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Experimental studies on some factors influencing phosphorus solubilization in connexion with the drawdown of a reservoir

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Abstract

The periodical drawdown of reservoirs affects the phosphorus cycle. During the dry period the sediments are in immediate contact with the atmosphere, while part of them are resuspended when the water rises again. Experimental studies on the sediments of the Puyvalador reservoir (Pyrenees, France), which is subjected to a considerable drawdown every year, show that the quantity of phosphorus solubilized after resuspension of these sediments varies according to the speed with which the water rises, the preceding desiccation of the sediments and the origin of the water used in the experiments. The intensity with which the sediments are stirred depends on the refilling rate. The observed differences related to the origin of the water of the affluent streams are attributed to their initial ortho-phosphate content and their difference in pH. These variations related to drawdown make it necessary to take this important phenomenon into account when studying the solubilization of phosphorus in reservoirs.

Introduction

Sediments can release phosphate under anaerobic conditions (Mortimer, 1941, 1942). More recently, it has been shown that phosphorus release can also take place under aerobic conditions (Lee *et al.*, 1977; Bates and Neafus, 1980). The causes are different from those of Mortimer's model, but under certain conditions, particularly in the case of shallow lakes, the water of which is stirred by the wind, they lead to the release of a quantity of ortho-phosphate (ortho-P) sufficiently large to influence water quality (Ryding and Forsberg, 1977).

These results, based on balance studies or laboratory experiments, apply only to lakes; so far no special studies on drawdown reservoirs have been done. Here, during the period of low water level, part of the sediments are temporarily dry and in immediate contact with the atmosphere. When the water level rises again, all these sediments are progressively covered by a thin water layer during a short period, thus temporarily imitating the conditions of a shallow lake.

The aim of this study is to demonstrate that the sediments of the Puyvalador reservoir, subjected to a considerable drawdown every year, can release ortho-P when they are again brought into contact with water, but that the quantity released varies with the experimental conditions, which simulate some of the factors occurring in situ directly related to the drawdown phenomenon.

The site

The Puyvalador reservoir lies at an altitude of 1 420 m in the Eastern Pyrenees. Its surface area is maximally 102 ha, its volume 10^7 m^3. Its catchment area of 134 km^2 consists mainly of plutonic rock. The landscape is mountainous, with some residual agricultural activity. Outside the tourist period, the population consists of about 900 inhabitants. The water is used for the production of electricity and, in dry summers, partially for irrigation.

The essential characteristic of the Puyvalador reservoir is its being subjected to a drawdown with an amplitude of about 22 m every year. It is full in summer, and gradually emptying in winter, when precipitation is stored in the form of snow on the catchment area. Towards the end of April the rapidly melting snow causes the water level to rise. Towards the end of July the reservoir is full again. Figure 1 gives the variations in water level for the year 1983, when the reservoir underwent 2 periods of drawdown: the spring period which returns every year, and a shorter summer period of lower amplitude which occurs only occasionally.

The spring drawdown causes 80% of the sediments to fall dry. Two groups can be distinguished: one consists of deep deposits, close to the streams and rich in nutrients, the other of shallow deposits, far from the streams and poor in nutrients (Fabre and Patau-Albertini, 1986). The sediments used in this study have been collected in May 1986 and belong to these 2 groups.

The reservoir is fed by 2 streams, the Aude and the Galbe, the natural flow rates of which are almost identical. The presence of a reservoir upstream in the Aude allows to control its flow rate.

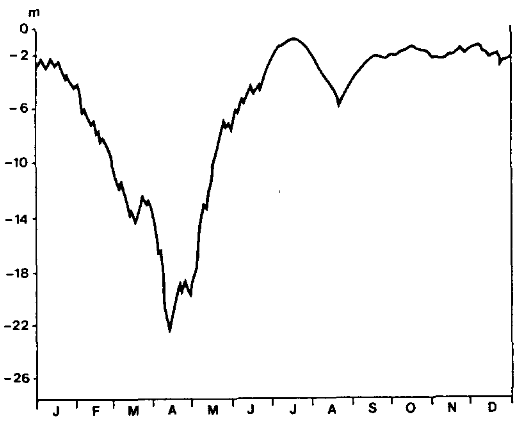

Fig. 1. Variations in the water level of the Puyvalador reservoir in the course of the year 1983 (Data from GRPH – subdivision Axat).

