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**THE CONTROL OF A SMALL DAM IN NUTRIENT INPUTS TO AN
HYPERTROPHIC ESTUARY**

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Abstract

A two-year study was carried out in the lower part of the Palmones River to describe the role of a small dam controlling the nutrient fluxes to the estuary. Results showed an important spatial heterogeneity in the nutrient content and water properties of lowland catchment outstanding to the dammed water and the effluents of a sewage treatment work. Attending to the values of hydraulic retention time, the dam could be considered as an optimally dimensioned pre-dam. On average, it removed more than 25 % of total phosphorus (TP) and 6 % of total nitrogen (TN), rising values of 55.4 and 79.8 %, respectively during the dry season. Palmones River exported to the estuary 11.3 TonsP y^{-1} of TP and 76.6 TonsN y^{-1} of TN, showing important seasonal differences. From the total amount of nutrient, less than 10 % was exported during low flow conditions, while in three months with important flooding events, the percentage of total nitrogen reached the 64.5 %.

Keywords: eutrophication, municipal sewage, nutrients forms, Palmones River, pre-dam, self depuration

1. Introduction

Over the last few decades there has been an increased interest in quantifying the fluxes of nutrients into estuaries and the environmental effects such nutrients have on water quality (e.g. Nedwell et al., 2002; Tappin, 2002; O'Higgins and Wilson, 2005). Coastal areas in worldwide are submitted to an increase in eutrophication levels, mainly in shallow estuaries. This problem is because of the increase in the nutrient content that

1 has led to a decline in environmental quality. As a result, important changes in the
2 composition of the primary producers are evident, with the replacement of sea grass
3 meadows by the dominance of phytoplankton and fast-growing macroalgae (e.g. Viaroli
4 et al., 1996; Cardoso et al., 2004).

5 Phosphorus is usually considered the limiting nutrient for primary producers in
6 freshwater while nitrogen is mainly considered in marine systems, thus their reduction
7 from river channels is of paramount importance (Rigler, 1979; Neal, 2001). Several
8 studies have shown the application of riparian vegetation and pre-dams as traps, that
9 reduce nutrients and suspended particulate matter (SPM) from the water column (e.g.
10 Paul et al., 1998; McKergow et al., 2003). In both cases, an important increase of the
11 hydraulic retention time (HRT) is produced and as consequence, settling of particles,
12 interactions between sediment and water column and elimination of dissolved nutrients
13 by the primary producers becomes stronger. According to Benndorf and Pütz (1987) if a
14 pre-dam is optimally dimensioned, the removal of SRP can be expected higher than
15 70% and lower values for inorganic nitrogen (Paul, 2003). Furthermore, pre-dams
16 produce important changes in nutrient speciation and nutrient ratios in rivers that as
17 have been demonstrated, affect to primary producers in estuaries and coastal regions
18 (Justic et al., 1995; Hunt et al., 2005).

19 In the inner part of the estuary of Palmones River (southern Spain), there is a small
20 dam that acts as a barrier for the seawater at high tide, allowing only freshwater
21 discharge. The hydraulic changes produced by the dam, increase the HRT and the
22 possibility of nutrient removal from water column. The main sewage treatment works
23 (STW) in the catchment flows into the dammed water, modifying its characteristics and
24 increasing nutrient concentrations (Avilés, 2002).

1 Climatic conditions influence the behaviour of shallow estuaries in the south of
2 Spain, since they are characterised by small catchment areas and a subarid climate. The
3 hydrology of Palmones River is characterised by low flow conditions during most part
4 of the year, with short intense flooding events in winter and spring seasons (Avilés and
5 Niell, 2005). In summer, the river discharges are almost lower than 0.05 m s^{-1} , similar
6 values than the effluent flows by the STW.

7 Since 1980s several studies have been realized in the estuary of Palmones River in
8 order to characterize the nutrient concentration in water column and sediments and the
9 progressive eutrophication increase (Clavero et al., 1992; 2000; Izquierdo, 2001;
10 Palomo et al., 2004). However, no studies relating to the seasonal inputs from the river
11 and the role of the dam have been made.

12 The main objectives of this study are to describe the influence of the dam in the
13 seasonal variation of water properties and nutrient concentrations in the lowland
14 catchment of Palmones River and to quantify its role in the fluxes of phosphorus and
15 nitrogen from the river to the estuary.

17 **2. Study area**

19 **2.1. PALMONES RIVER**

20
21 Palmones River is located in southern Spain, with a drainage area of 302 km^2 and 42 km
22 length. In spite of its small surface, there is an extreme variability in geomorphological,
23 land uses and human pressure. Thus, well conserved environments as the Natural Park
24 of Los Alcornocales contrast with the presence of a reservoir (Charco Redondo) in the
25 upper part of the catchment and an important agricultural and industrial activity in its

1 lower part, modifying the natural hydrological and physico-chemical characteristics of
2 stream water.

3 The annual mean precipitations over the catchment have been ranged from 350 mm
4 to over 1500 mm per year in the last decade. In a similar way that success in other
5 Mediterranean rivers, precipitation events present irregular patterns of distribution,
6 dominated by short pulses of intense precipitation and long drought periods.

