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Retention of nutrients, suspended particulate matter and phytoplankton in a pondage associated with a run-of-the-river type hydroelectric power plant

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ABSTRACT

Reservoirs associated with run-of-the-river type hydroelectrical power plants (i.e. pondages) have short water residence times. For this reason, pondages are thought to have a limited impact on the fluxes of particles and solutes transported by rivers. The Malause reservoir (South West France) is such a pondage. Fed by both the Garonne and Tarn rivers, it has a water residence time of only a few days. Incoming and outgoing fluxes of nutrients, suspended particulate matter (SPM) and phytoplankton were measured weekly over the course of 1 year. Mass balance calculations showed that Malause pondage retained 24% of soluble reactive phosphorus (SRP) supplied by both rivers on an annual basis. SRP retention occurred mostly in spring–summer, pointing to biological uptake. In addition, the pondage was a sink for SPM and phytoplankton, retaining 39% of SPM and 14% of chlorophyll *a* supplied by both rivers on an annual basis. The retention efficiency appeared to be constrained by water temperature and residence time. The pondage was a source of phytoplankton during summer, when temperature and water residence time was high. The pondage was a sink for SPM when water residence time was low (<1 day). Our observations highlight the need to reconsider the impact of minor hydrological discontinuities on the functioning of the river continuum. The shallow depth of the pondage and the presence of dense stands of submerged macrophytes have probably favoured the retention of nutrients and the sedimentation of particles within the pondage.

KEY WORDS reservoir; phytoplankton; mass balance; nutrient retention; sedimentation; residence time

INTRODUCTION

By building artificial impoundment structures on rivers, humans significantly affect the transport of sediments, organic matter and nutrients to coastal zones through the riverine continuum (Vörösmarty *et al.*, 2003; Friedl *et al.*, 2004; Teodoru *et al.*, 2006). Reservoirs are hydrodynamic discontinuities in which the water residence time is artificially prolonged, and turbulence is reduced. This favours sedimentation of suspended particulate matter (SPM) (Vörösmarty *et al.*, 2003). A reduction in turbulence may also influence sedimentation of riverine phytoplankton. On the other hand, an increase in water residence time will promote the development of a phytoplankton community adapted to the conditions in the reservoir itself (e.g. Walz and Welker, 1998; Oh *et al.*, 2001). Primary production of phytoplankton within the reservoir in turn causes consumption of nutrients and subsequent transfer of nutrients into benthic food webs. Thus, biological uptake of nutrients may result in a reduction of the nutrient flux to downstream reaches (e.g. Conley *et al.*, 1993; Humborg *et al.*, 2000).

Several studies have already demonstrated that reservoirs have a strong impact on the hydrological and physical characteristics of the river continuum, as well as on its biological activity and input/output balance of solutes and particulate matter (e.g. Hannan, 1979; Thornton *et al.*, 1990; Thébault *et al.*, 1999; Humborg *et al.*, 2000; Kelly, 2001). Most of these studies focused on large reservoirs with a long water residence time (i.e. storage reservoirs). Only few studies investigated the effects of reservoirs with short water residence time on the transport of planktonic organisms, nutrients and organic material (but see Schallenberg and Burns, 1997;

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Reid and Hamilton, 2007; Pimenta *et al*., 2012). Reservoirs associated with run-of-the-river type hydroelectric power plant are named pondages. Pondages show much shorter water residence times and storage capacity than storage reservoirs. They are mostly used as a simple and flexible way to manage peaks and shortages in runoff in order to assure a continuous supply of water for electricity production or irrigation throughout wet and dry seasons. The impact of pondages is thought to be relatively minor, as sedimentation and uptake of dissolved and particulate substances have been shown to correlate positively with water residence time (e.g. Maneux *et al*., 2001; Thomas *et al*., 2003). However, water residence time is not the only factor affecting retention of particles or solutes in reservoirs. Retention of SPM, for instance, is also influenced by reservoir depth, shape, the size distribution of particulate material and the presence of vegetation (Verstraeten and Poesen, 2000). In other words, the area of the sediment – water and vegetation – water interface also matters. The impact of such interfaces may be more important in pondages because of a much lower volume-to-area ratio than in storage reservoirs (Downing, 2010).

In a context of increasing demand for water and energy supply, over 500 storage reservoirs have been constructed annually worldwide since the 1960s (Halim, 1991). Storage reservoirs have a major impact on the fluxes of particles and solutes transported by rivers. Globally, Vörösmarty *et al*. (2003) estimated that about 45 000 storage reservoirs can intercept each year 4–5 Gt of the sediment fluxes to oceans. However, about 800 000 smaller impoundments such as pondages were not included in this estimate. Run-of-the-river type hydroelectric power plants are cost-effective and thought of as environmentally benign. As such, they are increasingly used for local production of electricity in developed and developing countries (Paish, 2002). Given the rapid increase in construction of pondages for electricity production, there is a real need to foresee the impacts of these types of reservoirs on the functioning of the river continuum to assess their impact on global biogeochemical cycles. However, so far, a lack of quantitative analysis of retention dynamics in pondages still hampers any wide-ranging evaluation of their impacts on the river continuum.

