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Nutrient dynamics in Mediterranean temporary streams: A case study in Pardiela catchment (Degebe River, Portugal)

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Abstract

Most of the streams in the Mediterranean region are temporary, following predictable seasonal of flooding and drying, with a transition from lotic conditions to shallow lentic conditions. The goal of our study was to assess the nitrogen and phosphorus dynamics in channel-bed processes of temporary streams between floods. Results show that, during winter, temperatures ranged between 9.5 and 11.2 °C and oxygen concentration ranged from 8.0 to 9.5 mg L^{-1}, whereas, during summer, temperatures varied between 21.2 and 26.8 °C and oxygen between 1.2 and 5.3 mg L^{-1}, with oxygen depletion in the pools during the night. The nitrate concentrations were far more abundant during winter (February), while ammonium concentration increased after stream fragmentation into pools (especially in July when oxygen depletion conditions favoured ammonification). Results on sediment profiles showed that the most active sediment layers for NH_4-N are the top 2–3 cm, corresponding to the sediment depositional sites of the stream. Phosphate concentrations had larger variability, yet concentrations decreased from winter to spring and increased again in summer, when the shallow water pools were formed. Sediment profiles at the sediment depositional sites showed that PO_4-P was more dynamic in the first 6 cm.

In Mediterranean temporary streams, nutrient dynamics vary seasonally, as the system transits from lotic conditions to shallow lentic conditions, evidencing the regeneration of nutrients from organic and inorganic matter during the flow cessation period.

Keywords: Temporary streams; Nitrogen; Phosphorus; Sediment profiles; Mediterranean

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Introduction

In running waters, nutrients generated at one location will be naturally transported some distance downstream before subsequent re-utilization, as interdependent processes described as "nutrient spiralling" (Allen, 1995; Dahm, Grimm, Marmonier, Valett, & Vervier, 1998). Yet, most of the streams constituting the Mediterranean catchments are temporary, becoming either intermittent or ephemeral (e.g. Acunã, Giorgi, Muñoz, Uehlinger, & Sabater, 2004; Froebrich, 2005; Morais, Pinto, Guilherme, Rosado, & Antunes, 2004; Tockner & Stanford, 2002). Over an annual cycle, these systems expand, contract, and fragment, following sequential, predictable, seasonal events of flooding and drying (Gasith & Resh, 1999). These temporary streams provide a large contrast in physical properties, in a similar way to that seen in comparative studies between streams from temperate regions and lakes (Essington & Carpenter, 2000): At one end, temporary streams are lotic systems with unidirectional flow and sometimes high flushing rate, and at the other end they form small lentic shallow systems. Thus, the nutrient dynamics in temporary streams are mainly determined by the characteristic sequence of dry periods and the following floods (Froebrich, 2005).

The dynamics of dissolved inorganic nutrients depend on their being transported from the catchment to the water column and on all the transfer processes linking the water column to the stream bed (Allen, 1995). Therefore, the main inputs contributing to the nutrient balance and status of these aquatic systems are the external point and diffuse sources plus the internal biogeochemical mineralisation processes. Additionally, the physical and chemical characteristics and the ecology of small Mediterranean streams, while highly complex and dynamic, are strongly influenced by the hydrologic regime (Acunã et al., 2004; Holmes, Fisher, Grimm, & Harper, 1998). Authors have predicted, for many Mediterranean areas, a rise in the demand for water up to 100% by 2025, which will lead to a major increase in streams' ephemerality (Tockner & Stanford, 2002). In addition, ephemerality can also be accentuated by changes in the flow and flood regime induced by climate change (Tockner & Stanford, 2002). Therefore, it is essential to understand the complexity of physical and chemical changes during the period of flow cessation followed by pool formation. During these dry periods, the shallowness of the water column associated with the low discharge and with late spring/summer high temperatures may enhance nutrient dynamics at the sediment/water column interface. In addition, the importance of benthic mineralisation to the trophic chain increases as the water column gets shallower (Capone & Kiene, 1998). Thus, in these spring/summer ephemeral pools, important biogeochemical processes may take place, in combination with water shallowness, high water temperature and low oxygen concentrations.

The objective of the present study was to assess the nitrogen and phosphorus dynamics in channel-bed processes of temporary streams during the period of flow cessation followed by pool formation. Therefore, a selected section of the Pardiela stream, which comprises a depositional zone and an eroding site, was studied between January and August 2004. The Pardiela stream constitutes one of the many small temporary streams in the Mediterranean region that has been studied within the scope of the European project TempQsim (EVK1-CT-2002-00112).

Material and methods

Study site

The Pardiela is a fourth-order Mediterranean stream, located in south-eastern Portugal (Fig. 1). Elevation in the Pardiela main stream ranges from 338 m at the headwater to 169 m at its confluence with the Degebe River. The catchment area is 514 km^2, where the streambed substrate is dominated by bedrock composed of siliceous and metamorphic rocks, with shallow overlying soils. Riparian vegetation mainly comprises *Fraxinus angustifolia* Vahlenberg, *Salix atrocinerea* Brotero*, Salix salviifolia* Brotero, *Populus alba* L. and *Populus nigra* L. The vegetation of the slopes is dominated by oxes, where they were immediately filte *Quercus rotundifolia* Lamark and *Quercus suber* L., whereas most parts of the catchment are essentially used as pasture. During spring, macrophyte biomass is dominated by the genus *Typha*, followed by the genera *Cyperus* and *Scirpus.* In the Pardiela catchment region, the mean air temperature ranges from 9 °C in winter (December–February) to 23 °C in summer (June–September). The mean annual precipitation is about 600 mm, yet most rainfall occurs seasonally, from late autumn to early spring. This precipitation regime results in an irregular stream hydrology with lower discharges during spring/summer, when precipitation is usually absent. However, there may be a strong inter-annual variation, in which spring floods may occur, or prolonged dry periods may prevail from early spring.

