Catchment Phosphorous Losses: An Export Coefficient Modelling Approach with Scenario Analysis for Water Management

Nuno-Gonçalo Matias · Penny J. Johnes

Abstract This paper presents the development of an export coefficient model to characterise the rates and sources of P export from land to water in four reservoir systems located in a semi-arid rural region in southern of Portugal. The model was developed to enable effective management of these important water resource systems under the EU Water Framework Directive. This is the first time such an approach has been fully adapted for the semi-arid systems typical of Mediterranean Europe. The sources of P loading delivered to each reservoir from its catchment were determined and scenario analysis was undertaken to predict the likely impact of catchment management strategies on the scale of rate of P loading delivered to each water body from its catchment. The results indicate the importance of farming and sewage treatment works/collective septic tanks discharges as the main contributors to the total diffuse and point source P loading delivered to the reservoirs, respectively. A reduction in the total P loading for all study areas would require control of farming practices and more efficient removal of P from human wastes prior to discharge to surface waters. The scenario analysis indicates a strategy based solely on reducing the agricultural P surplus may result in only a slow improvement in water quality, which would be unlikely to support the generation of good ecological status in reservoirs. The model application indicates that a reduction of P-inputs to the reservoirs should first focus on reducing P loading from sewage effluent discharges through the introduction of tertiary treatment (P-stripping) in all major residential areas. The fully calibrated export coefficient modelling approach transferred well to semi-arid regions, with the only significant limitation being the availability of suitable input data to drive the model. Further studies using this approach in semi-arid catchments are now needed to increase the knowledge of nutrient export behaviours in semi-arid regions.

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1 Introduction

The European Union Water Framework Directive (WFD 2000/60/EC) requires assessment of the anthropogenic impacts on water bodies to identify those water bodies at risk of failing to meet the environmental objectives of good and non-deteriorating status by the year 2015. However, the definition of good ecological status will need to be water body specific, the environmental conditions required to meet these standards will vary between water bodies and regions, and the management of anthropogenic impacts will also be, necessarily, catchment specific (Johnes et al. 2007).

In Portugal, lakes are uncommon and reservoirs are the most important lentic water bodies, providing a significant amount of water for irrigation, domestic supply, energy generation, fishing and recreational purposes (Matias et al. 2008). Eutrophication has been recognized as a serious water quality problem, particularly in the southern reservoirs in Alentejo Region because of the semi-arid climate, catchment land use (Matias and Boavida, 2005) and long residence times (Diogo et al. 2008).

Since Portuguese reservoirs have been impacted by nutrients exported from both point and diffuse agricultural sources, any management option must take into account not only the components of the reservoir, but also the human activities contributing to this export from the catchment (Cabecinha et al. 2009a). Identification of the main source of nutrient export is therefore necessary to identify the specific spatial origins and transport mechanisms, and determine the most effective measures to improve water quality (Salvia-Castellví et al. 2005).

Water quality modelling provides a range of approaches to support effective water resource management. One approach has been to develop physically-based models for assessing water quality in catchments (Lunn et al. 1996; Skop and Sorensen 1998, Styczen and Storm 1993; Cao et al. 2009). In Portugal, several studies have used these models (Cabecinha et al. 2009a, b; Diogo et al. 2008; Nunes et al. 2007) to assess water quality issues at catchment scale, but in some cases the results suggested that a better estimation of nutrient loads is required (Diogo et al. 2008). Also, as decision tools for planners and managers, the use of these models is often limited by the difficulty of satisfying high input data requirements (Lepistö et al. 2006), dependency on the availability of site-specific parameters, and model parameters require additional effort and expense to measure.

To make a model useful in water management it is therefore crucial that it can be applied despite limited availability of data, at the same time as it produces results that are acceptable in relation to observed conditions (Olsson and Andersson 2007). The Export Coefficient Model (ECM) has been recognized as reliable for modelling nutrient pollution in a wide range of studies (European Commission 2002; Ierodiaconou et al. 2005) since is simple and logical and the limited input requirements make the approach useful for catchment assessments and management (Johnes 1996; Johnes and Butterfield 2002). The ECM has been used successfully in several countries to predict catchment scale nutrient loading (Bowes et al. 2008; Johnes 1996; Salvia-Castellví et al. 2005; Soranno et al. 1996). Although the ECM does not directly simulate complex processes involved in diffuse source pollution and requires less data input, it has acceptable precision, especially suitable for areas where few observed data are available, and can meet the needs of long-term nutrient source pollution load simulation (Johnes 1999).

So, the relatively low input requirement makes ECM ideal for rural catchments in Portugal where routine water quality monitoring data is very often limited. In Portugal, the ECM approach has been applied uncalibrated in two earlier studies concerning reservoir ecosystems (Geraldes and Boavida 2003; Matias and Boavida 2005). However, since the developed models were not calibrated or validated to the local environmental controls on nutrient export behaviour, they could not give a correct estimation of potential catchment sources of nutrients. While nutrient sources, transport pathways and annual dynamics are well documented in temperate catchments (Johnes et al. 2007), studies relating catchment controls on nutrient export in semi-arid rural catchments are limited (Alvarez-Cobelas et al. 2010).

Here, the ECM approach has been developed to fit to local environmental controls on nutrient export in semi-arid regions, to allow examination of the specific origins of current nutrient loading on four Portuguese reservoirs, and the likely impact of a range of catchment management measures on nutrient export rates in each catchment.

2 Study Areas

The study areas are located in the Sado River basin in the Alentejo Region, the largest province of inland Portugal, situated in the south of the country (Fig. 1a). Most of the area is composed of low-sloped plains with a semi-arid climate. The region is affected by intense hot and dry periods without precipitation with almost 80% of the precipitation occurring between October and April. As a result the region has a strong temporal and spatial variability in its hydrological regime during the year (Matias and Boavida 2005). Such climatic variations become as important as anthropogenic activities in the catchment as an influence on intra-annual water quality variation. Water pollution from sewage treatment works (STW) and farming activities, water level fluctuations because of climatic conditions and perennial water abstraction for irrigation, and inadequate control and monitoring activities regarding STW and water quality (INAG 2009) all enhance temporal variation in the chemical quality of the water in these regions.

2.1 Reservoir Ecosystems

The four reservoir ecosystems comprise one of the five *homogeneous planning units* of Sado River basin (Fig. 1b) defined in the respective River Basin Management Plan (INAG 2002). Each unit is a sub-area of the Sado River Basin with quasi-homogeneous hydro-climatic, socio-economic, and nature conservation features for water resource planning and management purposes. The main characteristics of the four studied reservoir ecosystems are presented in Table 1. The lake shore of all four reservoirs is devoid of vegetation, and there are no macrophytes in the littoral zone of any lake.

Alvito Reservoir, besides the primary uses, works as a water level regulator of the downstream Odivelas Reservoir, and is a delivery point (from Alqueva Reservoir) to irrigation channels connected to more southern reservoirs (such as Odivelas, Roxo and Monte da Rocha reservoirs, among others) included in the multipurpose Alqueva project (this project comprises strategic water storage, hydropower production, irrigation, recreation and urban water supply, involving 19 municipalities in the Alentejo region), which will be fully implemented by the year 2015.