The main purpose of this study is to quantify the impact of a pondage reservoir on the transport of dissolved and particulate matter, and on the dynamics of phytoplankton. We specifically aimed to evaluate (1) whether pondages are a source or a sink for suspended particles, (2) whether pondages have a significant impact on retention/remobilization capacity of dissolved substances and (3) whether pondages can also affect the dynamics of drifting phytoplankton.

MATERIALS AND METHODS

Study site

The Malause pondage was created in 1972 at the confluence of the Garonne and Tarn rivers both to supply water to a hydroelectric power plant (Figure 1) and to supply cooling water for the Golfech nuclear power plant (located 15 km downstream) through a headrace channel connected to the dam. The power plant associated with the Malause reservoir is of run-of-the-river type. Therefore, reservoir's management aims mainly at maintaining a constant water level in the pondage rather than trapping a large volume of water during periods of high-flow to be released during periods of low discharge. The pondage has a large area (420 ha) and is relatively shallow, with a mean water depth of 3.6 m. Eighty per cent of the pondage surface is 2–6 m deep; 20% is <2 m deep (in grey in Figure 1). Because of this, the volume of the pondage is relatively small (25 10^6 m^3) compared with its average discharge (35 10^6 m^3 day^{-1}). Accordingly, the residence time of the water in the pondage is very short, usually

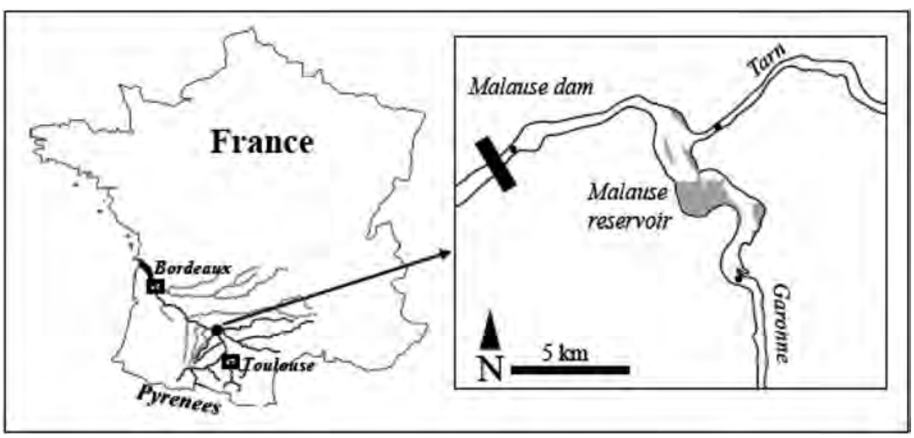

Figure 1. Study site. Left: major rivers and urban areas in Garonne's basin and location of the Malause pondage. Right: Malause pondage showing sampling stations (black points). Shallow zones (<2 m depth) in Malause are in grey.

<1 day during high-flow periods and up to a few days during low-flow periods in summer.

The Garonne River originates in the Pyrenees Mountains (Figure 1) and, as a result, has a pluvio-nival discharge regime. The Garonne River is a shallow river (generally <2 m deep) characterized by a relatively high water transparency. This allows benthic diatoms to form thick biofilm mats on the stony river bed (Ameziane *et al*., 2003; Majdi *et al*., 2012). At the same time, high-flow velocities generally limit the development of algae in the water column (Tekwani *et al*., 2013).

The deeper Tarn River has its origin in the Massif Central Mountains (Figure 1), and its discharge is regulated by rainfall in the catchment rather than snowmelt. Although the annual average discharge of the Garonne River into the pondage is higher than that of the Tarn River, the Tarn River shows higher discharge than the Garonne River during summer low-flow period (Figure 2a).

The catchments of both rivers are mainly agricultural. No major urban areas are present within the Tarn catchment. Toulouse (>1 million inhabitants) is a major city in the Garonne catchment and is situated about 100 km upstream of the Malause pondage (Figure 1).

Monitoring

Samples were collected between March 2004 and February 2005. During this period, the average annual discharge at Malause outlet was $324\,m^3\,s^{-1}$. Compared with a long-term mean inter-annual discharge of $398\,m^3\,s^{-1}$ over 1967–2007, the study period was relatively dry, presenting a hydrological deficit of 19% with respect to long-term discharge trends (Probst and Tardy, 1985; Probst, 1989).

