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CPES

Case Study Implementation Report (CSIR)

Case Study of the Lac au Duc, Yvel-Hyvet catchment, Ploërmel, France

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Foreword: Impact of the health crisis on the Lac au Duc pilot study

The health crisis linked to the COVID-19 pandemic has had a major impact on the Lac au Duc pilot study since it was launched in France in early March 2020, and is still disrupting the smooth running of the study at the time of writing of this report (January 2021). The main impacts have been, and are still being, felt in the following areas:

1) Staff assigned to the study. The post-doctoral student employed at the University of Rennes 1 (Morgane Le Moal) had to apply for a Special Absence Authorization (ASA) to keep her child at home during the entire period of confinement. Work of the administrations of the CNRS and the University of Rennes 1, was slowed down during this same period, delaying the processing of administrative documents such as requests for payments from the INTERREG program. During the lockdown period, the University's laboratories weren't accessible. Thus, the chemical technician from the University of Rennes1 was not able to carry out follow-up analyses of the water quality of Lac au Duc during this period. Confinement also penalized the work of a Master 2 student (Rino Iida) in charge of evaluating the capacity to financially value the attributes of anti-erosion hedges and permanent plant cover from the point of view of their capacity to store carbon in the soil, and thus to constitute elements for the creation of a local market for voluntary carbon compensation. The aim of this work was to broaden the offer of PES designed to improve water quality to the climate issue, this diversification of targets being made with the purpose of increasing the attractiveness of the Lac au Duc PES mechanism from the point of view of private companies. The period of confinement made this exercise very difficult and restricted it to an analysis of the bibliography and a few remote interviews with actors from the business community. Fundamental exercises such as the establishment of contacts in the form of workshops between farmers selling PES and potential buyers for the co-construction of contracts including a PES offer on water quality and climate/carbon and meeting the expectations of both sellers and buyers in terms of content and amounts had thus to be postponed indefinitely due to the COVID crisis.

2) Working with stakeholders, farmers and businesses, to set the process of negotiation and concrete implementation of PES contracts in motion. The impact on this part of the pilot study is considerable. In fact, contacts with farmers and companies have been at a standstill since the beginning of March 2020 with prospects for recovery not yet stabilized. Concerning farmers, the two months of the first confinement in 2020 spring have stopped the work of sizing PSE contracts initiated during the winter 2019-2020. This work could not be resumed once the confinement was over, as the period of exit from the confinement (May 2020) corresponded for farmers to the resumption of external work of sowing (corn, in particular) and harvesting, the farmers had neither time to devote to exchanges with scientists and the SMGBO nor possibilities to change their planning for 2020. A resumption of the dialogue could have been only possible towards the end of November 2020, once the corn silage work and the sowing of the winter crops are finished, but this resumption was interrupted by the second confinement

implemented in France in November at this time. An equivalent delay has been taken with the companies contacted to finance the PES. Many companies suffered shut down or disrupted of their operations during the time of containment. Many of them are now more concerned about ensuring their economic survival than about participating in the financing of PES. We thought that contacts with companies could be resumed in the fall of 2020. The start since September 2020 of a second, very virulent wave of COVID-19 contamination followed by a second confinement period has made this prospect very uncertain.

3) Production of deliverables. Delays in working with farmers and businesses will inevitably affect the timely release of deliverables from the Lac au Duc pilot study. In particular, we hoped to sign the first PES contracts by the end of 2020. It is clear that this target will not be met, not to mention the objective of evaluating the environmental effectiveness of the payments, which can only be postponed as well. At the time of writing this report, the delivery of these two main deliverables is only conceivable, at best, in the second half of 2021, which is why we have joined forces with the other partners in the CPES project to request an extension of the project beyond its current scheduled end (April 30, 2021).

4) Communication. Communication with sellers (farmers) and buyers of PES (private companies) has been totally interrupted for the reasons detailed in points 2) and 3). We are currently in the process of reactivating communication, knowing that both farmers and private companies will be difficult to reach and convince to enter the concrete process of signing PES contracts as long as the COVID crisis has the virulence that it has today.

Note : this symbol later in the report indicates the parts of the work strongly impacted (slowed down) due to the health crisis.

1- RECALL OF THE PROBLEM AND THE DIFFERENT PHASES OF THE PILOT STUDY

1.a- Motivations for setting up a PES mechanism on the Lac au Duc territory

Like many water reservoirs in Brittany, Lac au Duc is subject to eutrophication which results in the development of massive blooms of cyanobacteria during the summer periods (Figure 1). Cyanobacteria can harm the environment and human health because of their capacity to produce toxic metabolites and because of their allergenic potential (Wiegand & Pflugmacher 2005, Dittman et al. 2013, Lang-Yona et al. 2018). In addition, when their concentration becomes significant, swimming, boating, and fishing may be prohibited, following the regulations. The production of drinking water may also become difficult, more expensive, or even stopped.

Cyanobacterial blooms are triggered primarily by excessive nutrient inputs. In freshwater aquatic ecosystems, excess phosphorus (P) is generally seen as the factor responsible for the phenomenon.

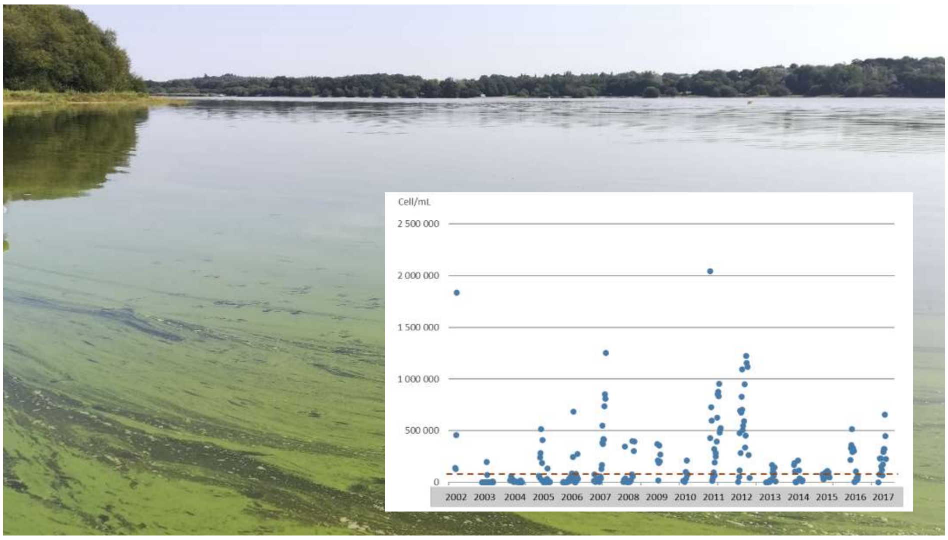

Figure 1 *- View of Lac au Duc from the Ploërmel Brocéliande Yacht Club, August 2018. Source: SMGBO. The graph inserted in the image, established by M. Le Moal, shows the cyanobacteria densities (in number of cells per ml) measured since 2002. Almost every summer, a peak is observed with densities above the health threshold of 100,000 cells/ml indicated by the red dotted line.*

The Lac au Duc extends over the communes of Loyat, Taupon and Ploërmel, in the Morbihan region (southwestern Brittany), and is fed by the Yvel-Hivet catchment, which straddles the departments of Morbihan, Côtes d'Armor and Ille-et-Vilaine. The volume of water stored is approximately 3,000,000 m^3. An identity sheet of the lake and its catchment is presented in Figure 2.

Yvel-Hyvet catchment characteristics)

Number of municipalities concerned : 22
Counties concerned : Morbihan, Côtes d'Armor, Ille-et-Vilaine
Source name : Saint-Vran
Population: 21 300 inhabitants
Total surface area: 37 328 ha
Total cultivated surface area : 26 183 ha
Number of farms in 2014 : 382
Length of river network : 380 km

Lac au Duc characteristics

Surface area : 250 ha
Volume : 3,5 millions de m^3
Tributaries : Yvel river; Moulin du Miny, Vieux Prés, and Saint-Jean streams
Usages : drinkable water production, tourism and recreational activies (fishing, nautical activities, bathing etc.)
Owners : Eau du Morbihan, Ploërmel Communauté
Municipalities implied in lake managment : Loyat, Taupont et Ploërmel

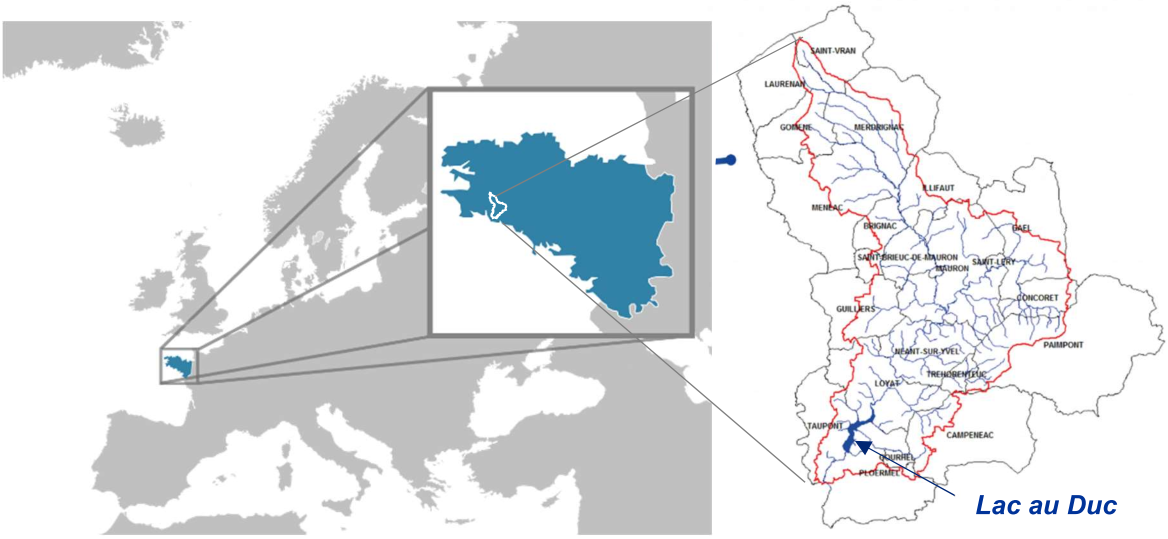

Figure 2 - Location and main characteristics of the Lac au Duc and its catchment (Yvel-Hyvet catchment).

The Yvel-Hyvet River has been identified for its high P concentrations since the implementation of the European Water Framework Directive in 2000. The Lac au Duc, on the other hand, a heavily modified water body, is downgraded until 2021, due to its eutrophication problems causing cyanobacteria blooms. As a result, the entire catchment of the Yvel-Hivet which feeds the lake is classified in zone 3B-1 by the "Schéma Directeur d'Aménagement et de Gestion des Eaux (SDAGE)", i.e. the directive set up to manage water quality in the Loire-Brittany area, and specific measures relating to P fertilization are defined.

Two main sources can contribute to the enrichment of Lac au Duc with P: 1) agricultural activities on the catchment (diffuse sources of P); 2) discharges from treatment plants and autonomous sanitation facilities in the river network feeding the lake (point sources of P).

Eight wastewater treatment plants have their discharges on the Yvel Hyvet catchment. The municipalities of Mauron and Merdrignac are equipped with an activated sludge treatment plant to which all the industries present in these municipalities are connected. The Concoret wastewater treatment plant operates with a bacterial bed and the newly created Tréhorenteuc wastewater treatment plant is of the reed filter type. The municipalities of Guilliers, Néant sur Yvel, Saint Brieuc de Mauron and Saint-Léry use a natural lagooning system. The municipality of Brignac has no collective purification equipment. In 2010, a study estimated that 45% of the on-site wastewater treatment facilities on the Yvel-Hyvet catchment had an increased risk of P leakage; only 20% were functioning properly, with the remaining 35% requiring monitoring.

Agriculture, for its part, is dynamic on the Yvel-Hivet catchment, representing the main economic sector. The agricultural land is stable since 2012 representing about 63% of the total area of the catchment. In 2018, there were 448 farms in the catchment, for an average area per farm of about 78 hectares. Dairy production is dominant in the north and south of the catchment, although it has been declining sharply in recent years. This decline is reflected in an increase in cultivated areas, to the detriment of grasslands. Above-ground pig and poultry farms are mainly located in the west and center of the catchment.

The farmers of the Yvel-Hivet catchment have been involved for a long time in actions to reduce non-point pollution, particularly in P. These actions involve : 1) a balance of P fertilization (at least 80% of the farmers were at equilibrium in 2018, according to a survey); 2) a subscription to Agroenvironmental and Climate Measures (MAEC) for a total amount of 520 603 € (in 2011, 98 farms were involved in a MAEC, including 52 in Rotational Agroenvironmental Measure - MAER2 for a total surface area of 2 645 ha, and 15 in Low Input Fodder System - SFEI, representing 306 additional ha) ; 3) an increasingly important practice of non-ploughing (23% of the total cultivated area concerned); 4) the systematic establishment of plant cover in winter (the catchment of Yvel-Hyvet is classified as a Complementary Action Zone (ZAC) since 2001; this means that, by law, all plots of land in the catchment must be sown either in winter cultivation or in Intermediate Nitrate Trap Cultivation (ICPAN) while waiting for the following spring cultivation; 5) systematic planting of grass buffer strips along the edges of the watercourses; since 2005, as part of eco-conditionality, the farmers of the Yvel-Hivet catchment are required to plant 3% of their declared surface area in cereals, oilseeds or frost, in grassed buffer strips of 5 meters minimum width, along the watercourses on their farm; and finally 6) the establishment or re-establishment of hedgerows, particularly under the Breizh Bocage program (€ 520,603 granted under this program over the period 2007-2020).

All of these measures have contributed to reducing the flux of diffuse P of agricultural origin entering Lac au Duc, as elsewhere in Brittany, where agricultural diffuse P fluxes have been reduced by an average factor of 2 in 25 years (Legeay et al. 2015). Nevertheless, despite these efforts, Lac au Duc continues to be regularly confronted with cyanobacterial blooms with numerous damages on:

Tourism and recreation - Lac au Duc is an important leisure centre in the Brittany region. Fishing (carp, pike-perch, etc.), sailing, water-skiing, pedal boats, canoe-kayak, stand-up paddle and a beach that attracts at least 800 people during the summer season for the practice of swimming are some of the activities practiced there. There are several hiking trails along the shoreline, including the 15 km-long "Tour du lac au Duc"and several cycling trails. A golf course is located at the southern end of the lake and takes advantage of the natural environment. Lac au Duc is also a place to hunt waterfowl. A campground, two hotels and several restaurants are located on the shores of the lake and take advantage of the natural character of the site. Specifically regarding swimming, the lake has been closed for a few days or even a week during the authorized swimming period in 2013, 2014 and 2015, which remains relatively acceptable to users. In 2016, swimming was closed for 3 weeks, and 6 weeks in 2017. These closures have had a significant impact on the use of the site, in connection with the loss of the recreational offer, and have caused economic losses for other activities (especially water sports) and structures around the lake. In addition, the local press very often reports on these eutrophication problems and the impacts on swimming, contributing to negative publicity for the area.

Purification of potable water - The drinking water production plant located downstream of Lac au Duc supplies 30,000 inhabitants for an average annual production volume of 2,500,000 m^3 of drinking water. This plant, built in 1972, has been adapted to meet the new requirements for the quality of water for human consumption and the increase in nominal treatment capacity from 400 to 600 m^3/hour. During the bloom period, cyanobacteria are difficult to retain by flocculation when they enter in the treatment plant, with variations according to species and their abundance. They then often accumulate in the filters and clog them. In the summer, the Lac au Duc plant compensates for this (and for the reserved water flow) by pumping water from the Herbinaye station located on the Oust river. In addition to the cost of this diversion, there is a risk of shortage if the water supplying the Herbinaye station is not available or itself of insufficient quality.