7

8 2.2. DAMMED WATER

9

10 In 1955 the dam of Celupal was built in the catchment at 5.5 Km from the mouth, with
11 the purpose to supply freshwater to a cellulose pulp plant. Nowadays, in spite that it is
12 out of function, it still acts as a barrier for seawater at high tide, allowing only
13 freshwater discharge. Upstream the dam, its influence is even higher. With a volume of
14 0.21 Hm^3 , a length of 8.6 km and a mean width of 32 m (Table I), the dammed water
15 presented a dimension enough to be considered as a pre-dam. This zone is characterised
16 by an heterogeneous siliceous and detritic geology, a mean slope of 0.15 % and an
17 intensive agriculture of orange trees and irrigated arable tilled. The main population
18 centre of the catchment is located in its shore with a sewage treatment works (STW)
19 that flows into the dammed water (Figure 1).

20

21 2.3. THE PALMONES ESTUARY

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23 The estuary of Palmones River is a small, shallow and hypertrophic system with small
24 tidal movements (maximal amplitude of 2 m) and a long emersion period (Niell et al.,
25 1989). The grain size composition in this estuary presents a great heterogeneity with

1 sandbanks and important mudflats (Moreno and Niell, 2004). As a consequence of the
2 construction of the reservoir of Charco Redondo and some severe droughts in the in last
3 two decade, an increase of estuary eutrophication has been expected, modifying the
4 nutrient fluxes and the biota composition (Carreira et al., 1995; Clavero et al., 1999).

6 **3. Materials and methods**

8 **3.1. SAMPLE COLLECTION**

9
10 As the study reported in this paper uses the ‘before and after’ approach to investigate
11 the role of the dam of Celupal in the nutrient fluxes to the estuary, samples of water
12 column were collected in 3 sampling sites (Figure 1). Site 1 is located up to the limit of
13 dammed water. This site acts as a control point, allowing to calculate the nutrient input
14 from the upper and middle part of the catchment. Site 2 is placed only a few meters
15 upstream the dam, quantifying the water and nutrient export to the estuary and finally,
16 Site 3 that is located in the inner part of the estuary, just after the dam that allow to
17 know the role of the dam in the water characteristics in the inner part of the estuary.
18 From April 1999 to May 2001, eight samples were collected with a frequency
19 conditioned by river discharge in order to complete monthly results of total nitrogen and
20 phosphorus obtained by the Environmental Agency of the Junta de Andalucía (regional
21 water authority). This paper discusses the results of water properties and nutrient forms
22 obtained, using the governmental data only for the quantification of sewage flows and
23 nutrient inputs from the river to the estuary.

24 Temperature and pH were measured using a multisonde WTW P3 pH/OXI and
25 salinity with a WTW konduktometer LF191. Two litres of water were taken from each

1 sites and placed in ice for transport to the laboratory. For the determination of
2 particulate forms of phosphorus and nitrogen, suspended particulate matter (SPM) and
3 chlorophyll *a* (Chl *a*), subsamples of water were filtered through Whatman GF/F
4 membranes, using the filtered water for the analysis of soluble nutrients, alkalinity and
5 calcium and unfiltered subsamples for the determination of total forms of phosphorus
6 and nitrogen.

7 8 3.2. SAMPLE PROCESING AND ANALYTICAL PROCEDURES

9
10 An exhaustive analysis of phosphorus and nitrogen forms from water column was
11 carried out through this study. Thus, soluble reactive phosphorus (SRP) was determined
12 using the malachite green method (Fernández et al., 1985) in a Technicon Autoanalyzer
13 AAII. From unfiltered water, filtered water and filters, total phosphorus (TP), total
14 soluble phosphorus (TSP) and total particulate phosphorus (TPP) respectively, were
15 analyzed by acid digestion with nitric and perchloric acids (Sommers and Nelson,
16 1972), followed by the determination with the malachite green method. The
17 concentration of soluble unreactive phosphorus (SUP) was obtained by difference
18 between the TSP and SRP according to Rigler (1973). The inorganic nutrients nitrate
19 (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) were analysed using a BRAN & LUEBBE
20 Technicon TRACCS 800. Nitrate and nitrite analysis were performed according the
21 Industrial Method N° 818-87T based in Shinn (1941) and Wood et al, (1967).
22 Ammonium ion was analyzed using the Industrial Method N° 786-86T (Slawyk and
23 MacIsaac, 1972). The term DIN refers to the sum of all soluble inorganic nitrogen
24 species ($\text{NO}_3^- + \text{NO}_2^- + \text{NH}_4^+$). Total particulate nitrogen from filters were obtained
25 with a CHN autoanalyzer Perking Elmer (model 2400 C), while total nitrogen (TN) was

1 determined according to Grasshoff et al. (1983) method. Dissolved organic nitrogen
2 (DON) was obtained by difference between TN and the sum of DIN and TPN.