The rising of the water in May and June takes place with a speed that varies from day to day according to the need for electricity. It causes resuspension of part of the sediments, increased by a wind that generally blows every day for between 5 and 8 hours.

Methods

6 cm long sediment cores were taken from the deposits uncovered by the drawdown, and placed in wide-mouth polyethylene jars with a surface of 64 cm^2, together with 750 ml water of different origin. The mixture was stirred moderately on a vibrator for 8 hours, followed by 16 hours rest. The alternating stirring and resting served to imitate the conditions of stirring of the water as they occur in the reservoir. This cycle was repeated for 5 days. Air was blown into the water in each jar daily. The experiment was carried out in the dark at 15 °C. At the end of the experiment samples of 40 ml water were filtered over a 0.45 μ membrane and the ortho-P determined with molybdene blue, and ascorbic acid as the reducing agent (Golterman *et al.*, 1978).

The experiment was carried out as a factorial experiment with 4 factors reflecting each of the conditions characteristic of the reservoir during the period of the rising of the water. Table 1 shows the set-up of the factorial experiment. Factor 1 represents the origin of the sediment used. It presents modes S1 (sediment from the deepest zones) and S2 (sediment from shallow zones). Factor II corresponds to the state of humidity of the sediment and presents modes H1 (sediment kept in the state of humidity in which it was sampled) and H2 (sediment subjected to desiccation by air at 15 °C for a week). This factor shows the effect of the desiccation of the sediment on ortho-P release. In situ, the desiccation of the sediment is the more pronounced as the deposit is shallower or spring has been drier. Factor III represents the refilling rate. VI (high speed) has been simulated by filling the jars at once, while V2 (low speed) corresponds to the filling of the jars in 3 days, 250 ml each day. Lastly, factor IV concerns the origin of the water used in the experiments. It presents 3 modes: R1 (Galbe water), R2 (Aude water) and R3 (water from the reservoir). At the start of the experiment the pH of these different waters was 7.4, 7.0 and 7.2 respectively, and the ortho-P concentrations were 2.8, 7.1 and 8.0 $\mu g\ l^{-1}$. Modes R1 and R2 have been included because their pH and ortho-P concentrations differ, and because it is possible to use varying proportions of water of different origins when the reservoir is filled. Mode R3 serves by way of comparison. All the water has been used after filtration over a 0.45 μ pore filter.

These 4 factors, presenting 2 or 3 different modes, led to $2\times 2 \times 2 \times 3 = 24$ determinations of ortho-P (Table 1) and reflect the sorption equilibrium. They were analysed by variance analysis, using procedure GLM of the SAS software (1982).

The effect of the pH was also studied in an independent manner. Half a gram of crude sediment from a deep deposit was suspended in 50 ml distilled water, the pH of which was adjusted by means of NaOH 0.1N or H2S04 0.1N. The obtained suspension was stirred for 8 hours and centrifuged; the supernatant was filtered over a 0.45 μ membrane. Ortho-P in these samples was determinated as above. Nine pH values between 3.4 and 9.9 were included, and all nine determinations were carried out in triplicate. The correlation between pH and ortho-P was fitted to the means of the triplicates.

Table 1. Factorial experiment with 4 factors (R_i = modes of the factor origin of the water, S_i = modes of the factor origin of the sediment, H_i = modes of the factor humidity of the sediment, V_i = modes of the factor refilling rate). The figures give the quantities of ortho-P in $\mu g\ l^{-1}$ for each combination.

