

Acknowledgments

The authors would like to acknowledge the financial support of LIFE program of CE, Confederación Hidrográfica del Júcar, Aguas de las Cuencas Mediterráneas, the Spanish Fundación Biodiversidad, the Universitat Politècnica de València and the company Técnica y Proyectos S.A. (Typsa) in our researches developed since 1995 to 2020 in the Albufera area. We also thank Generalitat Valenciana for the free available database on wetland water quality and the continuous lake monitoring.

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