Interreg
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Channel Payments for Ecosystem Services
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CPES

Synthesis of the Preliminary Work Conducted on the Lac au Duc Catchment for Implementation of Payments for Environmental Services to Reduce Phosphorus Inputs to the Lake

Determination of current and past phosphorus inputs
Location and apportionment of phosphorus sources
Phosphorus input reduction requirements
Costs/effectiveness/benefits of reduction of agricultural, diffuse phosphorus inputs

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Foreword

The purpose of this summary report is to present the results obtained during the studies carried out between January 2018 and September 2019 on the Lac au Duc catchment (Yvel-Hivet watershed) by the CNRS, INRA and Agrocampus-Ouest teams, and whose objectives were to:

1) estimate the flux of phosphorus (P) entering the lake, and the respective parts in thus flux of agricultural and domestic/urban P sources;
2) determine the objectives to be reached in term of P flux at the inlet of the lake, depending on the uses/services of the lake that one wishes to be able to preserve/restore (production of drinking water, fishing, nautical activities, bathing);
3) economically quantify the loss of well-being of lake users induced by cyanobacterial efflorescence and the restrictions of use to which these efflorescence lead; combine these costs with the costs of direct economic losses (for example extra cost of drinking water production) and indirect costs (curative actions on the lake) so as to quantify the total economic damages caused by excess P arriving at the lake, and by the cyanobacteria blooms that these excesses generate, in order to finally evaluate the economic benefits that would result of a decrease of the P flux coming from the watershed;
4) quantify the cost of reducing agricultural P emissions, and how this cost changes depending on the level of reduction of the P flux targeted at the lake inlet; evaluate different reduction scenarios, including whether the recommended measures to reduce diffuse P emissions are targeted or not (geographical targeting, targeting of the most cost-effective plots, etc.), and estimate the costs of the different scenarios.

The report is deliberately organized into a succession of chapters answering specific questions such as "What is the amount of P entering the Lac au Duc annually?" Or "How much will it cost to reduce this amount by a factor of 3?". The objective, in doing so, is to provide as clear a framework as possible for sizing and implementing Payments for Environmental Services to reduce agricultural P emissions in the catchment, and evaluate a priori how efficient this reduction will be regarding the lake's ecological status and the services the lake provides. The framework produced obviously depends on the evaluation procedures implemented in this preliminary analysis work, and in particular on the choice made by the economists of Agrocampus Ouest's SMART Laboratory of how evaluate the costs and benefits of a reduction of agricultural P emissions. The method followed in this study has consisted in conducting face-to-face surveys, involving farmers and scientists, based on the so-called choice method, during which different scenarios, previously estimated from an economic point of view, were proposed to the farmers. The results were then statistically analyzed in order to determine the economic willingness of the farmers to implement the proposed mitigation measures, and the costs of aggregate these measures at the catchment’s scale.

The questions we tried to answer

Question N°1: How the fluxes and concentrations of phosphorus at the inlet of the Lac au Duc have changed in the recent period? What are the amounts of phosphorus entering the lake today?

Question N°2: What are the respective proportions of domestic/industrial (point-source emissions) and agricultural (diffuse emissions) sources in the flux of phosphorus entering the Lac au Duc today?

Question N°3: Does a sub-catchment (headwater) approach reveals zones in the Lac au Duc catchment of particularly high diffuse phosphorus emissions? Are there sub-basins where targeting the implementation of Payments for Ecosystem Services (PES) could have the greatest impact on reducing the flux of phosphorus of agricultural origin at the lake inlet?

Question N°4: What objectives of phosphorus flux reduction at the lake inlet should be targeted in order to preserve/restore lake's uses/services? In other words, by what factor should we divide the current flux to preserve or restore basic lake's use/service such as drinking water production or bathing?

Question N°5: What technical attributes can be offered to farmers to reduce the flux of agricultural phosphorus entering the Lac au Duc? How to estimate the effect of the appropriation of these attributes by farmers on the reduction of this flux?

Question N°6: How can the costs of adoption by farmers of the different technical attributes proposed to reduce agricultural phosphorus losses be assessed? What average costs per hectare do we expect depending on the targeted attributes? How do these costs vary depending on farm types?

Question N°7: What are the costs of reducing the diffuse emissions of agricultural phosphorus arriving to the Lac au Duc? How do these costs evolve with the reduction level to be achieved?

Question N°8: Does a cost-effectiveness analysis of the reduction of P fluxes show an interest in targeting PES to certain parts of the catchment? Does this targeting correspond to the maximum phosphorus emission zones established from the monitoring carried out in the stream and river networks of the lake catchment?

Question N°9: How much costs the damages caused by the poor ecological status of Lac au Duc? What is the final balance between supply and demand for environmental services for the Lac au Duc catchment?

Question N°1

How the fluxes and concentrations of phosphorus at the inlet of the Lac au Duc have changed in the recent period? What are the amounts of phosphorus entering the lake today?

<u>Reminder of the methodology used</u>. Analysis of the data collected by the Syndicat Mixte du Grand Bassin de l'Oust (SMGBO) between 2007 and 2017 on the 10 monitoring points located in the Yvel-Hivet catchment, including the YV2 point equipped with a discharge monitoring station, and thus allowing measurement of water fluxes just upstream of the lake entrance. The measurement frequency at the monitoring points is usually 10 samples collected and analyzed per year, except at point YV2, where the measurement frequency is 20 samples collected and analyzed per year.

The analysis of the historical data collected by the SMGBO at the inlet of the lake between 2007 and 2017 shows a significant variability of the flux of total P on an inter-annual scale (Fig 1). This variability is mostly due to the inter-annual variability of rainfall frequency and intensity. The P flux at the inlet of the lake, expressed in Kg of total P (P_{total}) per hectare (ha) and per year, vary between 0.1 (2012) and 1.1 (2012), with an **average flux value** over the period of **0.23 kg P_{total}/ha/year**.

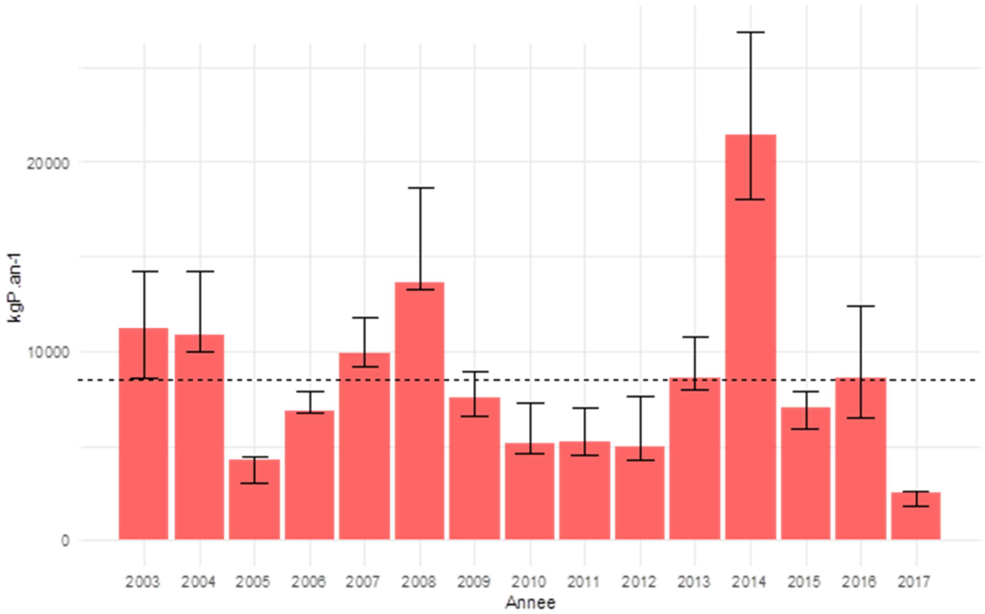

Figure 1 : Evolution of annual P_{total} fluxes at the inlet of the Lac au Duc over the period 2007 - 2017. The average annual flux over the period is 8506 Kg.P.year^{-1}.

No upward or downward trend is detected from the point of view of P_{total} inputs to the Lake au Duc for the 2007-2017 period, whether as regards annual fluxes (Fig.1), or instantaneous P_{total} concentrations (Fig. 2). This means that the annual average P_{total} flux of 0.23 KgP_{total}/ha/y calculated between 2007 and 2017 can be regarded as corresponding to the average value of the annual P_{total} flux entering Lac au Duc today.

Divided by the average annual water flux, this **average annual flux** corresponds to an annual average weighted P_{total} concentration at the lake inlet of **0.100 mg/l**. This value can be taken as the present value of the weighted mean P_{total} concentration at the lake inlet and therefore as the guiding concentration corresponding to the "0" state before any new action plan aimed at reducing P_{total} inputs to the lake. It should be noted that the absence of downward trends in P_{total} fluxes and concentrations is very different from the nitrate situation (Fig. 3), whose Lac entrance concentrations were reduced by a factor of 2 between 2007 (40 mg/L of NO_3 on average) and 2017 (20 mg/l of NO_3 on average). It should be noted that the P entering the lake is > 80% made of particulate P.