Biodiversity - Lac au Duc and its immediate surroundings constitute a remarkable natural space, whose proper functioning is threatened by the persistent degradation of the lake's water quality. In particular, the site includes a Natural Zone of Ecological, Faunistic and Floristic Interest (ZNIEFF). Environmental associations are working and making inventories of the various species of fauna and flora on the lake shore. In 2012, seven species of flora have been identified on the lake as protected species, including 6 under national protection. Among these species, we can mention the presence of the Coléanthe delicat (*Coleanthus subtilis*) which is only present in less than twenty Brittany lakes. In addition, cyanobacterial blooms alter the dynamics of other phytoplankton populations and the development of macrophytes through their capacity to consume light and nutrients efficiently, or through the effect of the toxins they emit into the environment (see, for example, Wiegand and Pflugmacher, 2005). Zooplankton are also affected by the low nutritional value of cyanobacteria, which leads to the disruption of the entire food chain and, ultimately, the proper functioning of the entire aquatic ecosystem (see for example Huisman et al., 2018).

1.b- Phasing of the study

Faced with the persistent degradation of the water quality of Lac au Duc and the inadequacy of the agricultural actions undertaken so far to reduce the flux of P entering the lake to levels sufficient to restore/guarantee its various uses (see below), the SMGBO and its partners considered it opportune to join the INTERREG CPES project under the argument that the innovative financial tools that are Payments for Environmental Services (PES) could constitute a lever to make the quantitative leap necessary to reach these levels. From the very beginning of the project, it was decided that the Lac au Duc pilot study would target private funders, with the dual idea of 1) being able to have access to significant funds, not subject to the volume limits and/or prior notification requests to the EU commission in Brussels to which public funds are subjected, and therefore to be attractive to farmers, and 2) responding to the demand expressed by the latter to have private funders rather than public funders whom they say they no longer trust.

The Lac au Duc pilot study is being carried out in four successive steps, in addition to the preliminary stage of defining the environmental status of the lake and identifying all the actors concerned by this status and by the different uses of the lake (see also Figure 3):

Step 1: Definition of the water quality objective and identification of the means to achieve it. This step includes a phase of estimating the flux of P currently entering Lac au Duc and quantifying the respective share of agricultural diffuse P and domestic point P sources within this flux. It also includes a phase of defining the objective to be achieved from the point of view of reducing the P flux entering the lake, and of calibrating this objective with the different uses of the lake that one wishes to preserve/restore. Even if the diffuse sources of agricultural P could appear the most important given the very agricultural context of the Lac au Duc catchment, the phase of quantification of the respective shares of the agricultural and domestic diffuse P fluxes constitutes an indispensable prerequisite for the choice of measures to be implemented to reduce the P fluxes entering the lake and to achieve the desired objective of restoring its water quality and restoring/sustaining the uses that it provides. This step 1 also involves locating the main sources of diffuse agricultural P emissions in the catchment and identifying the technical attributes that farmers could use to reduce these emissions and whose implementation could constitute their PES supply. The purpose of the source location work is to determine whether the deployment of these attributes could be targeted in priority on certain sectors of the catchment, with a view to reducing costs while being as efficient as possible from the point of view of achieving the objective of very significantly reducing the flux of P entering the lake. Finally, it includes a collection and interpretation stage of the 15 years of monitoring of cyanobacteria blooms affecting the lake. The data on the dynamics of the algae are related to those on the dynamics of nutrient availability and climatic conditions (temperature, sunshine, wind, precipitation). This analysis of historical data is completed by the acquisition of new data on the dynamics of cyanobacteria and zooplankton at three points in the lake, related to nutrient dynamics (P and N (N=nitrogen)).

Step 2: Assessment of the financing needs (willingness to receive or WTR) of farmers, including a comparison of this WTR with the economic value of a lake in good ecological condition. The aim here is to assess the financing needs of farmers according to the objectives to be achieved and whether or not to target actions on the most cost-effective plots. In other words, it is a question of calibrating the farmers' WTR according to the water quality objective targeted for the lake. It is also a question of comparing this WTR to the economic value of a lake in good ecological condition to evaluate the economic acceptability of a PSE scheme targeting better farming practices. It is also a question of comparing this WTR to the costs generated by the curative actions implemented at the lake level to reduce the intensity of cyanobacteria blooms and thus allow the maintenance of tourist uses (including swimming) as well as the production of drinking water. More generally, this stage involves defining the economic characteristics of the PES to be implemented to restore and perpetuate the good ecological status of Lac au Duc, by comparing the overall cost of the paid actions to all the costs generated by the inaction.

Step 3: Evaluation of companies' conditions of engagement and their willingness to pay (WTP). In this step, the aim is to identify the companies likely to participate in the financing of the supply of PES built by the farmers of the Lac au Duc catchment. It is also a question of evaluating their willingness to pay (WTP), and the possible adaptations to be made to the agricultural offer in case of WTP lower than the WTR.

Step 4: Construction and signing of contracts on the scale of an experimental territory. This last step involves building and implementing a first series of PES contracts on the scale of an experimental territory, after a negotiation stage aimed at bringing together the farmers' WTR and the companies' WTP. It is also a question of defining a legal framework suitable for both parties and allowing a secure deployment of the contracts. Finally, it is a question of defining the labelling processes and monitoring indicators to be set up to guarantee the environmental efficiency of the PES set up.

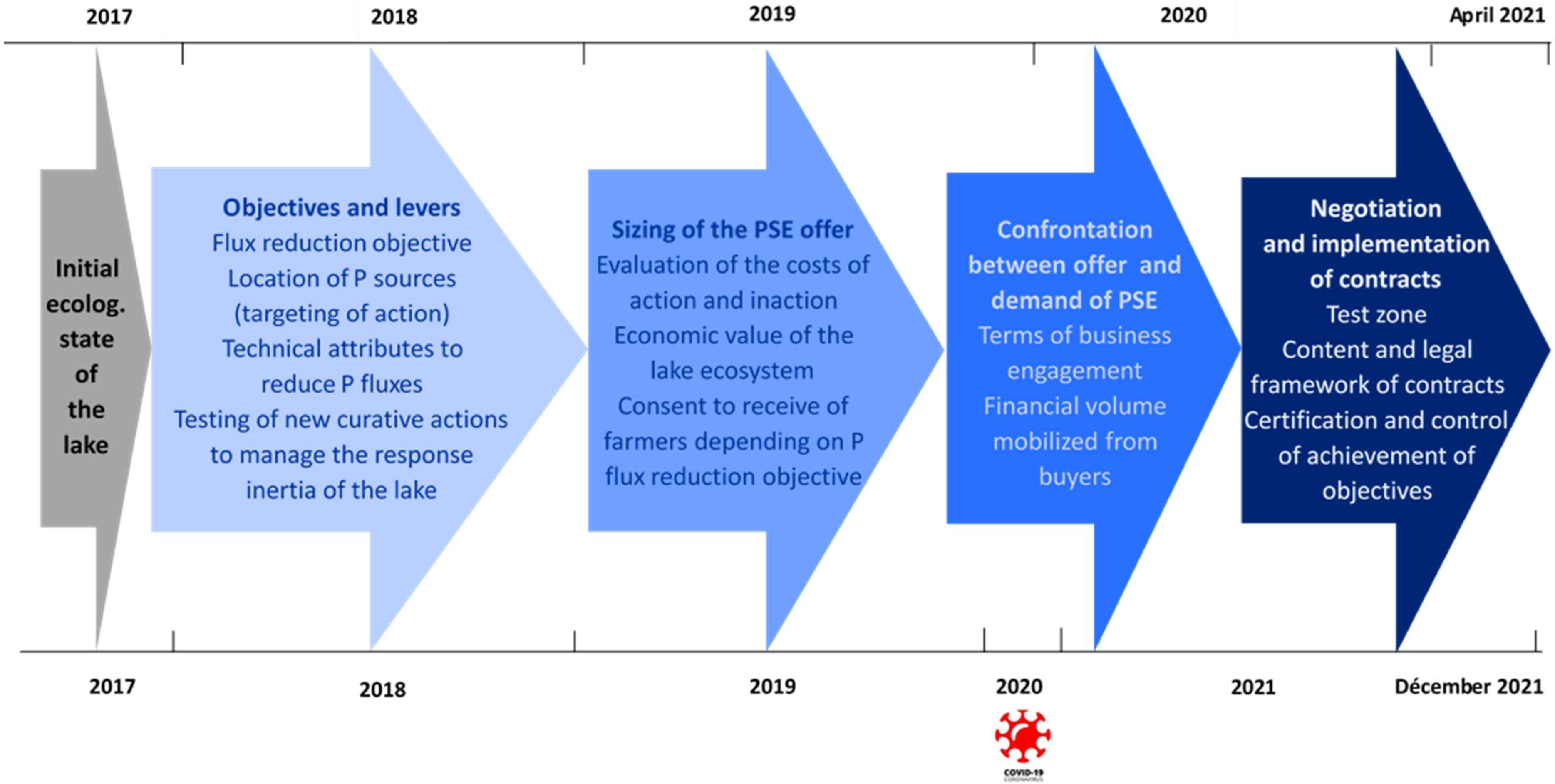

***Figure 3** : The different steps followed for the implementation of PES in the Lac au Duc case study. The schedule at the top of the figure corresponds to the initial planning of the study. The schedule at the bottom of the figure corresponds to the new schedule taking into account the delay in the study due to the health crisis of COVID-19 and the need to adapt the supply of environmental services to the demand of private companies.*

2- PHOSPHORUS EMISSION REDUCTION TARGET AND MEANS OF ACTION TO REACH THE TARGET

2.a-Quantification of P emissions and P sources in the catchment

The quantification of the P flux entering Lac au Duc was carried out by collecting and analyzing the P concentration measurements performed by the SMGBO between 2007 and 2017 on the 10 monitoring stations located in the Yvel-Hivet catchment, including station YV2 located just upstream of the lake, which is equipped with an automatic water flow gauging system. The measurement frequency is generally 10 samples collected and analyzed per year, except at point YV2, where the measurement frequency is 20 samples/year. The analysis of these data shows a significant inter-annual variability in the flux of P entering the lake (Figure 4), which is related to interannual variations in water flow and precipitation. Expressed in Kg of P per hectare (ha) and per year, P flux values vary between 0.1 (2017) and 1.1 (2014), with a mean value over the period of 0.23 KgP/ha/year. It should be noted that this flux places the Yvel-Hivet river in the category of rivers exporting the least P within the rivers of Brittany, even if the recorded P flux remains well above the eutrophication threshold of lentic water bodies such as the Lac au Duc.

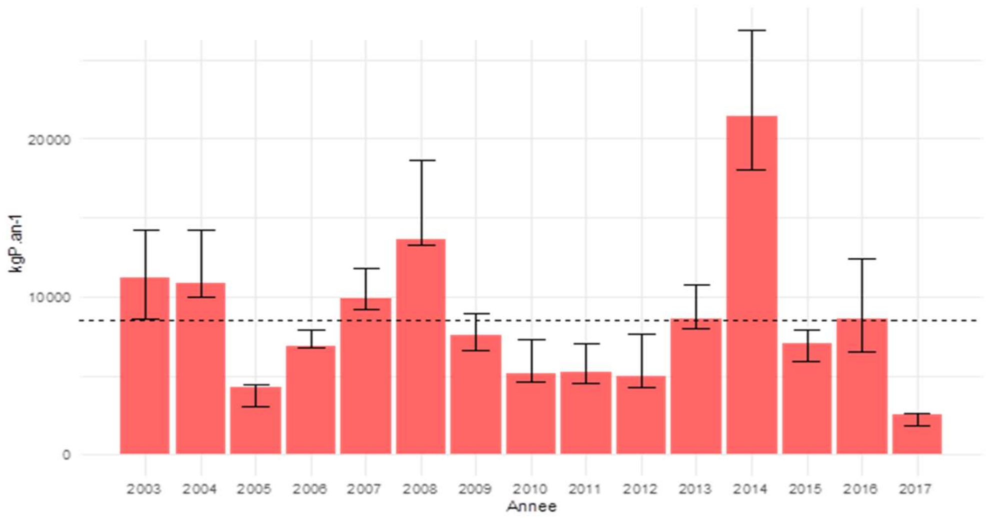

***Figure 4**- Annual flux of P calculated at the Lac au Duc inlet over the period 2003 - 2017. The average annual flux over the period is 8506 Kg.P.yr^{-1}.*

No upward or downward trend is detectable in this P flux over the considered period (Figure 4). This means that the average annual flux of P of 0.23 KgP_{total}/ha/year calculated between 2003 and 2017 can be seen as the average value of the annual flow entering Lac au Duc today. Divided by the average water flow, this average annual flux corresponds to an average annual P concentration weighted by the lake inlet water flow of 0.100 mg/l. This value can be taken as the guide concentration corresponding to the state "0" of the lake before any new action plan to reduce P inputs from the catchment. It should be noted that the absence of decreasing trends in P fluxes and concentrations is very different from the nitrate situation, where lake inlet concentrations decreased by a factor of 2 between 2007 (average NO_3 = 40 mg/l) and 2017 (average NO_3 = 20 mg/l). It should be also noted that the P entering the lake is >80% $P_{particulate}$.

Two measurement campaigns were carried out as part of the CPES project during the summer of 2018 upstream and downstream of the main treatment plants in the Lac au Duc catchment to estimate the P fluxes (P_{total} and P_{PO4}) emitted by these plants. The results obtained were compared to the self-monitoring data provided by the operators of these stations to the SMGBO, the whole being used to quantify the share of point-source (domestic) and diffuse (agricultural) inputs in the total P flux entering Lac au Duc. The flux of P of domestic/industrial origin is estimated by this method at **0.018 KgP/ha/year**, i.e. about 10% of the total flux entering the Lac au Duc, thus returning **the vast majority of this flux (90%) to diffuse emissions of agricultural origin**. It should be noted that 80% of the domestic/industrial point-source flux consists of the dissolved form P_{PO4}. It should also be noted that this result of 90% of the total P flux entering the lake of diffuse agricultural origin is an average feature hiding strong seasonal disparities. In summer, the domestic/industrial point-source flux indeed largely takes over, due to the hydrological disconnection of agricultural sources from the river network. Nevertheless, the impact remains limited, as the total flux of P entering the lake at this time of year is very low (Figure 5).