The climate for the region shows a typical Mediterranean pattern with a 4–5 month period of water stress from late spring to the end of summer. Mean annual rainfall (1990–2009, $N=20$; INAG 2010) was: Alvito, 564.3 mm; Odivelas, 514.8 mm; Roxo, 413.4; and Monte da Rocha, 480.0 mm. In terms of geology, metamorphic Palaeozoic formations
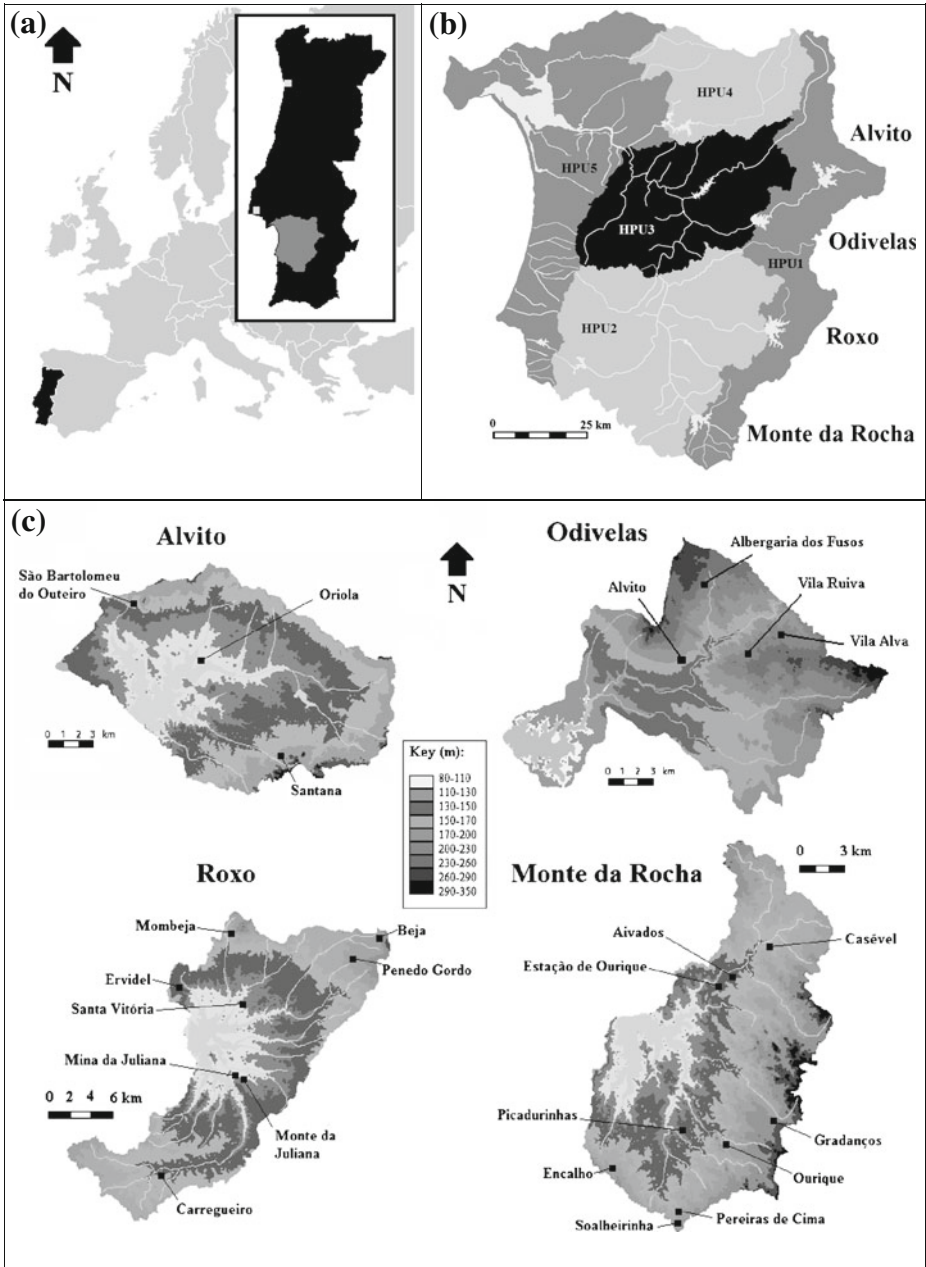
Fig. 1 Location of (a) Sado River Basin (grey area; Sado River total length = 180 km; basin area = 7692 km^2), (b) comprising *Homogeneous Planning Units* (HPU 1–5) and studied reservoirs, and (c) topographic maps of each reservoir ecosystem (black dots represent local villages)

dominate; this polygenic erosion surface cuts through very different lithologies: clay schists, grauwacke, diorites and gabbros, granites, and quartzites, among others (INAG 2002). Metamorphic formations, dominated by schists, have low susceptibility to chemical

Table 1 Main characteristics of the reservoir ecosystems (Source: INAG 2010)

| Characteristic	Reservoir ecosystem name			
	Alvito	Odivelas	Roxo	Monte da Rocha
Starting year	1965	1972	1967	1972
Exploited by	National Water Institute	Odivelas Farmers' Association	Roxo Farmers' Association	Campilhas and Alto Sado Farmers' Association
Primary uses	Irrigation and water supply	Irrigation	Irrigation and water supply	Irrigation and water supply
Main inflow [a]	Odivelas stream (23.1/0.7)	Odivelas stream (33.2/0.6)	Roxo stream (33.3/0.3)	Sado river (25.1/0.4)
Reservoir maximum capacity (× 10^6 m^3)	132.5	96.0	96.3	102.7
Mean reservoir volume (× 10^6 m^3) [b]	91.9 (69.4)	59.1 (61.6)	44.2 (45.9)	56.1 (54.6)
Reservoir area (ha) [c]	1480.0	973.0	1378.0	1100.0
$Z_{maximum}/Z_{mean}$ (m)	44.0/9.1	48.0/11.0	34.0/6.8	51.0/10.0
Water-retention time (years)	3.3	1.2	1.8	2.4
Catchment area (ha) [d]	21089	22124	35110	24494
Catchment altitude range (m)	169–396	85–333	109–268	119–268
Ratio Reservoir area: Catchment area [e]	1:14 (1:31; 1:17)	1:23 (1:29; :1:31)	1:25 (1:51; 1:51)	1:22 (1:46; 1:46)
Annual mean runoff (× 10^6 m^3)	40.0	80.8	53.3	43.3

[a] Figures between brackets refer to main inflow length (km) and mean slope (%) within each catchment, respectively

[b] Figures were calculated based on reservoirs' monthly stored water volume between 1990–2009 ($N=240$); and figures between brackets refer to the respective percent of reservoir maximum capacity

[c] Figures refer to reservoir area at maximum volume

[d] Figures include reservoir area and refer to 2007 land use data

[e] Figures refer to reservoir area at maximum volume; and figures between brackets refer to 1990 and 2007 land use data, respectively
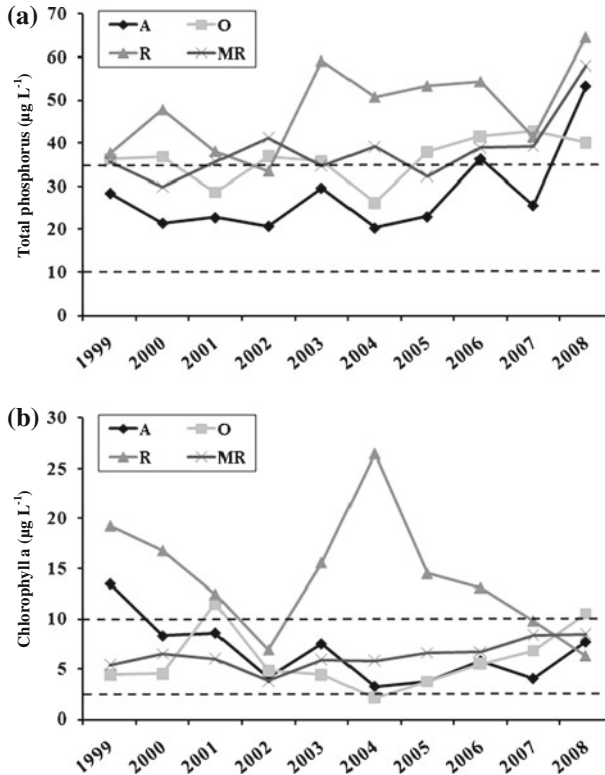
Fig. 2 Annual variation of reservoir total phosphorus (**a**) and chlorophyll a (**b**) concentrations between 1999 and 2008 (all figures refer to geometric means) at the four study areas: A, Alvito; O, Odivelas; R, Roxo; MR, Monte da Rocha. Horizontal lines refer to trophic state classification boundaries: $TP<10.0$ μg L^{-1}= oligotrophic, 10 μg $L^{-1}<TP<35$ μg L^{-1}=mesotrophic, $TP>35$ μg L^{-1}=Eutrophic; $CHLa<2.5$ μg L^{-1}= oligotrophic, 2.5 μg $L^{-1}<CHLa<10.0$ μg L^{-1}=mesotrophic, $CHLa>10.0$ μg L^{-1}=eutrophic (INAG 2010)

weathering, but favour superficial run-off action because of their relative impermeability (INAG 2002). This geological setting, together with the regional weather patterns, is the cause of extreme runoff regime typical in these systems (Nunes et al. 2007), with mean annual runoff dominated by extreme events associated with intense rainfall episodes, predominantly in the winter.

