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Effects of hydropower management on the sediment composition and metabolism of a small Alpine lake

Effets de la gestion hydroélectrique sur la composition des sédiments et le métabolisme d'un petit lac alpin

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Abstract – The ecological equilibrium of water reservoirs may differ from that of natural lakes. We questioned this difference by analysing the sediments of a small oligotrophic Alpine lake, whose management was modified for hydroelectric production since 1976. Corne Lake is formed by a shallow depression connected to a deep depression. The hydropower management induced water level fluctuations (+2 m in summer; −8 m in winter) that emptied the shallow depression during the winter months and promoted the erosion of littoral soils and tributary channel sediment and the sedimentation in the deep depression. The sediment of the original lake was a low-density organic mud. The sediment composition varied according to 3 phases, which chronology is debated. During a first phase we measured an increase in the ratio of Diatom/Chrysophycea and bioavailable P, as well as a decrease in the C/N ratio and bulk radiocarbon age of the sediment, suggesting a trophic surge. A second phase was characterised by a high rate of mineral sedimentation, an increase of benthic diatom genera in the deep depression of the lake and acidophilic diatoms in the shallow depression. In the third phase covering the last upper cm of the cores, the sediment tended to return to its initial composition, but the algae community differed from its initial state. We suggest that the management of Alpine lakes as reservoirs induce long-term ecological changes in relation to water level fluctuations and littoral habitats degradation.

***Key words* –** reservoir, diatoms, trophic state, radiocarbon age, water level fluctuations

Résumé – L'équilibre écologique des réservoirs peut différer de celui des lacs naturels. Nous questionnons cette différence en analysant les sédiments d'un petit lac alpin oligotrophe aménagé pour la production électrique en 1976. Le lac de Corne est constitué d'une anse peu profonde connectée à une dépression profonde. L'aménagement hydroélectrique a induit des variations actuelles de niveau d'eau (+2 m en été ; −8 m en hiver) qui vident l'anse durant l'hiver et favorisent l'érosion des sols de berge et des sédiments dans le lit du tributaire et la sédimentation dans la dépression profonde. Avant l'aménagement, le sédiment du lac est une vase organique de faible densité. Son évolution suit trois phases, dont la datation est discutée. Durant une première phase, l'augmentation du ratio diatomée/chrysophycée et de la teneur en P biodisponible ainsi que la diminution du ratio C/N et de l'âge radiocarbone du sédiment suggèrent une poussée trophique. Une seconde phase est caractérisée par une forte sédimentation minérale, une augmentation des genres de diatomées benthiques dans la partie profonde du lac et des diatomées acidiphiles dans l'anse. Dans la troisième phase couvrant les derniers cm, les sédiments tendent à retourner vers leur composition géochimique initiale, mais la composition de la communauté algale demeure différente de celle observée à l'état initial. Cette étude suggère que la gestion des lacs alpins en tant que réservoirs induit des changements écologiques à long terme liés aux variations du niveau d'eau et à la dégradation des habitats littoraux.

Mots-clés **–** réservoir, diatomées, statut trophique, âge radiocarbone, variation de niveau d'eau

1 Introduction

Since the beginning of the 20th century, the hydrographic network has been deeply modified by the creation of artificial reservoirs. This leads to a) the interruption of the ecological continuum of rivers (Jansson *et al.*, 2000; Nilsson *et al.*, 2005), b) changes in hydrological regimes (c) changes in sediment and nutrient fluxes (Jigorel *et al.*, 2007; Van Cappellen & Maavara, 2016), and (d) global changes in biogeochemical cycles (Friedl & Wüest, 2002; Cole *et al.*, 2007; Maavara *et al.*, 2017).

The trophic surge hypothesis (TSH) (Grimard & Jones, 1982; Kimmel & Groeger, 1986; Hall *et al.*, 1999; Turgeon *et al.*, 2016) summarizes the trophic dynamics associated with impoundment. It highlights a short period of "trophic upsurge" related to: i) the colonization of vacant ecological niches created in this new ecosystem, and ii) flows of organic matter and nutrients, especially phosphorus (Ostrofsky, 1978) from the flooded area, which support primary production (Ostrofsky & Duthie, 1980; Robbins *et al.*, 2020), greenhouse gas (GHG) emissions (Barros *et al.*, 2011; Prairie *et al.*, 2018) and feed the food web (Houel *et al.*, 2006). This phase is followed by a "trophic depression", and the establishment of a new "trophic balance". These phases vary depending on the systems studied and can range in duration from a few years to several decades.

However, there is some confusion about the effects of impoundment and water level fluctuations, which commonly occur in reservoirs. Water level fluctuations may lead to soil and sediment erosion (Félix-Faure *et al.*, 2019a, 2019b), littoral and benthic habitats degradation (Furey *et al.*, 2004; Milbrink *et al.*, 2011), sediment transfer (Blais & Kalff, 1995) toward the lake centre, and changes in lake metabolism (Houel *et al.*, 2006) which also impacts the lake's trophic status (Milbrink *et al.*, 2011; Hirsch *et al.*, 2017).

Unfortunately, there are few experimental measurements of trophic dynamics following impoundment (Lima *et al.*, 2016; Turgeon *et al.*, 2016) due to two major reasons. First, at least in France, most impoundments were established before the development of ecological monitoring programs (Pont *et al.*, 1989). Second, sediment reworking during management operations may hamper their study. A possible approach to overcome these problems is to study natural lakes that were modified for hydroelectric production (Christie & Smol, 1996). In this case, the sedimentary chronicle begins before the onset of hydroelectric management and may allow, by comparison, an analysis of management effects.

The Alps are presently the main source of hydropower in Europe (Spitale *et al.*, 2015). Reservoirs were generally formed by impounding portions of valleys, but natural lakes are also often used as reservoirs. These reservoirs are generally filled in the spring with snowmelt water and emptied in autumn-winter to support the electrical demand for heating (Spitale *et al.*, 2015). In winter, water is drawn from under the ice of high-altitude reservoirs, so that the ice cover breaks up, collapses and slides along the slopes. The combination of soil freezing and ice sliding within the drawdown zone (Hellsten, 1997) further contributes to soil and sediment erosion.

Our aim was to document the ecological changes occurring in a lake managed as a reservoir, in relation to water level fluctuations. Our objectives were 1) to measure the temporal variation of sediment composition in relation to soil and sediment erosion of a high-altitude natural lake that has been utilized for hydroelectric production since 1976; 2) describe the ecological evolution of this lake using diatom and chrysophyte communities conserved in the sediment. These communities are typically used as indicators of current and past ecological status of water bodies (Dixit *et al.*, 1992; Christie & Smol, 1996); and 3) discuss the relationships between the changes in water level and the ecological dynamics of lakes managed as reservoirs.

2 Material and methods

2.1 Study site

The plateau of Sept-Laux is a high altitude (about 2000 m asl.) valley in the mountain range of Belledonne (French Northern Alps). The peak elevation bordering the valley is about 2500 m asl. The granitic substrate of the plateau is homogenous and very poor in CaO (1.5 ± 0.1%wt) and MgO (0.7 ± 0.1%wt) (Gasquet, 1979; Debon *et al.*, 1994; Debon & Lemmet, 1999). Neither mines, nor Pb/Cu/Ag anomalies are known in the local granite (Gasquet D., pers. comm.). According to a local meteorological station (Météo-France) at the Rivier d'Allemont (altitude: 1250 m asl.), corrected for altitude (0.5 °C/100 m, 50 mm precipitation/100 m), the average annual rainfall and temperature at the elevation of

2000 m asl. is about 2200 mm and 3 °C respectively. From November to April, snow covers the landscape and the surface of lakes is frozen. The soils are shallow, rich in pebbles, coarse textured, acidic and rich in organic matter. They vary between shallow Umbric Leptosols, rich in organic matter, between bare rock surfaces, Cambic Leptosols (Hyperdystric) rich in coarse elements, developed on scree's slopes, and Entic/Humic Podzols on till or scree deposits close to the valley bottom. Shallow Histosols occur locally near waterbody (IUSS Working Group WRB, 2015). The soils are covered with subalpine meadows and ericaceous heaths below 2200 m asl. and alpine meadows above 2200 m asl., and show little evidence of erosion. The complete deforestation of the current landscape is linked to husbandry grazing and has not been locally dated. A small sheepfold was located on the north side of the lake (as reported on the IGN map dated from 1950 and on aerial pictures), and another close to lake Sagne, but they were presently ruined.