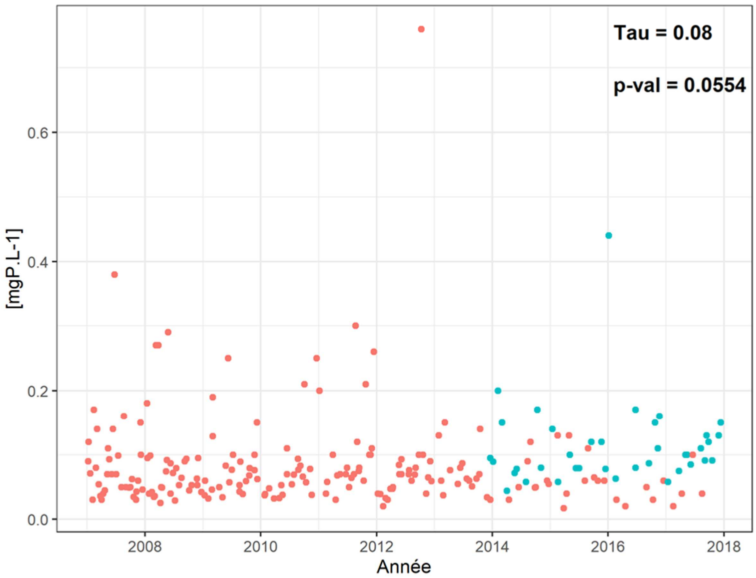

Figure 2 : Variation of P_{total} concentrations measured in the Yvel River at the inlet of Lac au Duc over the period 2007 – 2017. Red spots corresponds to sampling at fixed dates, whereas blue spots correspond to sampling when daily rainfall amount >10 mm.

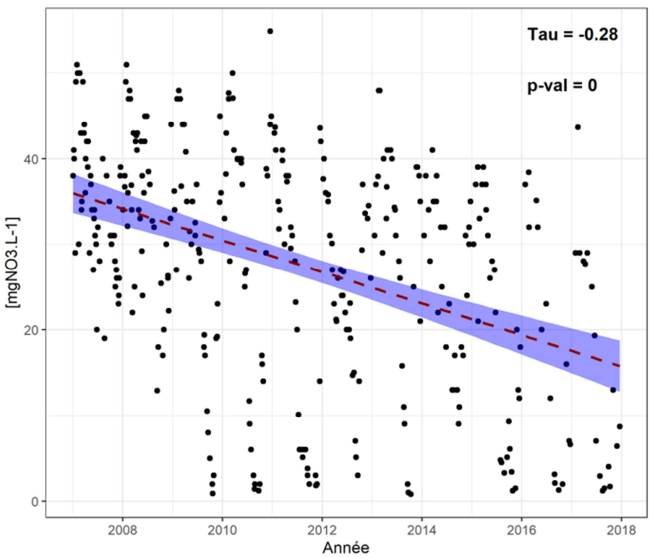

Figure 3 : Variation of NO_3 concentrations measured in the Yvel River at the inlet of Lac au Duc over the period 2007 - 2017

Several important remarks must come with these results:

1) The fact that P_{total} concentrations in rivers vary greatly with water flow usually leads to an underestimation of P_{total} fluxes from the measurement networks in place, which does not analyze the P_{total} concentration of water at the high frequency needed. In the present case (average value calculated from 20 measurements per year over 10 years), this underestimation could be as high as 25%, meaning that the annual average P_{total} flux and annual flow weighted P_{total} concentration at the lake inlet could be of the order of 0.30 kg P_{total}/ha/year and 0.130 mg P_{total}/l, respectively.

2) An average annual concentration of 0.100-0.130mg P_{total}/l classifies the waters entering the Lac au Duc in the category of waters in good ecological status (limit <0.200 mg/l of P_{total}). This relatively good "regulatory" ecological status of the incoming water body, in average condition, refers to the fact that significant efforts have already been made in the Yvel-Hivet watershed, as elsewhere in Brittany, to reduce P_{total} fluxes (division on average by a factor 2.5 of P_{total} fluxes in Brittany rivers over the last 30 years). It also demonstrates that the ecologically degraded state of Lac au Duc is the result of a very high sensitivity of stagnant water bodies as regards "phosphorus" (threshold concentration for the appearance of cyanobacteria much lower than the threshold concentration defining the regulatory good "ecological" status of rivers*), combined with the fact that lakes, by storing sediments, also store very large amounts of P (several tons accumulated per year), providing an internal P reserve degrading the ecological status of the lake.

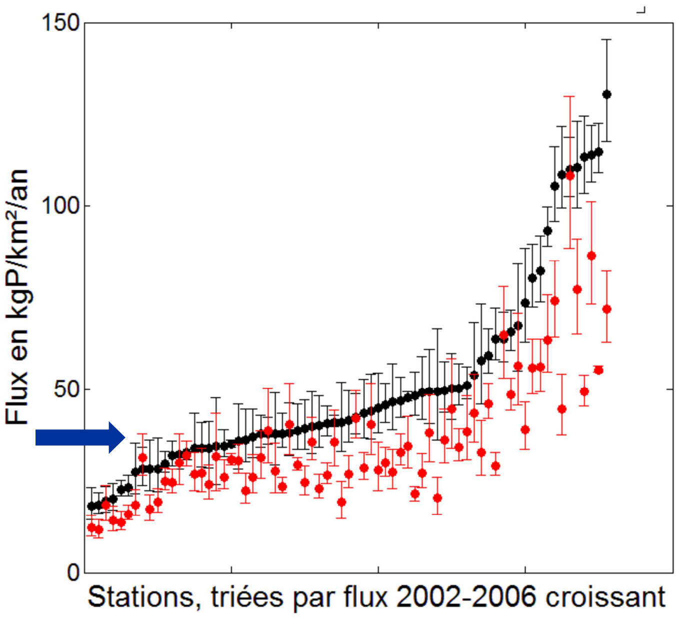

Figure 4 : Comparison of the the P_{total} flux emitted by the Yvel river at the entrance of Lac au Duc on average each year (blue arrow) with P_{total} fluxes measured in Brittany rivers. The rivers are ranked by increasing fluxes measured in 2002 (black symbols). Red symbols stand for fluxes measured in 2006.

**The limit of good ecological status is much lower for lakes and reservoirs (<0.050 mg/ l) than for rivers (<0.200 mg/l) because of the stagnant nature of the waters, which makes them more sensitive to micro-algae development.*

3) Compared with the other Brrittany rivers (Fig. 3), the Yvel river at the entrance of Lac au Duc falls into the category of the 50% of the Brittany rivers exporting the least amount of P_{total}. This reinforces the idea that the Lac au Duc watershed is a watershed in relatively good condition from the point of view of P emissions in the Brittany context, and that reducing these emissions in a such an already low-emission watershed will require the deployment on this watershed of mitigation actions necessarily more radical than all those undertaken so far.

What to remember : The Yvel-Hivet river is located in the lower half of all Brittany rivers as regards the amount of P_{total} exported annually. The mean annual flux of P_{total} exported by this river and entering the Lac au Duc is 0.23 kg/ha/yr, with significant inter-annual variations in phase with inter-annual variations in rainfall amounts. The flow weighted annual average P_{total} concentration (guide concentration for future remediation actions on the lake's catchment) is 0.100 mg P_{total}/l, among which > 80% consists of particulate P.

Question N°2

What are the respective proportions of domestic/industrial (point-source emissions) and agricultural (diffuse emissions) sources in the flux of phosphorus entering the Lac au Duc today?

Reminder of the methodology used. Two measurement campaigns carried out in the summer of 2018 upstream and downstream of the main waste water treatment plants installed on the Lac au Duc catchments to estimate the P_{total} and P_{PO4} fluxes emitted annually by these plants. The estimates thus obtained were then compared with estimates produced earlier(2011) by the SMGBO on the basis of emissions declared by plant operators.

Data obtained during the summer 2018 campaigns upstream and downstream of the water treatment plants of the Yvel-Hivet catchments allow estimation of the total amounts of P_{total} emitted by these stations to a cumulative total of 1.9 kg P_{total}/day, of which almost 80% is P_{PO4} (1.5 kg equivalent P/day). Calculated on an annual basis and expressed as a specific flux, these estimations correspond to a specific domestic/industrial total flux of 0.018 kg P_{total}/ha/year, thus representing 8% of the average specific flux of P_{total} calculated at the lake inlet. In other words and according to these data **92% of the P flux entering today in Lac au Duc would be of diffuse agricultural origin, against 8% having a domestic and/or industrial origin**.

These amounts and proportions are quite close to the estimates made by the SMGBO from the self-monitoring data of the plant operators: between 2 and 4 kg P_{total}/day. Considering the highest option of 4 kg P_{total}/day, this leads to an estimated proportion of P_{total}'s contribution from point-source origins to Lac au Duc equal to 13% of the annual P_{total} flux entering the lake, as against 87% of diffuse agricultural origin, two results not very different from the proportions estimated from the 2018 summer campaigns performed by Interreg CPES project teams.

The comparison of these coherent estimates therefore indicates that the P entering the Lac au Duc would be **92% of agricultural origin** on an annual basis, justifying the idea that the main prevention actions to be undertaken in the basin are actions dedicated to reduce diffuse emissions of agricultural origin.

This result, however, brings two remarks. The first is that this value of 92% of the influx P of agricultural diffuse origin is a value established on an annual basis. The situation is very different on a monthly basis. Indeed, in the summer months the proportion of P from domestic/industrial increases very strongly due to the reduction of river flows and disconnection of watercourses with soil P reservoirs. Thus, P contribution from point-source inputs may exceed that of diffuse inputs of agricultural origin in July, August and September, thus becoming preponderant at the Lake inlet at these times. The summer period corresponding to the period of development of cyanobacteria, the main ecological damage suffered by Lac au Duc, the question is posed of a role perhaps much more important than it appears on an annual basis of the contributions of P of domestic/industrial origin, which can act as a triggering factor for cyanobacteria blooms. This question, however, remains an open question of research today.