Long term water quality data for the region are limited, but for those available for the period 1999–2008 are presented in Fig. 2 (INAG 2010). These show no clear trend of water quality improvement in recent years on the basis of total phosphorus and chlorophyll a concentrations and suggest that P loading is sustaining continued algal abundance in each of the four reservoirs.

3 Material and Methods

3.1 Data Sources

The ECM application to the study sites followed the modelling structure outlined by Johnes et al. (2007). Land use data (1990 and 2006) were obtained from the CORINE Land Cover

(CLC) database provided by the Portuguese Environmental Agency (Portuguese Environmental Agency 2010). The minimum area classified within the CORINE methodology is 25 ha, and 100 m for linear elements. It should be noted that other land use databases may give significantly different proportions of land use in each catchment, but CLC has a uniform methodology and nomenclature across Europe, which facilitates comparisons with other European regions, and up-scaling from catchment to regional and European scale. The resident human population figures (structured by village and by individual settlement) were obtained from the National Statistics Institute (2001a), by overlaying the catchment boundaries on these data (1991 and 2001 Population Census) with the ArgGIS 9 Geostatistical Extension. Livestock data for each study area was based on parish densities provided by the Agricultural Census of 1989 and 1999 from the National Statistics Institute (2001b).

3.2 Catchment Land use Spatial Analysis

An analysis was undertaken to calculate the area of each land use polygon in each catchment. The digital catchment area data were obtained from the National Water Institute, and the CLC data were acquired from the Portuguese Environmental Agency (2010). For each study area, a 'spatial intersection' was carried out between 'catchment area' and 'land uses' themes through Geomedia® 3.0 Professional GIS software. This technique has been successfully used in previous studies aiming at a similar spatial data analysis (Anbazhagan et al. 2005). The spatial intersection results were then aggregated, and the respective total area for each land use type within the catchment was obtained. This operation was conducted on all four study areas for 1990 and 2006.

The CLC classes were then aggregated into six major land use classes (Artificial areas, Agriculture, Montado areas, Mediterranean Forest, Natural areas, and Water bodies) to give a baseline indicator of catchment land use (cf. European Commission 2006). These major catchment land use classes were mapped onto a map of Portugal (1:25000) from the National Centre for Geographic Information (Centro Nacional de Informação Geográfica, Portugal) using aerial photos and a GIS. Finally, field verification was conducted in each study area, during the spring-summer period of 2007, to determine the accuracy of the land use maps of 2006 in relation to the present catchment land use (year 2007).

3.3 Resident Population and Livestock Analysis

Population data was sub-divided by geographical sectors of the villages present in each catchment area. For the purposes of this study the data were then aggregated by catchment area. Livestock estimates were derived using parish density records for each major livestock type based on the Agricultural Census (National Statistics Institute 2001b) data for 1989 and 1999. The data converted into stocking densities per ha, and the total number of each type of animal (cattle, pigs, sheep, goats, poultry and horses) was estimated for each catchment.

Export coefficient model output for each catchment for 1990 was constructed using the 1991 resident population and 1989 livestock data. However, for 2007, the available data (2001 resident population and 1999 livestock data) could not be used directly. The population data were also organized into different socio-demographic variables: gender; age classes; and educational attainment. Accordingly, the 2001 population data (for each village and individual settlements present in each catchment) was compared and adjusted with reference to the 2007 records of school attendance and people entitled to vote held by each

parish in each catchment. The 1999 livestock data was compared and adjusted with reference to the 2007 Veterinary Health State Department records (Direcção Geral de Veterinária), in order to derive representative data for 2007.

3.4 Export Coefficient Model

The ECM approach has been extensively discussed in a number of earlier papers where full details on model equations and modelling procedures can be found (Johnes 1996, 1999, 2000; Johnes and Butterfield 2002). Here, the nutrient loss from each catchment to each reservoir was estimated for all possible sources of P (land use type; resident population; livestock; and rainfall) by defining appropriate export coefficients for use in semi-arid regions, and then applying them to the input data for each catchment. The obtained loading figures were divided by the annual mean runoff (as indicated in Table 1) to give a prediction of mean annual riverine phosphorus concentrations in streams draining into each reservoir as μg TP L^{-1}.

3.4.1 Export Coefficient Selection

Export coefficients for semi-arid regions were compiled from the literature, and the choice of values was conservative and kept them fixed for similar land uses types in all study areas since they have broadly similar topographies and belong to the same quasi-homogenous geoclimatic region type (after Johnes and Butterfield 2002). Here, field surveys (that included in situ conversations with residents and farmers about local issues) and official data helped develop familiarity with the local context to elaborate a list of export coefficients (with minimum and maximum TP load values) derived from the existing literature for all possible sources of P (land use types, sewage treatment plant types, livestock types, and rainfall). After, interviews were conducted with various experts[1] by presenting these figures to discuss the applicability of more specific values to the study area. In particular, these open-ended interviews took advantage from specialists' previous research about nutrient export, for example, in Montado, agricultural land, fertiliser application practices, and Portuguese soils, etc. The criteria for the selection of each set of export coefficients are explained as follows:

- P export from the human population

In each catchment, the number of people connected to STWs or collective septic tanks was provided by INSAAR (2009; Table 2). For the sewered population, the P load contributions were conducted for each separate STW present in each catchment, by using the following Eq. 1 based on Johnes (1996):

$$E_h = A_{ca} \times H \times M \times B \times R_s \times C \tag{1}$$

Where E_h is annual export of P from resident population (kg person^{-1} year^{-1}), A_{ca} is annual input of P per person to treatment facilities (1.16 kg P yr^{-1} per person), H is the number of people in the catchment, M is a coefficient for mechanical removal of nutrients during treatment (range 0.85–0.9, reflecting removal of 10–15% of the nutrient load), B is a coefficient for biological removal of nutrients during treatment (range 0.8–0.9, reflecting removal of 10–20% of the nutrient load), R_s is retention coefficient of the filter bed (range

Table 2 Main characteristics of sewage treatment works (STW) and collective septic tanks (CST) present in the study areas (Source: INSAAR 2009)