Several lakes and ponds are located on this plateau (Fig. 1A). Among them, Corne Lake (45°13'27"N, 6°04'40"E) has a surface of 8.4 ha and a volume of 1.45 hm^3. It consists of a shallow depression (about 4 m depth) with a surface of 2 ha, connected to a deep depression (28 m depth) with a surface of 6.4 ha (Fig. 1B). Naturally, Corne Lake (altitude: 2096 m asl.) is fed by a small creek (mean autumn and winter discharge: 0.06 $m^3.s^{-1}$; mean spring discharge: 0.25 $m^3.s^{-1}$) flowing from Jéplan Lake (altitude: 2210 m asl., maximum depth: 2 m, area: 1.7 ha). The water of Corne Lake flows naturally downstream to Sagne Lake (altitude: 2040 m asl., maximum depth: 17 m, area: 6.5 ha). Discharge is very low (1–10 $L.s^{-1}$) in the late summer, autumn and winter, and much higher (10–100 $L.s^{-1}$) in the spring and early summer due to snow melt. The maximum altitude of the watershed of Corne Lake is 2500 m asl. and the area is 1.4 km^2. Around Corne Lake, the dominant meadows species are *Nardus stricta*, *Carex curvula*, and *Carex sempervirens* on the western slope, and *Festuca rubra*, *Gentiana acaulis*, and *Homogyne alpina* on the steep slope along the northwest bank of the lake. The tributary (see below) crosses a small peaty area with *Carex foetida*, *Carex nigra* and *Eriophorum scheuchzeri* before flowing into the shallow depression, where *Sparganium angustifolium* is present. The lake is bordered to the north and east by coarse screes and is closed to the south by a small porous till deposit.

Since 1976, the water of Corne and Sagne lakes, which naturally flowed to the south, was pumped out and transferred to Cos Lake whose water naturally flows through Cottepens, Motte and Carré lakes to the North, in order to supply water to the hydropower plant of the Haut Bréda Valley (Fig. 1A). A small dike at the outlet of Corne Lake was built, rising its maximum water level by 2 m (to 2098 m asl.). Two pumping station were installed (Fig. 1B), one raising the water flow of Sagne Lake (intake depth 13 m) to Corne Lake, and another one raising the water flow from Corne Lake (intake depth 11 m below the natural level of the lake) to Cos Lake. At Corne, a pumping device was installed by (1)

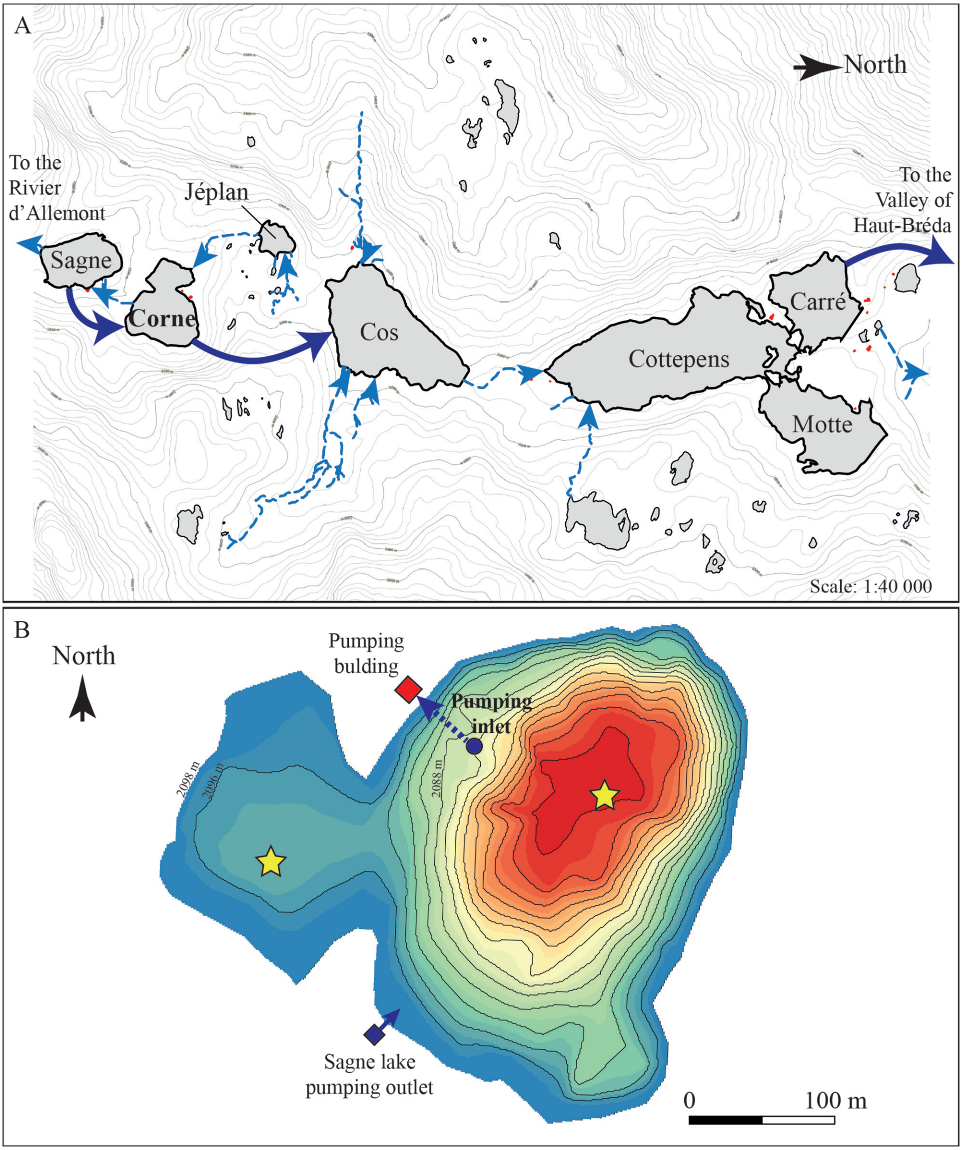

Fig. 1. A: Hydroelectric network of the Haut Bréda Valley. Natural or managed lakes are in grey. Originally lakes Jéplan, Corne and Sagne flowed south while lakes Cos, Cottepens, Carré and Motte flowed north. The blue dotted lines represent the main natural creeks. Arrows demonstrate the present routes of water pumped from Sagne Lake to Corne Lake, and from Corne Lake to Cos Lake. B: Bathymetry of Corne Lake. The yellow stars show the locations of the two sediment cores.

Fig. 1. A : Réseau hydroélectrique de la vallée du Haut Bréda. Les lacs naturels et réservoirs sont en gris. Initialement les lacs de Jéplan, Corne et Sagne se déversaient vers le sud alors que les lacs de Cos, Cottepens, Carré et Motte se déversaient vers le nord. Les lignes en pointillé bleu représentent les principaux ruisseaux naturels. Les flèches illustrent le trajet de l'eau pompée depuis le lac de Sagne vers le lac de Corne, et du lac de Corne vers le lac de Cos. B : Bathymétrie du lac de Corne. Les étoiles jaunes représentent les sites de prélèvements des carottes de sédiment.