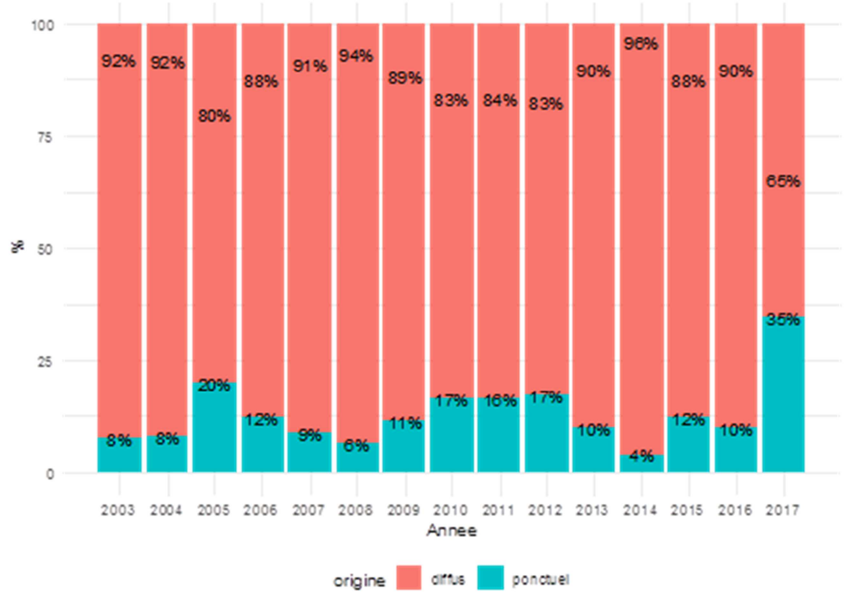

Figure 5 : Variations on the monthly proportions (in %) of P_{total} from agricultural diffuse origin (in red) and punctual, domestic and/or industrial (in blue) entering the Lac au Duc.

The second remark is that the monitoring carried out at the outlet in some headwater catchments of the Lac au Duc catchment between the beginning of 2018 and the end of 2019 shows certain anomalies likely to be related to point-source contributions of P, the main and most visible being the very high values of P_{PO4} concentrations observed downstream water treatment plant set in the municipality of Guilliers, likely indicating a a malfunction of this plant (Fig. 6). n increase over time in P_{PO4} concentrations in some headwater catchments impacted by lagoon-type water treatment plants also question the possibility that some old lagoons see their PPO4 releases increase due a progressive internal accumulation of sediments, and therefore an increase in the internal load in P. Clearly, actions to modernize waste water treatment plants in the catchment could be undertaken to reduce the point-source contribution of P to the Lac au Duc. These actions should be activated in parallel of the justified efforts requested to the farmers as to reduce the contribution of diffuse P emissions from agricultural soils.

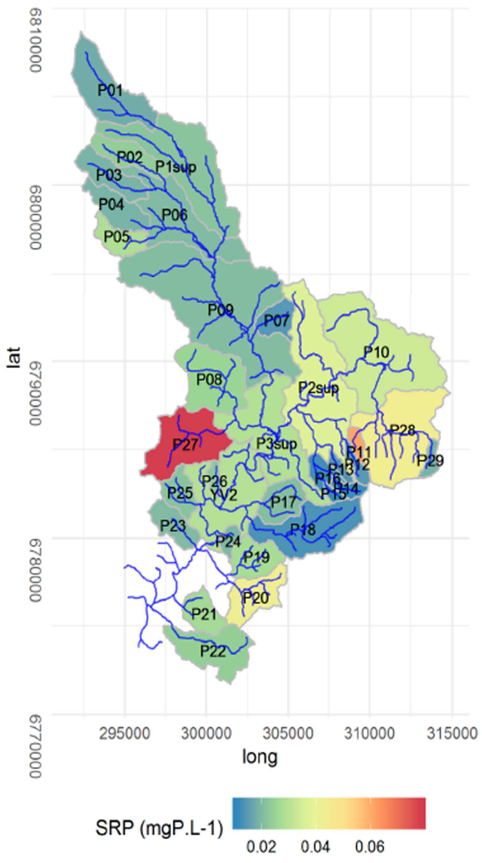

Figure 6. Sectorial map of P_{PO4} emissions in the Lac au Duc catchment showing the abnormally high emissions recorded in the sector of the municipality of Guilliers (red area). Emissions are shown as average SRP concentrations. SRP stands soluble reactive P or P_{PO4}.

What to remember : The proportion of diffuse agricultural emissions in the total P flux entering the Lac au Duc is estimated at 92%, the remaining 8% coming from domestic/industrial point-source emissions. Even if modernization of sewage treatment plants is to be envisaged, the preventive actions to be undertaken in priority to significantly reduce the flux of P entering the lake are therefore mainly actions aimed at reducing diffuse agricultural emissions.

These actions will inevitably be difficult and costly, the necessary emission reduction gains coming after an already significant reduction of agricultural P emissions in Brittany for 30 years (division by a factor of 2.5 of P fluxes on average).

Question N°3

Does a sub-catchment (headwater) approach reveals zones in the Lac au Duc catchment of particularly high diffuse phosphorus emissions? Are there sub-basins where targeting the implementation of Payments for Ecosystem Services (PES) could have the greatest impact on reducing the flux of phosphorus of agricultural origin at the lake inlet?

Reminder of the methodology used. With a view of revealing a potential sectorization of agricultural P emissions in the Lac au Duc catchment that could guide the implementation of PSE, the territory of the Lac au Duc catchment has been divided into 25 sub-catchments to the outlets of which monitoring of concentrations in P_{total} and P_{PO4} were carried out at the rate of one measurement every two weeks, between March 2018 and July 2019, so as to make them hierarchical with each other in terms of their capacity to emit agricultural P towards the Lake.

The results show significantly higher fluxes in the central and southern parts of the catchment (0.13 kg P_{total}/ha), compared to the northern part (0.11 kg P_{total}/ha), slightly less P-emitting (Fig. 7). This distribution is consistent with the existence of thicker (and therefore perhaps more infiltrating) soils in the northern part compared to the central and southern parts of the basin (Loyat, Guilliers, Néant sur Yvel, Mauron sectors) in which soils are shallower and therefore probably more sensitive to P transfer by runoff. These results would therefore tend to suggest PES targeting in the south-central part of the catchment for maximum effect on reducing P fluxes at the lake inlet.

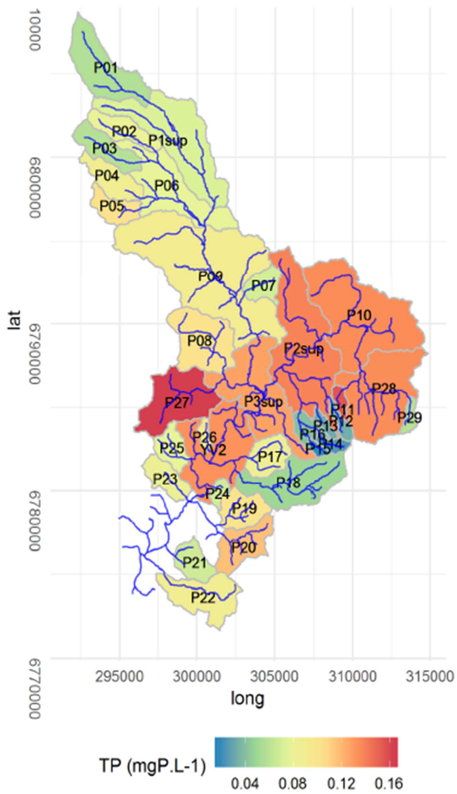

Figure 7. Map showing flow weighted average P_{total} concentrations at the scale of the 25 headwater catchments constituting the Lac au Duc catchment. The map show higher concentrations in headwater catchments located in the central and southern parts of the Lac au Duc catchment suggesting that PSE aiming at reducing P_{total} diffuse emission would be worth to implement in priority in those central and southern headwater catchments, for a maximum benefit on the ecological status of the lake. TP in the figure stands for total P.

Monitoring of P_{total} and P_{PO4} concentrations at the headwater catchment scale in the Yvel-Hivet catchment also made it possible to determine the basal concentrations of forest sub-catchments (pre-agriculture condition of the Yvel-Hivet catchment area) and sub-catchments dominated by permanent grassland (reference for plots with permanent vegetation cover). The results (Fig. 8) show average P_{total} concentrations of 2 to 3 times lower for forest sub-catchments than for arable sub-catchments, with sub-catchment under grassland occupying an intermediate position (division factor with respect to arable headwater catchments between 1.5 and 2). There is also a very strong reduction of flood P_{total} concentration peaks in forest sub-catchments denoting the absence of significant mobilization of total by runoff in these basins. An equivalent hierarchy is observed for P_{PO4} concentrations.