Name	Type	Municipality in charge	Starting year	Sewered population	Treatment Level	Outflow
		Alvito catchment				
Oriola	CST	Portel	70s–80s	82	–	Alvito Reservoir
Santana 1	–	Portel	70s–80s	518	–[a]	Monte da Vinha Brook
Santana 2	–	Portel	70s–80s	30	–[a]	Monte da Vinha Brook
São Bartolomeu Outeiro 1	CST	Portel	70s–80s	242	–	Tanques Brook
São Bartolomeu Outeiro 2	STW	Portel	70s–80s	297	Secondary [b]	Tanques Brook
		Odivelas catchment				
Alvito	STW	Alvito	1983	1360	Secondary	Odivelas stream affluent
Vila Ruiva	STW	Cuba	1991	429	Secondary [c]	Odivelas Stream affluent
Vila Alva 1	STW	Cuba	1990	555	Secondary [c]	Ervidal Stream
Vila Alva 2	CST	Cuba	1990	35	–	Ervidal Stream
Albergaria dos Fusos	CST	Cuba	1990	101	–	Odivelas Stream affluent
		Roxo catchment				
Monte da Juliana	CST	EMAS - Beja	1978	53	–[d]	Roxo Reservoir
Mina Juliana	CST	EMAS - Beja	1978	235	–[d]	Roxo Reservoir
Santa Vitória	STW	EMAS - Beja	1991	462	Secondary	Santa Vitória Stream
Penedo Gordo	STW	EMAS - Beja	1978	852	Secondary	Farrejais Brook
Beja – Bacia do Sado	STW	EMAS - Beja	1993	9490	Secondary [e]	Alvercas Brook
Mombeja	STW	EMAS - Beja	1991	445	Secondary	Mombeja Brooks
Ervidel	STW	Aljustrel	1992	1109	Secondary	Roxo Stream
Ervidel Bacia B	CST	Aljustrel	1992	200	–	Roxo Stream
Carregueiro	CST	Aljustrel	1978	98	–	Louriçais Stream
		Monte da Rocha catchment				
Estação de Ourique A	CST	C. Verde	1996	37	–	Aivados Stream
Estação de Ourique B	CST	C. Verde	1996	36	–	Aivados Stream
Aivados A	CST	C. Verde	1986	59	–	Aivados Stream
Aivados B	CST	C. Verde	1986	58	–	Aivados Stream
Casével	STW	C. Verde	1978	341	Secondary	Aivados Stream
Ourique	STW	Ourique	1951	1679	Secondary	Poço da Vila Stream
Picadurinhas	CST	Ourique	1992	21	–	Junqueira Stream affluent
Gradanços	CST	Ourique	1993	168	–	Gradanços Stream
Soalheirinha	CST	Ourique	1994	167	–[f]	Sado River affluent
Pereiras de Cima	CST	Ourique	1994	112	–	Sado River affluent
Encalho	CST	Ourique	1990s	11	–	Almarjão Stream affluent

The treatment level, starting year, and operation condition of each infrastructure was assessed with the help of local technicians; namely, Francisco Grave (Portel Municipality), Gois Pereira and Sergio Pola (Cuba Municipality), Marta Susano (Alvito Municipality), Carlos Martins (EMAS-Beja), Elisabete Benedito and Paulo Ferreira (Aljustrel Municipality), Dora Guerreiro and Marta Grazinha (Ourique Municipality), and António Simões (Castro Verde Municipality)

[a] Direct discharge

[b] Deficient operation

[c] Not working; because of deficient operation is going to be replaced by a 'Compact STW' with secondary treatment

[d] Because of deficient operation these two CST are going to be replaced by a single STW with tertiary treatment

[e] With tertiary treatment (i.e., macrophyte - Phragmites australis (Cav.)) since 2004

[f] Since 2008 a 'Compact STW' with secondary treatment (i.e., activated sludge)

0.1–0.8, reflecting retention of 90–20% of the nutrient load), and C is a coefficient for removal of P if phosphorus stripping takes place (range 0.1–0.2, reflecting removal of 80–90% of P load).

The resident population contribution connected to collective septic tanks was considered to be 0.38 kg P yr^{-1} per person, based on Johnes et al. (1996). It should be pointed out that the type of septic tank present in the study areas are collective infrastructures connected to the sewerage drainage system with discharges directly to a stream or a drain. Furthermore, during the field surveys (together with interviews with local residents) it was found that the unsewered proportion of each resident population includes houses with individual septic systems (in which the sewage decomposes in an underground tank) that are closed systems. Therefore, these systems do not have discharge openings to surface waters and/or into the soil. In this regard, nutrient contributions from the unsewered population might be in some cases overestimated, initially because the nutrient contribution from closed septic systems is considered to be zero.[2] Thus, the nutrient load from unsewered population was recalculated (and deducted to the respective total load), based on field surveys and local informant interviews, with the following Eq. 2:

$$No \cdot treatment, E_h = A_{ca} \times H \times PCIS \tag{2}$$

Where E_h is the annual export of P from resident population of unsewered areas (kg person^{-1} year^{-1}), A_{ca} is the annual output of P per person (1.16 kg P yr^{-1} per person), H is the number of people unsewered in the catchment, and $PCIS$ is a coefficient for the proportion of people connected to individual septic tanks (range 0–1, reflecting the percentage of unsewered population that do not contribute to the nutrient load because is connected to an individual septic system).

- P export from land use source areas

Export coefficients for urban areas were applied to all rural areas identified as having low permeability in the land use database. For agricultural areas, fertiliser application rates, derived from INIA-LQARS (2005) were multiplied by land use areas to calculate the total P load input to the agricultural land in each catchment. These rates were then multiplied by export coefficients selected from the published literature to reflect local conditions in the region. Examples of factors taken into account in selecting these coefficients include to low P status and organic matter content of the Alentejo soil in the region (Nunes et al. 2001). Other factors taken into account include the very flat and dry nature of the landscape in these regions, leading to a lower nutrient export potential than is observed in wetter and more steeply sloping areas reported in the literature for ECM applications in North Temperate Europe. Here, coefficients of 4% of P input (for permanently irrigated land) and 2% (for the remainder agricultural land uses) were the selected export coefficients.

For the 'Montado', 'Mediterranean Forest' and 'Natural Areas' categories, input rates cannot be readily estimated from literature values, and therefore export rates were expressed as amounts lost per unit area, based on published literature, rather than as percentages of a varying input. As for the more intensive land uses, it was necessary the use of lower than usual values in the calibration of the models. The adjusted coefficients derived from these sources are presented in Table 3. Here, field surveys and interviews with local experts identified mainly forestry (cork harvesting) and extensive grazing as the dominant exploitation activities for the Montado landscape. Thus, the export rates for Montado in

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[2] The accumulated organic matter in these systems are periodically pumped out and taken to a nearby STW for disposal.

Table 3 Selected phosphorus land use input rates (kg TP ha^{-1} year^{-1}) and export coefficients (% of input lost or kg TP lost ha^{-1} year^{-1})

CORINE Land Cover classes (at level 3)	Major land use classes [a]	Input Rates [b]	Export Coefficients	References
1.1.2. Discontinuous urban fabric	Artificial Areas	–	0.18	Jones and Lee 1982
2.1.1. Non-irrigated arable land	Agriculture	6.5	2%	INIA-LQARS 2005
2.1.2. Permanently irrigated land	Agriculture	22.0	4%	INIA-LQARS 2005
2.2.1. Vineyards	Agriculture	5.5	2%	INIA-LQARS 2005
2.2.2. Fruit trees and berry plantations	Agriculture	6.5	2%	INIA-LQARS 2005
2.2.3. Olive groves	Agriculture	5.5	2%	INIA-LQARS 2005
2.4.1. Annual crops associated with permanent crops	Agriculture	6.5	2%	INIA-LQARS 2005
2.4.2. Complex cultivation patterns	Agriculture	6.5	2%	INIA-LQARS 2005
2.4.3. Land principally occupied by agriculture	Agriculture	6.5	2%	INIA-LQARS 2005
2.4.4. Agro-forestry areas (*Montado*)	Montado Areas	–	0.005	Johnes et al. 1996
3.1.1. Broad-leaved forest	Mediterranean Forest	–	0.005	Johnes et al. 1996
3.1.3. Mixed forest	Mediterranean Forest	–	0.005	Johnes et al. 1996
3.2.1. Natural grassland	Natural Areas	–	0.007	Johnes et al. 1996
3.2.3. Sclerophyllous vegetation	Natural Areas	–	0.007	Johnes et al. 1996
3.2.4. Transitional woodland/shrub	Natural Areas	–	0.007	Johnes et al. 1996
4.1.1. Inland marshes	Natural Areas	–	0.06	Smith et al. 2005

[a] The CORINE Land Cover classes (at level 3) were aggregated into the following major/broad land use classes

[b] These input rates figures refer to fertilizer applications

these catchments were considered similar to the ones used for forest areas (the contribution from livestock being considered latter in this section). Areas of Mediterranean shrubs and scattered small oaks dominate the 'Natural grassland', 'Sclerophyllous vegetation' and 'Transitional woodland/shrub' land uses and export coefficients were selected for these regions based on dominant brushwood cover.