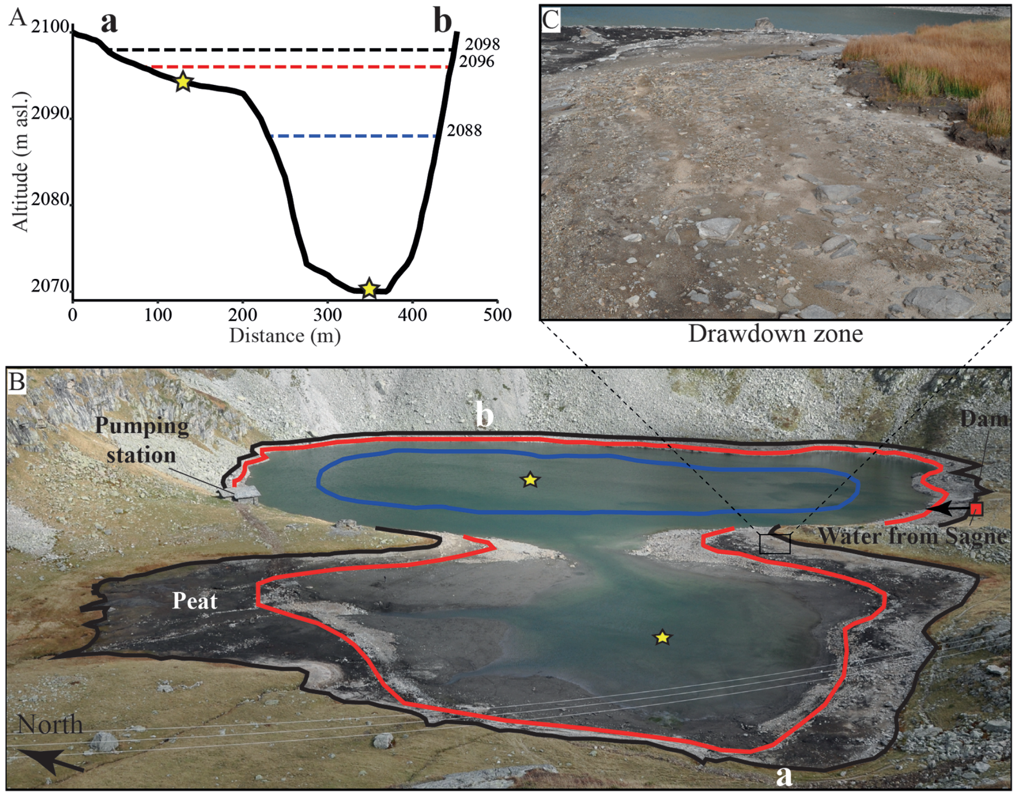

Fig. 2. A: Natural and modified lake water levels since the installation of hydroelectric facilities along a transect from the shallow (a) to the deep depression (b). B: Photo of Corne Lake during a partial emptying in the fall of 2014. The red line corresponds to the maximum water level of the natural lake; black and blue lines represent the maximum and minimum present water levels respectively. The yellow stars show the sampling locations of the two sediment cores. C: detail of eroded soils in the drawdown zone.

Fig. 2. A : Niveau d'eau naturel et modifié par les installations hydroélectriques, le long d'un transect de l'anse (a) à la dépression profonde (b) du lac de Corne. B : Photo du lac de Corne durant une vidange partielle à l'automne 2014. La ligne rouge représente le niveau d'eau maximum du lac naturel ; les lignes noir et bleue représentent respectivement le maximum et le minimum du niveau d'eau actuel. Les étoiles jaunes représentent les sites de prélèvements des carottes de sédiment. C : détail des sols érodés de la zone de marnage.

digging a 15 m deep vertical well in the moraine and the granitic bedrock (now covered by the building); (2) digging a 40 m long horizontal tunnel from the well bottom to the lake; (3) decreasing the lake water level to 2083 m asl.; (4) excavating and terracing about 400 m^3 of moraine above the new pumping inlet, at 2085 m asl. The last two steps lasted two months (June 20 to August 22, 1976).

Since these developments, the water level of Corne Lake experienced strong seasonal variations. The lake level is 2 m higher in the summer and about 8 m lower in winter, so that the shallow depression gets empty (2088 m asl., see Figs. 2A and 2B). In the summer, the soils on the northwest, west and south banks of the lake are eroded by waves. In winter, the ice cover of the lake, formed in autumn when the water level is high, breaks along the shores, slides and erodes soils and sediments along steep slopes in the drawdown zone. During the spring flood, the creek flows directly to the deep depression and transfers sediments and erosion products from the shallow to the deep depression. In addition, the soil is locally eroded at the outlet of the pipe raising water from Sagne Lake.

The drawdown zone extends over belts of flooded soils (surface area: 0.2 ha) and sediments (surface area: 0.3 ha) temporarily exposed to the air. The organo-mineral horizons of littoral soils are eroded, leaving an accumulation of coarse elements (Figs. 2B and 2C). Nevertheless, the original peaty zone north of the shallow depression is partly preserved. Lake sediments are partially eroded by the creek where the tributary reaches the shallow depression. Finally, the soils are eroded and only an accumulation of blocks remains at the outlet of the pipe which brings water from Sagne Lake.

The lake is dimictic and oligotrophic (Guénand, 2020; Guénand *et al.*, 2020), with summer (2014–2016) phosphorus concentration ranging from 0.005 $mg.L^{-1}$ to 0.012 $mg.L^{-1}$ and chlorophyll *a* from 4 to 5 $\mu g.L^{-1}$. The depth of the Secchi disk varies seasonally between 3 m and 5 m. Lake $[Ca^{2+} + Mg^{2+}]$ concentration is 0.08 $meq.L^{-1}$. Surface water pH varies between 5.6 in the spring and 8.1 in the summer. The concentration of dissolved organic carbon (DOC) is 1 to 2 $mg.L^{-1}$, and the conductivity is below 25 $\mu S.cm^{-1}$ at depth. The oxygen content of the lake is 8–10 $mg.L^{-1}$ at the surface and drops to 3–5 $mg.L^{-1}$ near the sediment (Électricité De France, 2003). The characteristics of Sagne Lake are very similar.

The biological inventory of the lake (Jacob, 2006) shows a phytoplankton community dominated by Zygnematophyceae (65% of the biomass) (mainly *Spondylosium planum*) and diatoms (23%) (mainly *Pinnularia* sp. and *Fragilaria* sp.). A zooplankton community dominated by rotifer (mainly *Conochilus unicornis*); Cladocerans (*Daphnia longispina*) and Copepods (*Cyclopoides* sp.) are poorly represented ($<$ 2%). The lake also holds a fish community resulting from the long-lasting introduction and breeding of minnow (*Phoxinus phoxinus*), loach (*Barbatula barbatula*), arctic char (*Salvelinus alpinus*), and brook trout (*S. fontinalis*). Presently, about 500 trout fry (*Salmo trutta*) are brought in each year for recreational fishing.

2.2 Sampling

Two cores of sediment were collected in November 2016 with a Uwitec gravity core sampler. The first core measuring 24.8 cm was taken at the deepest point of the lake (Deep depression core) and a second core measuring 29.5 cm was taken in the shallow part (Shallow depression core) (Figs. 1B, 2A and 2B).

After soil mapping, two Leptosols and two Podzolized soils were sampled below meadow and heathland. Soils were collected horizon by horizon from a soil pit during the summer of 2016. Samples were dried in an oven at 40 °C until constant mass, then passed through a 2 mm sieve.