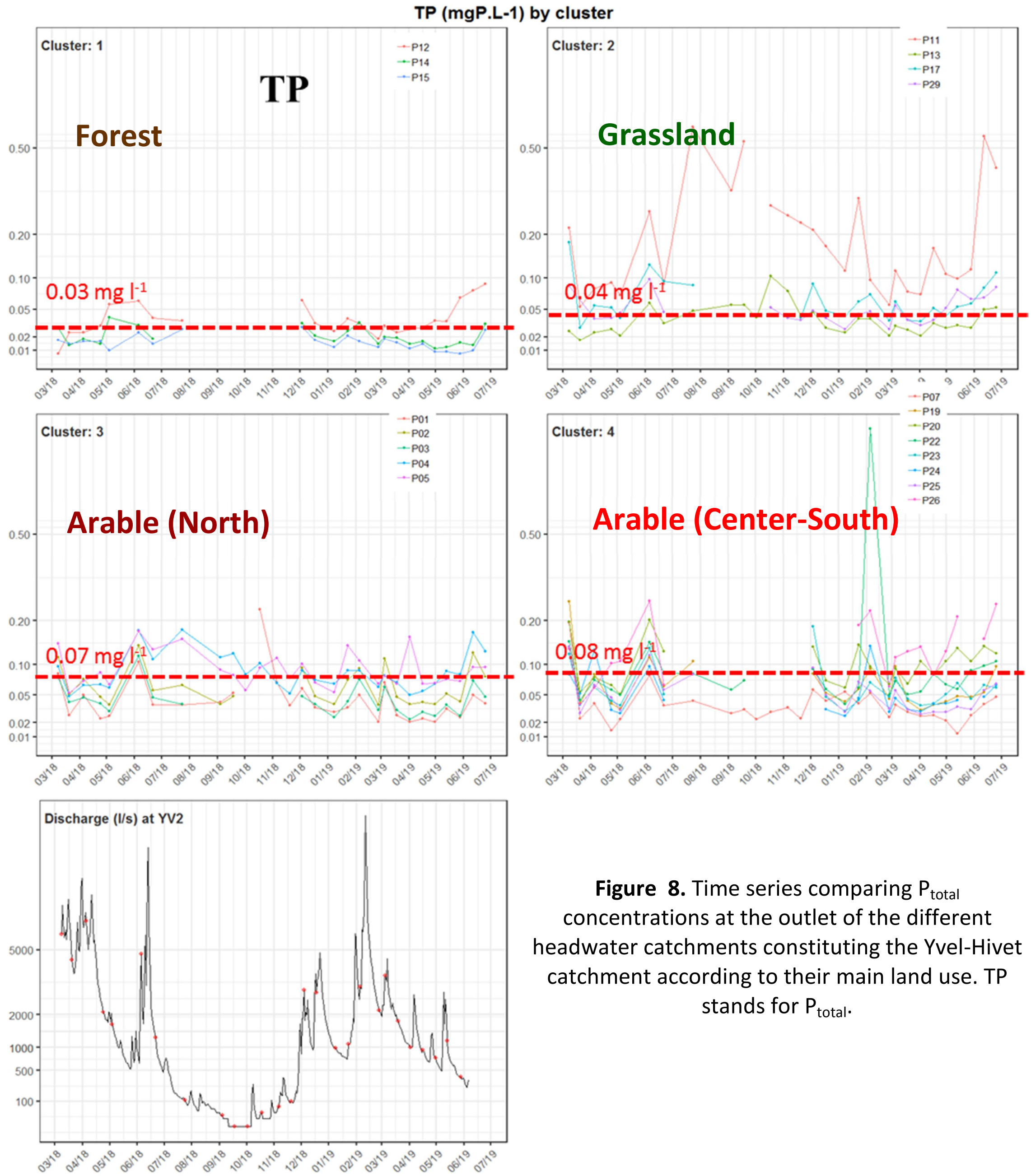

Figure 8. Time series comparing P_{total} concentrations at the outlet of the different headwater catchments constituting the Yvel-Hivet catchment according to their main land use. TP stands for P_{total}.

What to remember : Monitoring concentrations and P fluxes in the Lac au Duc catchment show that the central and southern parts of the catchment are more P-emitting than the northern sector.

Thus, priority targeting of PES in the south-central part of the basin could be very relevant, with a maximum effect on the reduction of P fluxes at the lake inlet.

Question N°4

What objectives of phosphorus flux reduction at the lake inlet should be targeted in order to preserve/restore lake's uses/services? In other words, by what factor should we divide the current flux to preserve or restore basic lake's use/service such as drinking water production or bathing?

Reminder of the methodology used. The methodology consisted in using the literature and the link that this literature establishes between P_{total} concentrations/fluxes and the trophic status of lakes, then classifying the various services provided by the Lac au Duc and their sustainability or restoration depending on the of the P_{total} flux to the lake.

The analysis of the scientific literature shows a certain disparity in the P content thresholds used to qualify the trophic levels and ecological status of shallow lakes like the Lac au Duc (maximum depth < 5 m). In this work, the most permissive thresholds (highest P contents) were retained (thresholds defined by Søndergaard et al., 2005; see Table 1), with a view to limit as much as possible the efforts needed to reduce P inputs to the lake. .

	Study	Ultra-Oligotrophic Excellent	Oligotrophic Good	Mésotrophic Moderate	Eutrophic Poor	Hyper-eutrophic Very poor
P total (µg/l)	1	[C]<5	5<[C]<10	10<[C]<30	30<[C]<100	[C]>100
	2	[C]<15	15<[C]<30	30<[C]<50	50<[C]<75	[C]>75
	3	[C]<25	25<[C]<50	50<[C]<100	100<[C]<200	[C]>200
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	[C]>50
	3	[C]<5	5<[C]<11	11<[C]<21	21<[C]<55	[C]>55
Secchi Disc Transparancy (m)	1	T>6	6>T>3	3>T>1,5	1,5>T>0,7	T<0,7
	2	T>3	T>3	3>T>2	2>T>1	T<0,9
	3	T>2	2>T>1,5	1,5>T>1	1>T>0,8	T<0,8

Tableau 1 : Links between total P content and trophic/ecological status in the case of shallow lakes.
1 : Nemery 2018 ; 2: Moss et al. 2003, 3 : Søndergaard et al. 2005.

A link was then established between P concentration, trophic level/ecological status of the Lac au Duc and the various services/uses provided by the lake. This connection was made from literature survey – not directly from data from the Lac au Duc - and is therefore subject to challenge or revision. The ultra-oligotrophic status ([C] in P <25 µg/l) is seen as the trophic status providing the strongest guarantee of the permanent provision by the lake of the "bathing" service, and therefor of all the other services (fisheries, nautical activities), the "bathing" service being indeed considered as the most restrictive both from a health point of view, and regarding the requirements it poses to the P flux reduction at the lake inlet. It is important to emphasize here that the target of an average P concentration <25 µg/l at the lake inlet is superimposed on the necessary decrease of the P stock present in the sediments of the lake. The export of this stored P out of the lake will necessarily take time, once a good quality of water will have been restored at the entrance of the lake.

It will be recalled that in France the regulation sets a concentration of 100,000 cyanobacteria cells per ml as the maximum authorized concentration for bathing and a concentration <0.1 µg/l in toxins produced by cyanobacteria (i.e. microcystin-LR) for the production of drinking water. It will be also recalled that the threshold of 100,000 cells/ml is exceeded almost every year in the Lac au Duc with peaks, of cyanobacteria concentrations of up to 2 million cells per ml (Fig 9). Indeed, the Lac au Duc can be described as hyper-eutrophic in terms of chlorophyll a content (Fig. 10). Finally, it should be recalled that for fisheries, the regulation implies the prohibition of the consumption of fish in the event of scum in areas of efflorescence (see http://baignades.sante.gouv.fr).

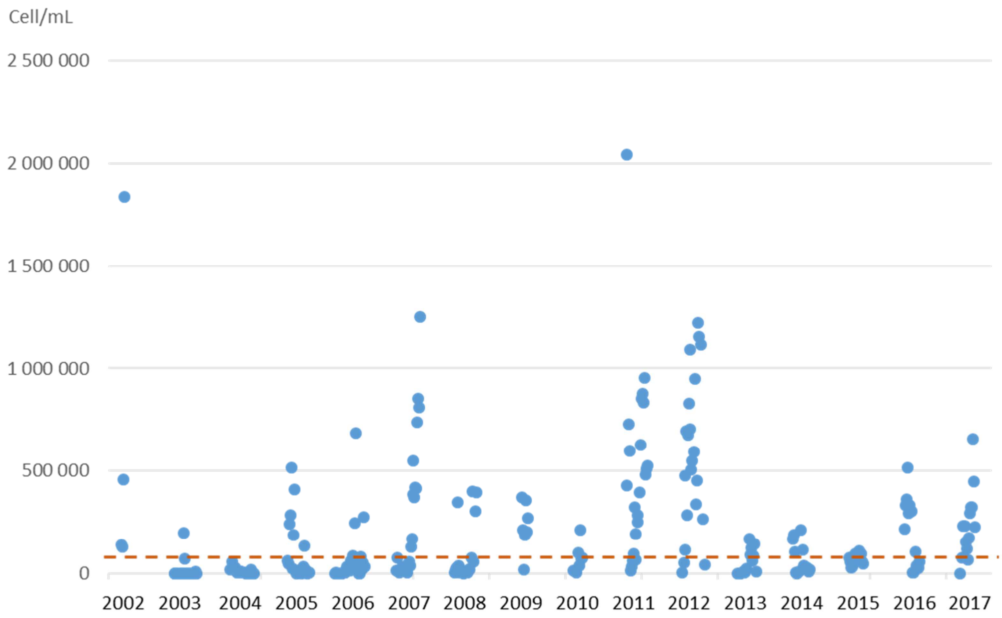

Figure 9. Concentrations of cyanobacteria recorded in the Lac au Duc between 2002 and 2017. The regulatory threshold of 100,000 cells / ml is indicated by the red dotted line.