3 Alkalinity was determined by titration 100 mL of water with 0.01 N HCl down to
4 pH 4.2 (Stumm and Morgan, 1981) and calcium was analyzed by ion chromatography
5 in a Metrohm 732. According to Neal et al. (2002), the saturation index of calcite
6 (SI_{Calcite}) is defined in a logarithmic form as:

$$7 \quad \text{Log}(SI_{\text{calcite}}) = \log_{10}(\{Ca^{2+}\} * \{CO_3^{2-}\}) - \log_{10}(K_{\text{Calcite}})$$

$$8 \quad K_{\text{Calcite}} = 13.534 - (0.040T) - (3000/T)$$

9 where K_{Calcite} is the solubility product of calcite at the temperature of the reaction (Plant
10 and House, 2002) and T is the temperature (°K).

11 For the determination of suspended particulate matter (SPM), filters were dried
12 and later weighed. Phytoplankton chlorophyll *a* was measured spectrophotometrically
13 after extraction with N-N Dimethylformamide (Stricklan and Parson, 1972).

15 3.3. STATISTICAL ANALYSES

16
17 Analysis of covariance between water variables were carried out. Two-way ANOVAs
18 have been used to examine the spatial and seasonal effects on the concentration of
19 nutrients. Multiple *a posteriori* comparisons among means were tested by Tukey test
20 (Sokal and Rohlf, 1995).

22 4. Results and Discussion

24 4.1. WATER CHEMISTRY AND NUTRIENT CONCENTRATIONS

1 A summary of the water quality is presented in Table II. Discharges measured in sites 1
2 and 2 showed a wide variability, with alternation of short flooding events and long low
3 flow periods with discharges lower than $0.05 \text{ m}^3 \text{ s}^{-1}$. During the summer, such low
4 discharges, doses of photosynthetic active radiation (PAR) higher than $14000 \text{ kJ d}^{-1} \text{ m}^{-2}$
5 (Aguilera et al., 2004) and temperatures up to $25 \text{ }^\circ\text{C}$ promoted an elevate phytoplankton
6 growth. The general trend of Chl *a*, with concentrations higher than $10 \text{ } \mu\text{g l}^{-1}$ in sites 2
7 and 3 (reaching almost values of $103.5 \text{ } \mu\text{g l}^{-1}$), is often taken to indicate persistent algal
8 blooms and eutrophic level (Iriate and Purdie, 2004). Stream water is characterised by
9 basic pH with mean values higher than 7.4 and a maximum of 8.8 obtained in Site 2
10 during summer 2000 sample. The seasonal variation of salinity in the inner part of the
11 Palmones Estuary (Site 3) is strongly influenced by the river discharge, showing
12 salinities lower than 0.2 during flooding events and up to 25 during drought periods.
13 The absence of significant differences of suspended particulate matter (SPM) between
14 sampling sites (ANOVA $n = 24$, $P < 0.05$) show that its reduction from the water
15 column was lower than in other pre-dams (Paul et al., 1998). This result is readily
16 explained by the importance of phytoplankton biomass in the SPM content during low
17 flow periods (e.g. in summer 2000, values of 63.4 mg l^{-1} of SPM and $98.2 \text{ } \mu\text{g l}^{-1}$ of Chl
18 *a* were recorded).

19 It is well known that the precipitation of calcium carbonate reduces phosphate
20 pollution in freshwaters because the co-precipitation caused by the interaction between
21 phosphate and the calcite surface during crystal growth (e.g. House and Donaldson,
22 1986; Neal, 2001). For instance, in River Kennet, Neal et al. (2002) showed the high
23 importance of this process in the remove of phosphorus from waters that receive
24 effluents of STW. However, stream waters of Palmones River are in general,
25 undersaturated with respect to calcite by a factor from 4 times to 32 times (-0.62 and -

1 1.51 on a logarithmic scale). The greatest mean undersaturation was detected in the
2 middle part of the catchment (Site 1), while the maximum oversaturation was obtained
3 in the inner part of the estuary (Site 3). Only this last sampling site showed a positive
4 mean $\text{LogSI}_{\text{calcite}}$ value, with a maximum of approximately 800 times that was obtained
5 during summer 1999. Results showed that the effect of calcite precipitation and co-
6 precipitation of phosphate as a self-cleansing phosphate mechanism could only be
7 important in Site 3 and during dry seasons in Site 2, having nearly no importance in the
8 phosphate depletion in the dammed water.

9 In the Table III a summary of the most important phosphorus and nitrogen forms is
10 presented. On average, soluble unreactive phosphorus (SUP) comprised the highest
11 phosphorus form in the study area, with a maximum mean value of 0.24 mgP l^{-1} in Site
12 2, while soluble reactive phosphorus (SRP) and total particulate phosphorus (TPP)
13 presented lower concentrations with very similar values. Table IV corroborates this
14 statement, showing high significant correlations between TP and SUP. In unperturbed
15 systems, SUP proceeds from exudation of organic compounds by the cellular
16 metabolism and lysis (Christman and Minear, 1971). Other explanation for these high
17 values could be found in the scarce importance of this form by the phytoplankton
18 growth due to the need for phosphatase activity. Thus, Hernández et al. (2000) showed
19 that in Palmones River, alkaline phosphatase is only used actively as a phosphate source
20 by bacteria and phytoplankton in the estuary. From the nitrogen forms presented in table
21 III, nitrate and DON were the most abundant in Site 1, while in sites 2 and 3 were
22 nitrate and ammonium forms.