Field and laboratory procedures

During the winter and spring of 2004, the sediment of the Pardiela stream was characterised for grain-size classification and nutrient composition at a depositional zone and at an eroding site. Sediment analyses were performed in a composed sample of three replicates. The grain-size analysis procedure consisted of the separation

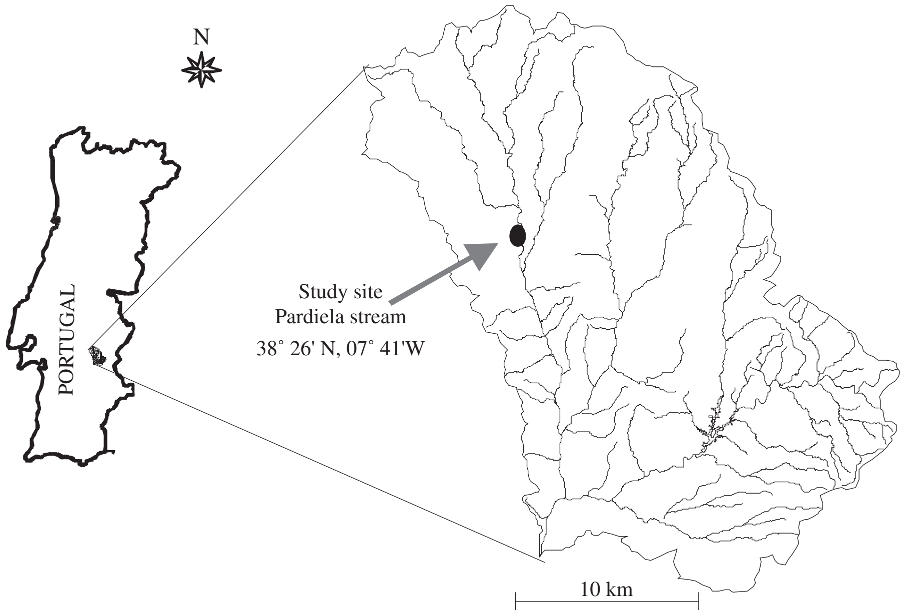

Fig. 1. The location of the study site, Pardiela stream, in the Degebe River catchment.

of grain size classes (Wentworth Lane scale, Pettijohn, 1975) by wet sieving (gravel–sand–silt–clay, Buller, & McManus, 1979), dry sieving (grain-size sand distribution), followed by the measurement of clay and silt distribution through an X-ray sediment metre. Grain-size classification was performed after the representation of clay, silt and sand proportions in a Shepard (1954 in Pettijohn, 1975) triangular diagram. For the analysis of nutrients and of organic matter, the sediment samples were smashed and homogenised in an agate mortar. Carbon and organic matter were also analysed separately in relation to the finest size fractions (sand–silt–clay). Total carbon was obtained through a Carbon analysis system using non-dispersive infra-red radiation (combustion at 1350 °C); total nitrogen was obtained through a Protein nitrogen analyser (combustion at 850 °C); total phosphorus was obtained by the Ignition Method (Saunders & Williams, 1955, as modified by Walker & Adams, 1958 in Olsen & Sommers, 1982).

Surface water, as regards temperature and the concentration of dissolved oxygen, was monitored during 24-h cycles, between February and July 2004 (oxygen metre-WTW Oxi 340i, programmed for 5 min resolution). During the same period, samples from the water column were collected hourly using an auto-sampler (ISCO 6712, equipped with a 710 ultrasonic flow module). The site to place ISCO was carefully chosen to ensure that it would always be in the shadow, being protected from the sun light by the riparian vegetation.

Sampling always started around midday, to ensure that night and morning samples would not experience the higher day temperatures. At early morning of the following day, samples already stored in the ISCO were collected, being the last ones collected just after sampling. Samples were transported to the lab in cool bred and kept frozen until analysis. Water samples were collected from a fixed point between the depositional zone and the eroding site, where a major pool was formed in May/June after stream fragmentation. At the end of July, the original depositional zone and the eroding site were split due to pool fragmentation. Both pools lasted over the summer, reaching their minimum size in August. The sampling site became about 20 m × 4 m with a mean depth of 30 cm, which disabled the use of the auto-sampler in the last month. Nitrogen (NH_4-N, NO_3-N and NO_2-N) were analysed with a Dionex DX-120 and dissolved reactive phosphate was analysed according to standard methods described in Limnologisk Metodik (1992).

Sediment nutrient profiles were studied by placing dialysis chambers (Kamp-Nielsen & Flindt, 1993) vertically at a depositional zone and at an eroding site without rooted vegetation. Each in situ dialyser was made of a Plexiglas sheet (12 mm × 150 mm × 225 mm), with slits 68 mm in width and 3 mm in height and with 2 mm between the slits in the top 7 cm and 8 mm between the slits from 7 to 20 cm depth. This method allowed discrimination between the nutrient profiles, with maximum resolution of 5 mm in the first top 7 cm, and 10 mm from 7 to 20 cm depth. For a more detailed description of the technique, see Kamp-Nielsen and Flindt (1993). In our case, the water samples were collected with a syringe and simultaneously the chamber was filled with distilled water. Water samples were analysed as described before. To evaluate the effect of autotrophic/heterotrophic processes of benthic autotrophs in pore-water nutrient dynamics, samples were taken after a 12 h exposure under dark conditions (night) and 12 h under light conditions (day)". Kamp-Nielsen and Flindt (1993) estimated 90% equilibrium after approximately 7 h for NH_4-N and approximately 9 h for PO_4-P.

Boxplots were performed with the SPSS program, version 14.0. The non-parametric Mann–Whitney test was applied to determine the significance of differences (95% confidence level) between the sediment nutrient profiles (Zar, 1996).