Three stations in the Malause pondage were sampled weekly using a small boat: a station situated in the Garonne branch (44°03′45′N; 1°03′23′E, called ‘Garonne’), one in the Tarn branch (44°05′01″N; 0°59′12″E, called ‘Tarn’) and one situated slightly upstream of the pondage outlet (44°05′01″N; 0°59′08″E, called ‘Malause’) (Figure 1). These stations were selected to represent incoming and outgoing fluxes of water, taking into account that sampling closer to the reservoir outflow was not allowed for safety reasons. Sampling was always performed between 11:00h and 17:00h, regardless of flow regime at the moment of sampling. At each station, the water column was sampled both at the surface and at 0.5 m above the sediment surface using a horizontal Niskin bottle. Temperature, dissolved O_2, pH, turbidity and conductivity were measured at each site and depth using submersible sensors (YSI 6600; YSI Inc., Yellow Springs, OH, USA). Water samples for analyses of phytoplankton, SPM and dissolved nutrients were stored in plastic containers and quickly returned to the laboratory in a cooler box.

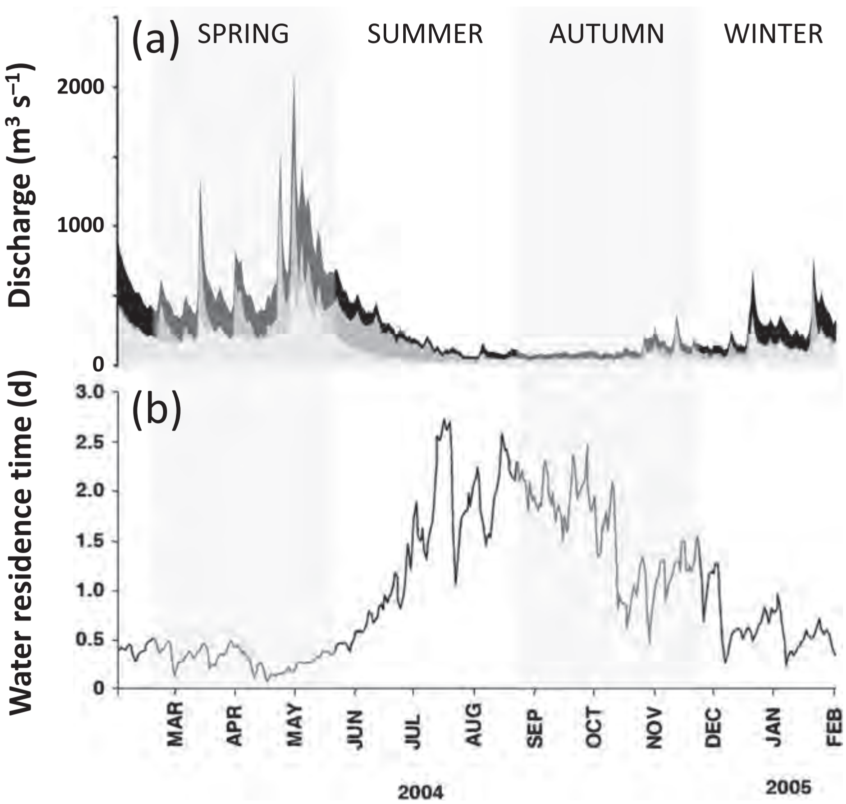

Figure 2. (a) Discharges of Tarn (white), Garonne (grey) and Malause pondage outlet (black). (b) Water residence time in Malause.

Water analyses

Suspended particulate matter was analysed by filtering 1–2 l of water on a pre-weighed glass fibre filter (GF/C, Whatman, Clifton, NJ, USA), which was dried at 105 °C during 24 h and weighed, then burned at 550 °C during 4 h and weighed to infer the dry mass and ash-free dry mass (i.e. organic content) of SPM in water samples.

For measurement of chlorophyll *a* (Chl *a*) and dissolved nutrient concentrations, a 1–2 l water sample was filtered through a glass fibre filter (GF/C; Whatman). Chl *a* was extracted from the filter in 10 ml 90% acetone and analysed spectrophotometrically using standard procedures (SCOR-UNESCO, 1966). The filtrate was analysed for soluble reactive phosphorus (SRP), dissolved silica (DSi), ammonium ($NH4^+$), nitrite (NO_2^-) and nitrate (NO_3^-) concentrations according to standard procedures (APHA-AWWA-WPCF, 1992). $NH4^+$, NO_2^- and NO_3^- concentrations were pooled to yield dissolved inorganic nitrogen (DIN) concentration.