2.3 Analysis

Sediment cores were cut in two halves and visually described. One of the halves was cut in 1 cm-thick slices and sampled. Bulk density was calculated after drying at 105 °C.

2.4 Sediment geochemistry

The semi-quantitative mineral composition of one undisturbed half of each core was analysed using an XRF Core Scanner (Avaatech Core Scanner) at a 2 mm pitch. The X-ray beam was generated from a rhodium anode and a 125 microns beryllium window allowing a voltage range between 7 and 50 kV with an intensity between 0 and 2 mA. The surface of the core cut in half was protected from contamination by a plastic film. Calibration was done at 10 kV and 1 mA for 10 s to detect Si, Ca, Al, Fe, Ti, K, Mn and S, and at 30 kV and 0.75 mA to detect Sr, Rb, Zr, Br and Pb. The Si/Ti ratio was used as a proxy for biogenic silica and the Zr/Rb ratio as a proxy for particle size (Bajard *et al.*, 2015). The concentration of bioavailable phosphorus, extracted by bicarbonate, was measured on 10 samples (1 cm-thick slices) from each core, as according to Olsen *et al.* (1954).

2.5 Comparison of soil and sediment geochemistry

To compare soils and sediments, the relative percentage of oxides of major elements was measured with a portable ED-XRF spectrometer (S1 TITAN Bruker). Samples of soil horizons and sediment samples were taken every centimetre and were dried in an oven at 40 °C to constant mass prior to being grounded in an agate mortar. The measurements were made in a plastic container (diameter 32 mm). All samples were made in triplicates according to the GeoChem Standard internal calibration for 60 s (Shand & Wendler, 2014). Ratios of oxide contents (CaO/TiO_2 for example) were used to compare the composition of soils and sediments.

The total carbon and total nitrogen contents as well as the $\delta^{13}C$ and $\delta^{15}N$ were measured at the Isotopie-Biochimie pole of UMR SILVA in Nancy (vario ISOTOPE cube Elementar, Hanau, Germany interfaced with a gas isotope ratio mass spectrometer IsoPrime 100).

2.6 Dating by radioelements

The activity of ^{137}Cs and ^{241}Am was measured using a HPGe gamma detector at the Chrono-Environnement laboratory (Besançon) and at the

Table 1. Diatom genera according to their ecological guild.
Tableau 1. Genre de diatomée en fonction de leur guilde écologique.

Genus	Ecological guild
Achnanthidium	Low-profile, Benthic, Neutrophilic
Aulacoseira	Euplanctonic, Planctonic, Neutrophilic
Cavinula	Motile, Benthic, Neutrophilic
Cymbella	High-profile, Benthic, Neutrophilic
Encyonema	High-profile, Benthic, Neutrophilic
Encyonopsis	Low-profile, Benthic, Neutrophilic
Epithemia	Motile, Benthic, Neutrophilic
Eunotia	High-profile, Benthic, Acidophilic
Fragilaria	High-profile, Benthic, Neutrophilic
Frustulia	High-profile, Benthic, Neutrophilic
Gomphonema	High-profile, Benthic, Neutrophilic
Navicula	Motile, Benthic, Neutrophilic
Nitzschia	Motile, Benthic, Neutrophilic
Pinnularia	Motile, Benthic, Acidophilic
Planothidium	Low-profile, Benthic, Neutrophilic
Psammothidium	Low-profile, Benthic, Acidophilic
Staurosira staurosirella/pseudostaurosira (*staurosiroforma* complexe SMOL)	High-profile, Tychoplanctonic, Neutrophilic
Stenopterobia	Motile, Benthic, Acidophilic/Neutrophilic
Tabellaria	Euplanctonic, Planctonic, Neutrophilic

Physics Department of the Autonomous University of Barcelona (Spain). High activity of ^{137}Cs and low activity of ^{241}Am is related to the Chernobyl accident in 1986 (Appleby, 2000; Klaminder *et al.*, 2012). However, ^{241}Am measurements had large standard errors and therefore were not used (values in Tab. S1, Supplement Material).

Eight 1 cm-thick samples from the deep depression core, and five from the shallow depression core, as well as one living Characeae (*Nitella* sp.) sample, were collected in September 2017 from the lake inlet and radiocarbon (^{14}C) dated at the LSCE laboratory (France). The ^{14}C dates were converted to calendar age using the IntCal13 calibration curve (Reimer *et al.*, 2013) in the R "clam" package (Wickham *et al.*, 2019; Blaauw, 2020; R Core Team, 2020). Variation of bulk sediment ^{14}C age is not related to the date of sediment deposition, but to the origin (atmospheric, terrestrial or mixed) of carbon atoms in the sediment (Tittel *et al.*, 2019).

2.7 Microalgal communities

The same technical protocol was used for all samples (Smol, 1983). Organic matter was removed using hydrogen peroxide at 90 °C for 24 h (Wilson *et al.*, 1996). Samples underwent 5 cycles of centrifugation at 4000 rpm for 10 min followed by rinsing with distilled water. Then sediment pellets were suspended in 20 ml of distilled water. These re-suspensions were then diluted (1/50 and 1/100) before being mounted on a thin blade using the Naphrax© resin (refraction index: 1.74). Optical microscope observations were made in phase contrast

(Zeiss AxioImager, 100x objective Immersion Oil). For each of the dilutions, diatom valves and Chrysophyte cysts were counted until at least 400 siliceous shells were obtained. Only diatom valves made up of at least two-thirds of an entire valve were counted. Diatom genera were determined using the identification guides of Krammer & Lange-Bertalot (1991) and Lange-Bertalot *et al.* (2017) (Tab. 1). Chrysophyte cysts were only counted.

Diatom genera were grouped in relation to their ecological preferences following Van Dam *et al.* (1994), Passy (2007) and Rimet & Bouchez (2012) (Tab. 1). Diatoms of the low-profile guild are favored in nutrient-poor and high disturbance habitats, while high-profile guild diatoms are favored in nutrient-rich sites and in conditions of low flow disturbance. The abundance of diatoms of the motile guild increases along the nutrient gradient and decreases along the disturbance gradient (Passy, 2007). Benthic diatoms live on the sediment surface of shallow waters, whereas planktonic diatoms live in the water column.

The Diatom/Chrysophyte ratio (D/C ratio) was calculated as the total number of diatom valves/total number of Chrysophyceae cysts. The D/C ratio is typically higher in lakes of higher trophic state because Chrysophytes are favoured in oligotrophic environments (Smol, 1983, 1985). Conversely the D/C ratio is lower in oligotrophic, acidic and deep lakes (Rivera-Rondón & Catalan, 2017).

3 Results and discussion

3.1 Description of sediment cores

3.1.1 Sediment core in the deep depression

From 24.8 cm to 16 cm, the sediment was a green-coloured mud with a very low bulk density (BD: 0.14 ± 0.08 g.cm^{-3}) (Fig. 3A). From 16 cm to 12.5 cm, the sediment was darker, and bulk density was slightly higher (0.16 ± 0.02 g.cm^{-3}). A white lamina occurred from 12.5 cm to 12.2 cm. From 12.5 cm to 6 cm, the sediment was a green-coloured mud, visually identical to the bottom of the core, but interspersed with white laminae a few millimeters thick. From 6 cm to 2 cm, the sediment showed a continuous sequence of fine white sandy laminae. Bulk density ranged between 0.81 g.cm^{-3} and 0.37 g.cm^{-3}. The last two centimetres consisted of a grey-green mud, with a lower bulk density (0.44 g.cm^{-3} to 0.33 g.cm^{-3}).