Results

The year 2004 at the Pardiela catchment region was classified as an average year, with the exception of

Table 1. (A) Monthly classification of the Pardiela catchments in the year 2004 according to precipitation percentiles and runoff percentiles

A	Classification of the year 2004			B	Precipitation percentiles since 1932 (mm)			C	Runoff percentiles since 1991 (mm)		
	Precipitation		Runoff		P20	P50	P80		P20	P50	P80
J	NORMAL	J	NORMAL	J	28	65	130	J	0.69	11.89	61.31
F	NORMAL	F	NORMAL	F	19	48	105	F	0.80	10.39	22.47
M	NORMAL	M	NORMAL	M	24	64	108	M	0.64	5.95	20.28
A	NORMAL	A	DRY	A	22	45	76	A	0.30	2.68	15.50
M	NORMAL	M	DRY	M	12	33	55	M	0.37	3.66	23.27
J	DRY	J	DRY	J	1	13	35	J	0.15	1.34	1.74
J	NORMAL	J	NORMAL	J	0	0	8	J	0.00	0.47	1.11
A	WET	A	NORMAL	A	0	0	7	A	0.00	0.46	1.08
S	NORMAL	S	NORMAL	S	0	17	49	S	0.00	0.92	3.06
O	WET	O	NORMAL	O	15	47	97	O	0.22	1.41	4.16
N	DRY	N	DRY	N	21	59	110	N	0.61	4.99	43.80
D	DRY	D	DRY	D	29	74	118	D	0.90	35.01	56.55

The percentiles were calculated for the Pardiela catchment based on (B) monthly precipitation (mm) since 1932 and (C) monthly runoff (mm) since 1991 available on the Portuguese National Water Institute, INAG, specifically on the National Water Resources System, the SNIRH website.
DRY – percentile 20, NORMAL – percentile 50, WET – percentile 80.

Table 2. Sediment characterisations of a depositional and an eroding site at the Pardiela stream in winter and spring conditions

2004	17 February		29 April	
	Depositional	Eroding	Depositional	Eroding
Grain size distribution (%)				
Gravel (∅ > 2 mm)	23.3	43.0	1.3	10.7
Sand (62 μm < ∅ < 2 mm)	73.1	55.5	75.8	87.9
Silt (2 μm < ∅ < 62 μm)	2.1	0.9	12.8	0.8
Clay (∅ < 2 μm)	1.5	0.6	10.1	0.6
Class term	Gravelly sand	Gravelly sand	Sand	Sand
Total sediment (milled)				
Water content (%)	22.7	24.8	18.9	19.4
pH (H_2O)	6.61	6.77	6.95	6.82
Ash free dry mass (%)	0.68	0.56	1.52	0.54
C_{total} (%)	0.106	0.075	0.113	0.063
Org. matter (%)	0.182	0.129	0.194	0.108
N_{total} (%)	0.06	0.074	0.068	0.061
P_{total} (%)	0.644	0.682	0.702	0.601
$P_{org.}$ (%)	0.577	0.563	0.570	0.506
$P_{inorg.}$ (%)	0.068	0.118	0.132	0.095
Fraction < 2 mm				
C_{total} (%)	0.504	0.115	0.172	0.190
Org. matter (%)	0.868	0.166	0.296	0.213

November and December, which were particularly dry. During the study period, from January until August, precipitation and runoff were mostly normal, and most rainfall occurred from winter to early spring (Table 1).

Sediment

Sediment composition and physical/chemical characteristics of the depositional and eroding sites are summarised in Table 2. Results from the grain size distribution of sediment show that the riverbed consists mainly of fine sand particles. The percentage of clay particles (∅ <2 μm) was higher at the depositional area, while the percentages of gravel particles (∅ > 2 mm) and sediment moistness were higher at the eroding site. The pH at sediment porewater was similar and ranged between 6.61 and 6.95. The percentages of organic matter and of total carbon were higher at the depositional area, and increased when considering the sediment fractions less than 2 mm (gravel). The percentages of sediment total nitrogen, total phosphorus, as well as the percentage of phosphorus organic and inorganic fractions were similar between sites (Table 2).

Surface water

For each sampling date, corresponding to a 24-h cycle, temperature and oxygen presented a highly significant positive linear relationship (always $N = 24$ and $p < 0.001$ except in May, $p > 0.05$), with higher oxygen concentrations following the daily increase in water temperature (Fig. 2A). Yet, on a seasonal scale, dissolved oxygen and temperature presented a highly significant negative linear relationship ($N = 144$; $p < 0.001$) (Fig. 2B). From winter to summer, there was an increase in daily temperature range, followed by an increase in the range of oxygen values, thus reflecting the transition from winter lotic conditions to summer lentic conditions (Fig. 2B, C). During winter, temperatures ranged between 9.5 and 11.2 °C and oxygen ranged from 8.0 to 9.5 mg L^{-1}, with a significant positive correlation (The Pearson correlation 0.742, $p < 0.001$); whereas during summer, temperatures varied between 21.2 and 26.8 °C and oxygen varied from 1.2 to 5.3 mg L^{-1}, with an even stronger positive correlation (The Pearson correlation 0.932, $p < 0.001$). As expected, the oxygen saturation index decreased seasonally with increasing temperature (median = 0.86 in February and median = 0.24 in July) (Fig. 3). Yet, during the summer period, the inter-quartile range increased and the maximum values corresponded to the higher daily temperatures (between 12.00 and 15.00) (maximum = 0.88 and minimum = 0.73 in February and maximum = 0.67 and minimum = 0.24 in July) (Fig. 3).