23 The STW of Los Barrios flows $1.84 \text{ Hm}^3 \text{ y}^{-1}$ (Table V) from a population of
24 approximately 15000 people. With mean concentration of 3.5 mgP l^{-1} of TP and 23.6
25 mgN l^{-1} of TN, it is easy to assume the great importance of STW in the nutrient content

1 downstream. The application of *a posteriori* Tukey test ($p < 0.05$) showed significant
2 differences between Site 1 and sites 2 and 3, probing the effect of STW effluents in the
3 increase of nutrient concentrations (mainly SUP and ammonium – Avilés, 2002). Only
4 nitrate did not show significant spatial differences due to its low concentration on STW
5 in comparison with the diffuse inputs from the agriculture. These spatial variations
6 emphasised that it is difficult to characterise the behaviour of a river with a single
7 monitoring point. Nutrients showed significant seasonal changes (ANOVA $n = 24$, $P <$
8 0.05) that were not correlated with the river discharges (Table IV). Seasonal distribution
9 of SRP, nitrate and ammonium in Site 2 (figure 2) confirm this statement. Thus, while
10 minimum values were obtained during low flow, maximums did not coincide with high
11 discharges.

12 Average concentrations of nitrate and phosphate in the sampling sites were higher
13 than average world river values obtained by Meybeck (1982), including Site 1 that is no
14 affected by STW effluents. Attending to the eutrophication index proposed by Carlson
15 (1977), the trophic states on sampling sites are usually eutrophic. In an attempt to
16 evaluate the control of nutrient over primary producers growth, lineal correlations
17 between nutrient content (SRP, NO_3^- and NH_4^+) and Chl *a* were made (Table IV).
18 Results indicated that nutrients did not correlate with phytoplankton biomass variability.
19 According to Justic et al. (1995) in base to requirements of diatoms, there is a
20 phosphorus limitation if DIN-SRP ratio is higher than 22 and nitrogen limitation if DIN-
21 SRP ratio is lower than 10. Data of mean DIN-SRP ratios (Table III) show values
22 higher than 22, so probably P-limited. However, during the summer, results obtained in
23 sites 2 and 3 presented the nitrogen as the limiting nutrient, with values of 1 and 2,
24 respectively. The C-N ratio showed maximum values two times higher than the relation
25 proposed by Redfield et al. (1963) for planktonic composition (14.7 in Site 1),

1 indicating the detritic origin of SPM. Interestingly, is the decrease of C-N ratio from
2 Site 1 to Site 3, in a clear relation with the increase of phytoplankton biomass.

3 4 4.2. THE ROLE OF THE DAM IN THE NUTRIENT REMOVE

5
6 The purpose of pre-dams located immediately up-stream of reservoirs or other water
7 mass (e.g. an estuary) is to improve the quality of the inflowing water by reduction of
8 the loads of suspended particulate matter and dissolved nutrients (Paul, 2003). Benndorf
9 and Pütz (1987) developed a procedure to predict the SRP elimination in pre-dams,
10 which can be expected higher than 70 % if the relative retention time $t_{rel} > 1 \text{ d}^{-1}$. t_{rel} is the
11 coefficient between the theoretical retention time t_{theor} in the “reaction space” and the
12 critical retention time (t_{crit}) that is function of temperature, underwater light intensity
13 and SRP concentration. Results of t_{rel} in the dammed water showed a markedly seasonal
14 variability ranged from 0.1 d^{-1} in winter 2001 to more than 30 d^{-1} in summer 1999. t_{rel}
15 were lower than one only during the scarce flooding events, so it could be concluded
16 that in spite of the different purpose of the built up of the dam, it could be considered as
17 an optimally dimensioned pre-dam attending to its potential on SRP remove.

18 A summary of annual phosphorus and nitrogen loads in Site 1, Site 2 and STW
19 effluent is given in table V. From Site 1 to Site 2, TP and TN loads changed from 9.6 to
20 $11.3 \text{ TonsP y}^{-1}$ and from 27.8 to $76.6 \text{ TonsN y}^{-1}$, respectively. With an increase of 1.7
21 TonsP y^{-1} of TP and $48.8 \text{ TonsN y}^{-1}$ of TN, it is evident the effect of the sewage
22 effluents increasing the nutrient fluxes to the estuary.

23 The HRT values obtained in this study ranged between one hour and more than
24 10000 hours (Table I). This extremely high seasonal variability produces important
25 differences in the relative percentage of phosphorus and nitrogen forms in Site 2 (Figure

1 3). While SUP with 79 % and TPN with 78 % were the dominant phosphorus and
2 nitrogen forms in summer; during flooding events were TPP the most abundant form of
3 phosphorus (65 %) and nitrate the dominant form of nitrogen (49 %). HRT is also the
4 main factor controlling the Chl *a* concentration, as probe the high correlation obtained
5 between the HRT and the concentration of Chl *a* (Table IV), in agree with the results
6 showed by Kawara et al. (1998) in the Asahi River Dam reservoir. The high
7 concentration of Chl *a* obtained in this sampling point during the summer (Table II)
8 illustrate SRP elimination does mainly result from the biological transformation of
9 dissolved to particulate phosphorus by the phytoplankton. However, total phosphorus
10 elimination can almost completely be explained by the SRP removal. Thus, the high
11 percentage of SUP obtained at the same time that maximum concentration of Chl *a*.