3.1.2 Sediment core in the shallow depression

The sediment was dark-grey. Between 29.5 cm and 23 cm it was slightly darker, and bulk density was lower (BD: 0.21 ± 0.03 g.cm^{-3}). Bulk density increased from 23 cm to 13 cm, and stabilized around 0.4 g.cm^{-3} above (Fig. 4A). From 23 cm to the top, the sediment was slightly less dark and interspersed with slightly reddish bands located between 22.2 cm and 21.8 cm, 15 cm and 13 cm, 9.3 cm and 8 cm, 5.3 cm and 4.5 cm and between 1.8 cm and 1 cm from the surface respectively.

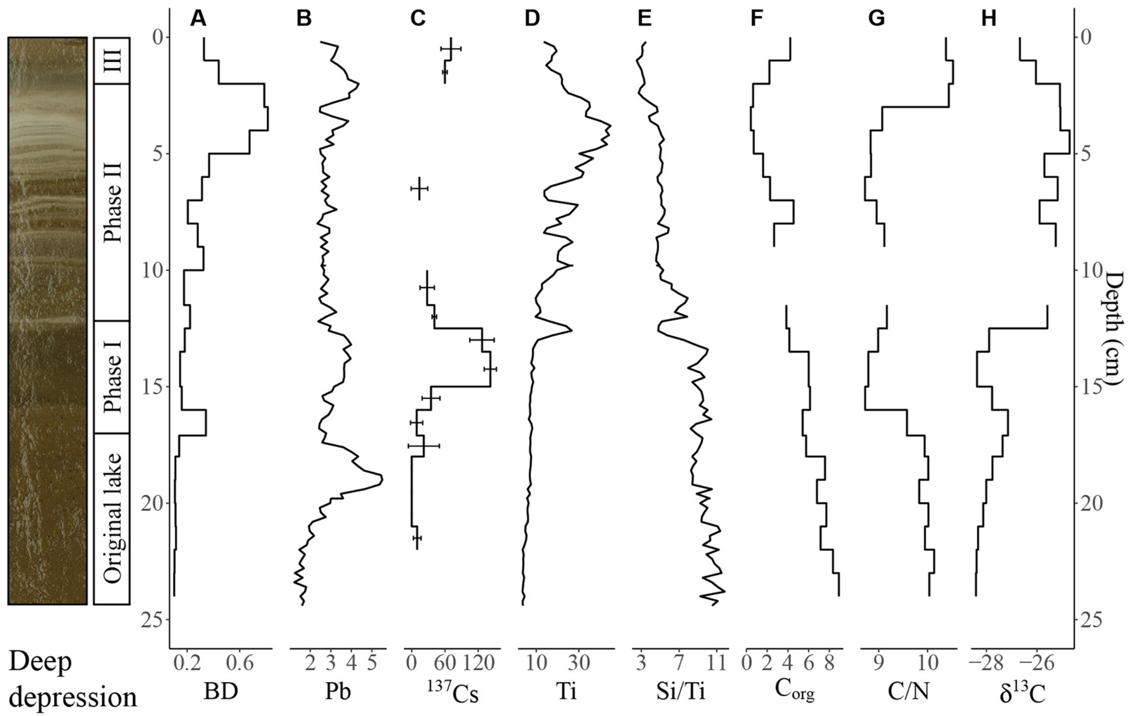

Fig. 3. Depth variation of the mineral and organic composition of the sediment core taken in the deep depression. A: BD: bulk density (g.cm^{-3}); B: Pb: total lead (cps); C: ^{137}Cs: 137-Cesium activity (bq.kg^{-1}); D: Ti: titanium (cps); E: Si/Ti: silicon/titanium ratio (cps/cps); F: C_{org}: organic carbon content (%); G: C/N: carbon/nitrogen ratio; H: δ^{13}C (‰).

Fig. 3. Composition minérale et organique en fonction de la profondeur de la carotte de sédiment prélevée dans la dépression profonde. A : BD : densité apparente (g.cm^{-3}) ; B : Pb : plomb total (cps) ; C : ^{137}Cs : activité du 137-Cesium (bq.kg^{-1}) ; D : Ti : titane (cps) ; E : Si/Ti : ratio silicium/titane (cps/cps) ; F : C_{org} : carbon organique (%) ; G : C/N : ratio carbone/azote ; H : δ^{13}C (‰).

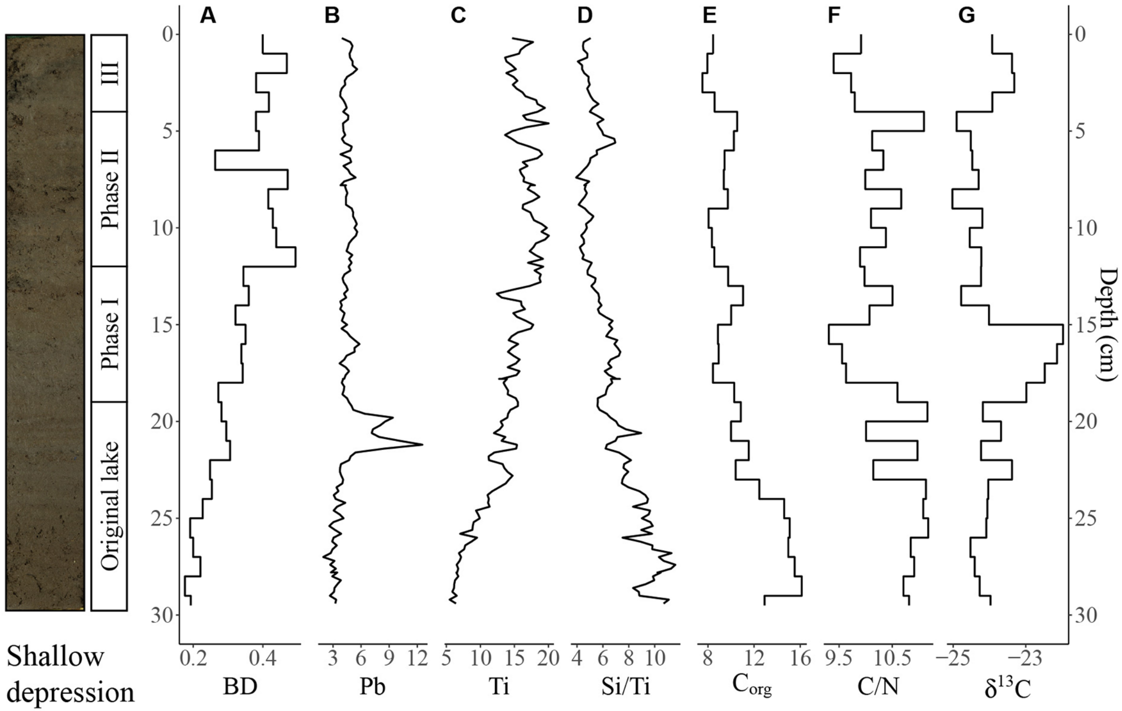

Fig. 4. Depth variation of the mineral and organic composition of the sediment core taken in the shallow depression. A: BD: bulk density ($g.cm^{-3}$); B: Pb: total lead (cps); C: Ti: titanium (cps); D: Si/Ti: silicon/titanium ratio (cps/cps); E: C_{org}: organic carbon content (%); F: C/N: carbon/nitrogen ratio; G: $\delta^{13}C$ (‰).

Fig. 4. Composition minérale et organique en fonction de la profondeur de la carotte de sédiment de l'anse. A : BD : densité apparente ($g.cm^{-3}$) ; B : Pb : plomb total (cps) ; C : Ti : titane (cps) ; D : Si/Ti : ratio silicium/titane (cps/cps) ; E : C_{org} : carbon organique (%) ; F : C/N : ratio carbone/azote ; G : $\delta^{13}C$ (‰).