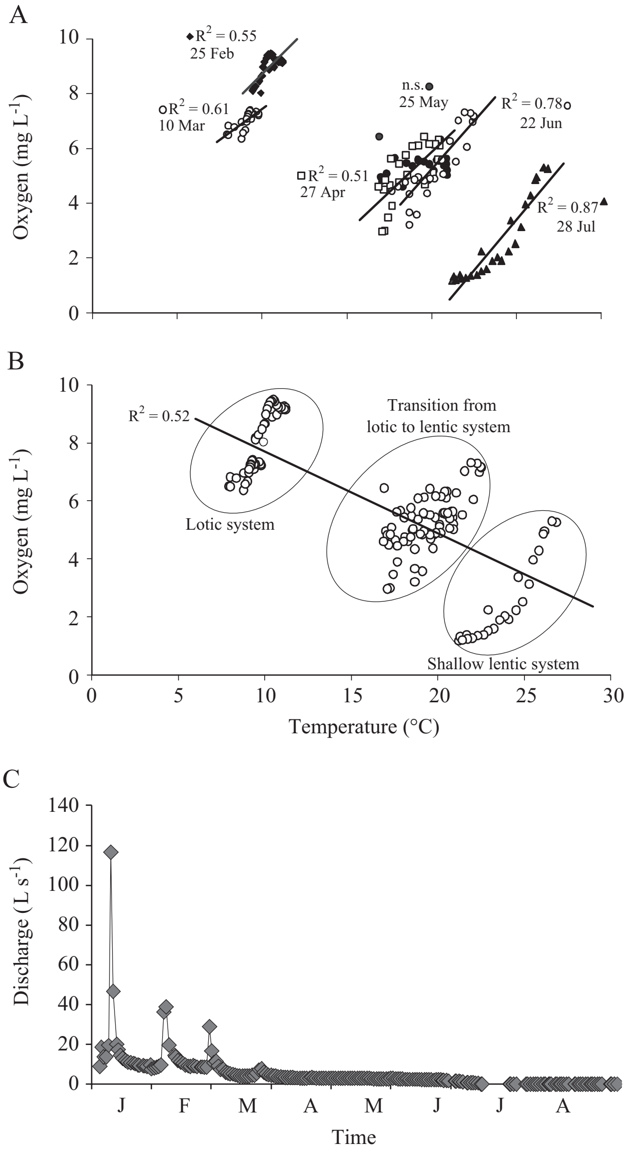

Fig. 2. Linear relation between oxygen and temperature during 24-h cycles at each sampling date (A) and throughout the period of study, with indication of lotic versus lentic conditions in the system (B); Pardiela stream discharge during the period of study (C).

The running waters of the stream during winter carried higher concentrations of dissolved inorganic nitrogen (DIN = NO_3-N + NO_2-N + NH_4-N) and reactive inorganic phosphorus (PO_4-P) (Fig. 4). In February, there was a significant positive correlation between nitrate and ammonium concentrations (The Pearson correlation 0.619, $p < 0.05$), and between nitrate and dissolved reactive phosphorus concentrations (The Pearson correlation 0.749, $p < 0.001$). While in spring both nutrients reach minimum concentrations, nitrate concentrations, during the 24-h cycles, no longer correlated with ammonia or with dissolved reactive phosphorus concentrations. During summer, after the pools formation, the mineralisation processes (endogenous sources) were enhanced, probably by the low oxygen concentrations recorded, especially during the night (Fig. 4). However, the DIN concentrations remained ten times lower than winter maximum concentrations, while phosphorus concentrations were regenerated in more than 50%.

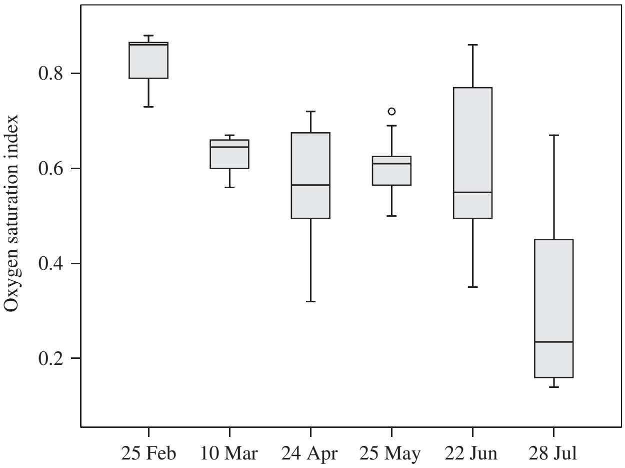

Fig. 3. Boxplots of oxygen saturation index during 24-h cycles at each sampling date. The box displays the minimum, the lower quartile, the median, the upper quartile and the maximum concentrations ($N = 24$; ○ outlier).

Nitrate concentrations were far more abundant during winter (February), while ammonium concentration increased after stream fragmentation into pools (especially in July when oxygen depletion conditions favoured ammonification). In fact, during the flow cessation period, the concentration of nitrate during each 24-h cycle decreased, while the concentration of ammonium increased (Table 3).

Analysing the boxplots of daily values of NH_4-N and PO_4-P (each 24 h) during the pool cessation period, although the concentrations of phosphate had larger variability, both nutrients showed the same trend, with decreasing concentrations during spring, which corresponds to the transition between lotic and lentic conditions, and increasing again in summer, when the shallow water pools were formed (Fig. 5).

Porewater profiles

The concentration of ammonium (NH_4-N) and reactive inorganic phosphorus (PO_4-P) in the sediment porewater, at a depth of 20 cm and during the day, presented a comparable profile during the period of flow cessation, with a specific profile for the depositional zone and the eroding site.

At the depositional zone, during the winter period, the sediment porewater profiles of ammonium showed a similar concentration along the top 20 cm of sediment, varying between 100 and 300 μg L^{-1} (Fig. 6A). During