- P export from livestock sources

The appropriate P export rates for each type of livestock (Table 4) were selected with the help of the Portuguese Veterinary Health State Department (Direcção Geral de Veterinária). In particular, the appropriate annual rates of TP from the major kinds of livestock were determined with reference to the native livestock breed characteristics, including the typical age structure of the herd, animal weight, and the typical feeding/grazing system in place. Based on local information it was assumed that all animals grazed outside all the year round, relying on fallow/pasture/rangeland for their feeding. The nutrient input to the catchment from livestock wastes was then calculated assuming a constant livestock density on grazing land across each catchment, with no loss of P through in-house storage of manure.

- P export from atmospheric deposition

Nutrient input to the land in the catchment via rainfall contributes to the other diffuse losses from land based sources and is added as an input to these components, and then multiplied by an export coefficient to derive its ultimate delivery to the reservoir system.

Table 4 Livestock input rates (kg head^{-1} year^{-1}) and export coefficients (% of input) for total phosphorus compiled from literature and adapted for the study areas

Livestock type	Input Rate	Export Coefficients	Reference
Cattle			
Dairy cow	13.0	0.95	European Communities 2006
Beef cattle (with >2 years old)	10.0	0.95	European Communities 2006
Beef cattle (between 12–24 months)	8.0	0.95	European Communities 2006
Calves [a]	3.0	0.95	European Communities 2006
Pigs			
Weaner [b]	1.4	0.85	Johnes et al. 1996
Sow [c]	4.7	0.85	Brandjes et al. 1996
Grower/others [d]	2.3	0.85	Brandjes et al. 1996
Sheep			
Adult ewe [e]	1.0	1.0	European Communities 2006
Lambs [f]	0.6	1.0	European Communities 2006
Goats	1.0	1.0	European Communities 2006
Poultry [g]	0.09	0.9	Brandjes et al. 1996
Horses [h]	8.0	0.75	European Communities 2006

Export coefficients derive from figures of manure voided directly by the animals into the catchment that will reach the drainage network (lost to runoff)

[a] Refer to young animals between 0–12 months

[b] A young animal recently weaned (with less than 20 kg of body weight)

[c] Female adult pig (with 50 kg or more of body weight)

[d] Dry meals (up to 23 weeks)

[e] Female and male sheep (more than 1 year old)

[f] Animals between 0–12 months

[g] Includes chickens, ducks and turkeys

[h] Includes donkeys

However, rainfall which falls directly onto reservoirs is not accounted for in these calculations. Therefore, the product of the rainfall input rate and the total surface area of the each reservoir was added to the P loading estimate from land based sources for each reservoir to give the total P load delivered to each reservoir. Based on Reckhow and Simpson (1980), the value used in this study was 0.15 kg P ha^{-1} because the study sites are located in rural areas without any significant P deposition from industrial activity. However, it should be noted that in semi-arid environments wind erosion and dust might be a key pathway for atmospheric P deposition in the reservoirs and this is a limitation of the approach adopted in this study, which could be addressed in the future through research into atmospheric P deposition rates in semi-arid regions.

3.4.2 Model Calibration, Sensitivity Analysis and Validation

A frequent problem in Portugal is the availability of data and, in particular, of riverine water quality records for smaller water courses. According to the National Water Institute records (INAG 2010), the only available TP riverine data was for Roxo stream (for 1990). Additionally, it was also possible to obtain riverine data from EDIA records (Empresa de

Table 5 Comparison between predicted model P loads and observed riverine P concentrations ($\mu g \, TP \, L^{-1}$). Note: The model calibration was performed with the 2007 Odivelas model output against the observed Odivelas stream P concentration; and the model validation was performed with the 1990 Roxo model output against the observed Roxo stream P concentration

	Calibration	Validation
Predicted riverine [P]	58.9	126.7
Observed riverine [P]	59.1	116.0
Model error (%)	−0.3	9.3

Desenvolvimento e Infra-estruturas do Alqueva, S.A.) for the Odivelas Stream (for 2007). Thus, observed riverine P concentrations and long-term historical water quality records were not available for all the study areas. The four models were therefore first calibrated for Odivelas catchment with the 2007 input data (resident population, livestock, and land uses), against observed P concentrations in the Odivelas Stream for 2007. A sensitivity analysis was performed to examine the sensitivity of the model output to the export coefficients, as outlined by Johnes (1996), with the outcomes of this analysis used, in conjunction with local and expert interviews to inform the adjustment of export coefficients to achieve a final fit to the observed data. In the final calibration, the Odivelas model predicted P loading in 2007 was within 0.3% of the observed riverine P concentration (Table 5).

In the validation step (after Johnes, 1996), the coefficients derived for Odivelas (2007) in the calibration step were then applied to the input data for 1990 for the Roxo catchment, with model output compared to the observed riverine P data for 1990 for the Roxo Stream. The Roxo model was then accepted as valid because the calibration coefficient set produced a P load estimate within 10% of the observed load in the Roxo stream (1990) (Table 5). Finally, the validated model was then run for 2007 and 1990 for each of the remaining reservoir catchments and years not included in the calibration and validation process.

3.4.3 Scenario Modelling

Models can also be used to predict and compare the effect of different scenarios (Olsson and Andersson 2007). There are a wide range of options available for reduction of P exports in rural catchments (Johnes et al. 2007). In particular, there were two main concerns explored in this study: (1) mitigation of P export from diffuse sources through land use or land management change; and (2) upgrade of septic tank systems and STWs processes to reduce P content in point source discharges. The objective was to determine the scale of change which might be necessary to reduce P loading to a level which could, potentially, sustain good ecological status in each reservoir. The scenarios were modelled in relation to catchment-specific P status for 2007. Scenarios were designed from specific results of the sensitivity analyses and projections from previous studies as explained below. These are summarized in Table 6.

Agricultural land abandonment in Portugal has been associated with the 2003 reform of the EU Common Agricultural Policy (CAP), which introduced decoupled income support for farmers. This Single Farm Payment scheme came into effect in 2005 in most Member States. Thereafter, concerns were raised about possible future land use and production changes (Tranter et al. 2007). For instance, Alves et al. (2003) stated that the ageing farming population in Portugal would contribute to the abandonment of land in the near

Table 6 Scenarios run for each study area

Dimension	Trends	Scenario	Modelled change
Land use	Decrease in cereal production (Tranter et al. 2007); elderly farm population and abandonment of agricultural land (Alves et al. 2003).	1	Reduction in cereals planted area by 7.5% (Soares and Coelho 2004)
	Adoption of good farming practices by farmers (MADRP 2000).	2	Reduction in P rates from arable land by 20% (Johnes and Heathwaite 1997)
Human population	Sewage treatment works deficient operation, lack of maintenance and upgrade programmes (Cerqueira et al. 2008; INAG 2009); fixing failing sewage treatment works and upgrading septic systems.	3	All sewers connected at least to secondary treatment plants (biological removal of P) [a]
		4	All sewers connected to tertiary treatment plants (P stripping) [b]

[a] Refer to $M=0.85$ and $B=0.8$ (see Eq. 1 of section *3.4.1 Export coefficients selection*)

[b] Refer to $M=0.85$, $B=0.8$, $Rs=0.2$ and $C=0.1$ (see Eq. 1 of section *3.4.1 Export coefficients selection*)

future. In this context, the arable sector estimates reveal a consistent decline for cereals (Tranter et al. 2007). In Portugal, Soares and Coelho (2004) projected for 2010 changes at around −7.5%, which are higher than the board projections for EU countries (−2.6% for 2009–2010). This projection was run through the model for each reservoir as scenario 1 (Table 6).