3.1.3 Mineral composition of the sediment in comparison to surrounding soils

Along both cores (Figs. 3D and 4C), Ti was strongly and positively correlated with K, Fe, Si, Al ($r = 0.99$, 0.98, 0.87, 0.79 and $r = 0.85$, 0.97, 0.96 and 0.91 in the deep and shallow depressions respectively) and therefore was used as a proxy for the mineral element content.

In the deeper layers, bulk density and mineral contents (kcps) were very low (Figs. 3D and 4C), slightly higher in the shallow depression in which the creek flows. Detritic mineral matter increased upwards. In the deep depression, the mineral content (Ti index) peaked for the first time in the first white lamina (between 13–12 cm), then rose continuously up to 3.8 cm in relation to the occurrence of whitish laminae. In the shallow depression, the mineral content of the sediment increased continuously between 29 cm and 12 cm, and remained stable from 12 cm to the top of the core. In the last upper 4 cm and 2 cm of the cores (in the shallow and deep depressions respectively), the bulk density and content of detritic particles (Figs. 3A–3D and 4A–4C) were stable (shallow depression) or decreased (deep depression).

The SiO_2/TiO_2 ratio of the sediment decreased from the base to the top, from about 160 to 80 in the deep depression, and from about 200 to 100 in the shallow depression. In comparison, the average SiO_2/TiO_2 ratios of surface and deep horizons of soils were 80 and 110 respectively (Fig. S2). The CaO/TiO_2 ratio decreased as well from the base to the top of the cores from 1.7 to 1.2 in the deep depression and from 1.7 to 0.8 in the shallow depression. In comparison, the average CaO/TiO_2 ratio was 0.7 in soil surface horizons and 1.3 at depth (Fig. S3).

3.1.4 Sedimentary phases and chronology according to geochemical tracers

We assumed that the original lake composition (before hydropower management) was registered in the deeper centimetres of the sediment in both depressions (Figs. 3 and 4), which composition appeared relatively stable in comparison to upper layers. Then, the variations of geochemical tracers suggested two possible alternative chronologies.

Hypothesis A) The major Pb peak in the sediments of the shallow and deep depressions, at 21 cm and 19 cm respectively (Figs. 3B and 4B), is related to the peak of emissions of tetraethyl-Pb in the years 1973–1974. This peak was observed in many lake sediments in this region of the Alps (Arnaud *et al.*, 2004; Giguet-Covex *et al.*, 2011; Wilhelm *et al.*, 2012), and more specifically in a small proglacial lake (Lac Blanc Belledonne) located 10 km from Corne Lake (Wilhelm *et al.*, 2012). Hence, the decline of this peak may date back to the starting of the hydropower management in 1976. The peak of ^{137}Cs between 15 cm and 12.5 cm in the deep depression and at 11.5 cm in the shallow depression, may date back from the Chernobyl nuclear accident, in 1986. This peak was also detected at Lac Blanc (Wilhelm *et al.*, 2012). In the deep depression, the ^{137}Cs peak was associated with an increase in total Pb, which may suggest that sediment reworking occurred and/or a possible contribution of the surface horizons of littoral soils. In this hypothesis, Phase I depicts the initiation of hydropower management.

Hypothesis B) The Cs peaks between 15 cm and 12.5 cm in the deep depression and at 11.5 cm in the shallow depression are related to the atomic bomb tests in the fifties. This peak is also detected at nearby lakes (Lac Blanc Belledonne in Wilhelm *et al.*, 2012; lake Bramant in Guyard *et al.*, 2007). The Pb peaks at 21 cm and 19 cm in the shallow and deep depressions respectively would be related to former local mining activities (Guyard *et al.*, 2007) or atmospheric deposition from local smelters. The plateau of high Pb concentrations between 14 and 12 cm in the deep depression would be related to emissions of tetraethyl-Pb. The initiation of hydropower operation would be marked by the end of this plateau, and by the occurrence of the first mineral laminae in the deep depression (at 12 cm) possibly resulting from the erosion of the sediments in the shallow depression or from the earthworks made to set up the pumping devices. In this hypothesis, Phase I depicts a change in ecological conditions (possibly related to husbandry pressure?) and Phase II the initiation of hydropower management.

Phase II is related to the maximum in bulk density values in the shallow depression and to occurrence of mineral laminae in the deep depression (from the depth of 12 cm). The sequence of mineral laminae might be related to the extreme spring floods of 1982, 1987, 1995, 1999, 2002, 2004, 2005 and 2016, measured at Font-de-France. The fact that no lamina was noticed in the shallow depression is most likely related to their formation during the spring flood, when the shallow depression is by-passed. In addition, the activity of Chironomidae (living individuals were observed in the shallow depression's core) might have diluted mineral inputs into the bulk sediment.

Phase III corresponds to the upper centimetres of the core, and refers to the present state of the lake.

3.1.5 Organic composition of soils and sediments of the original lake

The carbon content of the organo-mineral A horizon of the soils ranged from 4% (Leptosol) to 12% (Entic Podzol). This content dropped below 4% in Entic Podzol at the depth of 30 cm. The C/N ratio of A horizons of Cambic and Umbric Leptosols was 10.5 and 14 respectively. In podzolised soils, the C/N increased from 14 to 16 with depth. Soil $\delta^{13}C$ varied with depth, from −26.3‰ in the 0–15 cm layer to −25.3‰ below.

Along both cores in the shallow and deep depressions, the carbon content decreased upwards. In the original lake, while the two depressions were continuously connected, the carbon content in the shallow depression (13.4 ± 2.2%) was higher than in the deep depression (7.2 ± 1.2%). This may be related to higher benthic productivity in the shallow depression, and to the direct input flux of nutrients from the tributary. The higher $\delta^{13}C$ in the shallow depression (−24‰) in comparison to the deep depression (−28‰) is in agreement with the general difference described by (France, 1995) between pelagic and

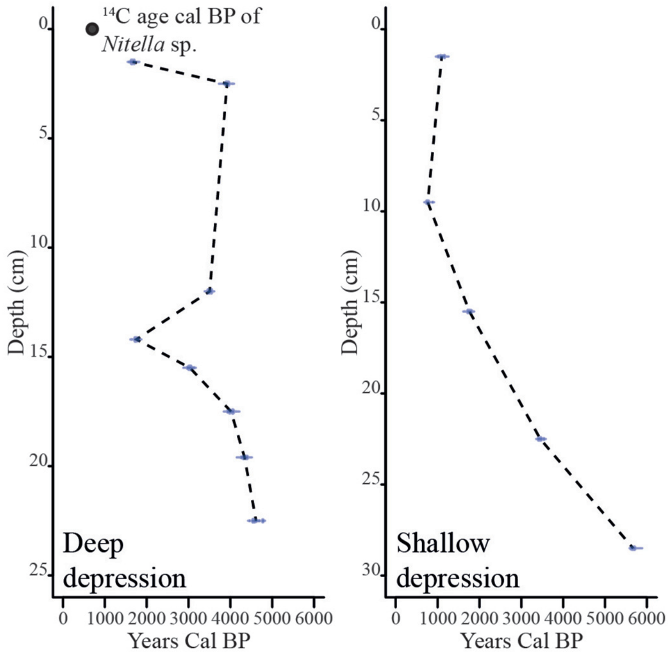

Fig. 5. Depth variation of bulk sediment radiocarbon age (years cal. BP) in the deep and shallow depressions.