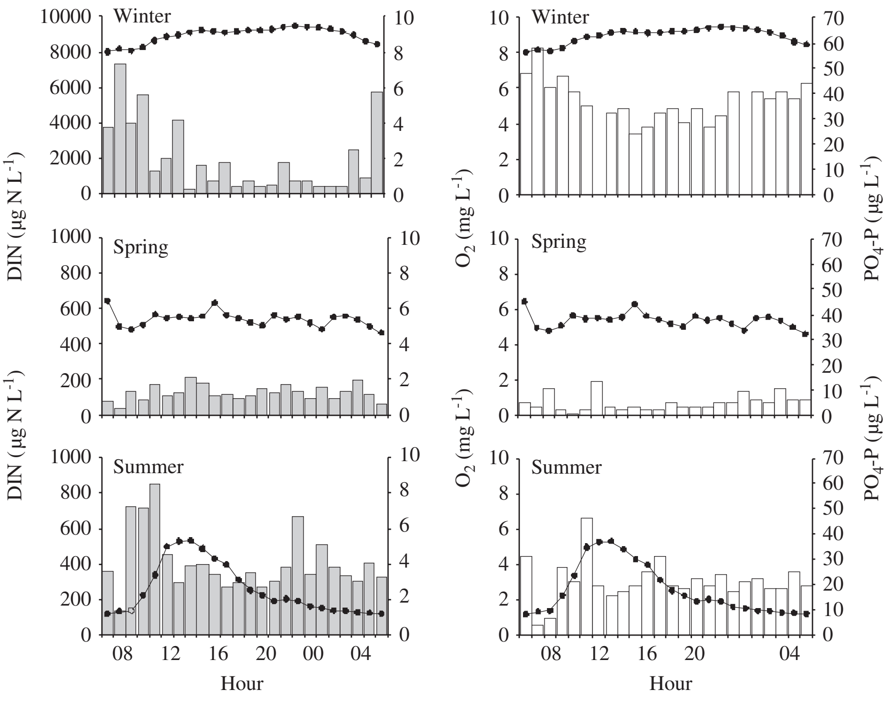

Fig. 4. The variation of the concentration of oxygen (●), nitrogen, NH_4-N + NO_3-N + NO_2-N (▨) and phosphorus (□) in the water column during 24-h cycles, in winter (25 Feb), spring (26 May) and summer (28 July) (The scale for DIN in winter is one order of magnitude higher).

Table 3. The concentration of the nitrate and ammonium forms of nitrogen in the DIN (NO_3-N + NO_2-N + NH_4-N) pool during each 24-h cycle through the period of flow cessation (median $\mu g\,N\,L^{-1} \pm$, maximum and minimum concentrations)

2004		25 February	10 March	25 May	22 June	28 July
NH_4-N	Median	28	9	18	62	265
	Max.	96	20	57	129	363
	Min.	9	4	9	6	211
NO_3-N	Median	1074	116	101	14	96
	Max.	7317	474	194	430	563
	Min.	216	24	2	1	34
DIN	Median	1097	127	120	73	353
	Max.	7349	489	214	504	851
	Min.	278	33	37	24	265

spring, the concentrations in the top 2–3 cm were lower (less than $140\,\mu g\,L^{-1}$), increased with depth and reached concentrations between 300 and $550\,\mu g\,L^{-1}$ from 10 to 20 cm. From the end of May until August, the concentrations of ammonium in the top 2–3 cm of the sediment increased from $400\,\mu g\,L^{-1}$ to a maximum of $1200\,\mu g\,L^{-1}$. Between 10 and 20 cm depth, ammonium concentrations increased in May and June (varying between 600 and $1000\,\mu g\,L^{-1}$) and decreased again in July and August (between 200 and $600\,\mu g\,L^{-1}$).

The eroding site showed similar trends, but the absolute concentrations and the concentration range were much lower. During winter and spring, the ammonium porewater profiles along the top 20 cm of sediment varied between 0 and $180\,\mu g\,L^{-1}$ (Fig. 6B). In July and August, the ammonium concentrations also increased (between 300 and $600\,\mu g\,L^{-1}$, in the first 10 cm) but without expressing the same depth profile as the depositional zone.

The sediment porewater profiles of phosphate at the depositional zone, during the winter period, showed a similar concentration along the top 20 cm of sediment, varying between 100 and $300\,\mu g\,L^{-1}$ (Fig. 7A). After this period, the phosphate profiles of the depositional zone showed a profile in the top 6 cm distinct from 6 to 20 cm of depth (Fig. 7A). During spring, the concentrations were lower, with concentrations mostly below $100\,\mu g\,L^{-1}$ in the top 6 cm, and below $200\,\mu g\,L^{-1}$ in the 6–20 cm of depth. From the end of May until August, the concentrations of phosphate in the top 6 cm of the sediment increased gradually, from $100\,\mu g\,L^{-1}$ to a maximum of $450\,\mu g\,L^{-1}$. Between 6 and 20 cm depth, phosphate concentrations increased in May and June (varying between 150 and $300\,\mu g\,L^{-1}$) and decreased again in July and August (between 50 and $200\,\mu g\,L^{-1}$). At the eroding site, the top 6 cm showed similar trends, but the absolute concentrations and the concentration range were much lower (Fig. 7B).

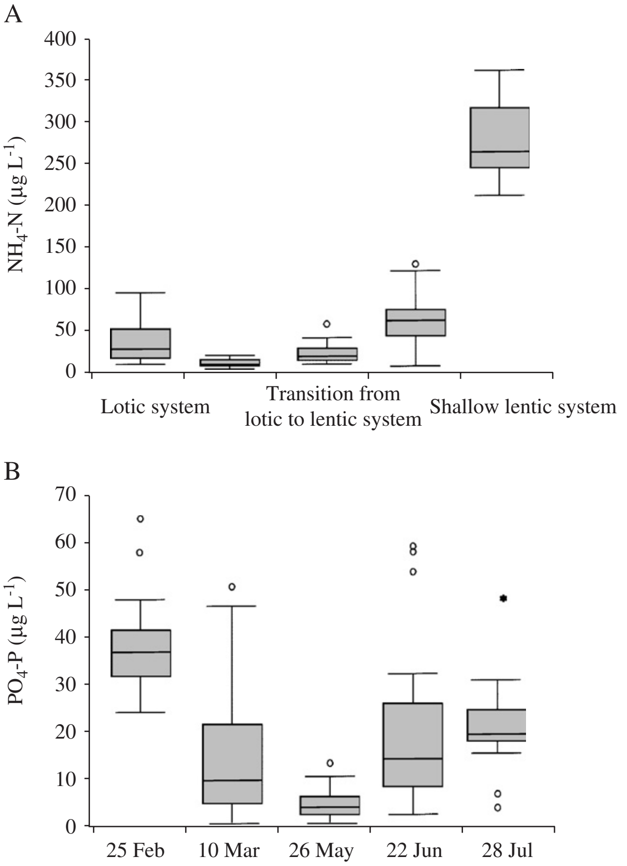

Fig. 5. Boxplots of the daily concentration of ammonium (A) and of dissolved reactive phosphorus (B) during the flood cessation, with indication of lotic versus lentic conditions in the system. The box displays the minimum, the lower quartile, the median, the upper quartile and the maximum concentrations ($N = 24$; ○ outlier; * extreme value).