Scenario 2 was designed based on farmers' voluntarily adhering to the Code of Good Agricultural Practice (MADRP 2000), growing cover crops in the winter and controlling the timing and application of manure and fertilizers (INIA-LQARS 2005; Johnes and Heathwaite 1997). Also, avoiding build up of soil P levels above those necessary for crop production will reduce P loss from agricultural land (INIA-LQARS 2005; MADRP 2000). Accordingly, it was hypothesised that farmers' voluntary adherence to good farming practices would produce a reduction in P export rates from arable land by 20%, based on scenarios originally tested in North Temperate catchments by Johnes and Heathwaite (1997) (Table 6).

The Urban Waste Water Treatment Directive (UWWTD; 91/271/EEC) has been effective in reducing point sources of P in some catchments with large STWs with a population equivalent of 10,000 or more. However, in rural areas small STWs and septic tank systems are rarely upgraded to include P stripping and can represent a significant source of P export to waters (Johnes 1996; Jarvie et al. 2006). Similarly, Diogo et al. (2008) showed that STWs are a significant source of P loading in the Alentejo Region. The gravity of the situation in Portugal is reinforced by the fact that a significant number of the STWs present serious operating deficiencies due to, among other reasons, poor project design, lack of qualified staff to operate facilities, and scarcity of investments devoted to maintenance and upgrade programmes (Cerqueira et al. 2008). These findings (together with field surveys undertaken in this study) demonstrate the primary need for point source phosphorus mitigation not only for rural towns, but also for small point source discharges to waters. Thus, scenarios 3 and 4 assess the likely effect of the degree of treatment in the STW on the concentrations of TP in the reservoir waters assuming (scenario 3) all residential areas, which do not have STWs or have STWs with preliminary or primary treatment, will have STWs with secondary (biological) treatment; and (scenario 4) all residential areas, which do

not have any STWs or have STWs with preliminary, primary or secondary treatment, will have STWs with tertiary treatment (Table 6).

3.4.4 Ecological Significance of Model Output

To interpret the ecological 'meaning' of the model output, it was necessary to calculate the typical P concentrations that might be generated in each reservoir, given the rate of P loading from the catchment and from direct deposition as predicted by the model. This was possible by using the standard regression relationship linking inflow and lake nutrient concentrations in reservoirs published by OECD (1982). In particular, this model can be used to determine the phosphorus load reduction necessary to achieve a desired state of water quality. Based on Foy et al. (2003), the OECD general regression equation has been used in this study to convert the predicted riverine TP concentrations to typical reservoir concentrations for each study area, depicted in Eq. 3:

$$P_{Lake} = \frac{1.234 \times \left(P_{input}\right)^{0.991}}{\left(1 + \sqrt{R_t}\right)^{1.13}} \tag{3}$$

Where P_{Lake} is lake TP concentration ($\mu g\ L^{-1}$), P_{input} is inflow TP concentration ($\mu g\ L^{-1}$), and R_t is reservoir water retention time (in years); the retention time used was estimated for the year 2007 for each studied reservoir (Table 1)

Equation 3 generates an estimate of the average reservoir TP concentration as a function of the TP concentration in streams flowing into the reservoir and the retention time of the reservoir. This relation assumes that the root cause of eutrophication in the water body is due to an excess abundance of nitrogen over phosphorus. Phosphorus is assumed to be the limiting nutrient, such that reduction in phosphorus load will decrease the algal response with respect to chlorophyll-a production.

4 Results and Discussion

4.1 Export Coefficient Modelling Output

The total P loadings and the proportions of the total P loadings attributable to the various sources for 1990 and 2007 are presented in Fig. 3. In the following sections, the predicted P loading budget for each study area is presented individually, with the basin-specific sensitivity analysis for 1990 and 2007 for each study area presented in Table 7.
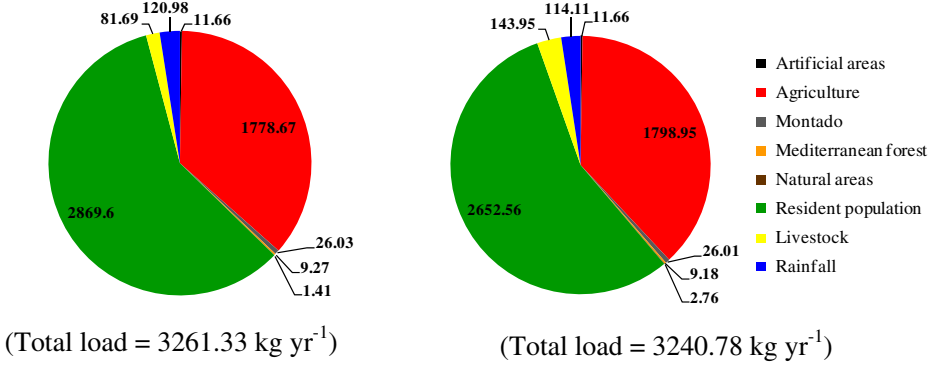
4.1.1 Alvito Catchment

Total P export from the catchment for 1990 was 0.16 kg ha^{-1}, of which 58% was derived from the point source and septic tank discharges and 35% from agricultural land. In 2007, while there was a marginal decrease in total P export (<1%), a different pattern was observed, with an increase in TP export from agriculture (to 41%) and a decrease in TP export from the human population (48%). Livestock was a much lower proportion of the total load (1–2%) in both 1990 and 2007, with cattle and sheep being the key livestock contributors for both years. The observed changes in P export from each sector, between 1990 and 2007 resulted from a decrease in the resident population (rather than an increase
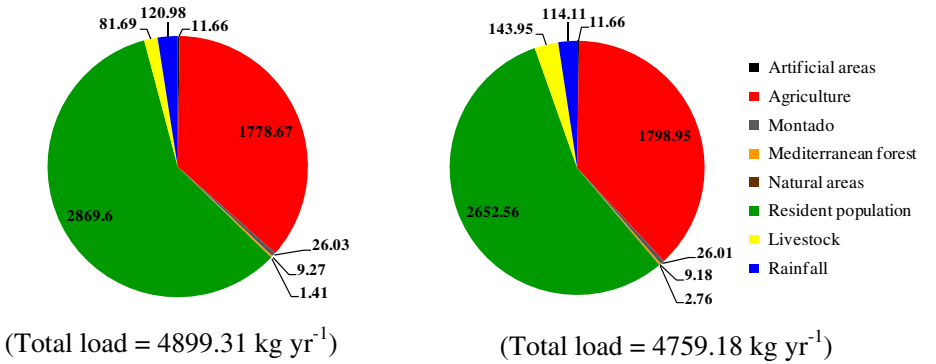
in P removal at STWs), and an increase in the area of permanently irrigated land used for agricultural production. A slight increase in the amount of P contributed from rainfall was attributable to an increase of the surface area of the Alvito Reservoir.
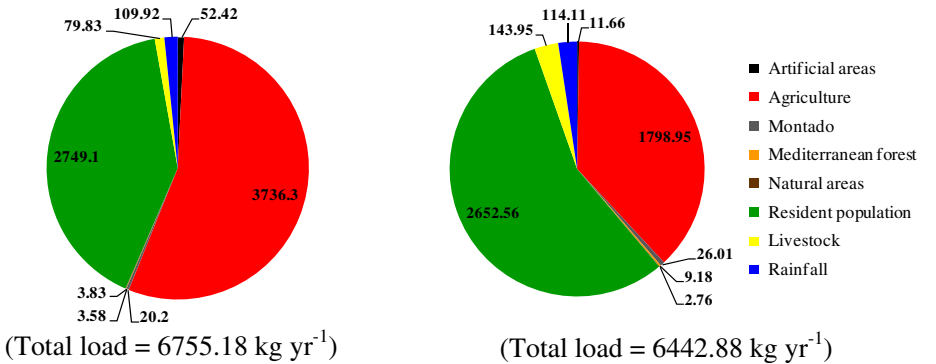
Alvito catchment

(Total load = 3261.33 kg yr^{-1})

(Total load = 3240.78 kg yr^{-1})

Odivelas catchment

(Total load = 4899.31 kg yr^{-1})

(Total load = 4759.18 kg yr^{-1})