Initial ortho-P concentrations in $\mu g\ l^{-1}$			R1 2.8	R2 7.1	R3 8
S1	H1	V1	9.7	8.0	8.3
		V2	20.9	16.3	16.7
	H2	V1	12.5	12.2	11.5
		V2	23.8	20.5	18.1
S2	H1	V1	9.4	8.0	8.0
		V2	20.9	18.4	14.2
	H2	V1	11.9	10.1	8.7
		V2	22.9	16.9	15.6

Results

Table 1 shows that, except for one combination ($S2 \times H1 \times V1 \times R3$), the resulting ortho-P concentration is higher than the initial concentration in the waters used in the experiment. The concentrations, however, vary considerably between combinations. Only variance analysis allows to bring out the significant differences between the factors. Factors II (humidity of the sediment), III (refilling rate) and IV (origin of the water) are significant ($P < 0.05$). Both factor I and the interactions are not significant. Figure 2 gives the means and the significant differences between the various modes of each factor (Duncan's range test). These differences are clearly significant for the 2 modes of factors II and III. As to factor IV, only mode R1 (Galbe water) differs from modes 2 and 3 (water from the Aude and from the reservoir) which do not differ from each other.

Factor III (refilling rate) leads to very different

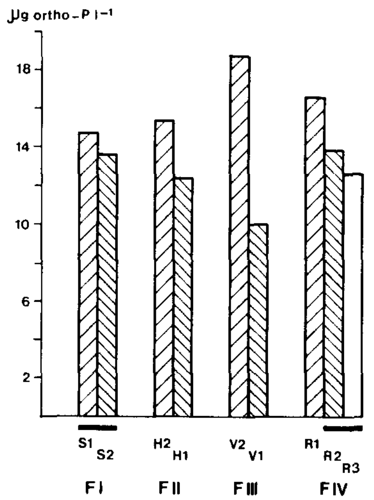

Fig. 2. Quantity of ortho-P for the different modes of the factors: origin of the sediment (S), humidity of the sediment (H), refilling rate of the water (V) and origin of the water (R). (The unbroken lines under two modes of the same factor indicate that the differences are not significant according to Duncan's test).

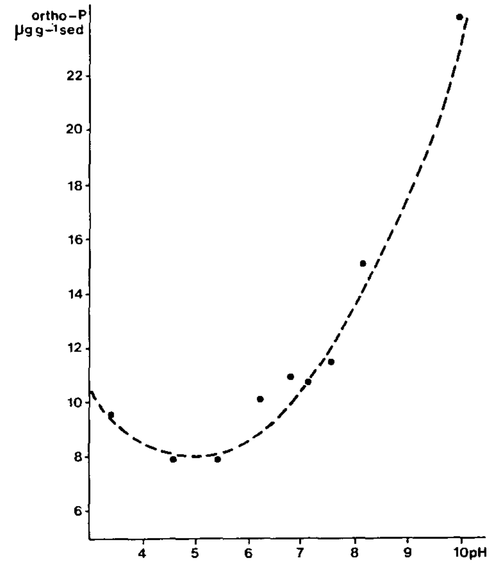

Fig. 3. Correlation between ortho-P and pH.

quantities of ortho-P from one mode to another. Mode V2 (low refilling rate) leads to a value close to 19 μg l^{-1}, while mode V2 (high refilling rate) only leads to a value of the order of 10 μg l^{-1}. The increase is 90% for the second mode compared to the first. This factor is by far the most importants as to its differential effect. Factor IV has less effect. On the average Galbe water causes an increase of the order of 20% compared to Aude water. Lastly, the factor humidity of the sediment leads to an increase of 17% at mode H2 (desiccated sediment) as compared to mode H1.

The relationship between the mean values of ortho-P and pH (Fig. 3) were fitted to a parabola:

$$\text{o-P} = 22.446 - 5.873\ \text{pH} + .5987\ \text{pH}^2 \qquad R^2 = 0.988$$

in which o-P is μg of ortho-P released from 1 gram of sediment in the experimental conditions.

Application of the parameters of this equation shows that the lowest ortho-P value (8.04 μg g sed^{-1}) is obtained for a pH of 4.9. Although they have not been fitted, the curves presented by Rippey (1977) or Jacoby *et al.* (1982) suggest the same type of correlation.

Nevertheless, the results are strongly influenced by other parameters like the ratio sediment weight/water volume.