Results from the non-parametric Mann–Whitney test, comparing differences (95% confidence level) between day and night porewater concentrations (Table 4), showed no significant differences in the NH_4-N profiles at the depositional zone. On the other hand, PO_4-P concentrations were significantly different during spring, with higher concentrations during the night (at the depositional zone in 7 and 27 of April and at the erosion site at 7 of April) (Fig. 8).

Discussion

In temporary rivers of Mediterranean catchment areas, hydrodynamic variability has severe implications for the physical and chemical environment. In both situations (lotic and lentic conditions), there was a highly significant positive linear relationship between

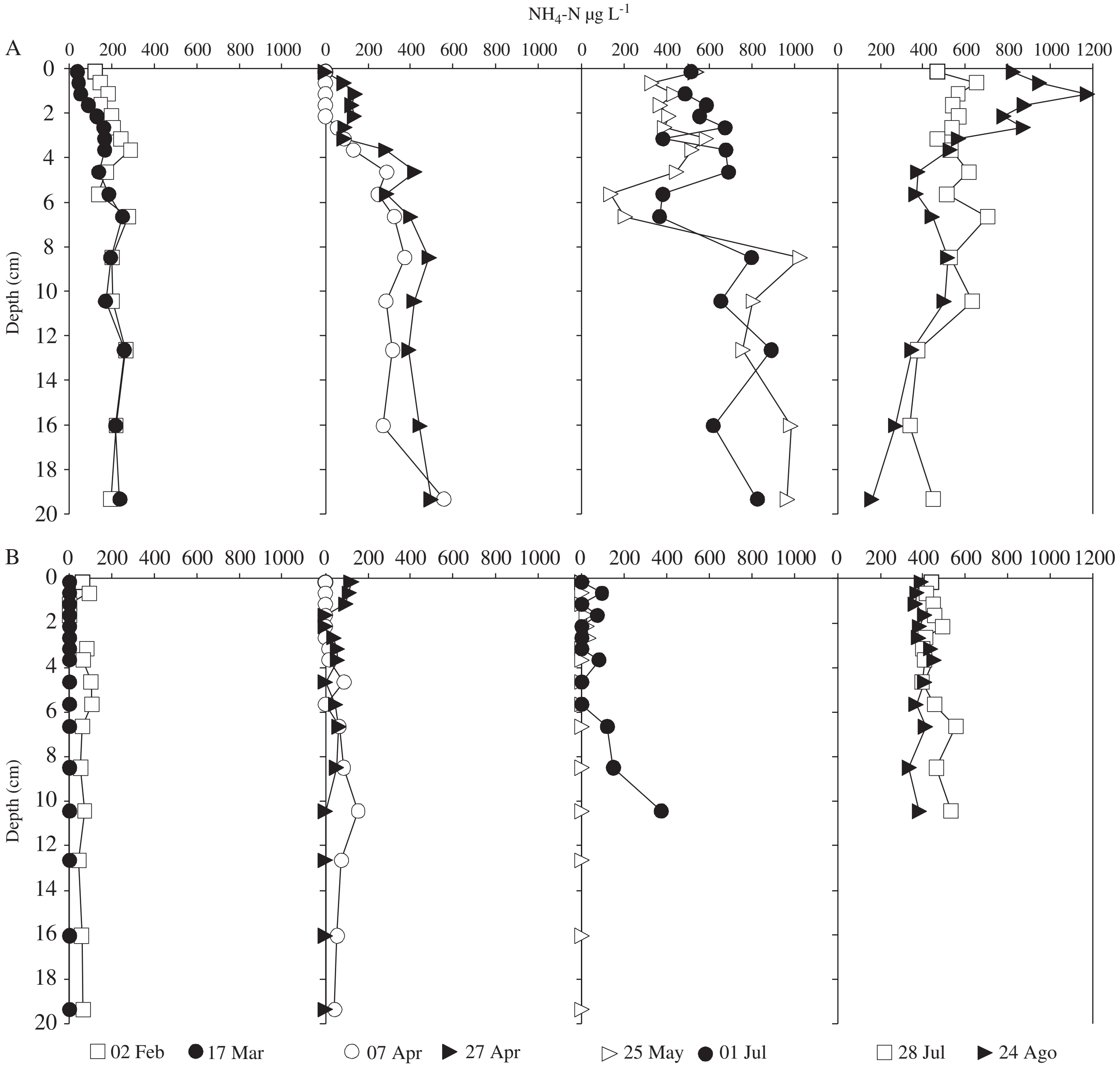

Fig. 6. The concentration of ammonium in the sediment pore water profiles in the first 20 cm of depth during the day, between February 2004 and August 2004, at the depositional zone (A) and the eroding site (B).

daily variation in mean water temperature and dissolved oxygen concentration, with higher oxygen concentrations following the increase in the temperature of the water during the day. This daily variation was sequentially more evident during the transition from lotic to lentic conditions, in which the temperature range was much higher, with oxygen depletion during the night. During winter, the oxygen saturation index was higher and with small inter-quartile variation, whilst, in summer, the oxygen saturation index decreased but showed a much higher inter-quartile variation. Results are in agreement with the principle proposed by Odum (1958) in Guash, Armengol, Martí, and Sabater (1998), in which photosynthesis, respiration and aeration are responsible for the diurnal fluctuations of oxygen in streams. However, on a seasonal scale, there was a highly significant negative linear relationship between the mean water temperature and the dissolved oxygen concentration. At the seasonal level, the higher oxygen concentrations and higher oxygen saturation index correspond to the winter lotic conditions and the lower correspond to the summer lentic conditions. These results suggest a higher contribution of the aeration factor during winter, being gradually replaced by