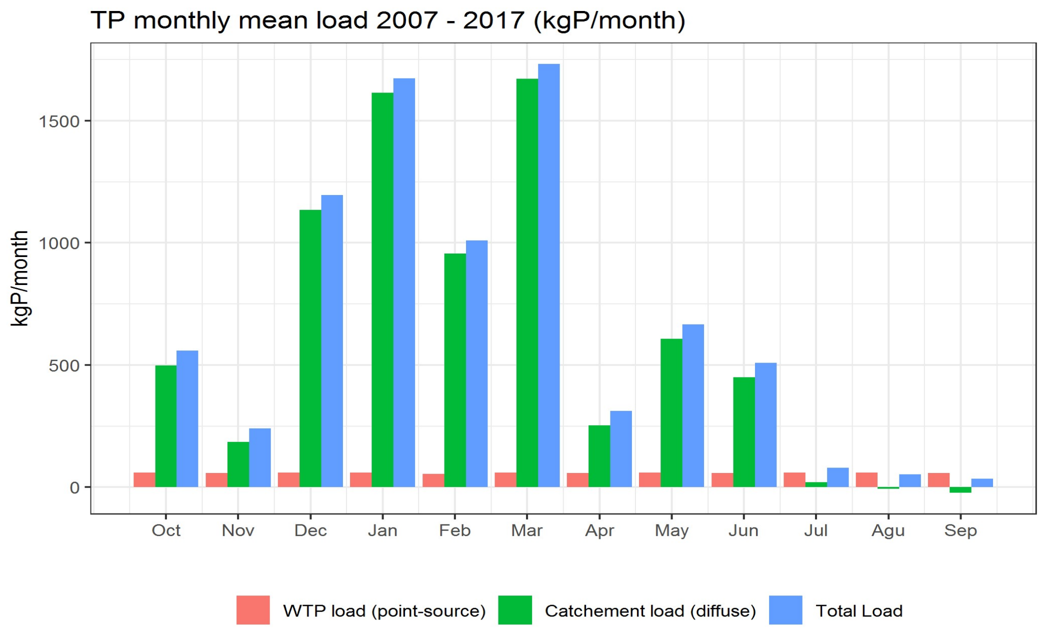

***Figure 5** : Variations on a monthly basis in the loads of P entering Lac au Duc from diffuse, agricultural sources and point, domestic and/or industrial (WTP) sources, in relation to the total P load.*

In order to assess whether a sectorization of agricultural P diffuse emissions exists within the Lac au Duc catchment with the corollary of targeting PES implementation to the most emitting areas, the Lac au Duc catchment was divided into 25 sub-catchments at the outlets of which monitoring of P_{total} and P_{PO4} concentrations was carried out between March 2018 and July 2019. A total of 31 sampling campaigns were carried out as part of the CPES project, providing a mapping of the spatial variability of diffuse agricultural P emissions in the catchment. The results show significantly higher fluxes (by a factor of 1.5 on average) in the central and southern parts of the catchment, compared to the slightly less P-emitting northern part (Figure 6). This distribution is consistent with the existence of thicker soils (and thus possibly more infiltrating) in the northern part compared to the central and southern part of the catchment (Loyat, Guilliers, Néant sur Yvel, Mauron sectors) where the soils are thinner and thus probably more conducive to P transfer by runoff. These results tend to suggest that targeting PES to reduce diffuse emissions of agricultural P in the south-central part of the catchment could have a maximum effect on the reduction of P fluxes at lake entrances.

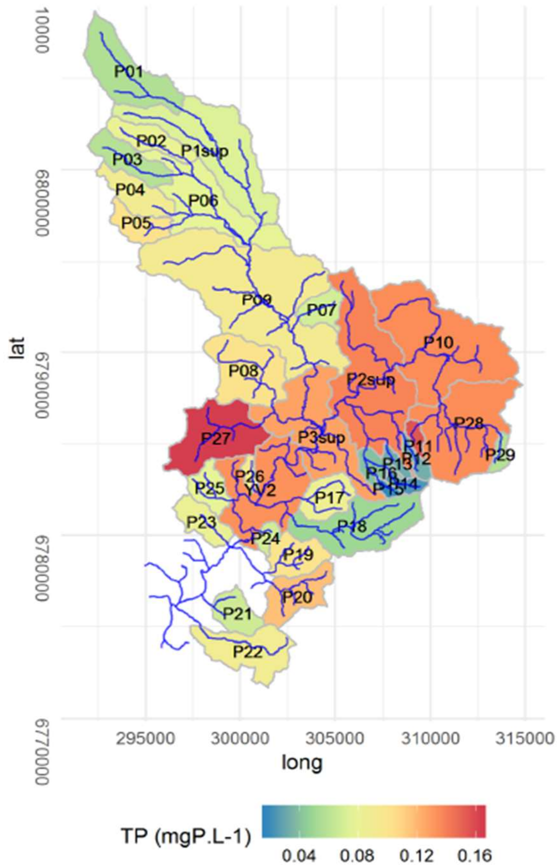

Figure 6. *Distribution map of P-weighted water flow concentrations in the heads of the sub-catchments making up the Lac au Duc catchment, showing higher concentrations in the central and southern parts of the catchment, compared to the northern part.*

2.b-Analysis of the seasonal dynamics of phytoplankton and nutrients in the lake

Plankton and nutrient (P and N) dynamics were analyzed over a complete seasonal cycle (2018-2019) at the inlet, middle and downstream of the lake. The three stations showed very similar levels and dynamics of nutrient concentrations (Figure 7A), with total nitrogen, total dissolved nitrogen and nitrate-nitrite showing maximum concentrations in winter, while P_{total}, total dissolved P and orthophosphate concentrations were highest in summer. Total nitrogen concentration ranged from 0.8 mg N-NO_3^- L^{-1} in summer to 10.3 mg N-NO_3^- L^{-1} in winter. Total P concentrations were near or below the limit of quantification (0.019 mg PL^{-1}) from January to May, but reached 0.3 mg PL^{-1} by the end of summer 2018. This contrast in seasonal dynamics may be related to intense denitrification processes in summer combined with the release of P from sediments while there is very limited water entering the lake (Søndergaard et al. 2002, Dolman et al. 2016). From June to December, total P was mainly composed of particulate P. These high concentrations of P classify Lac au Duc as of poor water quality or hypereutrophic (see Table 1). These high concentrations coincide with the period when the river's inflow to the lake was reduced or stopped, and probably originate in the sediments that serve as an intermediate storage reservoir for the P brought by the river.

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***Figure 7**. A) Nutrient concentrations at the inlet, middle and lower basin of the lake during the 2018-2019 seasonal cycle. TN: total nitrogen; TDN: total dissolved nitrogen; TP: total phosphorus; TDP: total dissolved phosphorus. Shaded area: limit of quantification.*
B) Phytoplankton dynamics during the same period and at the same locations in the lake.

Phytoplankton dynamics also appeared very similar at the entrance, middle and downstream parts of the lake during the same period (Figure 7B). There were no cyanobacteria in winter and spring, while cyanobacteria dominated the phytoplankton community by 70-100%, first from June to December 2018 and then from June to August 2019. An interesting feature of the seasonal cycle is the high inter-annual variability observed between the summers of 2018 and 2019: while cyanobacterial blooms reached 1.5 million cells mL^{-1} in 2018, they were a factor of 10 lower in 2019.

The eukaryotic phytoplankton community (other genera and species constituting phytoplankton in addition to cyanobacteria) ranged from 200 mL^{-1} cells in winter to 72,000 mL^{-1} cells in early summer (July 2018). Chlorophytes dominated this community by 60-92% most of the year, except in the spring (March-May) when diatoms accounted for 30-60%. In contrast to a common pattern of higher densities in summer than in winter, the three stations monitored differed in the abundance of the zooplankton community, with abundances 5 times lower than those observed in the middle and lower part of the lake. The composition of the zooplankton in Lac au Duc is typical of eutrophic water bodies, with a dominance of small taxa to the detriment of larger ones, such as the Daphnids (Neuvalainen and Luoto 2017).

2.c- Evaluation of climatic and nutritional factors on cyanobacterial dynamics

Analysis of the 13 years (2007-2019) of cyanobacterial dynamics within Lac au Duc has revealed a strong inter-annual variation not only in the density but also in the nature of the dominant strains (Fig. 8). Whereas up to 2013, the cyanobacterial community was dominated by *Plankthothrix agardhii* (functional group S1), species of the genus *Microcystis* (mainly functional group M: *M. aeruginosa*) became dominant from 2013 onwards, despite low densities in 2013, 2015 and early 2019, accompanied in some years by a codominance of *Dolichospermum* sp. (2017, 2018 and 2019). Microcystin and saxitoxin toxins were only measured in the second part of the time series, from 2013 onwards, and each time in low concentrations (< 2 µg L^{-1}). This appearance coincided, each time, with the presence of *Microcystis* sp. and *Dolichospermum* sp. This change in dominance of cyanobacteria in 2013 can be clearly attributed to a change in climatic and hydrological conditions: before 2013, with the exception of 2009, summers were characterised by strong and frequent winds, whereas since 2013, summers have been generally warmer, sunnier and drier.

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Figure 8*. Abundance of functional groups of cyanobacteria (in biovolume) and concentrations of toxins in the downstream part of Lac ay Duc between 2007 and 2019. The functional groups are those developed by Reynolds (2002) and Padisak (2006).*

In fact, *P. agardhii* is known to develop during windy summers, this taxon of the genus *Planktothrix* being tolerant of the low average light conditions characteristic of turbid mixed waters (Van Liere and Mur 1980, Reynolds 2006). Indeed, thanks to their specific accessory pigments, phycobilins of the genus *Planktothrix* are efficient light catchers (Kurmayer et al. 2016). This predominance of *P. agardhii* before 2013 is not specific to Lac au Duc. The same predominance is observed for all water bodies in Brittany (Pitois et al. 2014).

Although *Planktothrix* sp. are known to form toxic blooms in temperate freshwater ecosystems (Sivonen and Jones 1999, Paerl and Huisman 2009), no microcystin was detected in blooms of *P. agardhii* in Lac au Duc. It has been shown that populations of *P. agardhii* in natural blooms can be composed of microcystin-producing and non-microcystin-producing genotypes, and that the proportion of each can vary considerably within an efflorescence (Kurmayer et al., 2004; Briand et al. 2008).

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Figure 9. *Canonical Correspondence Analysis (CCA) showing how environmental parameters select the groups of cyanobacteria present in summer in Lac au Duc. The data compiled are those of blooms from 2007 to 2019. ResTim: water residence time. Wind: wind intensity. Light: light intensity. NO3: nitrate content. The functional groups used are those developed by Reynolds (2002) and Padisak (2006): M: dominated by Microcystis sp; H1: dominated by Dolichospermum sp; S1: dominated by Planktothrix agardhii; H1aph: dominated by Aphanizomenon sp; K: dominated by Ahanothece and Aphanocpasa.*

Since summer 2013, the dominance or co-dominance of *Microcystis* sp. and *Dolichospermum* sp. is linked to generally calmer wind conditions which can lead to longer periods of stratification of the water column, even in a shallow lake such as Lac au Duc. In particular, the presence of *Microcystis* sp. appears to be strongly correlated with light intensity and temperature (Figure 9). These two genera take advantage of the stability of the water column by using their buoyancy to concentrate their population in the illuminated zone near the surface of stable lakes (Huisman et al. 2004, Li et al. 2016). The co-dominance of *Dolichospermum* sp. can be explained by the fact that this genus is able to fix and transform dinitrogen (N_2) from the atmosphere into a bioavailable form of nitrogen, which gives this cyanobacterium an ecological advantage in aquatic environments without nitrogen (Reynolds et al. 2006) as it was the case in Lac au Duc in 2018 (Figure 7A).

However, there is increasing evidence that N_2 fixation is not sufficient to significantly compensate for N deficiency in the aquatic environment (see e.g. Scott & Grantz, 2013, Kolzau et al. 2018, Shatwell and Köhler 2019), pointing out that the reduction of cyanobacterial blooms in a lake such as Lac au Duc requires first and foremost a reduction in N and P inputs from the catchment area.

What to remember

Background

The collection and processing of the results of the water quality monitoring carried out since 2007 on the Lac au Duc catchment has made it possible to estimate the annual flow of P entering the lake at **0.23 KgP/ha**, i.e. approximately **9 tonnes of P per year**. This flux corresponds to a water flow-weighted annual average concentration of the water entering the lake of **0.100 mg/l of P**. This concentration represents the state "0" of the lake from which to define an objective of reduction of the P flux entering the lake and to build a PES mechanism to reach this objective.

The monitoring carried out as part of the CPES project at the outlet of treatment plants discharging P into the catchment combined with the self-monitoring data provided by the operators of these plants show that the **share of agricultural diffuse P emissions represents about 90% of the total P emissions entering the lake**, confirming the hypothesis that the reduction efforts should focus primarily on the reduction of the diffuse P emissions from farms set up on the catchment.

The monitoring at the outlets of the 25 defined upstream sub-catchments in the framework of the CPES project shows that **agricultural P emissions are significantly higher in the central and southern parts of the catchment**, advocating in favour of **targeting PES as a priority in these parts of the catchment**.

Concerning the dynamics of the nutrients in the lake, the monitoring conducted in the framework of the CPES project shows that the concentrations of total nitrogen, total dissolved nitrogen and nitrate-nitrite are maximum in winter, those of **total P, total dissolved P and phosphates being on the contrary maximum in summer, most probably due to the release from the P stock in the sediment**. Phytoplankton dynamics have been very homogeneous within the lake during the 2018-2019 seasonal cycle, with a bloom of **cyanobacteria reaching a maximum of 1.5 million cells mL^{-1} in 2018**. The 2019 bloom was a factor of 10 less intense, demonstrating the enormous inter-annual variability in phytoplankton dynamics.

Analysis of the chronicles of cyanobacteria populations available since 2007 has revealed a **strong variation not only in density, but also in composition and dominance of cyanobacteria** strains. While ***Planktothrix*** sp. dominated the blooms until 2013, coinciding with **cool and windy summers**, the **shift to hotter and drier summers**, coupled with a decrease in nitrogen load led to a dominance of ***Microcystis* sp. and *Dolichospermum*** sp.

These investigations on the dynamics of nutrients and cyanobacteria populations, and the understanding of the factors behind the variations observed in the density and composition of cyanobacterial blooms were conducted by the full-time employed post-doctoral student (Morgane Le Moal). A publication is being finalised for submission to an international journal before the end of the year.

From the point of view of the tools/methodologies to be mobilized to deploy a PES mechanism targeting the reduction of P

Two types of tools/methodologies have been constructed/validated:

1-A methodology to locate diffuse emissions of agricultural P in catchments and to prioritise or implement PES to obtain the best environmental efficiency.

2-A methodology to decompose the share of agricultural diffuse emissions and domestic/industrial point emissions in the total P flow.

It should be noted that this part of the work, in particular the monitoring of the 25 upstream sub-catchments, required 18 months of work and mobilised a full-time post-doctoral student (Sen Gu) and part of the working time of a doctoral student (Antoine Casquin) paid for by the CPES project. The results were promoted through a publication in the journal Science of the Total Environment (Casquin et al., 2020); another publication was submitted to the journal Water Ressources Research (Gu et al., submitted). A third publication (Casquin et al., in prep.) is being finalised for submission to an international journal before the end of the year.

2.d-Calibration of the emissions reduction target to lake uses

The objective of restoring / perpetuating the uses of Lac au Duc involves relating the trophic state of the lake to the fluxof P entering the lake, or the average concentration of P at the lake entrance. Establishing this link is a crucial step in the construction of PES which are supposed to improve the ecological state of the lake. It should be noted that this linkage is very different from PES studies where the target is directly to lower a content below a regulatory threshold. Here the target is more complex since it is aimed at the ecological status of the lake and the services that the lake provides, depending on its ecological status.

Not all authors agree on the P content to be retained to qualify the trophic levels and the ecological state of shallow reservoirs of the Lac au Duc type (Table 1). We have chosen here to use the most permissive thresholds (highest P contents; Søndergaard et al. 2005), with a view to limiting as much as possible the effort to be made to reduce the flow of P at the entrance to the lake.