Fig. 5. Age ^{14}C (years cal. BP) du sédiment en fonction de la profondeur des carottes de sédiment de la dépression profonde et de l'anse du lac de Corne.

littoral communities. Higher values may also be associated with a higher contribution of aquatic plants (Thevenon *et al.*, 2012). In fact, Characeae individuals were observed in the littoral zone of the shallow depression. In both depressions, the C/N ratio (shallow depression: 10.8 ± 0.4; deep depression; 9.9 ± 0.2), suggests a mixed allochthonous (dissolved organic matter, suspended matter) and autochthonous (phytoplankton) origin of organic matter. This is confirmed by the high Si/Ti ratio (Figs. 3E and 4D) which indicated that biogenic silica (Bajard *et al.*, 2015) was dominant. Bioavailable P was low: 0.036 ± 0.003‰ and 0.029 ± 0.006‰ in the deep and shallow depressions respectively.

The ^{14}C age of bulk sediment carbon was old: from 4500 to 4300 years cal. BP in the deep depression and 5650 years cal. BP to 3450 years cal. BP in the shallow depression (Fig. 5 and Tab. S2). This very old age means, in the absence of carbonates in the watershed, that the carbon feeding the sediment, directly or through the trophic loop, does not come (or in a very small proportion) from atmospheric CO_2. As dissolved organic carbon of pristine ecosystems is generally modern (Schiff *et al.*, 1997; Marwick *et al.*, 2015), this "old" carbon may originate from three processes. (i) Erosion and transport of soil carbon by the creek. For similar soils in the same environment, Egli *et al.* (2009) and Favilli

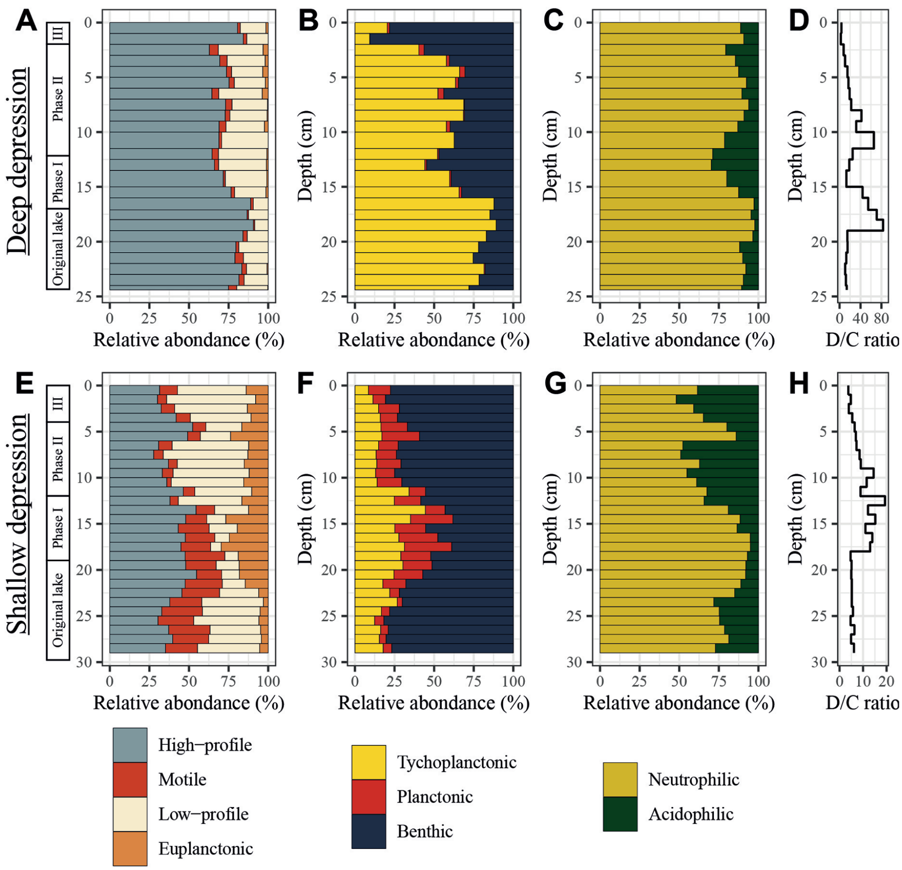

Fig. 6. Depth variation of the diatom community composition by guild and D/C ratio in the deep (A, B, C, D) and shallow (E, F, G, H) depressions of Corne Lake.

Fig. 6. Composition de la communauté de diatomée et ratio D/C en fonction de la profondeur des sédiments des carottes de la partie profonde (A, B, C, D) et de l'anse (E, F, G, H) du lac de Corne.

et al. (2009) indicated that bulk soil ^{14}C age range from approximately modern in upper horizons to about 2000 years cal. BP in Bs horizons, while recalcitrant organic matter or peat may be much older. This carbon input may cycle through deposition–resuspension cycles thereby enhancing remineralization and aging (Newbold *et al.*, 1982); (ii) Atmospheric deposition of soot particles containing fossil carbon (Rose, 2015); (iii) Sediment carbon recycling: carbon annually mineralised, assimilated in the trophic chain, and back-sedimented (Abbott & Stafford, 1996; Wolfe *et al.*, 2004).

3.1.6 Biological composition of sediments of the original lake

The composition of micro-algal communities preserved in the sediment reflected the oligotrophic status of the lake. The Diatom/Chrysophyte ratio (D/C in Figs. 6D–6H) was very low (13.2 ± 1.8 and 5.4 ± 0.5 for the deep and shallow depressions respectively). Neutrophilic species dominated in both depressions (Figs. 6C and 6G) but acidophilic diatoms were more abundant in the shallow depression, possibly in relation to the presence of the Histosols along the shore.

In the shallow depression, benthic diatoms were dominant (75%). The percentages of high-profile, low-profile and motile diatoms were balanced (Fig. 6E), and (Fig. 6F). In the deep depression, tychoplanctonic diatoms (mostly species of the *Staurosira* genus) were dominant (80%) over benthic species, and diatoms belonged mostly (80%) to the high-profile guild (Fig. 6A) (Rimet & Bouchez, 2012) and (Fig. 6B). These compositions reflected the shallow water and physical disturbance by the creek in the shallow depression and conversely the depth and stability of water in the deep depression.

3.2 Processes driving the evolution of lake sediments according to the different phases

3.2.1 Trophic upsurge and changes in water level in Phase I

During Phase I the C/N ratio of the sediment decreased down to 8.8 in the deep depression and to 9.3 in the shallow depression. The ^{14}C age of the bulk sediment decreased sharply to 1750 years cal. BP in the shallow depression (at the depth of 15 cm), and to 3000 years cal. BP and 1750 years cal. BP (at depths 15 cm and 13.5 cm respectively) in the deep depression. In addition, bioavailable P roses both in the deep (0.058‰) and shallow depressions (0.057‰). These changes might result from littoral soil flooding (hypothesis A) or as a consequence of changes in husbandry pressure in the vicinity of the lake (hypothesis B). Meadow soils along lakes are often enriched in P by cattle faeces (Bajard *et al.*, 2018). According to hypothesis A (Phase I follows the initiation of hydropower management), the flooding and erosion of young (^{14}C age < 200 years) topsoil organic matter, with a C/N higher than that of the sediment, resulted in a decrease in bulk sediment C/N and ^{14}C age. The input of soil organic matter (and P) might have increased lake primary production (Ostrofsky, 1978; Bajard *et al.*, 2018) and possibly atmospheric CO_2 assimilation. The increase of $\delta^{13}C$ in the shallow depression might also reflect an increased primary production (Thevenon *et al.*, 2012), and/or a larger contribution of macrophytes. In addition, sediment drying and rewetting possibly increased P availability (Dieter *et al.*, 2015). But an increase in husbandry pressure might have the same effects (hypothesis B). In fact, it may be noted that. the decrease of C/N in the shallow depression began earlier than Phase I (when total Pb peaked, at depth about 22 cm).