Budget calculations and statistical analyses

Daily discharge data were obtained from the nearest gauging stations of the French water management authority (DIREN Midi-Pyrénées): upstream Malause on the Garonne (Verdun station) and Tarn (Moissac station), and downstream Malause outlet (Lamagistère station). The volume of the Malause pondage has been estimated by a compilation of bathymetrical maps drawn using geolocation of depth profiles using real-time data of a portable global positioning system coupled to an echo-sounder (PA500, Tritech, Westhill, UK) fixed to a small boat with a flat bottom. Bathymetrical maps and further details on the procedure can be found in Coynel (2005). The residence time of the water in the pondage was estimated by dividing the volume of the reservoir by the discharge downstream of the reservoir. Potential bias due to precipitation and evaporation at the surface of the pondage was corrected following Thébault (2004). Average correction was 2.2% over the year.

For each station and sampling occasion, we calculated instantaneous fluxes (*Fi*) of SPM, Chl *a* and nutrients by multiplying mean concentration (C_M) by the instantaneous discharge (Q_M). The average of the surface and near-bottom concentrations was used in the calculations. Annual fluxes (F_a) were estimated by multiplying mean annual discharge (Q_a) by annual instantaneous concentration ($C_a i$). $C_a i$ was calculated as follows:

$$C_a i = \sum_{i=1}^{n} CiQi / \sum_{i=1}^{n} Qi \tag{1}$$

Retention of dissolved and particulate substances passing through the Malause pondage was then estimated from the difference between the export at the reservoir outlet (output) and the imports from the Garonne and Tarn Rivers (inputs), based on the following dynamical budget formulation:

$$\begin{aligned} \text{Retention} &= \text{Output–Inputs} \\ &= C_M{\cdot}Q_M – (C_G{\cdot}Q_G + C_T{\cdot}Q_T) \end{aligned} \tag{2}$$

where C_G, C_T and C_M are component concentrations measured in the Garonne (G) and Tarn (T) Rivers and at the Malause outlet (M), respectively. Q_G, Q_T and Q_M are instantaneous discharges. A positive budget was expected to reflect remobilization or production of particles or solutes in the reservoir, whereas negative budget was expected to reflect retention or mineralization in the pondage. To estimate annual retention, instantaneous fluxes were averaged over the study period (i.e. from $kg\,s^{-1}$ to $kg\,y^{-1}$). The accuracy of our calculations was inferred from the retention efficiency of a conservative tracer (chloride, Teissier *et al*., 2008). Annual retention of chloride was 0.53%. Retention efficiency was expressed as a percentage of the inputs as follows:

$$\begin{aligned} \text{Retention } \% = 100\times[C_M{\cdot}Q_M – (C_G{\cdot}Q_G + C_T{\cdot}Q_T)] \\ / \; [C_G{\cdot}Q_G + C_T{\cdot}Q_T] \end{aligned} \tag{3}$$

Linear models (LMs) were used to assess the main effects of temperature and water residence time on retention of particles and solutes in the reservoir. When needed, response variables were log transformed to achieve homoscedasticity and normally distributed residuals. As the interaction between temperature and residence time was not significant, it was removed from all LMs. We compared contributions of Garonne and Tarn Rivers using pairwise *t*-test. LMs and *t*-tests were performed using STATISTICA software (version 8.0, Statsoft Inc., Tulsa, OK, USA).

RESULTS

Background

Discharge of the tributaries into the pondage averaged over the study period was higher for the Garonne River ($173\,m^3\,s^{-1}$) than for the Tarn River ($142\,m^3\,s^{-1}$) (*t*-test: $P = 0.02$). Because of snowmelt in the Pyrenees, the Garonne River showed an extended period of high discharge from April to June 2004 (Figure 2a). Discharge of the Tarn River displayed three short flood events in early June. In both rivers, discharge was low during summer–autumn and increased again gradually from November to the end of the study period in February 2005. Discharge of the Malause pondage reflected the combined discharges of the two tributaries (Figure 2a). Water residence time in the pondage was <1 day from the beginning of the study period until July 2004 (Figure 2b). Then, water residence time increased steadily up to 2.5 days in August and remained high (>1 day) during summer–autumn low-flow period. Water temperature ranged from 7 °C in winter to 27 °C in summer (*data not shown*). Water temperature usually differed little between the two tributaries except during spring, when temperature of the Garonne River was on average 5 °C lower than that of the Tarn River.