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Parameter	Reference source	Ultra-oligotrophic	oligotrophic	Mesotrophic	Eutrophic	Hyper eutrophic
Ecological strate		Excellent	Good	Medium	Poor	Very poor
Total phosphorus (µg/l))	1	[c]<5	5<[c]<10	10<[c]<30	30<[c]<100	100<[c]
	2	[c]<15	15<[c]<30	30<[c]<50	50<[c]<75	75<[c]
	3	[c]<25	25<[c]<50	50<[c]<100	100<[c]<200	200>[c]
chlorophyll a (µg/l))	1	[c]<2,5	2,5<[c]<8	8<[c]<25	25<[c]<75	25<[c]<75
	2	[c]<10	10<[c]<20	20<[c]<30	30<[c]<50	50<[c]
	3	[c]<5	5<[c]<11	11<[c]<21	21<[c]<55	55>[c]
Transparency to Secchi disk (m)	1	6<[T]	3<[T]<6	1,5<[T]<3	0,7<[T]<1,5	[T]<0,7
	2	3<[T]	3<[T]	2<[T]<3	1<[T]<2	[T]<0,9
	3	2<[T]	1,5<[T]<2	1<[T]<1,5	0,8<[T]<1,0	[T]<0,8

Table 1 : Relationship between total P content and trophic/ecological status in the case of shallow water bodies. 1 : Nemery, 2018 ; 2: Moss et al., 2013, 3 : Søndergaard et al., 2005.

A link was then established between P concentration, trophic level/ecological status of Lac au Duc and services/uses provided by this lake (Table 2). This link was made by experts and is therefore subject to challenge or revision. The ultra-oligotrophic trophic state ([C] in P < 25 g/l) is seen as the state providing the strongest guarantee of the permanent supply of the "bathing" service by the lake, and therefore by consequence of all the other services (fishing, nautical activities), the bathing service being considered as the most constraining, both from the point of view of the health risk that poor water quality generates and from the point of view of the strong requirement to reduce the concentrations of P that it imposes at the lake entrance. It should be remembered that in

France, legislation sets a concentration of 100,000 cyanobacterial cells per ml as the maximum authorised concentration for bathing and Lac au Duc experiences peaks in cyanobacteria concentrations of up to 2 million cells per ml (see Figure 1). It should be noted that the guarantee of the uses listed in Table 2, if it involves reducing the flux of P entering the lake, also involves a reduction in the internal load of the lake with P contained in the sediments. This reduction in the internal load will necessarily take time, hence the importance of setting up curative actions allowing access to the uses while waiting for the lake to purify itself in P in relation to the reduction in P fluxes entering the lake.

Content in total P (µg/l)	Ecological state	Guaranteed uses
[c]<25	Excellent	Bathing, fishing, natical activities
25<[c]<50	Good	Fisching, nautical activities
50<[c]<100	Medium	Nautical activities
100<[c]	Poor/very poor	None

Table 2 : Relating the P contents to be aimed at the entrance to Lac au Duc to guarantee this or that use/service provided by this lake.

On the basis of this comparison of the services rendered by the lake with the P concentration thresholds not to be exceeded at the lake entrance, it can be seen that the current annual average concentration of 100 mg/l measured at the entrance of the Lac au Duc classifies this lake in the poor/very poor category and requires a reduction of this concentration by a factor of at least 4 to make it fall into the very good category guaranteeing the delivery of all the uses it can provide, including the most restrictive use which is bathing.

What to remember

Background

The scientific literature situates the water quality requirement at the entrance of the Lac au Duc at an average concentration of P < 0.025 mg/l if this lake is to be able to deliver all the uses for which it is intended, including the most restrictive use from a water quality point of view which is bathing.

Given the current average lake inlet concentration of 0.100 mg/l, the objective to be assigned to a PSE mechanism set on the lake catchment is therefore to reduce the influx of P into Lac au Duc by at least a factor of 4.

From the point of view of the tools/methodologies to be mobilized to deploy a PES mechanism targeting the reduction of P

Two types of tools/methodologies have been constructed/validated:

1- Bibliographical references to link P content and trophic status in the context of shallow reservoirs;

2- An expert grid to set an objective for reducing the flux/concentration of P according to the use(s) of the shallow reservoirs that we wish to restore/perpetuate.

This part of the work was carried out by a post-doctoral student (Morgane Le Moal) paid by the CPES project.

2.e- Technical means that can be mobilized to reduce agricultural diffuse P emissions from the catchment

Soil P content and runoff at the soil surface are, according to experts and the scientific literature, the two main factors/mechanisms controlling the intensity of diffuse emissions of agricultural P in catchments (Sharpley et al., 2015; Kleinman, 2015; Daryanto et al., 2017). On this basis, three main levers of action appear to be likely to achieve the objective of reducing diffuse P emissions at the entrance of Lac au Duc. These levers or technical attributes include 1) stopping mineral phosphate fertilisation; the aim here is to reduce the size of the agricultural P reservoir at its source, i.e. at ground level; 2) the establishment of permanent plant cover; the aim here is to reduce the energy of rainfall on the ground while improving the structural stability of the soil, two factors which are known to reduce the capacity of rainfall events to trigger runoff phenomena conducive to the transfer of agricultural P from the soils to the hydrographic network ; and 3) the installation of anti-erosion hedges, perpendicularly to the slope at the edge of the plot; the aim here is to intercept the erosive flux before it reaches the watercourse, in the hypothesis that it would still be generated in spite of the installation of permanent plant cover.

Concerning the current situation of the Lac au Duc catchment with regard to these attributes, it should be noted that the average density of hedgerows is 70m/ha, of which only 30% have a proven anti-erosive role. It should also be noted that mineral phosphate fertilisers are used, notably as starter fertiliser for maize cultivation, and that P balances remain in surplus for about 50% of the farms (especially in the southern part of the catchment area), the surplus being partly caused by the addition of mineral P fertiliser. Finally, it should be noted that under-cover sowing to ensure permanent soil cover is practised on certain plots of the catchment, although this practice is for the moment totally excluded from the maize plots, which represent between 20 and 25% of the agricultural land of the catchment depending on the year.

Including these three technical attributes in a PES mechanism aimed at restoring the good ecological status of Lac au Duc implies quantifying a priori the capacity of each attribute to contribute to achieving the objective of reducing the P flux set at the lake entrance, i.e. a division by a factor of at least 4 of the current flow. This a priori evaluation of the impact of the attributes on the reduction of emitted fluxes was carried out by plot modelling for the fertilizer and permanent plant cover attributes. This modelling of the expected impact of adopting these two attributes (no input of mineral P fertilisation and permanent plant cover implementation) was carried out using the Annual Phosphorus Loss Estimator (APLE) model of the US Department of Agriculture (https://data.nal.usda.gov/dataset/aple-annual-phosphorus-loss-estimator-tool; Vadas et al, 2012). The model uses several input data that need to be entered in order to run it, namely soil characteristics (depth, clay and organic matter content, extractable P content), rainfall, runoff and erosion rate, organic and mineral P inputs, and finally P exports by crops. The output of the model is the P losses by runoff and erosion, distinguishing between dissolved and particulate forms of P. The impact of stopping mineral fertilization can be simulated by assigning a value of 0 to this input of the model. The impact of establishing a permanent vegetation cover on the erosive flux of P can be simulated by playing on a particular parameter of the model called the "c" factor, which integrates the type of cover and tillage. By construction, this "c" factor can lead to a maximum decrease in the erosive flux by a factor of 5, compared to an initial situation without cover. In this study, the choice was made to use this maximum value of 5 as a base value to simulate the effect of the establishment of a permanent vegetation cover on the reduction of P fluxes entering the Lac au Duc.

Concerning the impact of anti-erosion hedges, no model could be found in the literature to simulate the effect of their installation on the erosive fluxes of P. Hypotheses therefore had to be put forward. The bias adopted here was to attribute an arbitrary flux retention factor of 50% for a 100 m anti-erosion hedge located downstream of a 1 ha plot, this retention factor decreasing linearly and proportionally with the decrease in hedge length.

In the end, the reduction of the erosive flux of P emitted by the catchment according to the appropriation of the three technical attributes proposed to the farmers was simulated by comparing the current erosive flux (current flux) calculated by the APLE code and weighted by the current average density of anti-erosion hedges existing in the basin, with the erosive flux simulated ($Flux_{simulated}$) by the same APLE code by adopting the attributes stop mineral fertilisation and establishment of a permanent plant cover, the result being then weighted by the effect of the establishment of a line of anti-erosive hedges. The $F_{actual}/F_{simulated}$ ratio obtained at the end gives the reduction factor of the lake intrance flux expected due to the adoption by the farmers of the three proposed attributes.

Several flow reduction scenarios were tested. To do this, a typology of the plots of the catchment of Lac au Duc was conducted, taking as variables of this typology the depth of the soil, the land use, the rotations, the erosion risk, etc... From this typology, gradations in the implementation of anti-erosion measures were proposed, leading to variations in the P flux reduction factor at the lake entrance. In the end, the output variables of the simulation are the percentages of plots of each type on which permanent vegetation cover and a line of anti-erosion hedges are to be planted, as well as the location of these plots in the catchment, these percentages and location varying according to the flux reduction objective (see Figure 10).

2.f- Means that can be mobilized to rapidly reduce the intensity of cyanobacterial blooms in the short-term (curative actions)

Approaches to combating eutrophication of lakes and dam reservoirs can be divided into two main categories: those acting in the long term on the causes (nutrient inputs from the catchment area); and those acting in the short term (curative) on the most damaging consequences for uses, in this case cyanobacterial blooms. These curative actions can only constitute temporary solutions, developed on a case-by-case basis, with the aim of improving or restoring certain uses (drinking water purification, maintaining recreational activities, etc.). The techniques used include are physical, chemical or biological levers (Pearl et al. 2016) with, in all cases, the same objective: to directly reduce algal biomass either by using algicides or by modifying factors that promote their development: nutrient availability, water stratification, food web structure, etc.

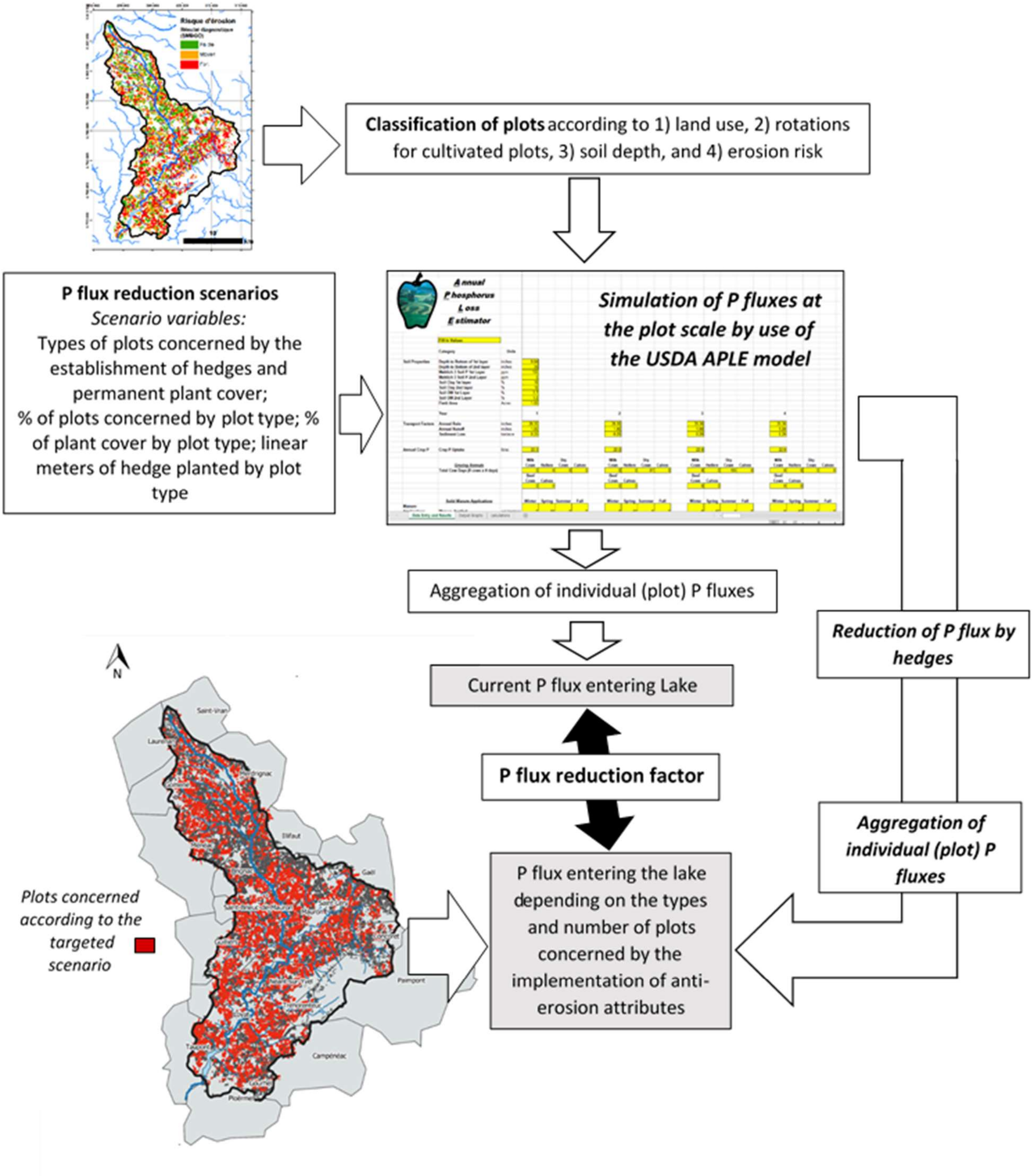


Figure 10 *- Logical flow chart used to simulate the effect of permanent plant cover attributes and anti-erosive hedges on the reduction of P flow at the entrance to Lac au Duc.*

The physical levers are based on reducing the residence time of the water, destratifying the water column, or disconnecting or removing the sediments storing P. In the case of Lac au Duc, there is no sufficiently large upstream reservoir to influence the residence time of the water during cyanobacterial blooms. Favouring the artificial renewal of the water could, on the other hand, be envisaged on a smaller scale, such as the bathing area. Concerning destratification, an air injection system was installed in the lower basin of the lake in 1994, near the pumping point of the drinking water purification plant. This aeration limited the release of reduced compounds harmful to the production of drinking water (NH_4, Fe, Mn, NO_2; Saunier-Techna, 2002) by oxygenating the water-sediment interface. However, this partial aeration had no impact on the development of cyanobacteria on the entire body of water (Luc Brient pers. com.). Concerning the elimination of the stock of P contained in the sediments, a study has estimated the cost at 20 million euros for sediment removal (Austruy 2012). This operation has never been realized, as the cost was considered too high.

A chemical method based on the addition of calcium carbonate was implemented between 2013 - 2015 in or near the bathing area, with the aim of precipitating the P in the form of insoluble calcium phosphate. Although the years 2013-2015 correspond to a decrease in the intensity of cyanobacteria blooms compared to years such as 2011 and 2012, densities nevertheless exceeded the health threshold above which bathing is prohibited in France (100,000 cells/ml).

The use of algicides is another possibility, as these products directly destroy the cyanobacteria. Copper sulphate spraying was carried out from 1996 to 2005 (Austruy, 2012; L. Brient, Y. Seyrig pers. comm.) with convincing effects judging by the low densities observed in those years (Figure 1). However, the use of copper sulphate is nowadays prohibited, as copper accumulates in the sediment and in the food web, preventing the use of this method.

The use of hydrogen peroxide (H_2O_2) appears to be a more acceptable alternative (Matthijs et al. 2016) due to its rapid degradation to water and oxygen. Unlike copper which accumulates in the sediment, H_2O_2 leaves no chemical traces in the environment. Furthermore, at low doses, it seems to be selective against cyanobacteria, causing few known severe effects on eukaryotic algae and aquatic fauna and flora. Its effect on micro-organisms naturally present in water and sediments with their role in recycling nutrients is however still unknown. **Within the framework of the CPES project, the use of H_2O_2 was tested in the laboratory and then in the natural environment in a delimited zone of the Lac au Duc corresponding to the bathing area**, as a possible curative solution pending the self-purification of the lake following the cessation of inflows from the catchment area (see below).