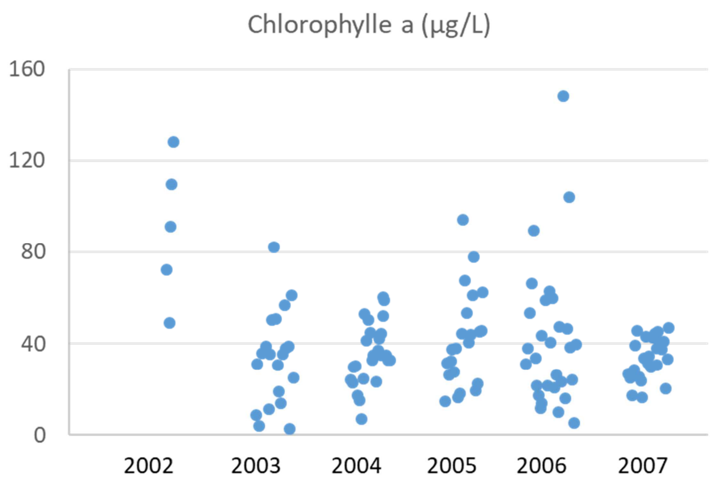

Figure 10. Chlorophyll a contents measured in Lac au Duc between 2002 and 2017, classifying the lake as hyper-eutrophic.

Considering the threshold of ultra-oligotrophy as the threshold guaranteeing all the services or uses of the lake, a declassification grid of the lake uses/services was built by threshold of increase of the trophic level, the declassification being done in the order bathing, fishing, nautical activities, as far as to the loss of all services for a eutrophic/hyper-eutrophic status. (Table 2). The relationships thus established between "Ptotal content", "trophic status" and "service/uses of the lake" provides a framework for defining P concentration thresholds to be reached at the lake inlet in order to ensure the sustainable supply (or restauration in the case of bathing which is currently subject to frequent prohibitions) of any given use/service provided by the lake over the long term.

Given the current average annual concentration of 100 µg/l of P_{total} at the lake inlet, it appears that a **division of current P emissions by a factor of 4-5 is necessary to guarantee all uses (inlet concentration <25 µg/L)**, including the "bathing" use seen as the most restrictive from the point of view of the trophic status of the lake. **A slightly lower division of the input concentration by a factor 2-3 could be sufficient to guarantee only the uses "fishing" and "nautical activities".**

P_{total} content (µg/l)	**Trophic level**	**Ecological status**	**Use/Service**
[C]<25	Ultra-oligotrophic	Excellent	Bathing, fishery, nautical activities
25<[C]<50	Oligotrophic	Good	Fishery, nautical activities
50<[C]<100	Mesotrophic	Moderate	Nautical activities
100<[C]	Eutrophic - Ultraeutrophic	Poor/Very poor	None

Tableau 2. Relationships between P contents to be targeted at the entrance of the Lac au Duc and the different uses/services provided by the lake.

It should be noted that the objective of reducing the flux of P at the entrance of Lac au Duc below the 25µg/l threshold is an ambitious goal that may require the mobilization of all the farmers in the lake catchment. An intermediate objective could be to reduce agricultural P flux at the scale of particularly contributing sub-catchments, such as those of the sub-catchments located in the central and southern parts of the catchment (see above). In this case, the flux reduction objective should be based on the flux measured today at the outlet of these sub-catchments.

It should also be noted that other indicators, more focused on the soils themselves, could be used to evaluate the effectiveness of changes in farming practices aimed at reducing agricultural P emissions to the Lac au Duc. For example, consider the saturation rate in P of the soil that provides an a priori estimate of the P concentration of a water solution in equilibrium with a soil (or a sediment derived from a soil). A goal of reducing the P saturation rate of the Lac au Duc catchment soils, calibrated on the targeted reduction of the P concentration to be reached for waters feeding the lake, could thus constitute the basis of the PES contracts proposed to the farmers of the catchment, instead of PES contracts directly targeting a reduction of the P flux at the lake entrance. Such "soil" PES contracts could be targeted on plots whose contributions to diffuse P emissions are the highest.

What to remember : In order to guarantee all the uses/services intrinsically linked to a good quality of the Lac au Duc water (bathing, fishing, nautical activities), the scientific literature shows that a P_{total} concentration of at most 0.025 mg/l must be guarantee at the entrance of the lake.

Compared to the current measured concentration of 0.100 mg/l, the objective that must be set is thus to reduce the flux of P entering the Lac au Duc by a factor of at least 4.

Reach this objective is superimposed on the necessary decrease of the P stock present in the sediments of the lake, which currently constitutes an internal P source that can counterbalance any improvement of the quality of the river water that feeds the lake. The export of this stored P out of the lake will necessarily take time, once a good quality of the river water will have been restored at the entrance of the lake.

Question N°5

What technical attributes can be offered to farmers to reduce the flux of agricultural phosphorus entering the Lac au Duc? How to estimate the effect of the appropriation of these attributes by farmers on the reduction of this flux?

<u>Reminder of the methodology used</u>. As erosion is the main mechanism for P mobilization in agricultural catchments, an inventory of the technical attributes capable of reducing P transferred by runoff and erosion in the context of the Lac au Duc catchment has been carried out. Reducing the amount of P in soils has been also targeted, as high P concentration in soils can also results in high diffuse P emission.

Three technical attributes were ultimately retained, including 1) the cessation of phosphate mineral fertilization, 2) the establishment of permanent vegetation covers; and 3) the establishment of anti-erosion hedges, perpendicular to the slope at the edge of plots. The aims of these attributes from the point of view of the erosive flux of P are different. The attribute "cessation of fertilization" aims to reduce the P content of soils, and therefore directly targets the source of the erosive P flux. The attribute "permanent vegetation cover" aims to limit the development of erosive P fluxes, by attacking a key factor of control of this flux (water runoff). The last attribute ("implantation of anti-erosive hedges") aims to intercept any erosive P flux produced, before it arrives in the stream.

Regarding the current situation of the Lac au Duc catchment with regard to these attributes, it should be noted that the average density of hedgerow is 70m/ha, of which only 30% would have a proven anti-erosion role. It should also be noted that phosphate mineral fertilizers are used, particularly as starter fertilizer for maize cultivation, and that P balance evaluations indicate surplus for about 50% of farms (particularly in the southern part of the catchment), the surplus being partly caused by the addition of mineral fertilizers (Fig. 11). Finally, it should be noted that under-cover sowing ensuring permanent soil cover is practiced on certain plots of the catchment, knowing however that this practice is for the moment totally excluded from corn plots, which represent between 20 and 25% of the farm lands of the basin depending on the years.

Estimating the cost of reducing the agricultural P flux emitted by the Lac au Duc catchment implies knowing the costs of adopting each of the three technical attributes selected by the catchment's farmers. This also implies being able to know a priori the potential impact of each attribute on the objectives to be achieved of reducing the P flux at the entrance of lake. For the attributes "fertilizer" and "permanent vegetation cover", estimations of their impacts were carried out using the US Department of Agriculture's Annual Lost Phosphorus Estimator (APLE) model. The model mobilizes several input data that need to be informed to make it work, namely soil data (depth, clay and organic matter content, extractable P content), precipitation, runoff and the erosion rate, organic and inorganic P inputs, and finally P exports by crops. The output of the model is the losses of P by runoff and erosion, in which the dissolved and particulate forms of P are distinguished. The impact of the cessation of mineral fertilization can be simulated by assigning the value "0" to this entry of the model. The impact of the establishment of a permanent plant cover can be simulated by playing on a particular parameter of the model called factor "c", which integrates the types of cover and tillage. This factor "c" can lead to a maximum decrease in erosive flow by a factor of 5, compared to an initial situation without cover. The choice was made in this study to use this maximum flux reduction value of a factor of "5" as a base value to simulate the effect of the implantation of a permanent vegetation cover on the reduction of the P flux entering Lac au Duc.

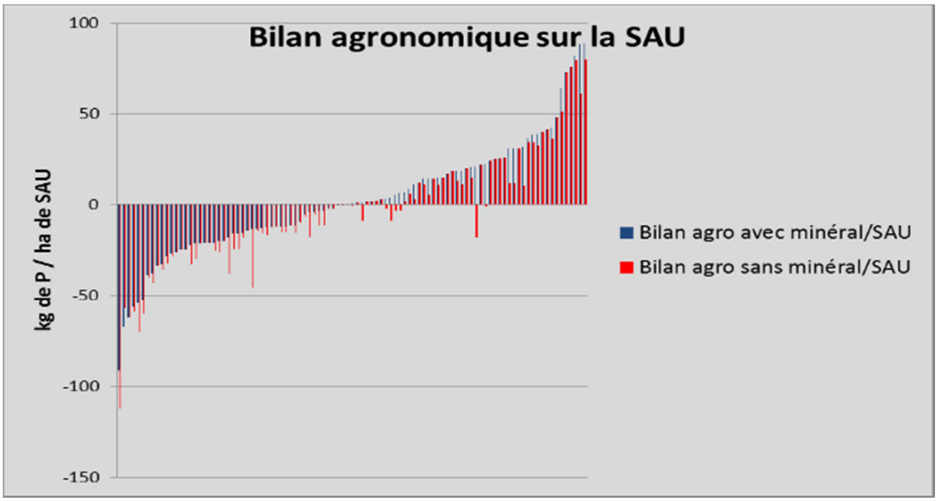

Figure 11. Balance of P inputs (fertilization) and outputs (crop export) for Yvel catchment soils. The data show approximately equal proportion of soils showing positive or negative balances (data source: SMGBO).

Regarding the impact of anti-erosion hedges on P fluxes, no model to simulate this effect could be traced back in the literature. Hypotheses therefore had to be set. The preoccupation retained here was to assign an arbitrary flux retention factor of 50% for a 100 m anti-erosion hedge located downstream of a 1 ha plot, this retention factor then decreasing linearly and proportionally with the decrease of the linear hedge.

In the end, the reduction of the erosive P flux emitted by the catchment according to the appropriation of the three technical attributes proposed to the farmers was simulated by comparing the current P flux (F_{actual}) calculated by the APLE code and weighted by the current average linear amount of anti-erosion hedges existing on the basin, with the simulated erosive flux ($F_{simulated}$) by the same code APLE by adopting the attributes "cessation of mineral fertilization" and "establishment of a permanent vegetation cover", the result being then weighted with an implantation effect of a given linear amount of anti-erosion hedges. The final $F_{actuel}/F_{simulated}$ ratio then gives the expected lake input P flux reduction factor due to the farmers' adoption of the three proposed attributes.