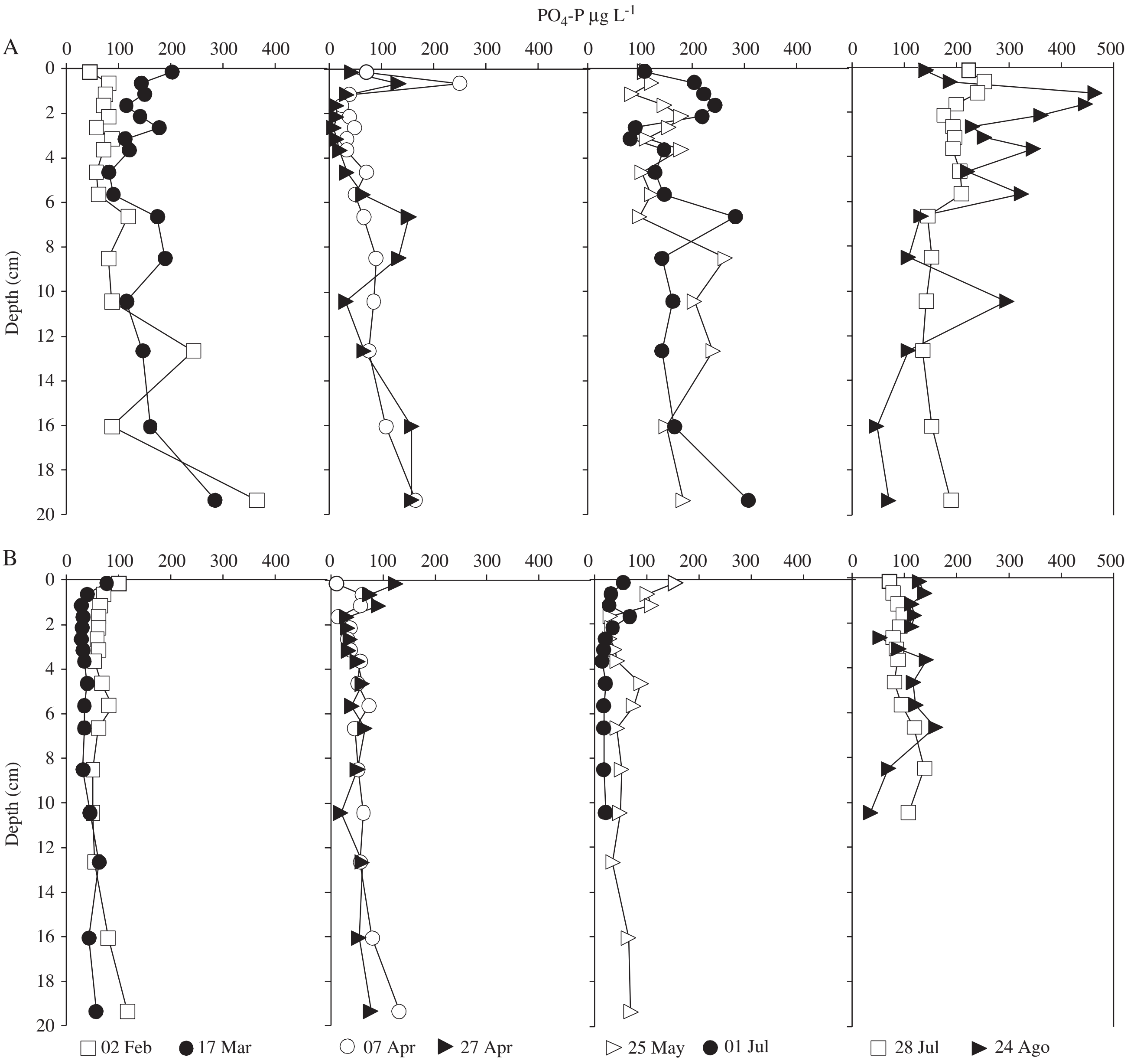

Fig. 7. The concentration of dissolved reactive phosphorus in the sediment pore water profiles in the first 20 cm of depth during the day, between February 2004 and August 2004, at the depositional zone (A) and the eroding site (B).

biological activity in spring. In summer, corresponding to shallow lentic conditions, the higher oxygen concentrations and higher oxygen saturation index during the day, especially between 12.00 and 15.00, were determined by biological activity. Results show that the catchment may supply much of the dissolved nitrogen and phosphorus to temporary streams but, after flow cessation, most of it may also be internally recycled within the temporary pools through biogeochemical processes. Since phosphorus is mostly transported as particulates and nitrogen often is as well (Allen, 1995), mineralisation of nutrients is strongly associated with the streambed process and, at the same time, strongly influenced by the hydrology of the system as it determines more depositional zones or eroding sites. In fact, in the Pardiela system during lotic conditions, February and March, total phosphorus (TP) ranged between 1070 and 250 µg L^{-1} (median 485 µg L^{-1}, $N = 12$) and SRP represented 2%–11% of TP (median 8%, $N = 12$). For the same period, total nitrogen (TN) ranged between 4266 and 428 µg L^{-1} (median 1408 µg L^{-1}, $N = 12$) and DIN represented 19%–91% of TN (median 75%, $N = 12$).

The sediment characterization of the Pardiela stream shows that the depositional sites are composed of a higher percentage of smaller grain size particles and a higher percentage of organic matter content and total carbon, especially in the sediment fraction below 2 mm, meaning that the depositional sites have comparatively higher potential for mineralisation processes as the system changes from lotic to lentic conditions. As the efflux of nutrients is a consequence of the primarily heterotrophic metabolism of the sediments, "benthic-pelagic" processes are more closely coupled under shallow lentic conditions (Capone & Kiene, 1998). After the sedimentation of particles, dissolved phosphate may be released from the sediment particulate organic matter by P-mineralisation and P-desorption, and thereby supply the efflux of phosphate to the water column (Allen, 1995; Lillebø, Neto, Flindt, Marques, & Pardal, 2004). This was observed from the water column data and from the sediment porewater profiles during lentic conditions, in which the temperature range was much higher, undergoing oxygen depletion during the night. Thus, internal P-loading may still persist in a similar manner to that known from shallow lakes (e.g. Andersen & Ring, 1999; Jensen & Andersen, 1992) showing hysteresis (Zhang, Jørgensen, Beklioglu, & Ince, 2003). In addition, the vertical distribution and relative abundance of inorganic nitrogen compounds in the sediment are controlled by the redox state (Valiela, 1995), and ammonification may be enhanced by re-mineralisation of particulate organic matter (Allen, 1995; Kemp, Boynton, Twilley, Stevenson, & Ward, 1984), while the nitrification process is generally limited by low oxygen concentrations, and ammonia may accumulate (Allen, 1995; Henriksen & Kemp, 1988). Thus, under anaerobic conditions, ammonium may diffuse upwards to the overlying water (Valiela, 1995), as observed from the water column data and from the