12 Paul (2003) stated that the nitrate reduction obtained during the summer in pre-dams
13 of Saldenbach reservoir (southeast Germany) were mainly due to the microbial
14 denitrification at the sediment more than the phytoplankton growth. This seems not to
15 be the case in this study due to the great dominance of particulate nitrogen and the low
16 percentages of nitrate and ammonium obtained in Site 2 that probe the importance of
17 phytoplankton in the DIN remove.

18 During high flows, SPM and particulate nutrients that were storage during low flow
19 periods are re-suspended and flow to the estuary. In agreement with Avilés and Niell
20 (2005) that showed how flooding events control the sediment phosphorus content in the
21 estuary of Palmones River, the percentage of TPP increased from 18 % in summer to 65
22 % during flooding events, as a consequence of scouring processes. However, nitrogen
23 showed a different trend with nitrate as the dominant form during events (49 %),
24 although in a less percentage than in Site 1 (66 %).

1 Table VI shows the nutrient remove produced by the dam by a balance between the
2 outputs (Site 2) and the inputs (Site 1 and STW).The annual remove of TP was higher
3 than 25 %, while for TN hardly reach 6 % (Table VIa). Attending to the seasonal
4 variability, the average percentage of TP and TN loads removed from June to
5 September were 55.4 and 79.8 %, respectively; while from February to May only a
6 remove of 1.8 % of phosphorus has been estimated and also an increase of 41.2 % of
7 nitrogen (Table VIb). Paul (2003) obtained that TP elimination did not much outreach
8 25 % even in the largest pre-dams in summer, showing the great efficiency of the
9 studied dam in the nutrient elimination from water column.

10 11 4.3. NUTRIENT EXPORT TO THE ESTUARY

12
13 Worldwide, the nutrient enrichment of shallow estuaries has led to a decline in
14 environmental quality, replacing benthic macrophytes by fast-growing opportunistic
15 algae and affecting their natural function as nurseries for several fish, crustaceans and
16 mollusc species. Estuarine processes are therefore of great interest both from ecological,
17 geochemical, economic and recreational point of view (Zwolsman, 1994).

18 The annual river loads of TP and TN from Palmones River to the estuary during the
19 study period were 11.3 TonsP y^{-1} and 76.6 TonsN y^{-1} , respectively. In spite of these
20 results were lower than those obtained by Nedwell et al. (2002) in rivers with similar
21 catchment areas, their effects over this shallow estuary are evident. Thus, the increase of
22 nutrient concentration in the estuary of Palmones River has led benthic red algae
23 (*Gracilaria bursa-pastoris*) and polichaetes (*Hedistis diversicolor*) disappeared
24 (Carreira et al., 1995) and the drastically reduction in the capture of species with
25 commercial interest as shellfish *Venerupis decussata* (Briones, pers. comm.).

1 The small surface of the Palmones catchment and the unpredictable precipitation
2 regime are responsible for the great variation on freshwater discharge (Avilés, 2002). In
3 order to establish the seasonal variability of nutrient loads from the Palmones River to
4 the estuary, a comparison between low flow (summer) and high flow conditions
5 (January to March 2001) was made in Table VII. In spite of the summer period account
6 for 33 % of total sampling time (from June to September), TP and TN loads were lower
7 than 8 and 5 % of total loads, respectively. In the other hand, in only three months (11
8 % of total sampling time) the loads of TP and TN correspond to 23.6 and 64.5 % of
9 total loads, respectively. Results show the importance of the dam in the control of
10 estuarine eutrophication. Thus, during the summer, when the nutrient needs for primary
11 production is highest, the scarce nutrient loads from the river reduce the appearance and
12 develop of blooms of *Gyrodinium* sp. (Mercado, pers. comm.). While during flooding
13 events, there is a scouring of nutrients that were storage in the dammed water during the
14 low flow periods and in the estuarine sediment, exporting these nutrients out of the
15 estuary to the Algeciras Bay (Avilés and Niell 2005).

16

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18

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1 **Figure legends**

2 Figure 1. Map of the Palmones River showing the location of sampling points.

3 Figure 2. Seasonal distributions of soluble reactive phosphorus, nitrate, ammonium and
4 river discharge in Site 2.

5 Figure 3. Average relative percentage of phosphorus and nitrogen forms in Site 2. Low
6 flow periods (a) and flooding events (b).