It should be noted that as far as the APLE model allows a maximum 5-time reduction in the erosion P flux of P as a function of implantation of a permanent soil cover, this model provides some sort of a posteriori validation of the choice of the attribute "permanent vegetation cover" as a lever that could achieve the objective of reducing agricultural P emission of a factor of 4 to 5.

What to remember: Three technical attributes have been identifies as possible levers to reduce agricultural P emissions in the Lac au Duc catchment, without affecting production systems and farm structure:

- stopping of phosphate mineral fertilization (objective: to reduce the size of the soil P stock);
- implantation of permanent plant covers (objective: to limit soil erosion during rain events);
- implantation of anti-erosion hedges, perpendicular to the slope, at the plot boundary (objective: to capture the erosive P flux before it reaches the watercourse, assuming the establishment of a permanent plant cover would not prevent its development.

Considering the APLE model that allows to estimate P losses from cultivated soils, the implantation of permanent plant cover on the Lac au Duc catcment soils has the potential to reduce these losses by a factor of 5, which corresponds to the reduction objective sets at the entrance of the lake.

Question N°6

How can the costs of adoption by farmers of the different technical attributes proposed to reduce agricultural phosphorus losses be assessed? What average costs per hectare do we expect depending on the targeted attributes? How do these costs vary depending on farm types?

Reminder of the methodology used. Here the question is to determine the price of the technical attributes identified, from the point of view of the farmers, so as to be able then to quantify the supply of environmental services likely to be made by the farmers of the Lac au Duc (in the sense of actions to improve the functioning of the catchment-lake ecosystem) with the aim of improving/restoring the uses/ ecosystem services provided by the lake. In other words, it is about quantifying the consent to receive from farmers (CRF).

To determine these prices, the "choice" experiments method was used. The method uses the results of face-to-face surveys in which several payment scenarios for environmental services (PES) are offered to farmers. The results also include data on the sociology of farmers (age, education level, etc.) as well as on the typology of farming systems. Four levels of establishment of plant covers have been proposed to farmers (20, 40, 60 or 80% of cultivated surface), with or without three levels of anti-erosion hedge (40, 70 and 100 m per hectare of cultivated surface). The "phosphate mineral fertilizer" category has been proposed according to an "authorized" or "prohibited" modality. Two modalities of duration of the contracts and four modalities of remuneration per hectare of cultivated area were proposed (100, 200, 300, and 400 €). It should be noted that the proposed PES are system PES, that is to say covering all the cultivated area of a given farm, even if the proposed technical attributes are implanted only on a fraction of the total cultivated area. The investigations were conducted by 6 investigators. In the end, 52 farmers responded from a total of 400 farmers cultivating lands of the catchment.

The statistical treatment of the results showed that the attribute "mineral fertilizers" was not a determining factor of the choice of the farmers (no effect on the asking price), certainly connected with the fact that the abandonment of the mineral fertilization in P does not require any investment. On the other hand, the cultivation of maize appeared to be a binding element of the asking price in the case of the attribute "permanent plant cover", with payments per hectare very strongly increasing (20% or more) in the case of the presence of maize on the farm (see Tables 3 and 4). This additional cost is most likely to be related to the technical difficulty of controlling plant covers under maize, and the risk of yield loss that the establishment of these cutlery makes in case of no control.

It should be noted that the costs estimated here - between 300€ and 600€ per hectare (Table 4), depending on the measures adopted and their adoption rate - are the result of "choice" experiments in which there is no questioning of farming systems, nor production volumes. The proposed PES are "system" PES per ha per year, established to cover the annual operating costs of the proposed technical attributes while incorporating certain benefits. Thus, for the "hedge" attribute, the proposed PES were constructed in such a way as to cover the costs of hedgerow maintenance and the crop yield losses associated with their implementation (edge effects), while integrating the possible benefits generated for biodiversity. The ranges of prices were established on the basis of the agri-environmental and climate measure type of assistance proposed by the Brittany Region in the framework of the EU Common Agricultural Policy, as well as the result of discussions with the farmers of the Lac au Duc catchment. The fact that the proposed PES did not generate rejection or massive adoption attitudes by the surveyed farmers indicates that these ranges probably reflect a certain cost reality.

Cost type	**Price models (consent to receive) depending on the presence or absence of maize on the farm**	
	Without maize	**With maize**
Fixed cost (commitment to the	130€/ha of cultivated land area (CLA)	130€/ha of CLA
Unit cost linked to the setting up a permanent plant cover	3,2€/ha of CLA and per % of covered CLA	3,2€/ha of CLA and per % of covered CLA + 0,054€ par % of the CLA in maize
Unit cost link to the setting up of anti-erosion hedges	1,1€ by m of anti-erosion hadge and by ha of CLA	1,1€ by m of anti-erosion hedge and by ha of CLA

Table 3. Consents to be received for the attributes "permanent vegetation cover" and "anti-erosive hedgerows" as obtained after analysis of the results of surveys conducted with farmers of the Lac au Duc catchment.

	% CLA under permanent getela cover	**Linear meter of hedgerow/ha of CLA**	**Payment/ ha of CLA**	**Total payment at farm level**
Farm A (only arable land) CLA = 80 ha 0% permanent grassland 25% CLA in maize	40%	20 m	334 €	26 720 €
	40%	100 m	422 €	33 760 €
	80%	20 m	516 €	41 280 €
	80%	100 m	604 €	48 320 €
Farm B (only arable land) CLA = 40 ha 0% permanent grassland 0% CLA in maize	40%	20 m	280 €	11 200 €
	40%	100 m	368 €	14 720 €
	80%	20 m	408 €	16 320 €
	80%	100 m	496 €	19 840 €

Table 4.Examples of costs per hectare of Cultivated Land Area and per farm for two fictitious farms in the Lac au Duc catchment as deduced from the results of surveys conducted with farmers in the basin. The presented costs/payments are yearly costs/payments.

We conclude by stating that the surveys did not reveal any major differences between the main types of farming systems present in catchment, except for the propensity of dairy farms to lead to slightly lower costs for the attribute "permanent vegetal cover", and a propensity of farms in pig production to lead to higher costs for this attribute, a difference likely due to a greater proportion of maize plots used for the spreading of pig manure in the latter. This question of the link between CRF and farming systems could not, however, be addressed with the desired level of precision because of a bias in the consulted farmer population, which included an overrepresentation of dairy farmers.

What to remember : Four main points are to remember:

• stopping the fertilization of the soil with phosphate mineral fertilizers does not lead to any cost;

• concerning the establishment of permanent plant cover and anti-erosion hedges, the prices requested by farmers are broken down into a fixed portion of € 130/ha of cultivated land area and a variable part depending on the effort made to rate of establishment of permanent plant cover and anti-erosive hedges;

• the cultivation of maize leads to higher amounts, probably because of the risk posed by the planting of plant cover crops on maize yields;

• In the end, the amounts requested by farmers vary between 300 and 600 €/ha depending on the percentage of permanent plant cover and the length of hedge to be planted, and the presence or absence of maize in the crop rotation.

Question N°7

What are the costs of reducing the diffuse emissions of agricultural phosphorus arriving to the Lac au Duc? How do these costs evolve with the reduction level to be achieved?

Reminder of the methodology used. The methodology deployed here consisted in classifying the catchment plots in major categories so that simulations of current P fluxes and of P fluxes after implementation of the three technical attributes proposed to farmers could be made using the APLE model. Individual reduction flux factor calculated for each plot category were then aggregated at the catchment scale based on the proportion of each plot category to calculate the total reduction in flux at the lake inlet. Sixteen classes of arable plots were defined, based on crop rotation (wheat-maïze alternation and wheat only), soil thickness (thick and thin) and risk of erosion (4 risk classes), to which was added a "grassland" class, characterized by a constant flux of P. A class "other" also declined in 8 categories according to the depth of the soil and the erosion risk was also added. The simulations were conducted over a period of 50 years. In each case, the result corresponds to the average of the last 30 years, after stabilization of emissions.

From this approach, the plot categories were ranked regarding the efficiency of establishing of a permanent plant cover on the reduction of erosive P flux (Fig. 12).