Concerning biological methods, a biomanipulation approach could limit the predation of fish on zooplankton, thus favouring the role of the latter as a predator of phytoplankton (and therefore cyanobacteria), but these manipulations have the shortcoming that they must be repeated over time. Another biological action could be to promote the growth of macrophytes in order to create competition with the phytoplankton for phosphorus and/or to allow the export of nutrients out of the lake, by mowing and exporting macrophytes. Even if a development of reeds and yellow water lilies has been observed for several years in the upstream part of Lac au Duc, this part of the lake is too small (approximately 4,000 m²) to envisage the capture and elimination of the quantities of P entering the lake (see paragraph below "Costs linked to the use of the natural purification capacity of P").

Application of hydrogen peroxide (H_2O_2) as a curative method for Lac au Duc

During the summer of 2018, curative H_2O_2 treatments were applied to the lake water, with an evaluation of the effect of this treatment on the phytoplankton and zooplankton communities evaluated both in the laboratory and in a 3,000 m² delimited area of the lake located in the bathing area.

In lake water incubated in the laboratory without H_2O_2, the biomass of cyanobacteria increased continuously during the 10 days of the test (Figure 11). If the same water was treated with H_2O_2, a strong increase in phycocyanin was observed on day 1, followed a rapid decline, indicating a destruction of the cyanobacterial cells (Figure 11). Cell counts confirm the growth of cyanobacteria without H_2O_2, and their decay if H_2O_2 is added. The treatment is effective under laboratorial conditions as soon as 2.5 mg/L H_2O_2 is added, allowing a reduction in cyanobacterial concentrations below the threshold of 100,000 cells/ml for a period of at least 9 days (Figures 11 and 12). Moreover, the eukaryotic microalgae community does not appear to be affected by H_2O_2 treatments, on the contrary, it increases in densities. The zooplankton community, however, is affected (Figure 12) with a three-fold decrease in abundance between treated and untreated aquariums.

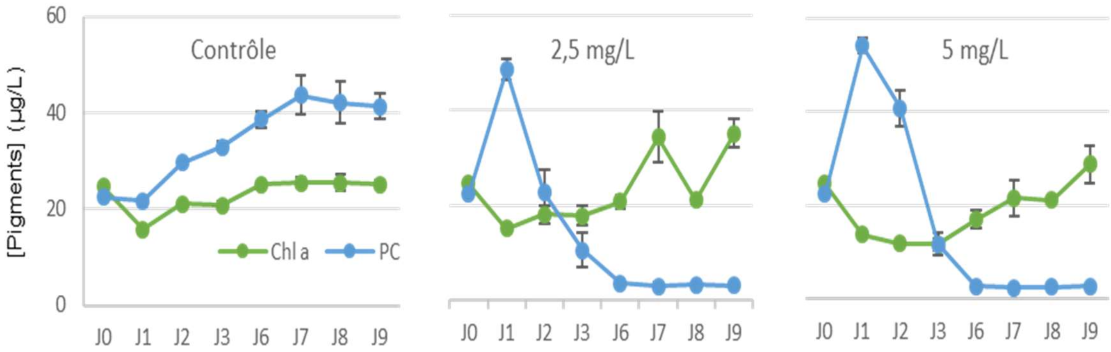


Figure 11. Results of tests conducted in the laboratory on Lac au Duc water taken on 11 June 2018 and incubated for 9 days at different H_2O_2 concentrations. In green, the concentration of chlorophyll a, which makes it possible to estimate the biomass of total phytoplankton; in blue, the concentration of phycocyanin, a pigment characteristic of cyanobacteria, which makes it possible to estimate their biomass.

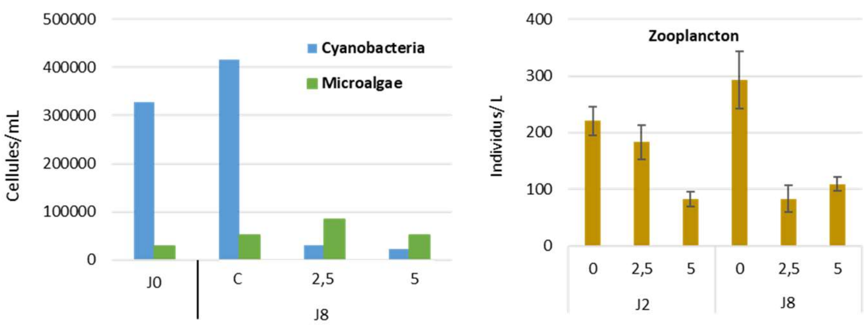


Figure 12. Abundance of phytoplankton (cyanobacteria and micro algae, left) and zooplankton (right) at the beginning (D0) and end (D8) of the experiment, in aquariums without treatment (C) and with treatment (2.5 and 5 mg/L of H_2O_2).

In parallel to the laboratory experiments, a field trial was experimented directly in the lake in the summer of 2018. An area was delimited by installing a waterproof plastic enclosure in the swimming area. Four successive treatments with hydrogen peroxide were applied in this area, with the area outside the enclosure serving as a control zone without treatment. **The hydrogen peroxide treatment significantly reduced the cyanobacteria populations** (division by factors of between 3 and 8), confirming the potential of the method.

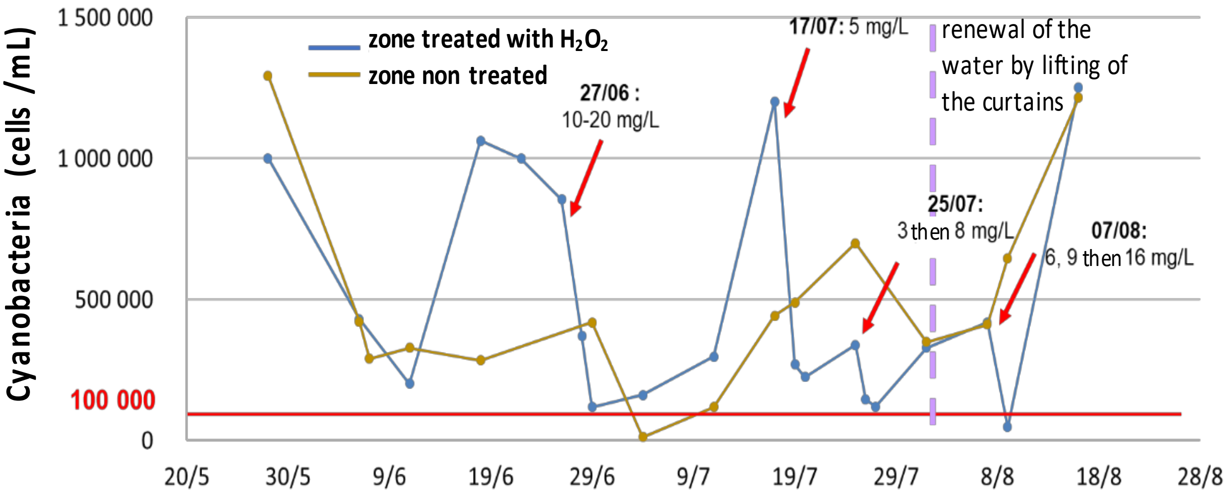


Figure 13. Abundance of cyanobacteria in the H_2O_2-treated lake area and in the untreated control lake area.

However, with the exception of the 4th treatment, these **reductions were not sufficient to permanently drop the cyanobacteria below the 100,000 cells/ml threshold**, despite the high concentrations and/or successive sprays applied on the same day. Probably the **peroxide was consumed too quickly, disappearing in 6 hours**, whereas in experiments on other water bodies conducted by the company providing the H_20_2 (Arcadis) and the University of Rennes 1, it disappeared only after 48 hours (Brient L. and Arcadis, pers. com., Matthijs et al. 2016). This very rapid disappearance in the case of Lac au Duc could be **linked to the presence of a high load of soluble and particulate organic matter** (other than cyanobacteria) in the water column, probably linked to a resuspension of the sediment in the shallow bathing area. Another possibility to explain this rapid disappearance of H_2O_2 is a leak in the enclosure separating the treatment area from the untreated lake.

The treatment nevertheless allowed the bathing area to be open for 18 days.

Curative actions are aimed at treating the effects (cyanobacterial blooms) but not their cause (P input from the catchment area). Their deployment is however necessary until the excess P brought to the lake or enclosed in the sediments is eliminated. These costs that must be taken into account (see Table 6 below "Summary of the costs generated by the poor water quality of Lac au Duc").

What to remember

Concerning possible measures reducing the input of agricultural P

Three measures can be envisaged to reduce emissions of agricultural P, the main sources of P entering Lac au Duc, without damaging production systems and farm structures:

1- Stopping mineral phosphate fertilisation (objective: to reduce the size of the soil's P stock);

2- Setting up permanent plant cover (objective: to limit soil erosion during rainy periods);

3- The installation of anti-erosion hedges, perpendicular to the slope at the plot boundary (objective: to capture the erosive flow before it reaches the watercourse, assuming that the installation of permanent plant cover would not sufficiently prevent the runoff).

From the point of view of the tools/methodologies to be mobilized to deploy a PES mechanism targeting the reduction of P

A main type of tool/methodology has been constructed/validated. It consists of a methodology to simulate the impact of the establishment of permanent plant cover and anti-erosion hedges on the reduction of P flow in watersheds. This methodology combines GIS approaches to classify plots into major types from the point of view of emission risk, with the simulation of P flux to the plot using the USDA's APLE model. This is an expert approach that does not simulate the real P flux but the reduction of the flow according to the plot location rate of the attributes that are supposed to reduce this flow, and the location of the plots in the catchment.

This part of the work was carried out by the Master 2 student Maixent Houenou - Hounsinou assisted by the doctoral student Antoine Casquin paid by the CPES project.

Concerning the need to deploy curative actions while waiting for the effect of preventive actions

The implementation of actions aimed at reducing the input of agricultural P from the catchment area will be delayed in terms of the quality of the waters of the Lac au Duc due to the presence of an internal stock of sediments rich in P. It is therefore advisable to be ready to deploy curative solutions in the event of the occurrence of major cyanobacteria blooms.

Various techniques have already been tested for this purpose in the Lac au Duc: air injection at the water-sediment interface to limit vertical transfers of P; addition of calcium carbonate to immobilise P; spreading of copper sulphate to directly eliminate cyanobacteria. As part of the CPES project, the use of hydrogen peroxide (H_2O_2) was tested both in the laboratory and directly in situ in the lake's bathing area. Although the laboratory test phase gave good results at low H_2O_2 concentrations, the application directly to the lake water gave contrasting results, allowing bathing for only 18 days, which is insufficient for a normal tourist season.

This part of the work was carried out by the post-doctoral student Morgane Le Moal paid by the CPES project and by the Master 2 student Emilian Mineaud.

3- Dimensioning of the agricultural offer of PES

3.a- Quantification of Farmers' Consent to Receive (FCR) at the farm level

The aim is to determine the price of the technical attributes identified from the farmers' point of view. This will enable to monetarily quantify the offer likely to be made by the farmers of the Lac au Duc catchment in terms of environmental services (in the sense of actions making it possible to improve the functioning of the catchment/lake ecosystem) in order to improve/restore the uses/services provided by the lake.

To determine these prices, the method used was the choice experiment method, i.e. implementing experiments in which several PES scenarios are proposed to farmers of the Lac au Duc catchment in face-to-face surveys. These surveys also collected information on the sociology of farmers and the typology of their farms. The surveys proposed four levels of plant cover (20, 40, 60 or 80% of the agricultural land), coupled or not with three levels of anti-erosion hedges (40, 70 and 100 m per ha of agricultural land). The "phosphate mineral fertiliser" modality was included as authorised or prohibited modality. Two contract duration modalities and four remuneration modalities per ha of UAA were proposed (100, 200, 300 and 400€). It should be noted that the proposed PES are system PES, i.e. covering the entire agricultural land of the farm even if the proposed technical attributes are only implemented on part of the agricultural land. The surveys were conducted by 6 investigators. In the end, 52 farmers responded out of a total of 400 calls.

Statistical processing of the results showed that the mineral fertilizer attribute was not a determining factor in farmers' choice (no effect on the asking price), most certainly linked to the fact that abandoning mineral P fertilization does not require any investment. On the other hand, if maize is cultivated on the farm, it appeared to constrain the price in the case of the attribute ″permanent plant cove″, with payments per hectare increasing sharply (20% or more, see Tables 3 and 4). This additional cost is most likely related to the technical difficulty of controlling maize crop canopy and the risk of yield loss to the crop if it is not controlled. In the end, the financing requirement is estimated at 300 to 600 €/ha depending on the degree of establishment of permanent plant cover and anti-erosion hedges, and the presence or absence of maize plots on the farm.

	Price model depending on the presence or absence of corn in the rotation	
	Without corn	With corn
Fixed costs = costs of engagement in the payment scheme	130€/ha UAA	130€/ha UAA
Costs related to the installation of permanent plant cover	3,2€/ha/% of covered UAA	3,2€/ha/% of covered CSA + 0,054€ by % of UAA in corn
Costs related to the installation of anti-erosion hedges	1,1€ by m of anti-erosion hedge/ha	1,1€ by m of anti-erosion hedge/ha

Table 3. *Consents to be received from the farmers of the Lac au Duc catchment area with regard to the attributes of permanent plant cover and anti-erosion hedges as obtained after analysis of the results of the surveys conducted among the farmers of the catchment area.*

It should be noted that the costs estimated here result from choice experiments in which neither operating systems nor production volumes are questioned. The proposed PES are per ha and per year PES systems, established to cover the annual operating costs of the proposed technical attributes while incorporating certain benefits. For example, for the hedgerow attribute, the proposed PES have been constructed to cover the costs of maintaining the hedgerows and the yield losses associated with their establishment (edge effects), while incorporating any benefits generated for biodiversity. The ranges of amounts were established on the basis of the MAEC-type aid proposed by the Brittany Region within the framework of the EU Common Agricultural Policy, as well as the result of discussions with the farmers of the Lac au Duc catchment. This choice to involve the farmers themselves in setting the price of the PES offer has the more than likely disadvantage of pushing prices upwards. On the other hand, it has the advantage of generating prices that are in principle attractive to farmers. It should be remembered that one of the principles underlying the PES mechanism is precisely that it offers more attractive prices than the systems commonly in place, such as the MAEC-type systems, with the idea that if the prices are attractive, the environmental outcome of the mechanism will be better (see Wunder et al., 2018; Martin-Ortegaa and Wayland, 2018). The fact that the fictitious PES offered to the farmers surveyed did not generate attitudes of rejection or mass adoption by the farmers surveyed indicates, moreover, that the price ranges obtained probably correspond to a certain cost reality.

This table contains confidential data preventing it from being reproduced at this stage of the study.

***Table 4**. Examples of costs per hectare of UAA (Utilised Agricultural Area) and per farm for two fictitious farms in the Lac au Duc catchment area as deduced from the results of surveys conducted among farmers in the catchment area.*

It is concluded by indicating that the surveys did not reveal any major differences between the main types of farming system present in the catchment, except for a tendency of dairy farms to lead to slightly lower WTR for the permanent vegetation cover attribute, and a tendency of pig farms to lead to higher WTR for this attribute due to a higher proportion of maize plots used for the application of pig manure. However, this question of the link between WTR and farming systems could not be addressed with the desired level of precision due to a bias in the population of responding farmers, which included an over-representation of dairy farmers.