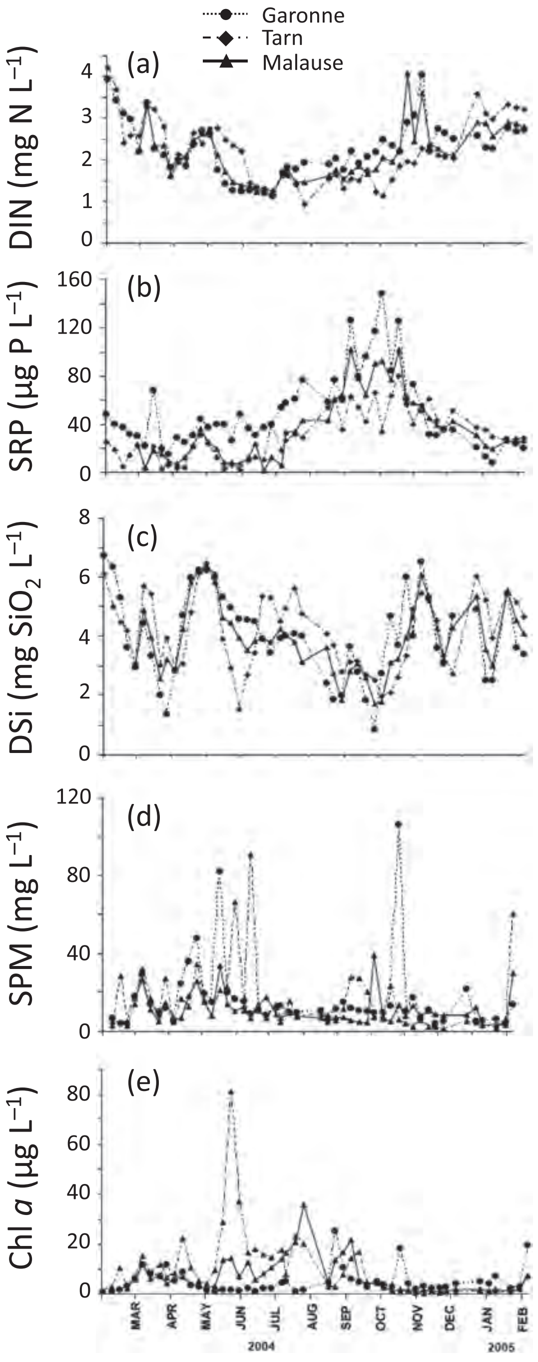

Figure 3. Concentrations of (a) dissolved inorganic nitrogen (DIN), (b) soluble reactive phosphorus (SRP), (c) dissolved silica (DSi), (d) suspended particulate matter (SPM) and (e) chlorophyll *a* (Chl *a*) in Malause outlet (plain line) and its tributaries (dotted lines).

The concentration of DIN was comparable in the two tributaries and at the outlet of the pondage throughout the study period (Figure 3a). The DIN concentration was high in winter (up to 4 mg l^{-1}) and declined in summer down to 1 mg l^{-1}. SRP concentration was higher in the Garonne than in the Tarn River (*t*-test: $P < 0.001$) (Figure 3b). In both rivers and near the pondage outlet, SRP concentration was higher during late summer and autumn low-flow period, showing values over 0.1 mg l^{-1} in the Garonne River and in Malause pondage. DSi concentration showed fluctuations across the three sites (Figure 3c). All sites showed high DSi concentrations in spring (>6 mg l^{-1}), which then decreased during summer before increasing again in autumn. DSi concentrations never dropped below 0.6 mg l^{-1}. Most of the time, the concentration of SPM was lower than 20 mg l^{-1} and, on average, the SPM concentration was higher in the Garonne than in the Tarn River (*t*-test: $P < 0.001$). Interestingly, important peaks in SPM due to major floods in the Garonne and Tarn rivers (50–110 mg l^{-1}) were strongly buffered by the pondage, as they did not result in a concomitant elevation of SPM load at Malause outlet (Figure 3d). Chl *a* concentration was twofold higher in the Tarn than in the Garonne River (*t*-test: $P = 0.04$), with Malause outlet showing intermediate Chl *a* concentration (Figure 3e). In the Tarn River, Chl *a* peaked up to 83 µg l^{-1} in June. At Malause outlet, the highest Chl *a* concentrations (up to 37 µg l^{-1}) were recorded from August to October.

Dynamical budget

To evaluate whether the Malause pondage was a net source or sink for particulate and dissolved substances, an annual budget was calculated in which inputs (through Tarn and Garonne rivers) were compared with outputs at the pondage outlet (Table I). Malause was a sink for SRP, retaining 23.9% of total inputs over 1 year. Retention of DIN and DSi was minor (1.3 and 1.2%, respectively). Malause was an important sink for SPM, trapping 39.3% of suspended particles supplied by both tributaries. Twelve per cent of organic particles were trapped, as well as 14.3% of phytoplankton biomass (Chl *a*) entering the pondage.