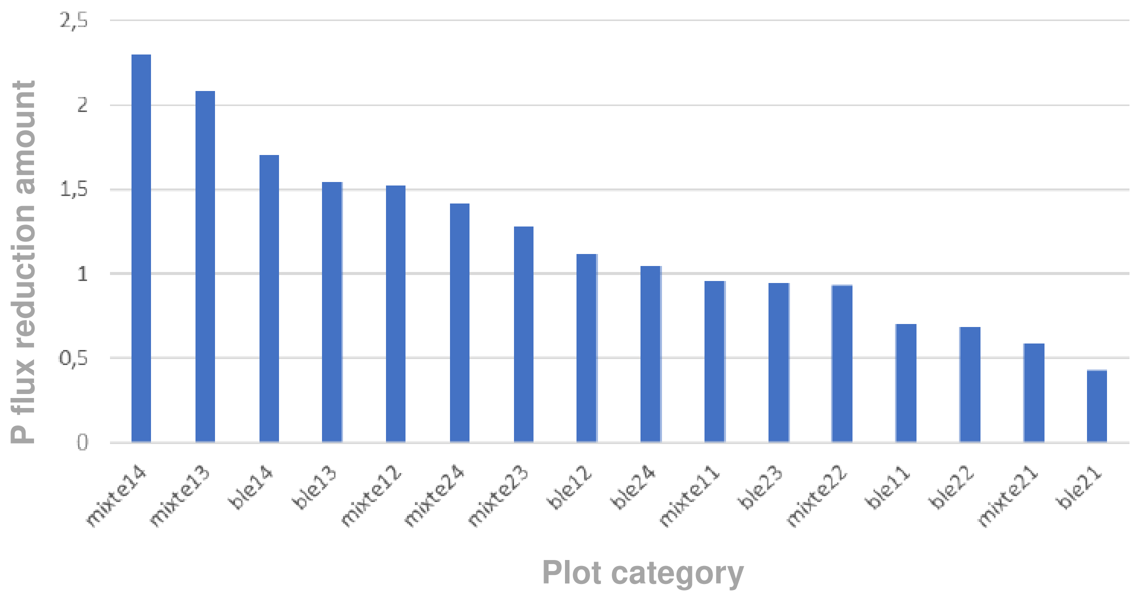

Figure 12. Classification of arable plots in the Lac au Duc catchment in decreasing order of effectiveness of P flux reduction following the establishment of a permanent vegetation cover (results from the APLE model). In the figure, "ble" stands "wheat", whereas "mixte" stands for "wheat-maize"

These results were then transformed into a cost-effectiveness ratio by classing the plots not only on the basis of the efficiency of reduction of the P flux due to the implantation of a permanent vegetation cover, but also on the basis of the cost of this implantation. Quite logically, this cost / efficiency ranking has led to the decommissioning of mixed plots that are *very erosive but contain maize (higher costs of planting a permanent plant cover) in favor of plots with the same erodibility, but grown only in wheat, and thus with lower costs (Fig. 13).*

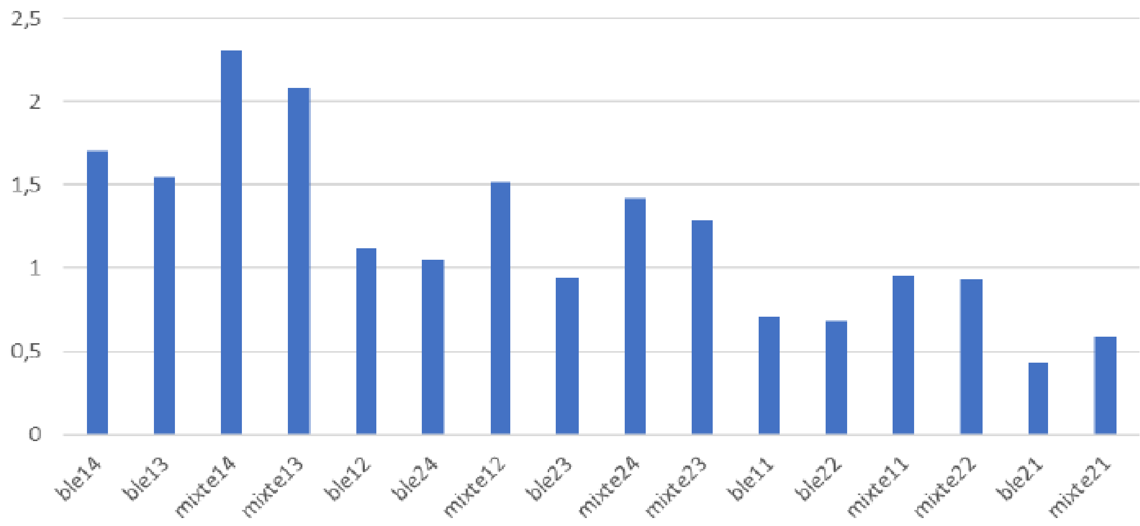

Figure 13. Classification of arable plots in the Lac au Duc catchment in relation to increasing cost / efficiency. The most cost effective plots on the left are high erosion risk plots grown in wheat.

Based on these rankings, cost-effectiveness scenarios for reducing the flux of P at the lake inlet have been constructed by aggregating at the scale of the catchment the flux reduction simulated at the plot scale due to implantation of a permanent vegetation cover, and by combining these simulations with different hedge planting rates. Three factors of reduction of the P flux at entrance of lake were targeted in these simulations: 2, 3 and 5.

The results of the simulations carried out (Table 5) show that reducing the flux of P entering the Lac au Duc by a factor of 2 or 3 can be done either by targeting the most cost effective plots and maximizing the linear of hedge to implement on these plots (100 m/ha), or by implanting less linear meters of anti-erosive hedges, in which case less cost/effective plots from the point of view of the permanent plant cover attribute must be enrolled in the simulation. In both cases we see that the non-targeting of the most cost effective plots with implantation of a high linear meter of hedges leads to an additional cost, extra cost particularly manifest in the case of a reduction of a factor 2 (factor 1.66).

Regarding the reduction of the P flux by a factor of 5, this is only achievable if all the plots are enrolled, with maximization on each plot of the linear amount of hedge (100 m/ha).

When compared each other, the different scenarios show that between 6 and 14 million euros per year are needed, depending on the reduction objective set and the targeting or non-targeting of the most cost/effective plots as regards the establishment of a permanent vegetation cover.

Factor and modality of reduction of P fluxes	% of plots with permanent vegetated cover	m/ha of anti-erosion hedge	Total cost/year in euros
2 (targeting)	50	100	6 170 000
2 (no targeting)	74	20	10 400 000
3 (targeting)	79	100	10 330 000
3 (no targeting)	100	37	11 900 000
5 (no targeting)	97	100	14 150 000

Tableau 5. Calculation of the costs induced by the reduction of P fluxes at the entrance of the Lac au Duc by a factor of 2, 3 and 5 depending on whether the measures are targeted or not on the most cost/effective plots as regards the establishment of permanent plant cover and anti-erosive

It should be noted that scenarios were also constructed to test the type of plots that would be enrolled, and the reduction in the flux of P that this enrollment would generate, if uniform payments close to the average CRF (i.e. not taking into account the additional costs related to the presence of maize) were proposed. The results show very clearly that the lack of enrollment of maize plots is very penalizing from the point of view of the reduction of P fluxes, even if the costs appear lower. Thus, a uniform payment close to the average CRF has the capacity to enroll all the wheat parcels in the basin, some of which are very cost/effective, for a relatively modest overall cost (2.4 million euros), but the overall reduction of the P flux at the entrance of the lake is low, not even reaching a factor of 2. Decreasing the P flux by a factor of 2 or more requires the enrolment of maize plots in the PES system, which inevitably increases costs.

In conclusion of these evaluations, it is important to point out some limits of the simulations carried out. A first limitation that should be mentioned is that the distribution of plots into a finite number of categories requires the mobilization of all plots of the same type in the modeling. This confers quite a strong rigidity on the results obtained. A second constraint is that the cost/efficiency ranking of plots is based on the current crop rotations, and the constraint that these rotations bring on the additional costs related to the cultivation of maize. In the hypothesis of the implantation of PSE on durations of 6-9 years, nothing says that the crop rotations observed today, plot by plot, will remain stable.

A third and final limitation is related to the fact that the choice has been made to freeze production systems in what they are today. By making this choice, it prevents significant changes that could be more effective and less costly from the point of view of reducing P fluxes such as stopping breeding or giving priority to certain animal productions, or totally stopping cultivation and switching all farms to grass or organic. Yet, we know that in economy constraints are necessarily costly. This being the case, the option of not seriously questioning the production systems was chosen because i) this option is the most realistic in the short term (a major reshuffling takes time), and ii) it is hard to imagine that the farmers surveyed, for whom quantifying the proposed changes already require considerable effort, are able to quantify what would cost a major overhaul of their production system.

What to remember : The payments to be committed to reduce the flux of agricultural P at the entrance to the Lac au Duc vary according to the targeted reduction objective flow and according to whether or not the most erosion-prone plots, and therefore the most cost effective from the point of view of the recommended flow reduction attributes, are targeted. Three main points must be noted:

• a factor 2 reduction of the flux can lead to significantly different payments depending on whether or not the plots most at risk are targeted; targeting in this case reduces the cost from 10.4 million €/year to 6.2 million €/year.

• the greater the targeted reduction effort of P flux at the lake inlet, the more the difference between targeting and non-targeting scenarios decreases;

• aimed at reducing the flux of agricultural P at the entrance of the lake by a factor of 4-5, requires enrollment of all the plots of the catchment in the PES at an estimated cost of 14 million € per year.

Question N°8

Does a cost-effectiveness analysis of the reduction of P fluxes show an interest in targeting PES to certain parts of the catchment? Does this targeting correspond to the maximum phosphorus emission zones established from the monitoring carried out in the stream and river networks of the lake catchment?

<u>Reminder of the methodology used</u>. The methodology deployed here is the same as the one deployed to answer question 7 except that the question here is no longer whether targeting reduces costs only, but whether targeting allow to identify certain parts of the catchments in which the implantation of PSE could be more particularly cost/effective as regard the objective of reducing P fluxes at the entrance of lake.

Here, we use the results of the scenario for estimating the costs of reducing the flux of P at the entrance of the lake by a factor of 2, achieved by targeting the most cost/effective plots. This scenario clearly shows a non-arbitrary distribution of plots on which it would be interesting to target PES, showing an overrepresentation of the suitable plots in the central/southern part of the catchment (Fig. 14). This location is not arbitrary since it also corresponds to the part of the most emitting P catchment, as determined from the monitoring of P concentrations/fluxes made at the headwater catchment scale (Fig. 14). We thus see a connection between the work done on the economic evaluation of costs and the work done on the spatialization of P fluxes. This link is not unexpected in that cost-based work prioritizes the most erosion-prone plots and to the extent that basin areas where erosion is expected be the strongest are also the most exporting areas of P.