What to remember

Background

There are four main points to remember:

1- Stopping the fertilization of the soil with phosphate mineral fertilizers does not lead to any cost;

2- Concerning the establishment of permanent plant cover and anti-erosion hedges, the amounts requested by the farmers can be broken down into a fixed part of 130€/ha of UAA and a variable part depending on the effort made in terms of the rate of establishment of permanent plant cover and lines of planted anti-erosion hedges;

3- Maize cultivation leads to higher amounts, probably due to the risk that under-cultivated plant cover reduces yields;

4- In the end, the amounts demanded by farmers varied between 300 and 600 €/ha depending on the percentage of permanent plant cover and the length of the hedge to be planted, and the presence or absence of corn in the crop rotation.

From the point of view of the tools/methodologies to be mobilized to deploy a PES mechanism targeting the reduction of P

A main type of tool/methodology was used:

It is a methodology of experimental economy based on choice experiments in which fictitious PES contracts, with variable contents in terms of commitment to implement attributes, price and duration, are proposed to farmers of the catchment in face-to-face surveys. The statistical exploitation of the results and their confrontation with the information collected on the sociology of the respondents, the types of farms, the cropping systems, etc., allows to establish price ranges with the capacity to generate a massive commitment of the farmers of the catchment to the PES mechanism set up to restore the good ecological status of the Lac au Duc. An interest of the method deployed here is that it takes into account the diversity of cropping systems present in the catchment. Another interest is that it leads to prices that should generate a strong commitment from the farmers.

This part of the work was carried out by a design engineer (Josselin Canlet) paid by the CPES project, assisted by a Master 2 student (Maixent Houenou - Hounsinou).

3.b- Evaluation of the total funding requirement

The aim here is to move from the scale of the farm to that of the catchment. The objective here is to assess the total financing needs on the farmers' side (cumulation of individual WTR), in terms of the flux reduction target and the ability, or not, to target funding to the most cost-efficient plots, i.e. with the highest [level of P flow reduction]/[farmer's WTR] ratio. These evaluations were carried out by using the plot typologies established to assess the impact of the different technical attributes retained in the study to reduce the diffuse agricultural P flux at the lake entrance (stopping mineral P fertilisation; establishment of permanent plant cover, establishment of anti-erosion hedges; see Figure 7), and by aggregating the plot costs at the catchment scale.

Three factors of reduction of the P flux at the lake entrance were targeted: 2, 3 and 5. The simulations (Table 5) evidenced that reducing the flux of P entering the Lac au Duc by a factor of 2 or 3 can be achieved either by targeting the most cost-effective plots from the point of view of establishing permanent vegetation cover and maximising the hedge line on these plots (100 m/ha), or by being less constraining on the hedge line and enrolling more plots, including plots that are less cost-effective from the point of view of the permanent vegetation cover attribute. In both cases it can be seen that not targeting the most cost-effective plots leads to additional costs, which are particularly obvious and significant in the case of a reduction in flow by a factor of 2 (cost higher by a factor 1.66 in the scenario not targeting the most cost-effective plots).

The reduction of the P influx by a factor of 5 can only be achieved if all the plots are enrolled, with a maximisation of the linear metre of hedge (100 m/ha) on each plot. Up to 14 million € per year would be necessary in this scenario (see Table 5).

Targeted phosphorus flux reduction factor	Tageting to the most cost-efficient plots	Percentage of arable plots with permanent cover crop	Linear meters of hedgerow per ha	Total cost of actions per year (in euros)
2	Yes	50	100	6 170 000
2	No	74	20	10 400 000
3	Yes	79	100	10 330 000
3	No	100	37	11 900 000
5	No	97	100	14 150 000

Table 5*. Calculation of the costs induced by the reduction of lake inlet P flux by a factor of 2, 3 and 5 depending on whether or not the measures are targeted on the most cost/effective plots from the point of view of establishing permanent plant cover and anti-erosion hedges.*

Note that scenarios were also constructed to test the type of plots that would be enrolled, and the reduction in flux that this enrolment would generate, if uniform payments close to the average WTR (i.e. not taking into account the additional costs associated with the presence of maize were proposed) were applied. The results show very clearly that the absence of maize plot enrolment is very penalizing from the point of view of reducing the fluxes, even if the costs appear to be lower. Thus, a uniform payment close to the WTR average has the capacity to enrol all the wheat plots in the basin, some of which are very cost/effective, for a relatively modest overall cost (2.4 million euros), but the reduction in P flux is small, not even reaching a factor of 2. Reducing the P flux by a factor of 2 or more means that maize plots have to be enlisted, which inevitably increase the costs.

In conclusion to these evaluations, it is important to point out three limitations of the modelling carried out. A first limitation is that the distribution of plots into a finite number of types requires the mobilisation of all plots of the same type in the modelling. This gives a certain rigidity to the results obtained. A second constraint is that the cost-effectiveness ranking of the plots is based on current crop rotation, and constrains it by the fact that these rotations lead to additional costs related to maize cultivation. Assuming that PES schemes should be established over 6-9 years, there is no guarantee that the crop rotation observed today, plot by plot, will remain stable. A third and final limitation is that the choice has been made to freeze production systems as they are today. By making this choice, we prevent major changes that could prove more efficient and less costly in terms of reducing P fluxes, such as stopping livestock rearing or favouring certain animal productions to the detriment of others, or even stopping crops and switching to grass or even organic farming. This being the case, the option of not profoundly questioning production systems was chosen because i) this option is the most realistic in the short term (a major overhaul takes time), ii) it is difficult to imagine that the farmers surveyed, for whom quantifying the proposed changes would have a considerable effect, would be able to put a figure on the cost of a major overhaul of their production system, if they were willing to go through with it, which is not at all certain.

What to remember

Background

The amounts of plots to be committed to reduce agricultural P fluxes at the Lac au Duc inlet vary depending on the flux reduction requirements being targeted and whether or not the plots most at risk from an erosion point of view, and therefore the most cost effective in terms of the recommended technical attributes of reduction, are targeted. Three main points should be kept in mind:

1- A reduction of the P flux by a factor of 2 can lead to significantly different overall costs depending on whether or not one targets the plots that are most at risk; targeting in this case reduces the cost from €10.4 million/year to €6.2 million/year.

2- The greater the targeted effort to reduce the flux of agricultural P at the lake entrance, the greater the difference in costs between targeting and non-targeting;

3- Targeting a reduction of the flux of agricultural P at the lake entrance by a factor of 4 and more requires to embark all the plots of the catchment in the PES mechanism tested here, for a total estimated cost of €14 million per year.

From the point of view of the tools/methodologies to be mobilized to deploy a PES mechanism targeting the reduction of P

A main type of tool/methodology was used:

It is a modelling methodology that allows to quantify the costs of reducing the flux of agricultural diffuse P at catchment scale, according to the erosion risk at the plot level and the cost of implementing technical attributes to reduce this risk. One advantage of the method used here is that it takes into account the differences in risk at the plot level and therefore the [risk reduction]/[cost of risk reduction] ratio and thus makes it possible to analyse the impact of targeting actions on the most cost-efficient plots on the overall cost of flux reduction.

This part of the work was carried out by the Master 2 student Maixent Houenou - Hounsinou.

3.c- Evaluation of the cost of doing nothing and the economic value of the lake

The objective is to compare the cumulative WTR cost to farmers to restore the good ecological status of Lac au Duc with the cost of the damage currently being done to the lake and the economic value of an ecologically healthy Lac au Duc. The objective of this comparison is to determine whether the farmers' cumulative WTR is economically justifiable, or whether it is disproportionate to the economic value of an ecologically healthy lake.

Damage was assessed by summing the damage (and the additional costs) caused by cyanobacterial blooms on the various uses of the lake (swimming, fishing, nautical activities) and the resulting economic activities (hotels, camping, restaurants, etc.), as well as the costs of the various curative measures deployed on the lake itself to try to limit algal blooms, or the cost of dredging the sediments, it being considered that the sediments are a relay source of P for the cyanobacteria.

This initial estimate was supplemented by an approach aimed at financially evaluating the loss of well-being to which the prohibitions of uses to which Lac au Duc leads, with three targeted uses: swimming, fishing and nautical activities. This loss of well-being was estimated on the basis of surveys in which fictitious lakes allowing the practice of such activities were proposed to users of the Lac au Duc (285 individuals surveyed). The distance between the proposed fictitious lake and the home of the users was used to convert the loss of well-being and economic cost (based on the cost of the petrol needed to make the journey). Aggregating the results at the scale of 180,000 people residing within the lake's catchment area makes it possible to estimate the economic value of a Lac au Duc in good ecological status, which can then be compared to the overall WTR requested by the farmers to achieve precisely this good ecological status.

Direct costs on the uses of the lake	Total cost (€)	Annual cost (€)
Drinking water use		
Infrastructure (costs incurred by improving treatment capacities to produce drinking water from Lac au Duc water)	?	?
Infrastructure (costs related to the investment works necessary to bring water from the river Oust)	?	?
Additional cost / loss of income associated with using water from the Oust river to produce drinking water	?	350 000
Tourist activities		
Nautical club	?	?
Camping	?	?
Restaurants	?	?
Fishing	?	?
Indirect costs felt by lake users (loss of well-being)	**Total cost (€)**	**Annual cost (€)**
In case of prohibition of any activity (swimming, fishing, nautical activities)	-	34 000 000
In the event of a ban on swimming, but maintenance of fishing and nautical ac	-	14 000 000
If only nautical activities are maintained	-	29 000 000
Indirect costs related to the various curative treatments already oper	**Total cost (€)**	**Annual cost (€)**
Aeration ramp		
Installation	?	?
Operation (électricity)	?	7 000
Management	?	?
$CuSO_4$ speading (2003-2005)		
3000€ by speading (2 or 3 spreadings by year)	between 18 000 and 27 000	between 6 000 and 9 000
$CaCO_3$ spreading (2012-2015)		
Dam construction and installation to isolate the bathing area (10,000 euros/year?)	40 000	10 000
Spreading (10 000 euros/an)	40 000	10 000
H_2O_2 spreading (2018)		
Total cost including the spreading, the dam construction to isolate the bathing area	-	220 000
Sediment cleaning (effective for 30 years. Not carried out)	20 000 000	830 000

***Table 6**. Summary of the costs generated by the poor water quality of Lac au Duc*

Some difficulties were encountered in providing figures on the direct economic losses caused by the poor state of the lake (Table 6). These losses, however, are likely to be relatively limited. This is the case, for example, of the yacht club, which has diversified (thus invested in) its activities to compensate for the swimming bans. The same applies to hotel, restaurant and camping activities, on which the ecological damage to the lake seems to have relatively small impacts. Whatever the actual figures, it is very unlikely that the cost of direct economic damage comes even close to the costs of the willingness to receive (WTR) by farmers. The costs of curative actions to control cyanobacteria growth in the lake are also far below the farmers' estimated WTR. The maximum cost is that induced by the application of H_2O_2 in 2018, which was around 220,000 €, that is 30 times less than the overall WTR required for permanent bathing activity (reduction of the diffuse flux of agricultural P by a factor of 5). On these bases, it can be considered that the supply and demand of environmental services are not balanced, and that neither the private actors benefiting from the services provided by the Lake, nor the local authorities financing the curative actions deployed on the lake are able to release the financial resources necessary for the deployment of the PES required to sufficiently reduce agricultural P emissions on the lake' catchment.

The situation is very different if we look at the results of surveys aimed at quantifying in monetary terms the welfare losses suffered by the users of the lake. Here, the estimated amounts are close to or even exceed (up to a factor of 3) the costs of the PES needed to be installed in the catchment to reduce the diffuse agricultural flux at the lake entrance to a level that guarantees the achievement and sustainability of good quality lake water. Thus, the results evidence the existence of a potential willingness to pay (WTP) much higher than the farmers' WTR, which constitutes a theoretical sine qua non condition for the implementation of a PES mechanism (Wunder et al., 2018). The problem here, however, is that this WTP is a theoretical WTP, the financial manna it represents being fictitious, impossible to capture in practice (for example, instituting a toll mechanism to access the various activities offered by the lake to capture it is unthinkable insofar as this mechanism would inevitably harm the lake's attractiveness). In any case, and to conclude, we can see that the economic value of a Lac au Duc in good ecological condition allowing the maximum number of uses far exceeds the overall WTR requested by farmers, demonstrating that it is not economically disproportionate.

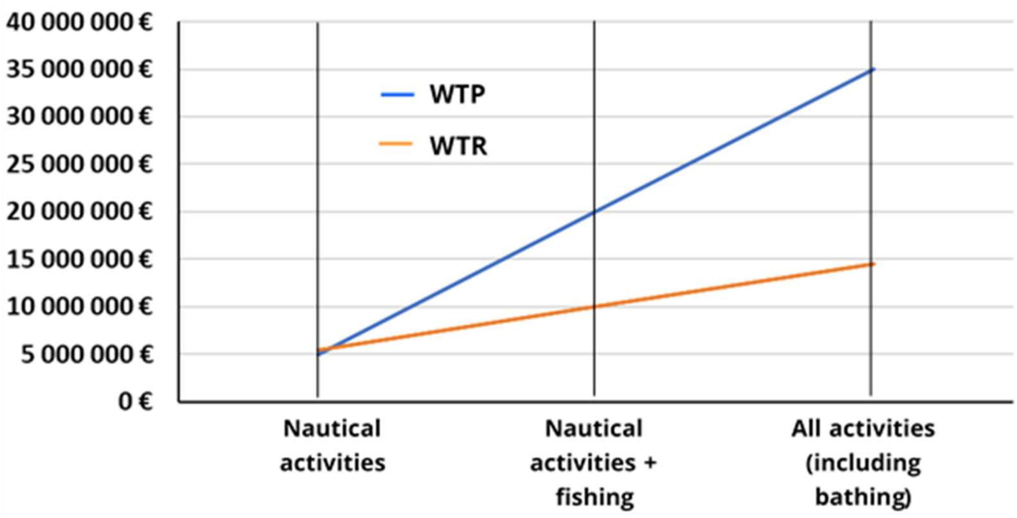


Figure 14 *- Comparison of the overall value of the WTR requested by the farmers and the WTP of the lake users according to types of use.*

What to remember

Background

The cost of the damage induced by the poor ecological condition amounts to several million €/year. By far the highest costs are the indirect costs related to the loss of wellbeing of the users, which can go up to >30 million €/year if all uses of the lake are banned.
Capturing this manna that could finance PES offered to farmers according to a user-pays principle remains however a challenge without any obvious solution today.

From the point of view of the tools/methodologies to be mobilized to deploy a PES mechanism targeting the reduction of P

A main type of tool/methodology was used:

This is a survey methodology to assess the economic cost of the loss of well-being caused by ecological damage to an ecosystem such as Lac au Duc, and the loss of uses that this damage causes. Approaching this cost is interesting to compare the WTR requested by actors whose changes in practices would lead to the restoration of these uses to the users' WTP, thus making it possible to judge the economic admissibility of the requested WTR.

This part of the work was carried out by a design engineer (Josselin Canlet) paid by the CPES project.

3.d- Mobilization of stakeholders and conditions of engagement of farmers

The issue of managing the good ecological status of Lac au Duc and access to the various services provided by this lake concerns a very large number of public and private stakeholders (Figure 15).