To detect temporal differences in retention intensity, we plotted outgoing–incoming instantaneous fluxes of particles and solutes in the pondage over time (Figure 4). We considered ‘significant’ retention or production events when outgoing fluxes exceeded ±20% of incoming fluxes. Dynamics of DIN were affected by only one production peak in November. Retention of SRP was strong during spring–summer. DSi dynamics showed little temporal fluctuations. The pondage was an important sink for SPM during most of the year and especially during spring flood events (Figure 4). The pondage was a sink for Chl *a* during winter–spring and became a source during summer.

Table I. Annual inputs and outputs of soluble reactive phosphorus (SRP), dissolved inorganic nitrogen (DIN), dissolved silica (DSi), suspended particulate matter (SPM), particulate organic matter (POM) and chlorophyll *a* (Chl *a*), entering and leaving the Malause pondage.

Suspended particles and solutes	Inputs (tons year^{-1}) Garonne	Inputs (tons year^{-1}) Tarn	Output (tons year^{-1}) Malause	Annual budget (%)
SRP	230	96	225	−23.9
DIN	11 200	10 700	21 610	−1.3
DSi	23 670	19 570	42 690	−1.2
SPM	128 000	84 000	131 000	−39.3
POM	10 796	26 630	32 965	−12.0
Chl *a*	26	44	60	−14.3

Positive and negative annual budgets correspond to the pondage acting as a source or a sink, respectively.

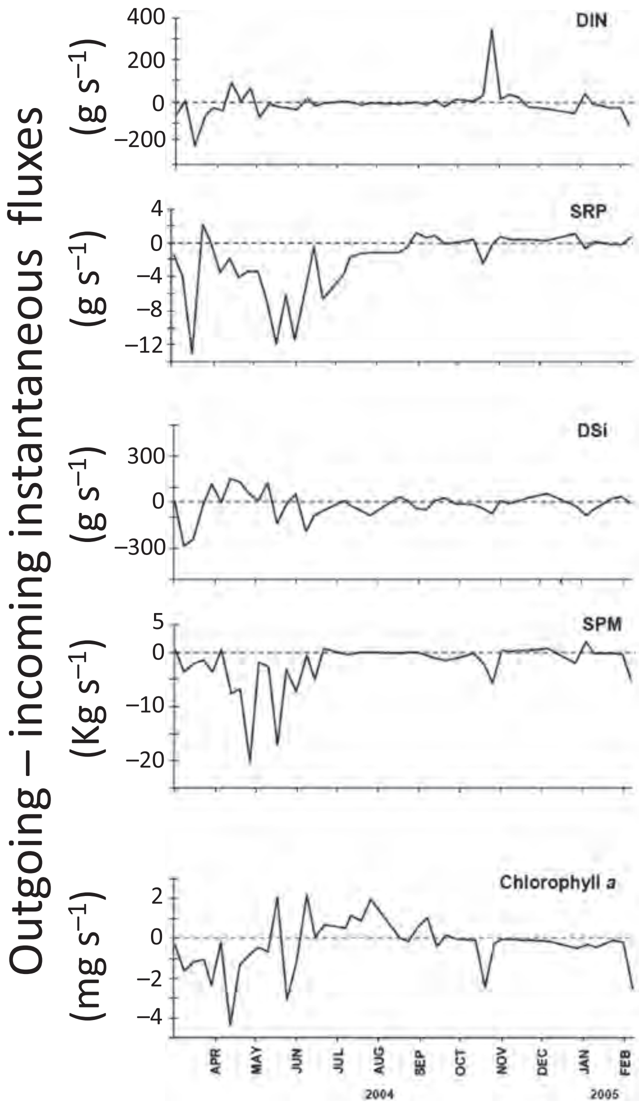

Figure 4. Outgoing–incoming instantaneous fluxes of dissolved inorganic nitrogen (DIN), soluble reactive phosphorus (SRP), dissolved silica (DSi), suspended particulate matter (SPM) and chlorophyll *a* in Malause pondage. Malause acted as a source above equilibrium (dotted line) and as a sink below equilibrium.

Effects of water residence time and temperature

We used LMs to disentangle the effects of temperature and water residence time on retention of particles and solutes in the pondage. A summary of the models is shown in Table II. Water residence time influenced the retention of SPM and SRP significantly, with short residence times (<1 day) causing consistent deviations from observed/expected equilibrium in SPM towards retention in the pondage (Figure 5a). The ratio of observed/expected SRP increased significantly with residence time but was often <1, highlighting the predominance of phosphorus retention processes in the pondage (Figure 5b). Water temperature significantly affected the retention of Chl *a* and SRP (Table II). The strongest deviations from equilibrium in observed/expected ratio occurred for Chl *a*, which showed a clear increase in the pondage when temperature exceeded 17 °C (Figure 5c). Two Chl *a* production events ('algal blooms'), resulting in much higher output than expected (>450%), occurred in July and August. At the same time, there was an increase in SRP retention/mobilization in the pondage when temperature increased (Figure 5d).