1 Table I. Some physiographical characteristics of dammed water

2

3

Mean slope (%)	0.15
Longitudinal extent (km)	8.6
Mean width (m)	32
Mean depth (m)	0.75
Dammed volume (Hm ³)	0.21
River flow (m ³ s ⁻¹)	0.0 - 57.8
Hydraulic retention time (h)	1 - >1000

4

5

Table II. Water quality summaries for sampling sites

		Discharge (m ³ s ⁻¹)	T ^a (°C)	pH	Salinity	logSI _{calcite}	SPM (mg l ⁻¹)	Chl <i>a</i> (µg l ⁻¹)
Site 1	Mean	1.2	17.1	7.41	0.13	-1.10	20.0	2.3
	Max	6.0	24.9	7.95	0.19	-0.62	45.3	11.0
	Min	0.0	11.5	6.80	0.08	-1.51	6.8	0.0
Site 2	Mean	1.6	19.6	7.67	0.14	-0.62	38.1	41.3
	Max	7.1	27.1	8.80	0.23	0.65	97.3	103.5
	Min	0.0	13.4	7.25	0.03	-1.18	5.5	0.5
Site 3	Mean		20.6	7.63	7.43	0.81	44.8	32.4
	Max		30.6	8.52	25.49	2.90	64.6	85.9
	Min		13.2	6.95	0.14	-0.65	16.4	0.0

Table III. Nutrient concentrations in water column

		SRP	SUP	TPP	NO ₃ ⁻	NO ₂ ⁻	NH ₄ ⁺	DON	TPN	C/N	DIN/SRP
		(mgP l ⁻¹)	(mgP l ⁻¹)	(mgP l ⁻¹)	(mgN l ⁻¹)	(mgN l ⁻¹)	(mgN l ⁻¹)	(mgN l ⁻¹)	(mgN l ⁻¹)	ratio	ratio
Site 1	Mean	0.03	0.04	0.03	1.09	0.02	0.07	0.85	0.23	10.6	67
	Max	0.13	0.10	0.08	2.01	0.05	0.18	1.33	0.84	14.7	158
	Min	0.00	0.01	0.01	0.10	0.01	0.00	0.69	0.10	7.5	4
Site 2	Mean	0.11	0.24	0.11	0.95	0.12	1.24	0.38	0.63	8.5	34
	Max	0.39	1.05	0.23	2.20	0.28	2.26	0.60	2.02	9.9	96
	Min	0.01	0.01	0.02	0.02	0.00	0.00	0.06	0.21	5.6	1
Site 3	Mean	0.14	0.18	0.10	0.81	0.21	0.86	0.63	0.64	7.5	30
	Max	0.24	0.79	0.16	2.06	0.46	2.11	0.77	1.68	10.2	132
	Min	0.01	0.01	0.07	0.02	0.00	0.10	0.39	0.19	5.6	2

Table IV. Correlation coefficients between water variables in the study area (n = 24; n = 16 for discharge and n = 8 for HRT)

	Disch.	T ^a	SPM	Chl <i>a</i>	HRT	SRP	SUP	TPP	TP	NO ₃ ⁻	NO ₂ ⁻	NH ₄ ⁺	DON	TPN	TN	
Disch.	1															
T ^a	-0.57*	1														
SPM	0.63**	0.21	1													
Chl <i>a</i>	-0.54	0.51	0.13	1												
HRT	-0.56	0.88**	-0.04	0.93**	1											
SRP	0.15	-0.05	-0.21	0.09	-0.28	1										
SUP	-0.19	0.43*	0.09	0.46*	0.75*	0.16	1									
TPP	0.08	0.48*	0.53*	0.69**	0.70*	0.17	0.74**	1								
TP	-0.09	0.40	0.10	0.50*	0.71*	0.45*	0.95**	0.79**	1							
NO ₃ ⁻	0.06	-0.54*	-0.11	-0.27	-0.13	0.01	-0.45*	-0.35	-0.41	1						
NO ₂ ⁻	-0.04	-0.29	0.00	-0.10	-0.52	0.30	-0.14	0.04	-0.01	0.27	1					
NH ₄ ⁺	-0.06	-0.12	-0.11	0.23	-0.44	0.49*	-0.06	0.26	0.14	0.05	0.52*	1				
DON	-0.15	-0.43*	-0.31	-0.26	-0.03	-0.16	-0.35	-0.53**	-0.40	0.53**	0.07	-0.17	1			
TPN	-0.12	0.61**	0.39	0.65**	0.79*	0.04	0.85**	0.88**	0.82**	-0.50*	-0.21	-0.09	-0.43*	1		
TN	-0.09	-0.28	-0.06	0.22	-0.04	0.38	-0.04	0.24	0.13	0.57**	0.59**	0.75**	0.25	-0.06	1	

* P<0.05, ** P<0.01

Table V. Annual nutrient loads in Site 1, Site 2 and STW

Mean annual load in Site 1		Mean annual load in Site 2	
TP (TonsP y ⁻¹)	9.6	TP (TonsP y ⁻¹)	11.3
TN (TonsN y ⁻¹)	27.8	TN (TonsN y ⁻¹)	76.6

Mean annual STW load	
Flow (Hm ³ y ⁻¹)	1.84
TP (TonsP y ⁻¹)	5.5
TN (TonsN y ⁻¹)	44.1

Table VI. (a) Annual percentage of total phosphorus and nitrogen removed by the dam and (b) seasonal variability of the removed percentage through the study period

(a)