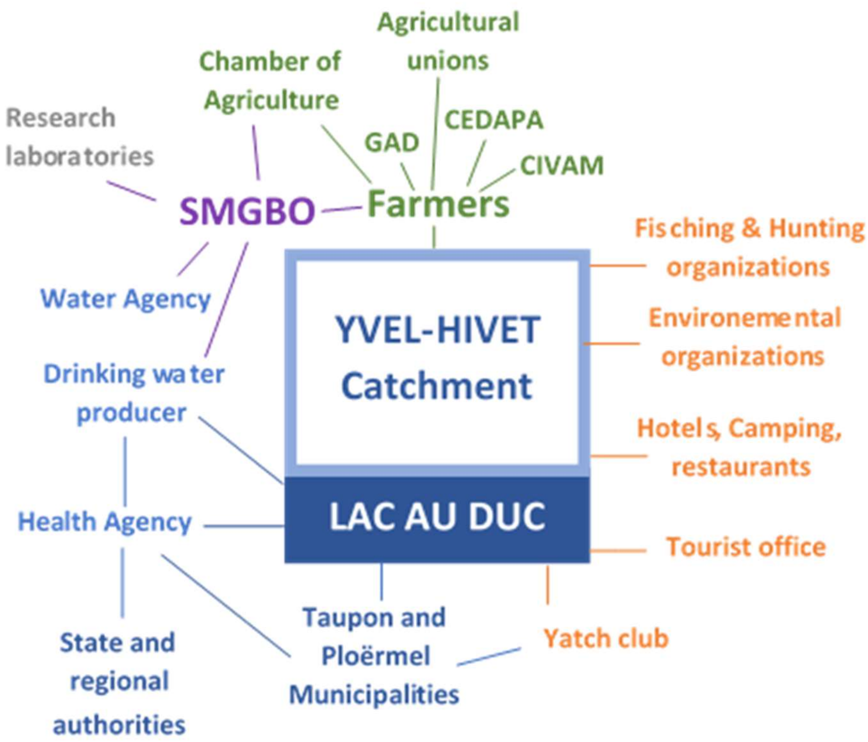


Figure 15 *- Panel of public and private stakeholders concerned by the management of the ecological status of Lac au Duc*

Several public meetings have been organised to meet these different actors and to present the objectives of the INTERREG CPES project in general and of the Lac au Duc pilot study in particular. These public meetings and the ensuing contacts provided access to information important to conduct the study. However, failures are to be deplored in the mobilisation of the actors, the main one being the actors in the production of drinking water (SAUR and Eau du Morbihan) who have never deigned to provide the requested data on the additional costs of treatment during the water purification process generated by the presence of cyanobacteria, nor on the volumes of water to be brought in from another resource in the event of a halt in production imposed by the presence of the cyanobacteria.

With regard to the surveys of farmers, there was an unabashed weariness in responding to what was for many of them a survey among many others already carried out, the results of which they might never see. This lassitude, which is general in the Brittany agricultural world, probably stems in part from the fact that action programmes to restore water quality have been in constant succession in Brittany for more than 30 years, initially linked to a nitrate (eutrophication-green tide problem), followed more recently by phosphorus (eutrophication-cyanobacteria problem) and pesticides. In this respect, the situation of the Lac au Duc case study is very different from those of the other two French case studies set in the Paris Basin where the targets are groundwater reservoirs where the issue of poor water quality is a more recent declaration and essentially results in exceeding a chemical limit (nitrate and pesticide levels).

This weariness of Brittany farmers in general, and of those of the catchment of the Yvel-Hivet in particular, also stems from a fear very often expressed by these farmers that participation in work initially presented as experimental research work will eventually turn into new standards and regulations. These fears explain in part why only 52 farmers out of a total of 450 asked agreed to participate in the surveys.

Concerning the commitment of farmers in the Lac au Duc catchment to enter into a PES scheme, four criteria have emerged as determining factors:

1) Attractive prices ;
2) A long contract duration of at least 5 years;
3) An adaptation of the content of the contracts to the characteristics of the farms;
4) Private financiers and private contract management.

This need for private-private type contracts was strongly expressed during the two plenary meetings organised with the farmers of the the Yvel-Hivet catchment in June and December 2019, a need that stems from the very opinion of the farmers' present, who were fed up with the delays in the administration's management of MAEC, not to mention the vision increasingly propagated within the Brittany agricultural profession of a critical administration obsessed with control (Fig 16).

It should be noted that communication is a determining element in the mobilisation of stakeholders necessary for the construction of a PES mechanism and that all possible vectors (press releases, stands in festive events organised in the territory of action, organisation of information meetings for the general public, films, etc.) must be mobilised for this purpose (Figure 17).

Figure 16 *- Views of the meetings for the feedback of surveys and presentation of the results of the INTERREG CPES project organised with the farmers of the BV of Yvel-Hivet.*

Figure 17 *- Example of communication vectors used to mobilise the stakeholders concerned by the Lac au Duc pilot study. A-information evening organised in the commune of Ploërmel on the occasion of Green Week 2019; B-information stand on the objectives of the pilot study during the Lac au Duc 2019 festival; C-article published in the newspaper Ouest-France announcing the launch of the study; D-information letter to farmers on the progress of the study.*

What to remember

Background

There are three main points to remember:

1- Public and private stakeholders are globally interested in participating in the elaboration of a PES mechanism and understanding its ins and outs;

2- A difficulty in mobilizing farmers to get involved in the construction of a PES-type mechanism, explained by a weariness caused by a long series of action programs deployed in Brittany to fight against diffuse agricultural pollution, coupled with a fear that participation would lead to more regulation and more control;

3- Farmers are more motivated to sign private-private PES contracts that are long-term financed rather than short-term contracts and managed by the public authorities or their representatives.

From the point of view of the tools/methodologies to be mobilized to deploy a PES mechanism targeting the reduction of P

In addition to the information they provide, survey procedures are a means of publicizing the project to stakeholders and explaining what a PES mechanism is. Communication, in all its forms, is of great importance to mobilize the different stakeholders.

4-CONFRONTATION THE DEMAND AND COMMITMENT CTRITERIA OF COMPANIES

4.a- Strategy deployed to generate and analyze companies' demand

The objective here is very concretely to find private funders likely to abound a PES Lac au Duc fund. The strategy developed consists in identifying both the companies in the area that are large enough to be significant financiers of this fund, and companies located outside the area that could be interested in participating in this fund. A list of the companies surveyed (and contacted for some of them) is provided in table 7.

The strategy also consists of analysing the conditions likely to motivate companies to engage in the envisaged PES scheme, even if it means modifying agricultural supply to better match company demand. This analysis involves a theoretical analysis of the criteria for engaging companies in PES-type environmental projects. It also involves interviews with organisations familiar with the Brittany business world. Finally, it involves an analysis of studies aimed at setting up agricultural PES financed by companies in contexts equivalent to that of Lac au Duc.

4.b- Analysis of companies' engagement criteria

Corporate interest in financing environmental projects through agriculture is growing nationwide. We wanted to find out what the situation was at the regional level. Two interviews were conducted for this purpose. The first was with Roland Cariou, director of environmental projects at the Regional Chamber of Commerce and Industry of Brittany (CCI), the second with Clothilde d'Argentré, environmental project manager at the ABEA (Brittany Association of Agri-food Companies).

It emerged from these interviews that the motivation of companies depends first and foremost on the conviction and environmental sensitivity of their managers. This conviction and sensitivity of managers to the environmental issue far outstrips aspects relating to other considerations (typology/field of activity, improvement of image, etc.). This result confirms the results of the VOCAL study (I4CE, 2017) or those obtained previously by other studies (Gherib and Bergu-Douce, 2008).

Company Name	Name of the refernce person	Location city	Financial amounts discussed
Eau du Morbian	A. Kergueris	Vannes	-
VINCI	R. Chene	Vannes	500 K€
VINCI	R-C. et L. Gromelon	Vannes	500 K€
VINCI	R-C. et L. G & J-Y. UZEL	Vannes	500 K€
LIGER	M. Le Mercier	Locminé	50 K€
LIGER	MLM	Locminé	50 K€
LiIGER et SAUR	MLM & E. DURAND	Locminé	50 K€
AIR France	J.-C. Corvaisier	Evriguet	500 K€
Yves ROCHER	B. & J. Rocher	La Gacilly	500 K€
MIX BUFFET	P. Le Hir	Guer	-
FENETREA	Mr. Lamballe	Beignon	-
KERMENE	Mr. Aube	Collinée	-
GROUPAMA	Mr. Cocherel	Ploërmel	-
Crédit Agricole	Mme Barbier	Vannes	-
EUREDEN	S. Le Bars	Theix	-
Bretagne PELLETS	J-C. Corvaisier	Mauron	-
BRAZEO	Mr. H. Gabillet	Ploërmel	50 K€
GALEWPET	Mr. H. Gabillet	Ploërmel	50 K€

Table 7 *- List of companies identified for their ability to finance the envisaged PES mechanism.*

Another piece of information from the interviews conducted with the CCI and ABEA is that Brittany companies are inclined to attach great importance to the territories in which they are established. This characteristic is a priori favourable for a financial commitment to local projects such as the Lac au Duc PES project. Moreover, we were told that the Brittany food-processing companies (of rather medium size) had a strong link with agricultural professionals, this strong link often being expressed through personal links between the managers of the companies and those of the representative agricultural organisations (project leader of the AEBA). These links could be a plus for the companies' commitment to finance agricultural projects to improve the environment that are territorially established, as this commitment makes it possible to support local farmers or even to guarantee the supply of raw materials to the contributing companies. From this point of view, the nature of the project financed can be a major criterion for the companies' commitment, with a bonus for clear, simple projects co-constructed directly with the companies.

It also emerges that the communication around the project must be adapted to the business world, translating the precise aims of the projects into simple language and explaining the links with the environmental impacts of their activities. Ignorance of the concrete issues and/or environmental risks faced by the territories can be a hindrance to their commitment. From this point of view, it is the responsibility of agricultural project leaders to make the stakes of these projects understandable to businesses, by showing how these same businesses could be impacted in their activity if nothing is done. For example, with regard to the issue of water quality, it is possible that poor quality water could become a long-term constraint for the smooth running of businesses. It remains to make this constraint and its deadline known to companies.

As an approach to responsible behaviour in companies, Social and Environmental Responsibility or SER can be used as a lever for financing, particularly in large or mid-sized companies. However, approaching companies through this channel is not necessarily a good idea, given that many companies use this leverage more for internal operations than external ones (for example, reducing energy or waste consumption or improving employee well-being).

At present, there are no schemes specific to the CCI or ABEA encouraging companies to adopt sustainable development approaches. Many are still at the stage of looking for subsidies enabling companies to reduce their environmental footprint. The situation may be significantly different for ABEA member companies, as ABEA is essentially interested in sustainable agriculture, even if this interest has come to a halt as a result of the economic crisis caused by the Covid 19 pandemic.

To conclude, the interviews demonstrated that in the current situation where a collective approach to sustainable development is not being put in place at regional/local level, there is a need to think about concrete, locally anchored projects targeting environmental service packages, rather than a particular service, such as water quality. Moreover, it appears from interviews and contacts with companies that the water quality service is of low importance to companies, unlike a service such as voluntary carbon offsetting, which benefits from a strong aura and visibility at the national and international level. This visibility benefits companies, seeing the object of the transaction in concrete terms and relate it to simple and omnipresent elements of their activity, such as their energy expenditure or their greenhouse gas emissions.

4-c- Evaluation of the capacity of the agricultural offer PSE Lac au Duc to be valorizable from a carbon storage point of view

This evaluation is a direct result of the interviews conducted with the CCI and ABEA and the exchanges that took place with the companies identified as potential financiers of a Lac au Duc PES scheme. These exchanges and interviews show that companies are much more interested in financing carbon/climate PES than water quality PES. As the attributes of plant cover and anti-erosion hedges have the capacity to store carbon in the soil (Chenu et al., 2014; INRA, 2019), we sought to assess how high the carbon valuation of these attributes would make it possible to cover the €300 to €600/ha WTR required by farmers to establish them. In the hypothesis that this valuation would cover the WTR requested by the farmers, we could then enter into a virtuous and interesting circle for the Lac au Duc territory in which companies interested in storing carbon would be able to finance a PES mechanism initially aimed at a water quality service, without additional financing specifically dedicated to this service having to be sought.

Three types of carbon price were used in the simulations carried out (Iida, 2020): 1) the 2020 price of the European carbon trading market (92 €/tC); 2) the price of the carbon as set in the Climate and Energy Contribution of French taxation on the consumption of petroleum products (202 €/tC); 3) the 2030 tutelary value of carbon used to assess the profitability of public investments in the field of greenhouse gas emission reductions in France (918 €/tC).

The valuation associated with the additional carbon storage (Figure 18) of the planned attributes only covers between 0.2 and 37% of the farmers' WTR, depending on the different references used (carbon price and theoretical quantities of additional carbon storable by plant cover attributes and anti-erosion hedges).

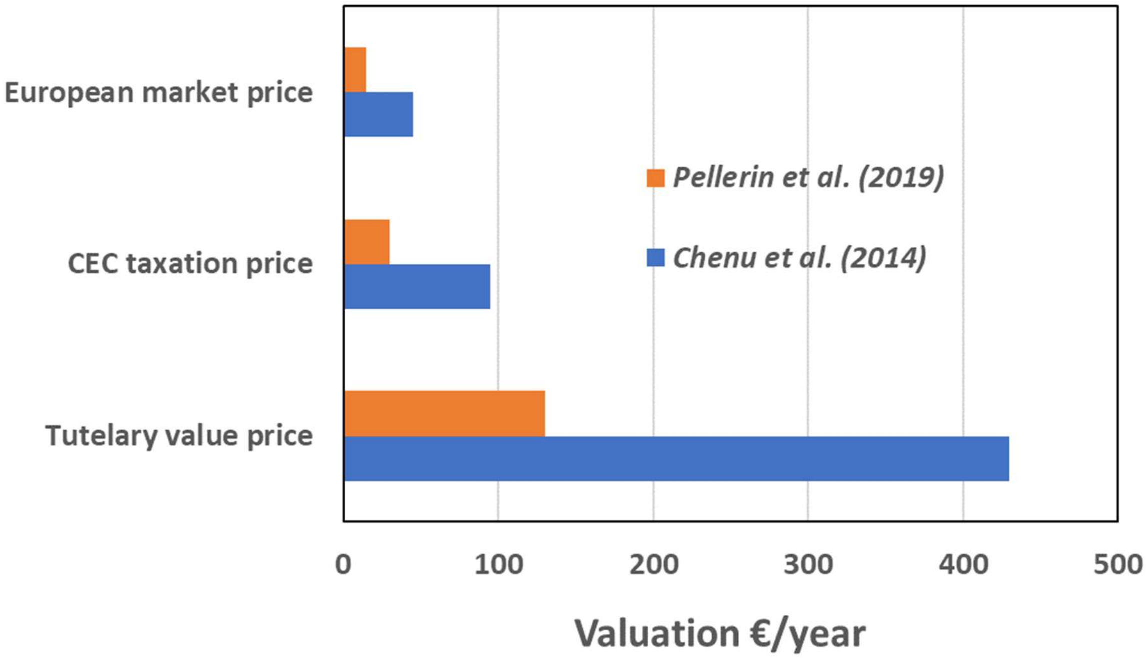


Figure 18 *- Simulation of the valuation of plant cover attributes and anti-erosion hedges in terms of their capacity to store carbon, depending of the carbon price used.*

These first results, which are very preliminary because they are based on very theoretical and highly uncertain elements, show the existence of a significant gap between the price of the PES offer designed in this study and calibrated with a water quality objective, and the price that can be obtained for this same offer in terms of its capacity to increase carbon storage by the soil. As the water quality objective is intangible in view of the degraded state of the Lac au Duc, there is no question of technically modifying the PSE offer (absolute maintenance of the percentages of plant cover and the lines of anti-erosive hedges). Two solutions are then offered to companies that a priori wish to finance only carbon storage: 1) either the farmers reduce their WTR for the same level of attribute implementation; 2) or the companies accept within the framework of a negotiation process to increase their WTP, under the argument that the carbon-storing attributes also generate a water quality service, and that this double service provision justifies a higher price.