Roxo catchment

(Total load = 6755.18 kg yr^{-1})

(Total load = 6442.88 kg yr^{-1})

Fig. 3 Predicted total phosphorus exports (kg yr^{-1}) for 1990 (right pies) and 2007 (left pies) in the study catchments

Monte da Rocha catchment

(Total load = 4036.7 kg yr^{-1})   (Total load = 4026.91 kg yr^{-1})
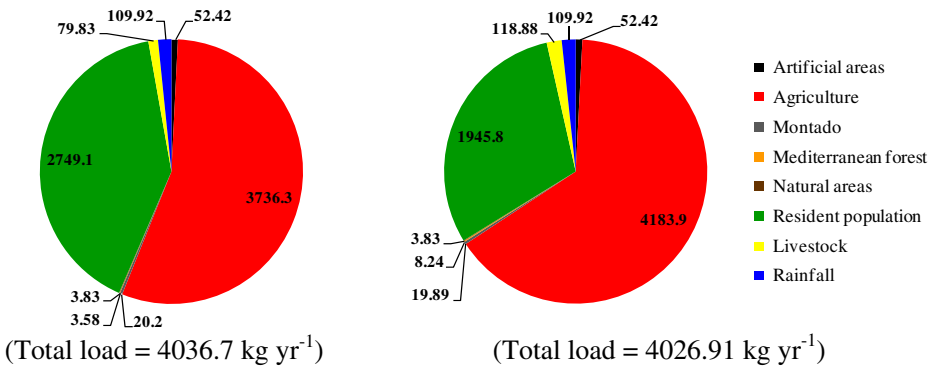
Fig. 3 (continued)

4.1.2 Odivelas Catchment

In 1990, the key sources of total P loading on the reservoir were the human population (59%) and agriculture (36%). The next most important contributors were, by decreasing order, rainfall (~2.5%) and livestock (~1.7%). Total P export decreased from 0.23 kg ha^{-1} in 1990 to 0.22 kg ha^{-1} in 2007, of which the key contributors were again the human population (56%) and agriculture (38%). Livestock (~3.0%) and rainfall (2.4%) were the next most important sources of P loading. Overall, human contribution decreased between 1990 and 2007 because of resident population decline and, to a lesser extent, an increase in the size of the sewered population (with a concomitant decrease in the size of non-sewered population). The major sources of increase in P loading from Odivelas catchment were an increase in the cattle population in the catchment, and an increase in the area of permanently irrigated land and vineyards.

4.1.3 Roxo Catchment

Predicted total P loading for 1990 was 0.20 kg ha^{-1}, of which 55% was from agriculture and 41% from the human population. This is in contrast to the situation in the Alvito and Odivelas catchments. In 2007, the largest sources of P export to the reservoir were again agriculture (65%) and the human population (30%). Livestock and rainfall were minor contributors to P export in both years. Overall, total P export decreased between 1990 and 2007 due to a decline in P export from the human population through an expansion in the number of STWs in the catchment. In contrast, the input from agriculture to the total P loading increased between 1990 and 2007, due to an increase in the permanently irrigated land area. Similarly, the contribution to the total P loading from livestock also increased because of an increase in stocking densities for both cattle and sheep.

4.1.4 Monte da Rocha Catchment

Total P export from the catchment for 1990 was the lowest of the 4 reservoirs studied, at 0.17 kg ha^{-1}. The key contributors were the human population (56%) and agriculture

Table 7 Basin-specific sensitivity analysis for the study areas

P source	% Change in model output by adjustment of each parameter by 10%							
	Alvito		Odivelas		Roxo		Monte da Rocha	
	1990	2007	1990	2007	1990	2007	1990	2007
Land use (Total)	(3.492)	(3.652)	(3.707)	(3.884)	(5.791)	(6.281)	(3.959)	(3.470)
Artificial areas	–	–	0.024	0.025	0.078	0.081	0.019	0.085
Agriculture	3.301 [a]	3.458 [a]	3.608 [a]	3.780 [a]	5.531 [a]	6.494 [a]	3.788 [a]	3.221 [a]
Montado	0.096	0.097	0.053	0.055	0.030	0.031	0.096	0.095
Mediterranean forest	0.087	0.087	0.019	0.019	0.005 [b]	0.013 [b]	0.050	0.050
Natural areas	0.008 [b]	0.010 [b]	0.003 [b]	0.006 [b]	0.006 [b]	0.006 [b]	0.005 [b]	0.019 [b]
Resident population	5.835 [a]	3.920 [a]	5.857 [a]	5.573 [a]	6,715 [a]	2,273 [a]	5.609 [a]	4.916 [a]
Livestock (total)	(0.227)	(0.416)	(0.167)	(0.303)	(0.120)	(0.180)	(0.217)	(0.265)
Cattle	0.038	0.246	0.051	0.191	0.051	0.102	0.086	0.142
Pigs	0.140	0.030	0.021	0.012	0.020	0.004	0.025	0.020
Sheep	0.025	0.120	0.088	0.095	0.045	0.076	0.083	0.088
Goats	0.019	0.015	0.002 [b]	0.002 [b]	0.001 [b]	0.001 [b]	0.015	0.011
Poultry	0.002 [b]	0.002 [b]	0.002 [b]	0.002 [b]	< 0.001 [b]	< 0.001 [b]	0.002 [b]	0.002 [b]
Horses	0.002 [b]	0.003 [b]	0.003 [b]	0.001 [b]	0.001 [b]	0.001 [b]	0.005 [b]	0.002 [b]
Rainfall	0.331	0.606	0.247	0.239	0.163	0.171	0.210	0.211

The sensitivity analysis aims to assess which of the model parameters exerted the greater control over model output. Each of the model parameters (the export coefficients for each P source) was adjusted by an arbitrary value of ±10% in turn whilst holding the other parameters constant. Thus, the net effect on model output was assessed for each parameter to determine which had the greatest effect on model

[a] Refer to the most important factors contributing to P loading

[b] Refer to the less important factors contributing to P loading

(38%); livestock (~2.2%) and rainfall (~2.1%) were, again, minor contributors to the total load exported to the reservoir. Of the total P export from livestock, cattle (~0.9%) and sheep (~0.8%) were the key contributors to the total load. For 2007, the total export of P from the catchment slightly decreased marginally, with the patterns of contribution from the various catchment sources remained largely the same as in 1990.

Overall, these results suggest that a reduction in the total P loading delivered to the drainage network in each of the 4 catchments would require the introduction of management measures to reduce P export from farming as well as more efficient removal of P from human wastes prior to discharge to surface waters.

*4.1.5 Scenario Analysis: Impacts of Management Intervention on P Export to Each Reservoir*

The sensitivity of the export coefficient modelling approach to changes in P export at the large catchment scale indicates the suitability of this approach for the evaluation of basin-scale management strategies (developed scenarios) to reduce nutrient loading to the drainage network of the study areas (cf. Johnes and Heathwaite 1997). Here, the impact of four possible scenarios (Table 6) on P export to each reservoir was evaluated. The data are

presented as the change in predicted riverine TP concentrations from the 2007 baseline for each study area (Fig. 4a).

Scenario 1 results in a small impact on predicted P loadings in the study areas: Alvito, −2.3%; Odivelas, −2.0%; Roxo, −4.5%; Monte da Rocha, −2.4%. This scenario clearly produces the greatest reduction in the Roxo stream where cereal production is a dominant land use in the catchment. Scenario 2 produces a greater reduction in P loading: Alvito, −7.8%; Odivelas, −7.6%; Roxo, −13.0%; Monte da Rocha, −7.1%. Again, this scenario produces the greatest reduction in the Roxo catchment, because it has the largest proportion of agricultural land of all catchments modelled. This scenario illustrates the need for suitable farming practices that can achieve a compromise between economic, social and environmental considerations, and it may be not necessarily be the cheapest option to implement. In particular, it may require a significant reduction in the agricultural output and efficiency (Johnes 1996) with knock on consequences for food security and the local economy. Nevertheless, only a very small percentage of the farmer population in each catchment currently adheres to environmental schemes or good farming practices (National Statistics Institute 2001b). Thus, there may be the potential to achieve environmental benefit through encouragement of farmers to comply with this guidance.