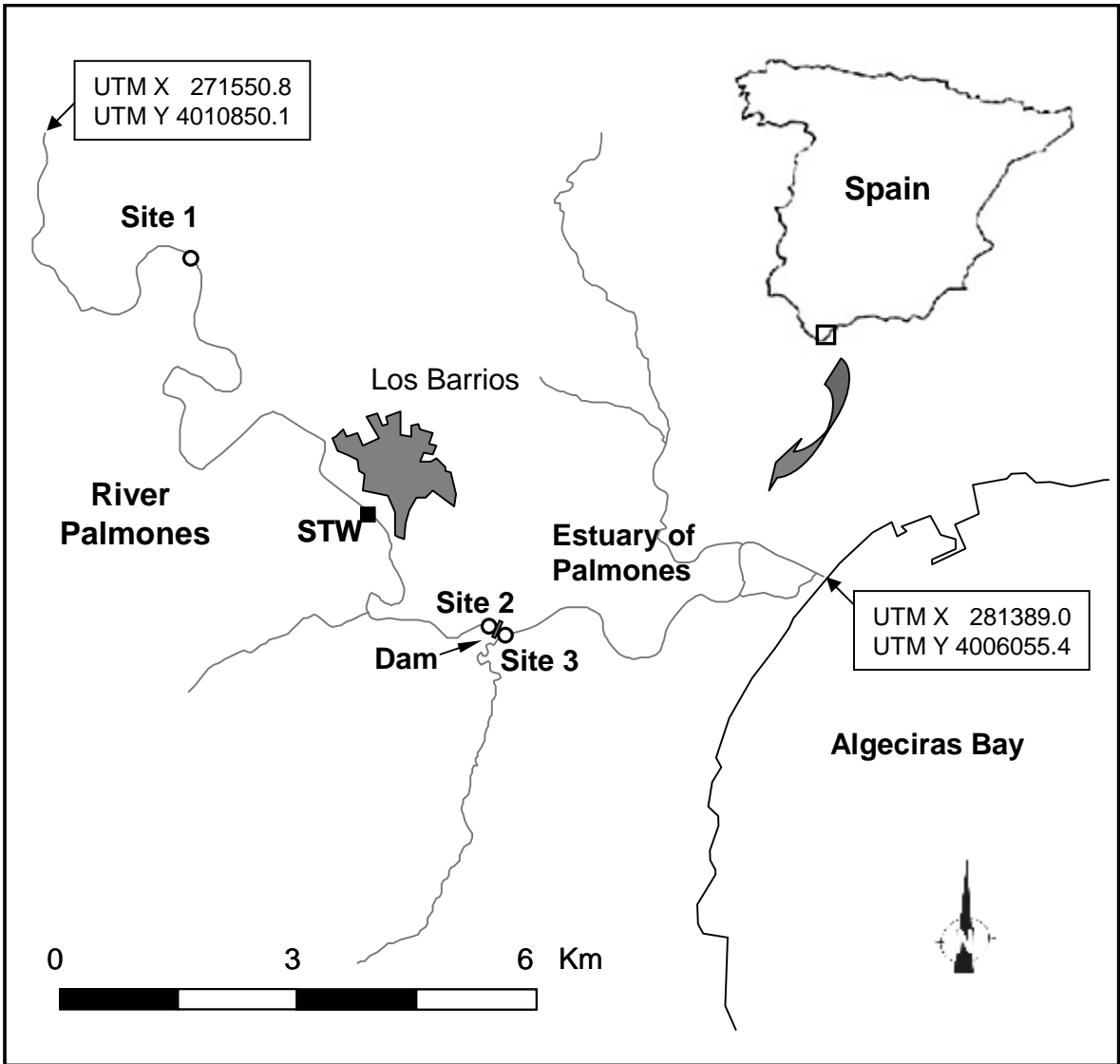
	Inputs	Outputs	Removed
	Site 1+ STW	Site 2	%
TP (TonsP y-1)	15.1	11.3	25.2
TN (TonsN y-1)	71.9	76.6	6.1