Discussion

The refilling rate plays an essential part in the release of ortho-P, since the quantity increases by 90% depending on the mode of this factor. This result can be explained by the increased resuspension of the sediments when the water rises slowly, as simulated here by successive additions. During the experiment a far stronger turbidity is indeed noted when the water is added in three steps. This is due to the fact that the intensity of stirring is the same whichever jar is chosen, but the effect of setting the water mass in motion, therefore its ability to resuspend the sediment, is far greater when the water is added discontinuously. This effect of the resuspension of the sediments on the release of soluble phosphorus agrees with the results of Andersen (1974), Rippey (1977), Ryding and Forsberg (1977), Bates and Neafus (1980).

The origin of the water used also affects, although less, the quantity of ortho-P released. The water of the Galbe stream causes a significantly higher ortho-P increase compared with the Aude stream or the reservoir.

It is generally known that a low phosphorus concentration in the water favours its release from the sediment into the water (Golterman, 1973; Kamp Nielsen, 1974; Rippey, 1977). The far lower phosphorus concentrations in the Galbe water probably explain part of the result. The effect of the higher pH of the Galbe water, however, can also contribute. Simple calculations using the parameters of the parabola relating the ortho-P to the pH (Fig. 3) show that the quantities of ortho-P released at pH 7 (Aude water) or 7.4 (Galbe water) are 10.7 and 11.8 μg g^{-1}sed respectively.

In these conditions the difference in pH between the two streams would explain an increase in ortho-P of 10.3%. This effect of the pH, moderate in spring, certainly plays a more important part in summer, when it easily attains 8.5 in the water of the reservoir. Such a difference would lead to an increase in ortho-P of the order of 48%. This phenomenon, already pointed out by Lijklema (1977) plays an even more important part in the Puyvalador reservoir because a considerable part of the sediments lies under shallow water, even when the reservoir reaches its maximal filling capacity.

The effect of desiccation on ortho-P release has been pointed out or proven by numerous authors (Dommergues and Mangenot, 1970; Bartlett and James, 1980; Brookes *et al.*, 1982). Its mechanism, however, is still disputed. According to Haynes *et al.* (1985) physico-chemical causes predominate, while according to Sparling *et al.* (1985) it is mainly the lethal effect of desiccation on part of the bacterial biomass which causes it. Taking the ortho-P values 10 or 19 μg corresponding to the two modes of the factor refilling rate and considering that these quantities have been released by sediment surfaces of 64 cm^2, values of ortho-P between 1.6 and 3 mg m^{-2} are obtained. These values may not be compared with those obtained by other authors who all worked on sediments permanently covered by water, in which case part of the dissolved phosphorus must come from the interstitial water. The sediments used in this study remained in situ in direct contact with open air. They have therefore been subjected to important water loss and the effect of oblique or vertical washing by the frequent rains that preceded their sampling.

As to the bioavailability of the ortho-P when the water in the reservoir rises, it must be stressed that our results depend only on soluble phosphorus. Golterman (1977) has in fact shown for *Scenedesmus* sp., that the sediments may constitute a phosphorus source, probably in the form of iron-bound phosphorus. This use of phosphorus is facilitated in shallow lakes, like Puyvalador at the moment that the water rises, because there is then contact between the sediment and the photic zone (Golterman, 1980). In the Great Lakes, Williams *et al.* (1980) showed that *Scenedesmus quadricauda* could use between 8 and 50% of the total phosphorus in the sediments. Although many questions remain open (Golterman, 1984), the role of the sediments as phosphorus source therefore appears important. Consequently, the values found in this study are probably an underestimate of the really bioavailable quantities of phosphorus.

Conclusion

The experimental approach used in this work has allowed to demonstrate the effect of several ecological factors resulting directly from the drawdown. The factor refilling rate is related to the climatic conditions prevailing in the catchment area in winter (storage of the precipitation in the form of snow), but also in spring (mean temperature speeding up, or on the contrary slowing down the melting of the snow), and to the need for hydro-electricity.

The factor humidity of the sediments is essentially controlled by the pluvio-thermal regime prevailing during the months April till June, which shows a great variability in this part of the Pyrenees from year to year. As to the factor origin of the water, this is also partly related to the climatic conditions and the possibilities offered by the hydroelectric constructions in the catchment area.

Drawdown is an important phenomenon which is generally not sufficiently taken into account in the study of reservoirs. Nevertheless, of all the reservoirs of France intended for the production of electricity, 35% are subjected to drawdown, often with large amplitudes.

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