Table 4. Results from the non-parametric Mann–Whitney expressing the significance of differences (95% confidence level) in sediment PO_4-P and NH_4-N profiles, between day and night concentrations at a depositional zone (A) and an eroding site (B)

Day/night	PO_4-P		NH_4-N	
	A	B	A	B
02 Feb.	*	***	n.s.	***
03 Mar.	n.s.	n.s.	n.s.	n.s.
07 Apr.	***	**	n.s.	**
27 Apr.	**	n.s.	n.s.	n.s.
25 May	n.s.	n.s.	n.s.	***
01 Jul.	n.s.	**	n.s.	n.s.
27 Jul.	**	n.s	**	n.s.
24 Aug.	n.s.	n.s.	n.s.	***

$^*P<0.05$, $^*P<0.01$, $^{***}P<0.001$.

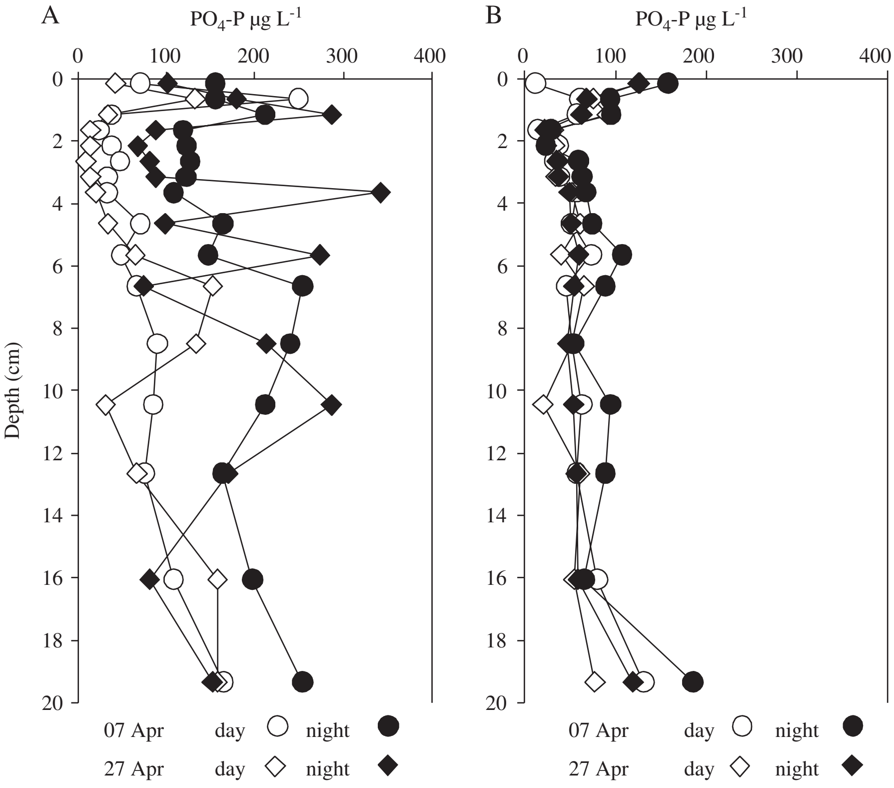

Fig. 8. The concentration of dissolved reactive phosphorus in the sediment pore water profiles in the first 20 cm of depth, in spring 2004, under day and night conditions, at the depositional zone (A) and the eroding site (B).

sediment porewater profiles during lentic conditions. Moreover, during the transition from lotic to lentic conditions, sediment profiles show that the most active sediment layer for dissolved reactive phosphorus is the top 6 cm, while ammonium-nitrogen is more dynamic in the first 2–3 cm.

The organic content of the sediment can express the potential availability of nutrients, since sediment bacteria are capable of the complete oxidation of a broad range of organic compounds (Capone & Kiene, 1998). This may explain the lower phosphorus and nitrogen concentration in the eroding site profiles compared with the higher concentration and more dynamic profiles at the depositional site. Yet, nutrient cycling and transformation occur by both abiotic and biological processes (Allen, 1995; Bridgham, Johnston, Schubauer-Berigan, & Weishampel, 2001). The significant differences between day and night spring profiles (7 and 27 April, at the depositional site, and 7 April at the eroding site), with higher phosphate concentrations during the night, may result from oxygen depletion due to respiration, which during the day may be compensated by autotrophic oxygen production from epibenthic periphyton (Dodds, 2003). In addition, the reduction in phosphate concentration during the day may also result from biological uptake during the photosynthetic active period (Dodds, 2003). Primary producers, microbes and organic matter form the three primary biological *P* pools in wetlands, (Bridgham et al., 2001), explaining the higher *P* dynamics at the depositional site comparative to the eroding site. There were no significant differences between day and night spring profiles of ammonium at the depositional site, probably due to the complexity of factors involved in the nitrogen cycle, especially the central role of bacteria in the transformation from one nitrogen form to another (Allen, 1995). However, micro-algae and filamentous algae may be responsible for the reduction in concentrations of nitrogen and phosphorus in the first centimetres of sediment depth and in the water column during spring. In fact, these primary producers reach the highest biomass in April/May (Morais et al., unpublished data) contributing to the oxygen depletion during the night period, especially observed after the formation of pools. During summer, the algae biomass decreased, contributing also to the organic enrichment of the lentic systems, in a way similar to that suggested for other aquatic systems (e.g. Bridgham et al., 2001).

Results show that, in temporary streams, nutrient dynamics vary seasonally, suggesting that, during the first flow and first flush events following late spring/summer pools, the external source of nutrients into downstream water reservoirs does also include the regeneration of nutrients from organic and inorganic matter during the flow cessation period.

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