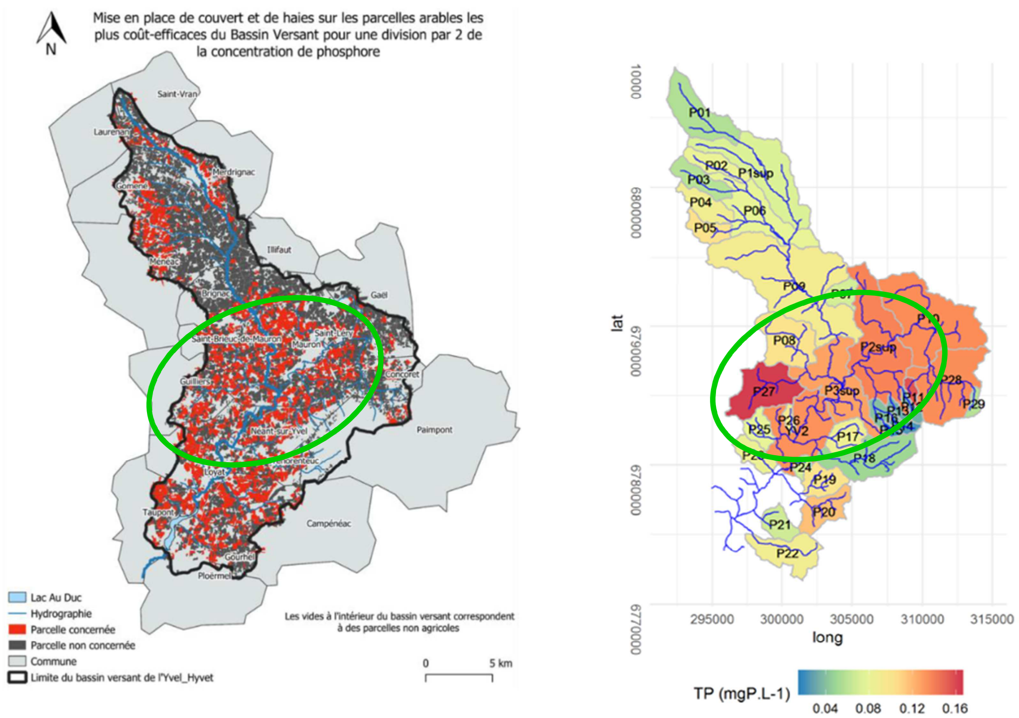

Figure 14. Figure showing the overlap between maximum agricultural P emission areas in the Lac au Duc catchment and areas of concentration of the more cost effective plots from the point of view of the reduction of P fluxes.

The sectoral targeting that appears here is clearly limited in scope since it only reduces the flux of P entering the Lac au Duc by a factor of 2. Indeed, reducing this flux by a factor of 3 to 5, the reduction rate necessary to ensure all uses of the lake, would require that all catchment plots be integrated into the P flux reduction process. However, this result can be used to define catchment sectors in which to start implementation of PES, knowing that PES established in these sectors will have a maximum effect on the reduction of the p flux at the lake entry..

Moreover, the concentration in these areas of very erosive and very cost/effective plots as regard the establishment of permanent plant covers and anti-erosion hedges can make these areas particularly conducive to an ex-post evaluation of the effects of the corrective measures recommended. Indeed, the effects on the reduction of the P flux are expected to be maximum because of the high concentration in these sectors of plots with high erosion risk. In other words, the implementation of PES in headwater catchments of the Lac au Duc basin concentrating plots of high "erosion" risk, even if it leads at the entrance of the lake to a division factor of no more than 2 should lead to a much larger decrease in P flux at the outlet of the headwater catchments in question, and thus, in the short term, to a more easily detectable effect of the adoption of attributes .

We will recall here that PES contracts are in theory contracts conditioned to the achievement of an objective, and that it is necessary to be able to demonstrate this achievement in order to demonstrate the environmental effectiveness of the PES scheme put in place. Implementing PES in headwater catchments with a high proportion of high erosion risk plots is also a way to verify the environmental effectiveness of PSE built on the two measures recommended here, and also to calibrate, under real conditions, the conditionality of these PES to achieve the specific goal of reducing P fluxes at catchment scale.

What to remember : Targeting the most cost-effective plots regarding P emission decrease tends to localize the effort to implement PES in the central and southern part of the basin, but this targeting can, at best, lead to a reduction in the flux of agricultural to the P flux at the entrance of the lake of a maximum factor of 2.

This targeting corresponds to the most emitting sectors of agricultural P as determined by the analysis of P concentrations carried out in the hydrographic network, demonstrating the coherence of the two approaches.

Nevertheless, it should be remembered that a reduction in the lake P influx by a factor of >3 necessarily imply also mobilizing low-risk, less cost-effective plots. In this case, the area of PES implantation increases and eventually encompasses the entire catchment.

Question N°9

How much costs the damages caused by the poor ecological status of Lac au Duc? What is the final balance between supply and demand for environmental services for the Lac au Duc catchment?

<u>Reminder of the methodology used</u>. The methodology deployed here consisted on the one hand in estimating the damages caused by cyanobacteria blooms on the various uses of the lake (bathing, fishing, nautical activities) and on the economic activities that rely on these activities (hotel, camping, catering, etc.). On the other hand, we try to estimate the costs of the various curative measures deployed on the lake itself to try to limit the algal blooms either by using biocides ($CuSO_4$; H_2O_2) or by preventing the availability of P present in the water column ($CaCO_3$). The cost of sediment dredging has also been estimated, since sediments can be considered a source of P for cyanobacteria. Finally, the damage was evaluated by attempting to approach the loss of well-being to which the prohibitions of uses of which the Lac au Duc is subjected leads, with three targeted uses: swimming, fishing and nautical activities. This loss of well-being by lake users (true or potential) was estimated on the basis of surveys in which fictitious lakes allowing the practice of such and such activity were proposed to Lac au Duc users (285 individuals surveyed), the distance between the lake fictitious proposed and the home of the users being used to estimate monetarily the loss of well-being (on the basis of the cost of the gasoline necessary to make the trip). The aggregation of results at the scale of the 180,000 people residing in the lake's catchment area has made it possible to reach a quantitative estimate of the cost of poor ecological status from the point of view of its potential users, this cost being transformed into a financial amount that these same users could be able to mobilize to help restore a good ecological status of the lake (assessment of willingness to pay - or WTP – of inhabitants or the potential demand for environmental services existing within the area influence of the lake).

The results obtained to date are not complete, as information on direct economic losses is particularly difficult to obtain (Table 6). For the latter, it is likely that they are limited. This is the case, for example, of the nautical club, which has diversified its activities to compensate for bathing bans. Same for the hotel, restaurant and camping activities where the ecological damage suffered by the lake seems to have relatively low impacts. Regardless of the actual numbers, it is very unlikely that the cost of direct economic damage will approach the costs of farmers' consents to receive (CR) to reduce dissolved P fluxes at the lake's entrance.

The costs of curative actions deployed to combat the development of cyanobacteria in the lake and allow the permanence of bathing, fishing and nautical activities is also well below the estimated CR of farmers. The maximum cost is that induced by the application of H_20_2 in 2018, which was around 220 000 euros, 30 times less than the CAR necessary to allow the permanence of the bathing activity. On these bases, we can consider that the supply and demand for environmental services are not balanced, and that neither private actors benefiting from the services provided by the lake, nor the communities financing the curative actions deployed on the lake are able to release the financial resources necessary for the deployment of the PES required to reduce P fluxes at the entrance to Lake.

Direct damage costs on lake uses	**Total cost (€)**	**Annual cost (€)**
Drinking water production use		
Infrastructure costs of the Lac au Duc plant	?	?
Cost of pumping, treating and transporting water from another resource (Oust river)	?	?
Cost surcharge/ low of income for the Lac au Duc Plant in ace of use of the Oust water	?	350 000
Tourist activities		
Yacht club	?	?
Camping	?	?
Restaurants	?	?
Fisching	?	?

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 case of prohibition of swimming, but maintaining fishing and nautical activities		14 000 000
In case of maintenance of nautical activities only		29 000 000

Indirect costs related to various curative treatments operated (or projected)	**Total cost (€)**	**Annual cost (€)**
Aeration ramp		
Set up	?	?
Operation (electricity)	?	7 000
Maintenance	?	?
$CuSO_4$ (2003-2005)		
3 000 euros by spreading operation (2 ou 3 spreadings per year)	between 18 000 and 27 000	between 6 000 and 9 000
$CaCO_3$ (2012-2015)		
Construction and installation of a dam delimiting the bathing area (10 000 euros/year)	40 000	10 000
Spreading (10 000 euros/year)	40 000	10 000
H_2O_2 (2018)		220 000
Sediment removal (30 years efficiency if the P inlux is not drastically reduced. Not done so far)	20 000 000	830 000

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

The situation is different if one examines the results of the surveys aimed at quantifying the losses of well-being 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 implemented in the catchment in order to reduce the P flux at the entrance of Lake to a level guaranteeing the attainment and sustainability of a good quality lake water. Thus, the results show that there is a potentially sufficient demand to abound a fund to finance PES in the Lac au Duc catchment. However, the question remains of how to capture this manna (institution of direct tolls to access the various activities offered by the lake, establishing a toll at the parking lot, etc.) without drying it up.

What to remember : The cost of damage caused by the poor ecological status of the Lac au Duc amount to several million €/year. The highest costs are by far the indirect costs related to the loss of well-being of lake users, which can go up to> 30 million €/year in case of prohibition of all uses of the lake.