DISCUSSION

Changes in water residence time in reservoirs can affect biogeochemical cycles in rivers through an alteration of sedimentation and sequestration processes of suspended material, inorganic nutrients and phytoplankton (Curtis, 1998; Algesten *et al*., 2004; Reynolds *et al*., 1994; Schallenberg and Burns, 1997). Large artificial hydraulic discontinuities, such as storage reservoirs, are well known to affect the functioning of rivers (e.g. Vörösmarty *et al*., 2003; Syvitski *et al*., 2005; Zhang *et al*., 2012; Martínez *et al*., 2013). However, so far, much less attention has been paid to the effect of small hydraulic discontinuities, such as pondages, on riverine transport. With this study, we show that a pondage with a very short water residence time (0.1–2.5 days) was an important sink for suspended particles, trapping about a

Table II. Summary of linear models assessing the effects of water residence time and temperature on observed/expected ratio in response variables.

Model component		SPM				SRP				Chl *a*			
	df	*SS*	*F*	*P*		*SS*	*F*	*P*		*SS*	*F*	*P*	
Residence time (days)	1	0.64	5.47	0.024	*	1.45	10.78	0.002	**	1.18	2.08	0.157	
Water temperature (°C)	1	0.05	0.40	0.531		1.14	8.47	0.006	**	2.59	4.57	0.039	*
Error	40	4.64				5.37				22.69			
Total	42	5.49				6.93				34.41			

SPM, suspended particulate matter; SRP, soluble reactive phosphorus; Chl *a*, chlorophyll *a*; df, degrees of freedom; SS, Sum of squares.
Only variables showing significant effects are displayed.
Significance-level: *, $P < 0.05$; **, $P < 0.01$.

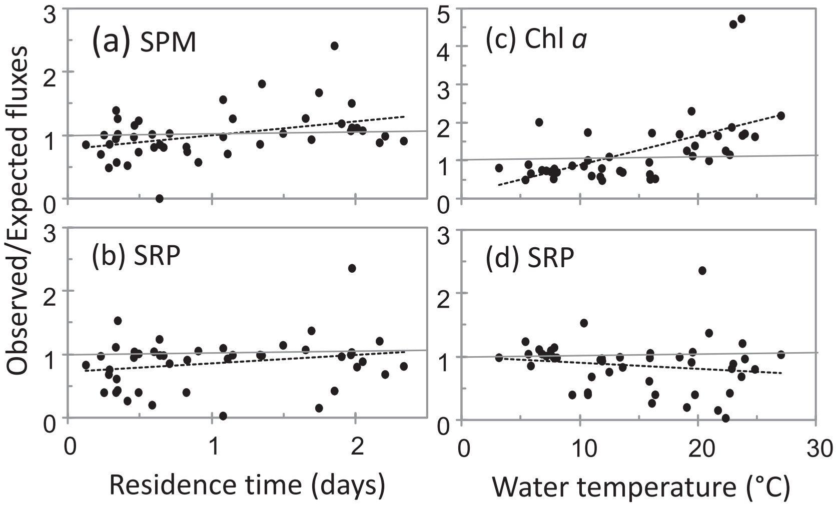

Figure 5. Ratio of observed/expected masses of (a) suspended particulate matter (SPM), (b, d) soluble reactive phosphorus (SRP) and (c) chlorophyll *a* (Chl *a*) versus water residence time and temperature. Dotted lines are significant linear correlations. Continuous lines are proxies for equilibrium state between observed inputs from tributaries and output at Malause outlet.