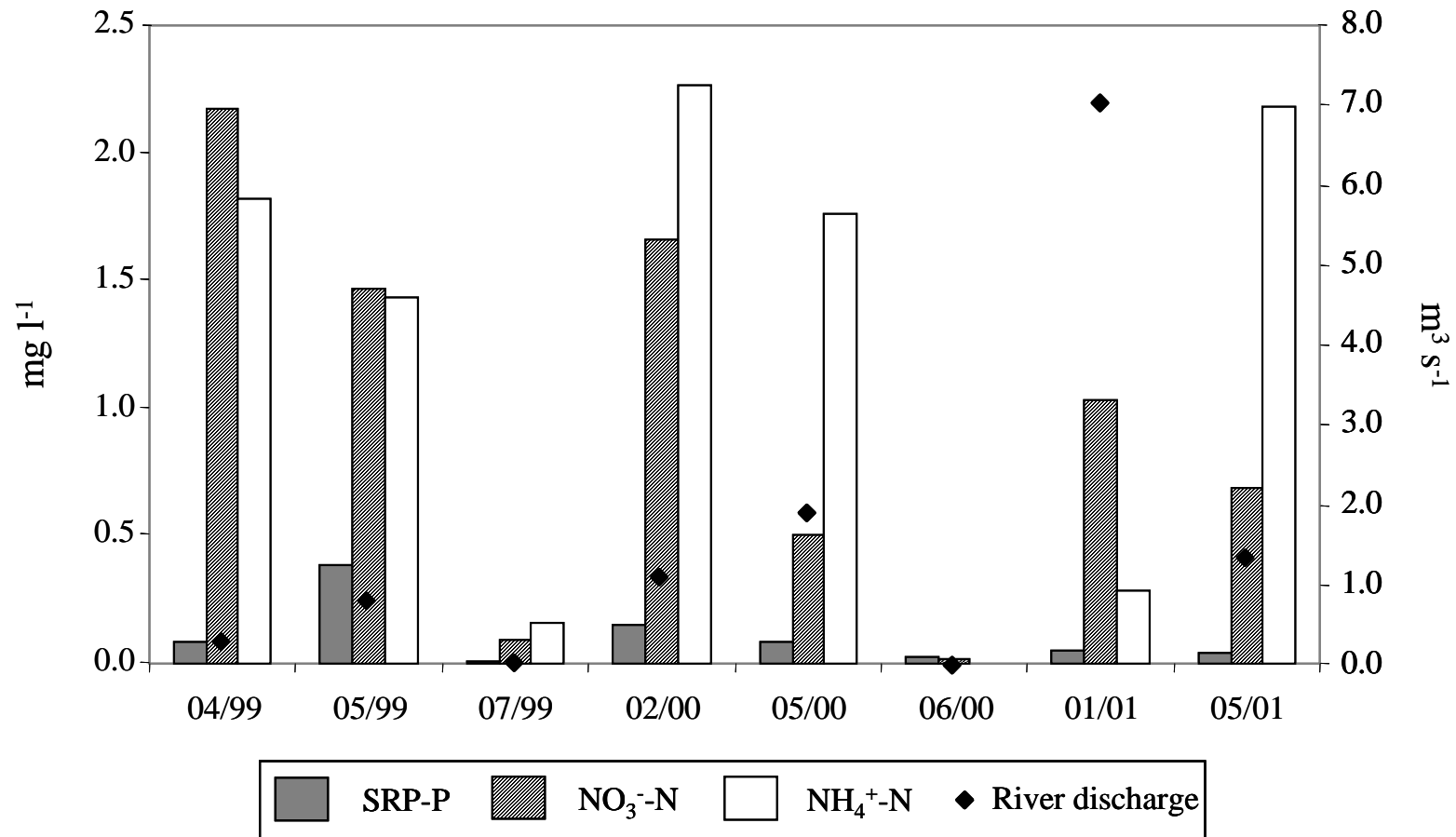
(b)

	June-Sept	Oct-Jan	Febr-May
TP (%)	55.4	44.0	1.8
TN (%)	79.8	-18.0	-41.2

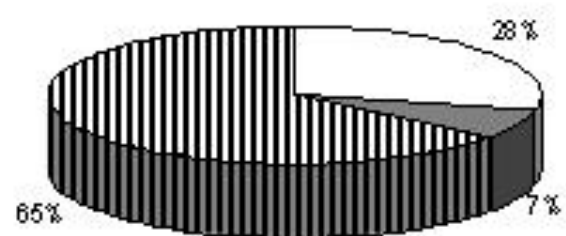
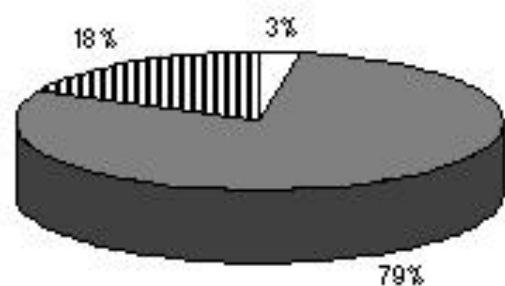
Table VII. Total load and percentage of total load in Site 2 during low flow and high flow conditions

Site 2	Total	Low flow	High flow
	Tons	%	%
TP	26.3	7.7	23.6
TN	168.7	4.4	64.5



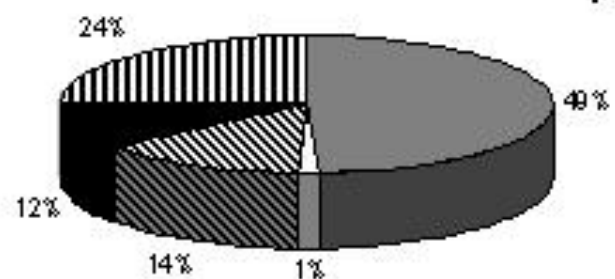
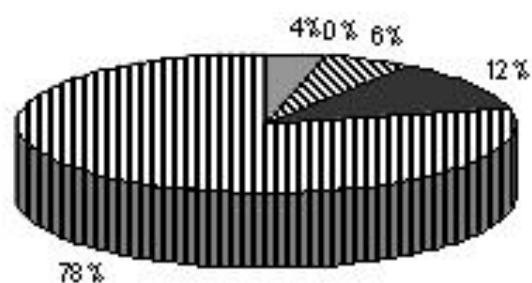


Phosphorus



□ SRP ■ SUP ▨ TPP

Nitrogen



■ NO₃⁻ □ NO₂⁻ ▨ NH₄⁺
 ■ DON ▨ TPN