What to remember

Background

There are four main points to remember:

1. There is a panel of local and regional companies ready to discuss financial participation in the PES mechanism designed to improve the water quality of the Lac au Duc;
2. The analysis of the criteria for companies' commitment to environmental projects shows the important role of the environmental sensitivity of the managers; the simplicity and territorial anchoring of the projects are also highlighted; the co-construction of the projects with the companies and the communication to the companies of the environmental stakes to which their activity is subjected today and will be even more so tomorrow are also pointed out as important elements of their commitment.
3. The analysis of companies' commitment criteria also shows that companies are a priori more inclined to finance projects aimed at storing carbon with a view to mitigating global warming than projects aimed at improving water quality.
4. In the current state of the carbon and WTR prices demanded by the farmers of the Lac au Duc catchment to establish anti-erosion hedges and permanent plant cover at a sufficient density level to restore the lake's water quality, it does not seem imaginable to be able to finance a water quality PES mechanism such as the one envisaged for the Lac au Duc catchment solely through its carbon co-benefits. Specific funding for the water quality service will have to be found.

From the point of view of the tools/methodologies to be mobilized to deploy a PES mechanism targeting the reduction of P

The analysis of the environmental co-benefits provided by devices designed to reduce P emissions such as anti-erosion hedges or permanent plant cover is one of the preliminary stages in the design of the PES mechanism to be set up, insofar as these co-benefits have the power to attract other funders than those specifically interested in the water quality objective. The approach presented here, which consists of carrying out a literature review of these co-benefits and simulating the potential financial returns provided by these co-benefits, is one possible way of proceeding.

5- NEGOCIATION AND IMPLEMENTATION OF CONTRACTS

5.a-Strategy implemented

After the design phase of the PES scheme and the analysis of the criteria for the commitment of sellers and buyers, the aim was to negotiate and concretely implement private-private PES contracts in the Lac au Duc catchment. As indicated above, this phase has been delayed by more than 6 months due to the health crisis linked to the COVID-19 pandemic. At the time of writing of this report (January 2021), the following strategy is deployed to implement this phase of concrete contract signature.

Definition of an experimental territory within the Lac au Duc catchment and mobilisation of the territory's farmers. Given the size of the Lac au Duc catchment and the large number of farmers operating in it (>400), it seemed unreasonable to begin implementation of PES contracts on the whole catchment. It was considered more realistic to start by setting up an experiment on the scale of a smaller area. The choice was made for the Rézo sub-catchment, in the sector of the municipalities of Saint-Brieuc de Mauron, Guilliers and Loyat. This sector, with a surface area of 3600 ha, was chosen as a priority because : 1) it is located in the south-central part of the Lac au Duc watershed, the part that emits the most agricultural P; 2) it is close to the lake; 3) it contains a substantial number of plots that have been the subject of a risk parcel diagnosis that can be used as a guide to target actions to control diffuse P emissions; 4) it also contains a large number of plots that have been the subject of a MAEC project, a characteristic that indicates a certain sensitivity of farmers in the sector to environmental issues; lastly, 5) it is characterised by a fairly low density of hedgerows, indicating the presence of considerable possibilities for the establishment of hedgerows, bearing in mind that hedgerows are one of the most effective technical attributes for combating soil erosion, and the diffuse P emissions that this erosion entails.

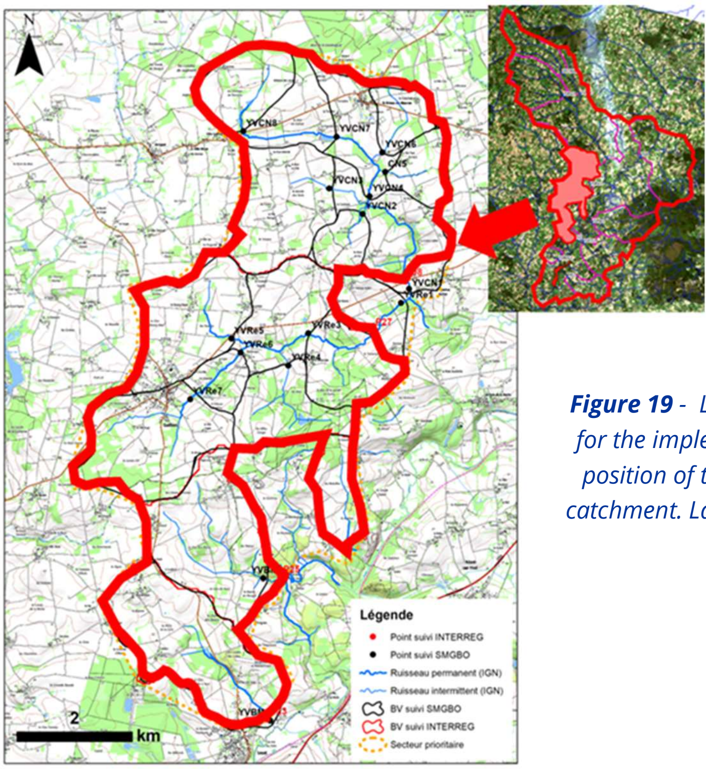
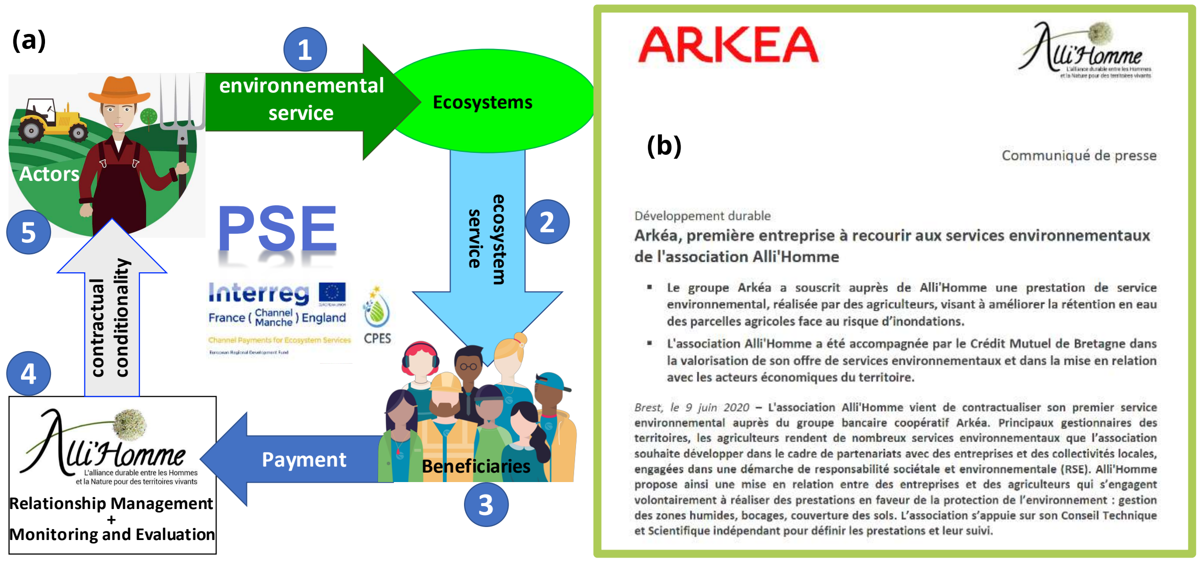


Figure 19 *- Limits of the Rézo sub-catchment retained for the implementation of the first EPS contracts, and position of the sub-catchment within the Lac au Duc catchment. Lac au Duc is located south-east of the sub-catchment.*

Fifteen farmers in this sub-catchment were contacted and expressed their willingness to engage in a process of negotiation and implementation of PES contracts. By restricting the work to these 15 farmers, we hope to become more efficient and to be able to put in place a proven negotiation and contracting strategy, both in terms of the content of the contracts and their legal status, allowing for a later and rapid extension to the other farmers of the Lac au Duc catchment.

Establishment of a collaboration with the association Alli'Homme and the Chamber of Agriculture of Brittany. As the PES mechanism envisaged by Lac au Duc is a private-private mechanism, it is necessary to set up an intermediary structure to collect funds from companies and to manage and distribute the funds collected to farmers. This structure must be given an ad hoc legal status, enabling it to fulfil this role. Initially, the search for this structure was to be carried out by Sara Hernandez Consulting, which for internal reasons was unfortunately forced to refocus its activity on the pilot study of the BAC of Tremblaye in Normandy. After a research and negotiation phase lasting more than 6 months conducted by the remaining partners of the Lac au Duc case study, a partnership was established with the association Alli'Homme.

Alli'Homme is an association under the law of 1901, active since January 2018. Founded by the Fédération Départementale des Syndicats d'Exploitants Agricoles du Finistère (Departmental Federation of Farmers' Unions of Finistère), the purpose of this association is to enhance, maintain and improve the environmental functionality of rural and agricultural areas by promoting and developing agricultural and forestry practices that provide environmental services. In the long term, Allii'Homme aims to be the operator for the deployment of environmental services provided by agriculture on the scale of the four Breton departments, within the framework of win-win partnerships between farmers and private companies in the form of PES contracts. The interest of the partnership with Alli'Homme is threefold: 1) Alli'Homme has expertise in the design and legal status of PES contracts between farmers and private companies, as demonstrated by the signature of a first contract in 2020 in the Quimper region (see Figure 20); 2) because of its status as an association, Alli'Homme is able to act as an intermediary between companies and farmers and as a manager and provider of private funding to farmers; 3) as an offshoot of the agricultural profession, Alli'Homme has the means to motivate farmers to sign PES contracts.



Communiqué de presse

Développement durable

Arkéa, première entreprise à recourir aux services environnementaux de l'association Alli'Homme

- **Le groupe Arkéa a souscrit auprès de Alli'Homme une prestation de service environnemental, réalisée par des agriculteurs, visant à améliorer la rétention en eau des parcelles agricoles face au risque d'inondations.**
- **L'association Alli'Homme a été accompagnée par le Crédit Mutuel de Bretagne dans la valorisation de son offre de services environnementaux et dans la mise en relation avec les acteurs économiques du territoire.**

Brest, le 9 juin 2020 – **L'association Alli'Homme vient de contractualiser son premier service environnemental auprès du groupe bancaire coopératif Arkéa. Principaux gestionnaires des territoires, les agriculteurs rendent de nombreux services environnementaux que l'association souhaite développer dans le cadre de partenariats avec des entreprises et des collectivités locales, engagées dans une démarche de responsabilité sociétale et environnementale (RSE). Alli'Homme propose ainsi une mise en relation entre des entreprises et des agriculteurs qui s'engagent volontairement à réaliser des prestations en faveur de la protection de l'environnement : gestion des zones humides, bocages, couverture des sols. L'association s'appuie sur son Conseil Technique et Scientifique indépendant pour définir les prestations et leur suivi.**

Figure 20 *- (a) place of the association Alli'Homme in the PES mechanism set up on the Lac au Duc catchment by the INTERREG CPES project; (b) joint press release between the association Alli'Homme and the company Arkéa on the occasion of the signature of the first private-private PES contract in Brittany.*

As the Regional Chamber of Agriculture of Brittany (CRAB) is a partner of the Alli'Homme association, in particular via the staff it delegates to this association, the partnership between the INTERREG teams of the Lac au Duc pilot study and the Alli'Homme association also involves a partnership with CRAB. This second partnership is interesting in itself for three reasons: 1) CRAB has been able, via the Carbocage project that it is piloting, to label the hedgerow by the low carbon label project set up by the Ministry of the Environment and Ecological Transition to stimulate voluntary carbon offsetting in France ("low-carbon" label obtained officially in October 2020). This labelling will help to enhance the financial value (from the point of view of carbon storage) of the anti-erosion hedge attribute at the heart of the Lac au Duc PES mechanism. 2) CRAB is leading the PES reflection carried out at the national level by the Permanent Association of French Chambers of Agriculture; 3) CRAB has technical know-how and plot references in the field of soil erosion control and P transfers, technical know-how and references that could be mobilized by farmers to build their PES offer.

It should be noted that this partnership with the Alli'Homme association and the CRAB was sealed through the joint construction and submission of a project in response to the call for experiments aimed at setting up payment for environmental services (PES) launched in January 2020 by the Loire-Brittany Water Agency. This project which was approved and launched officially in September 2020, financed to the tune of €37,000, will enable the Alli'Homme association and the CRAB to ensure their participation in the Lac au Duc pilot study until the end of 2021.

5.b- Content and schedule of actions in progress

The work of negotiating the first PES contracts in collaboration with the association Alli'Homme and the CRAB started at the beginning of October 2020, when a joint working group was set up.

The goals of this group are:

1) **Building a toolbox for farmers to build their PES offer**. This toolbox will be based on the risk plot diagnosis developed by CRAB, which classifies agricultural plots into three categories depending on erosion risk. The use of this diagnosis familiar to farmers will make it possible to target the plots on which PES are targeted. An easy-to-use algorithm based on scoring the risk and the effectiveness of the attributes chosen to reduce it will be developed to quantify a priori the erosion effectiveness of the supply formulated by the farmer (evaluation of the rate of supply reduction in relation to the current erosion flow). The objective for this toolbox is to be operational by the1st quarter of 2021.
2) **Include in this toolbox elements to assess the carbon and biodiversity co-benefits** attributes selected by the farmer, including the anti-erosion hedge attribute. The criteria developed within the framework of the Carbocage project to evaluate additional C storage of hedges according to their type and management method (Figure 21), and those included in the hedge management specifications of the hedge label (https://labelhaie.fr/) to define a hedge in good ecological condition will be used here. The objective is that these additional elements, which make it possible to assess the potential for co-valuation of water quality attributes in relation to carbon and climate services, should also be ready and validated by the 1st quarter of 2021.
3) **Building a presentation and communication brochure** of the project to the attention of companies.
4) **Identify one or more companies** likely to enter into an active process of co-construction and contract negotiation with one or more of the Rézo sub-BV. The deadline set here is the 2nd quarter of 2021, provided that we are out of the health crisis.

5.c-Outstanding issues and risks

One important point remains unresolved which is the control of the environmental efficiency of PES built and proposed by farmers. As the signature of PES cannot, for the reasons explained above, concern all farmers, a monitoring of the flux of P at the lake entrance is not likely to be able to serve as a justice of the peace for the environmental efficiency of the proposed PES. An evaluation at the plot or farm level should be envisaged with, for the time being, only one truly possible option, based on a verification of the means implemented and their sustainability, the question raised here being that of the person or authority responsible for this verification.

Another issue concerns certification and labelling, both of which can be decisive for the commitment of companies. A specific label has been obtained for the hedge from the point of view of carbon storage via the Carbocage project. However, there is currently no equivalent label for water quality. The question of thinking about the construction of a label associating several environmental services and the specifications to be associated with this label is clearly raised.

Figure 21 - *Presentation brochure of the Carbocage protocol for the valuation of carbon stored by hedges*

Concerning the risks, the immediate and most important risk is that generated by the health crisis linked to the COVID19 pandemic which not only restricts face-to-face meetings and group work (fundamental in a PES construction process), but also and above all weakens the economic actors, with the risk of diverting them from the objective pursued, which is to encourage them to contribute to the Lac au Duc PES fund.

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