third of the SPM that was imported from the tributary rivers on an annual basis. Entrapment of SPM varied over the course of the year, and we showed that variation in retention was directly linked to water residence time. Interestingly, the highest retention efficiency for SPM occurred when the water residence time was short (<1 days). Our results provide empirical support to the suggestion of Vörösmarty *et al*. (2003) that minor impoundments may have impacts on sediment transport in disproportion to their relative reduction of water residence time. In the Iron Gate I reservoir (Danube River), which is a large pondage showing an average water residence time of 6.5 days (Klaver *et al*., 2007), Teodoru and Wehrli (2005) reported a retention of suspended sediments of 56%. Important retention of SPM by the Malause pondage was unexpected because SPM retention is generally considered to be low in reservoirs with short water residence times (Kelly, 2001; Egré and Milewski, 2002; Paish, 2002). According to empirical relationships between trapping efficiency and water residence time (Ward, 1980), a trapping efficiency <5 % would have been expected for the Malause pondage with an average water residence time of 1 day. A trapping efficiency of 30% would only have been expected in summer, when water residence time exceeded 2 days. In the Malause pondage, efficient retention of SPM throughout the year might be ascribed to the very shallow water column in several zones of the pondage (<2 m, shown in grey in Figure 1). These shallow areas may help SPM to settle down more quickly. In addition, those shallow areas are covered by dense stands of submerged macrophytes (mostly *Myriophyllum spicatum* L.). It is known that submerged macrophytes can dampen turbulence in the water column and thus stimulate particle sedimentation (Jones, 1990; Schulz *et al*., 2003). This may be particularly true for *M. spicatum*, which possesses numerous finely dissected leaves. As a consequence of sedimentation of SPM, high sediment accumulation rates (up to 4 cm year^{-1}) have been reported for the Malause pondage (Coynel, 2005), causing an important decrease of the reservoir volume since its creation in 1972.

The Malause pondage also trapped living particles (e.g. phytoplankton), with a yearly retention amounting to 14% of the Chl *a* inputs from the tributary rivers. Like the bulk of suspended particles, phytoplankton is susceptible to sedimentation. This is particularly true for taxa typically adapted to shear-stress constraints met in turbulent rivers (e.g. benthic diatoms from the Garonne; Tekwani *et al*., 2013), which have no specific adaptations to overcome sedimentation in sluggish waters. It is likely that the large shallow water areas covered by macrophyte stands may have dampened locally the transport of phytoplanktonic cells and hence may have stimulated their sedimentation, as well as their possible settlement as epiphytes (e.g. Munteanu and Maly, 1981; Bahnwart *et al*., 1998; Köhler *et al*., 2002; Schulz *et al*., 2003). Although the Malause pondage was a net sink for phytoplankton on an annual basis, it became a source of Chl *a* during summer. The period showing net Chl *a* increase in the pondage coincided with low-flow periods in the tributaries. During these periods, water residence time in the pondage was >2 days. Nevertheless, LMs showed that the development of algal biomass was mainly attributed to an increase in temperature rather than a decrease in residence time. This points to the development of phytoplankton blooms within the pondage and highlights the potential of pondages to stimulate primary production locally.

The Malause pondage not only influenced the transport of particles like SPM and phytoplankton but also affected the transport of solutes. The pondage emerged as a net sink for SRP on an annual basis. The fact that the retention of SRP increased with water temperature suggests a biological uptake of SRP by a growing phytoplankton biomass in the pondage. However, the SRP retention period exceeded that of phytoplankton growth in the pondage. Therefore, other processes than uptake by phytoplankton probably contributed to SRP retention. It is possible that submerged macrophytes and their associated epiphytes may have contributed to SRP retention over longer periods than phytoplankton 'blooms' in the pondage. Submerged macrophytes develop from early spring to late summer in the Malause pondage (A. Dutartre, pers. comm.), which corresponds well with the period of SRP retention. In that case, SRP is less likely to be exported from the pondage as particulate phosphorus and is more likely to be sequestrated in the sediment as sinking plant detritus. Furthermore, SRP retention overlapped partially with SPM retention (Figure 4). Potential adsorption of phosphorus to sinking particles may also be responsible for the massive retention events observed in the pondage during high flow conditions. In contrast to SRP, no significant retention of DIN was observed in the pondage. In comparison with SRP, DIN concentrations were relatively high in the Malause pondage. The N : P molar ratio averaged 300 (range 21–2700), indicating that the pondage was mostly a P-limited system (Mainstone and Parr, 2002). In P-limited systems, biological processes are expected to have a much higher impact on P than on N. No significant retention was observed for DSi. DSi is not bound to organic material; however, the Malause pondage might have an impact on Si transport by trapping biogenic Si. Reservoirs have been shown to be a major sink for Si by trapping biogenic Si in the form of diatom frustules (Ittekkot *et al*., 2000). Further monitoring of biogenic Si and of the dynamics of drifting diatoms in the Malause pondage is needed to corroborate this issue.

In conclusion, our results confirm that, as suggested by a few earlier studies (Verstraeten and Poesen, 2000; Downing, 2010), small reservoirs such as the Malause pondage can have a significant impact on the transport of some particulate and dissolved components within a river continuum. Small reservoirs are currently excluded from global estimates of the impact of humans on riverine transport of particles and solutes leading to a potential underestimation of sequestration processes in anthropized catchments. In a context of a booming construction of pondages worldwide, we believe that a better understanding of the magnitude and trajectory of their impacts is necessary to apply efficient management practices.

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