In comparison to the original lake, the proportion of benthic species progressively decreased in the shallow depression (while planktonic species increase), but increased in the deep depression, most likely as a result of the higher water level in the shallow depression, and of the physical transfer of sediment and benthic species from the shallow to the deep depression (hypothesis A). The proportion of high-profile and neutrophilic diatoms was also higher, while the D/C ratio and P concentrations were high, suggesting a trophic upsurge. However, all these changes did not occur simultaneously. For example, the major increase in the D/C ratio occurred in both depressions at 18/19 cm while the increase of benthic diatoms in the deep depression occurred later (16 cm). This suggests that the upsurge registered in the sediment during phase I did not only reflect the change in hydrology imposed by hydropower management (hence supporting hypothesis B).

3.2.2 Particle transfer and trophic depression in Phase II

When mineral sedimentation peaked (between 13 cm to 4 cm in the shallow depression and between 12.5 cm to 2 cm in the deep depression), the CaO/TiO_2 and SiO_2/TiO_2 ratio of soil A horizons and sediments converged (Figs. S2 and S3). Nevertheless, the organic composition of cores in the shallow and deep depressions diverged. In the shallow depression, the C/N ratio, $\delta^{13}C$ and bioavailable P returned toward the original lake values. But the radiocarbon age of the sediment remained young (< 1000 years cal. BP) possibly in relation to a larger contribution of atmospheric CO_2. In the deep depression, with the increased contribution of detritic material, sediment $\delta^{13}C$ increased significantly (down to -25.3 ± 0.4‰) to reach values in the range of old sediments of the shallow depression (about -24.1 ± 0.3‰) or soils (-25.6 ± 0.4‰). In this phase the bulk sediment carbon reverted to an old age (> 3500 years cal. BP). The increase in ^{14}C age paired with the low C/N in the deep depression (compared to the shallow depression) may reflect the mineralisation and recycling of old carbon from different sources (soil horizons, shallow depression sediments).

The D/C ratio increased in both depressions in the beginning of this phase and later decreased (as in the beginning of Phase I), suggesting a new "upsurge-depression" cycle. In the shallow depression, the proportions of low-profile and acidophilic (mainly *Psammothidium*) and benthic (mainly *Fragilaria*) diatoms increased, which, in addition to the decrease in the D/C ratio, suggested a trophic depression. In the deep depression, the proportion of low-profile and benthic diatoms remained high in comparison to the original lake.

3.2.3 Present state

In the upper centimetres of the cores (phase III), the detritic contribution decreased, especially in the deep depression. In fact, the fine material of soils in the drawdown zone has been eroded and the detritic pavement of gravels and stones slowed further erosion down. In addition, extreme spring floods did not occur between 2005 and our study. The D/C ratio reached minimal values, as well as the Si/Ti (biogenic silica index) while the detritic input (Ti index) decreased. Both indicators suggested that the lake reached a very low trophic level. Benthic (mainly *Fragilaria*) replaced tychoplanctonic (*Staurosira*) genera in the deep depression, while the proportions of other guilds remained comparable. Interestingly, the sediment carbon age returned young: 1650 years cal. BP and 1100 years cal. BP in the deep and shallow depressions respectively, which is close to that (700 years cal. BP) of a living macrophyte (*Nitella* sp.) sampled underwater close to the stream inlet (data on Fig. 5). It may be assumed that the carbon provided by the watershed (in the form of DIC, DOC or POC) has not changed in the last 50 years. The decrease of bulk carbon age may be related to an increased CO_2 input. In fact, monitoring of lake CO_2 concentration and exchange with the atmosphere showed a diffusion of atmospheric CO_2 into the lake in the summer, whereas the lake emitted CO_2 towards the atmosphere during the spring thaw (Chanudet *et al.*, 2020).

4 Synthesis and perspective

The ecological evolution of Alpine lakes results from multiple pressures. Our study was designed to measure the effects of hydropower management on the sediment composition of a lake, assuming deep sediment layers could be used as a control. We therefore assumed that hydropower management was the main environmental agent changing the sediment composition and that the initiation of hydropower management would be easy to detect. As the application of classical dating methods to sediment cores was not conclusive, we used major changes in the biological and geochemical composition of the sediment to suggest a chronology in relation to water level changes. Nevertheless, the proposed chronology remained hypothetical and other environmental changes (*e.g.*, increased husbandry pressure) may also have influenced the geochemical and biological evolution of the lake.

Our observations showed the erosion of littoral surface soil and sediment in the littoral zone, and an increase in the transfer of erosion products from the shallow depression to the deep depression. In a first phase, the C/N and ^{14}C age of bulk sediment, decreased while the proportion of high-profile diatoms and the Diatom/Chrysophyte ratio increased. Concurrently benthic diatoms decreased in the shallow depression and increased in the deep depression. This evolution suggested a trophic surge (Grimard & Jones, 1982; Smol, 1983, 1985; Kimmel & Groeger, 1986; Turgeon *et al.*, 2016), probably initiated by water level fluctuations. A second phase was characterized by a high rate of mineral sedimentation, mirroring the erosion of mineral soils of the drawdown zone, an increase in acidophilic genera within the shallow depression and a general long-lasting decrease of the D/C ratio. This upsurge-depression cycle is consistent with the observations of Milbrink *et al.* (2011) who demonstrated that the management of Nordic lakes for hydropower alters littoral ecosystems and contributes to increasing resident fish sizes in the short term, but conversely leads to a long-term decrease in size. In the current period, as littoral soils are eroded, the supply of soil particles from the drawdown zone to the lake has decreased. The mineral pavement of the drawdown zone breaks the continuum between the terrestrial and aquatic environments, especially in the shallow depression (Spitale *et al.*, 2015). Over the long term, we suggest that the change in hydrology has resulted in a shift in microalgal communities towards planktonic genera in the shallow depression, and benthic genera in the deep depression.

The studied lake is representative of many subalpine lakes located on acid rocks. The very old radiocarbon age of deep sediment layers suggests that the metabolism of pristine Alpine lakes depends mainly on the input of old carbon, and on the internal recycling of sediment carbon (Caraco *et al.*, 2010; Thevenon *et al.*, 2012; Guillemette *et al.*, 2017) and little from atmospheric CO_2 input. Conversely, the young age of sediment carbon in recent years suggests a higher contribution of atmospheric CO_2.

Supplementary Material

Figure S1. Depth variation of the diatom community composition by genera in the deep and shallow depression of Corne Lake.

Figure S2. Profiles of SiO_2/TiO_2 ratio in A) two Leptosol and two Podzolized soils which were characteristic of Corne Lake watershed, and B) sediment of the deep and shallow depression.

Figure S3. Profiles of CaO/TiO_2 ratio in A) two Leptosol and two Podzolized soils which were characteristic of Corne Lake watershed, and B) sediment of the deep and shallow depression.

Table S1. Values of ^{137}Cs and ^{241}Am in relation to depth in the deep and shallow depression of Corne Lake.

Table S2. Values of radiocarbon analyses by depth in the deep and shallow depression of Corne Lake.

The Supplementary Material is available at https://www.hydroecologie.org/10.1051/hydro/2021003/olm.

Authors contribution

Jim Félix-Faure: Study design, data acquisition and analysis, writing of manuscript.

Mathieu Ramon: Data acquisition and analysis.

Christine Hatté: Data acquisition, data analysis and writing of manuscript.

Frédéric Rimet: Data acquisition and analysis.

Jérémie Gaillard: Data acquisition and analysis.

Vincent Chanudet: Study design, data analysis, writing of manuscript.

Anne-Lise Develle: Data acquisition and analysis.

Jordi Garcia-Orellana: Data acquisition and analysis.

Etienne Dambrine: Study design, data acquisition and analysis, writing of manuscript.

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