Scenario 3 also produces a significant reduction on predicted riverine P concentrations in three of the catchments: Alvito, −9.5%; Odivelas, −14.6%; Monte da Rocha, −3.7%, but an increase in riverine P concentrations in the Roxo catchment (12.8%). This reflects the export coefficients applied to the collective septic tanks, which result in less P loading than for STWs with secondary treatment (biological removal of P). Scenario 4 has the greatest effect on predicted riverine P concentrations in all four catchments: Alvito, −48.0%;

Fig. 4 Predicted riverine (a) and lake (b) total phosphorus concentrations of the study catchments (A, Alvito; O, Odivelas; R, Roxo; MR, Monte da Rocha) for scenario runs (for description of scenarios see Table 5) compared with the models 2007 baseline. Note: dashed horizontal lines refer to OECD (1982) trophic class boundaries: TP<10.0 μg TP L^{-1}= oligotrophic, 10 μg TP L^{-1}<TP< 35 μg TP L^{-1}=mesotrophic, TP> 35 μg TP L^{-1}=Eutrophic
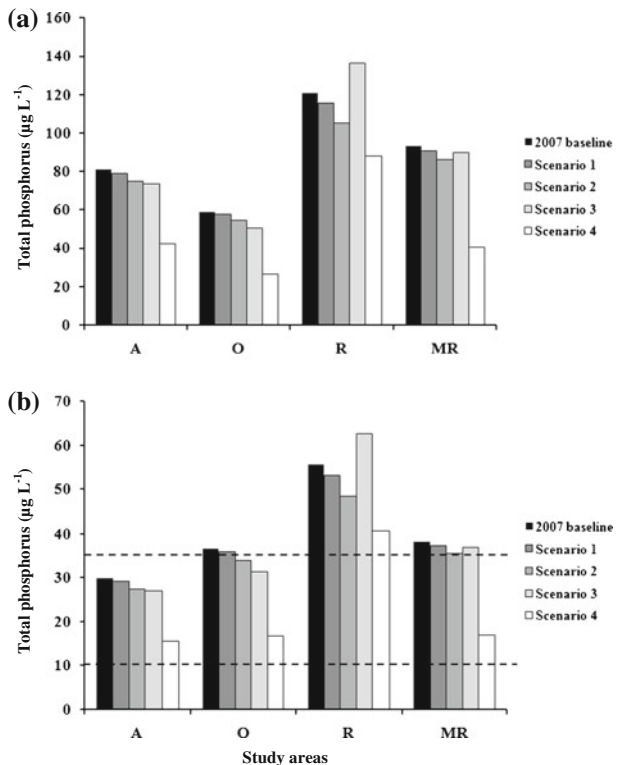
Odivelas, −54.8%; Roxo, −27.0%; Monte da Rocha, −56.3%. Accordingly, it is concluded that measures to reduce P-inputs to reservoirs should focus on reducing effluent P concentrations by tertiary treatment (P-stripping) of effluents from residential areas, in combination with the introduction of measures to mitigate diffuse P export from agricultural land.

4.1.6 Changes in Lake TP Status Predicted by the Model Runs

For 2007, the measured in-lake TP concentration of each reservoir (INAG 2010) was: Alvito, 29.6 µg TP L^{-1}; Odivelas, 48.1 µg TP L^{-1}; Roxo, 59.2 µg TP L^{-1}; Monte da Rocha, 43.2 µg TP L^{-1}. The application of Eq. 3 (OECD 1982) to calculate average in-lake TP concentrations (for 2007) from predicted inflow P concentrations (Fig. 3) generated a mean reservoir concentrations as follows: Alvito, 29.8 µg TP L^{-1}; Odivelas, 36.6 µg TP L^{-1}; Roxo, 55.6 µg TP L^{-1}; Monte da Rocha, 38.3 µg TP L^{-1}. The difference between measured and predicted in-lake P concentrations for each reservoir was: Alvito, 0.8%; Odivelas, −23.8%; Roxo, −6.0%; Monte da Rocha, −11.4%, with a reasonable fit for three of the four reservoirs, but a 24% underestimate of water column TP concentration in the Odivelas reservoir. Two main factors may provide possible explanations for these differences:

1. It may be that the characteristics of the Odivelas catchment mitigate (hydrological, chemical and physical sinks that buffer nutrient transport to surface waters) more strongly against the delivery of P loads to the reservoir than in the other three catchments. Therefore, P retention or remobilization by catchment processes associated with phosphate adsorption/desorption within the river bed, sedimentation/transport of particles and biological uptake/release may be significant in the Odivelas catchment in particular.
2. An important assumption in the derivation of Eq. 3 is that the lake is well mixed and at steady state, so that the TP concentration throughout the lake and in the outlet stream can be characterised by a single value (Brett and Benjamin 2008). However, longitudinal differences along the path from the inflow to the dam are a unique limnological feature of reservoirs and have great implications for water quality (higher phosphorus retention). Moreover, it is recognised that this interpretation ignores several potentially important processes, such as the release of P from lake sediments stores (Brett and Benjamin 2008). In particular, the high water level fluctuations may be the cause of the in-lake higher nutrient availability. That is, the resuspension of bottom sediments, plus the turbulence generated by water level rising and the periodical exposure of littoral sediments to cycles of drying and wetting could explain the particular observed in-lake higher phosphorus concentrations (Geraldes and Boavida 2003). Furthermore, the specific effects are likely to vary between reservoir types and morphologies, and as a function of the specific pattern of drawdown.

Any model predictions must therefore be viewed as uncertain, and trends evident in the present model output should be interpreted in this light. The range of lake TP concentrations predicted by the model for the 2007 baseline and for each of the scenario runs is presented in Fig.4b. In terms of ecological status, for the 2007 baseline the model predicts mesotrophic conditions in Alvito, mildly eutrophic conditions in Odivelas and Monte da Rocha Reservoirs, and eutrophic conditions in Roxo Reservoir.

The scenario analysis suggests only a slight improvement in the ecological status of all reservoirs for scenarios 1 and 2, with the greatest reduction predicted in the lake P concentration of Roxo Reservoir. To achieve a greater rate of P reduction from diffuse agricultural sources would require substantial changes in land use and management at a local scale, through the implementation of on-farm management measures, whole farm planning to achieve a P balance at farm scale, and the redistribution of high-risk land uses to areas of the catchment with the lowest nutrient export potential (Johnes et al. 2007).

Model output for scenario 3 predicts a greater reduction in lake P concentration in three out of the four reservoirs. Specifically, the model suggests this scenario would support a reduction in water column P concentrations to support moderately mesotrophic conditions in Odivelas reservoir but, by contrast, an increase in water column P concentrations in Roxo Reservoir, which will likely accentuate its eutrophic status.

Model output for scenario 4 predicts an improvement in the ecological status of all four reservoirs: Alvito Reservoir, is predicted to move from moderately mesotrophic to mildly mesotrophic conditions; Odivelas and Monte da Rocha Reservoirs, are predicted to recreate mildly mesotrophic conditions; and Roxo Reservoir, is predicted to move from strongly eutrophic conditions to mildly eutrophic conditions. Overall, while the most appropriate mitigation measures will vary between the four catchments, a programme with a dual focus on reducing effluent P concentrations by tertiary treatment (P-stripping) of effluents from residential areas, with a secondary focus on reducing P loss from fertilised, permanently irrigated land is likely to deliver the greatest reductions in water column TP concentrations.

5 Conclusions

This study demonstrates the efficiency of the ECM approach to estimate phosphorus export at catchment scale over a semi-arid region, which suggests some important considerations to the sustainable management of water resource in such regions. In contrast to findings often reported for North Temperate European catchments, the dominant source of P loading in these semi-arid catchments is effluent discharge from point source STWs and diffuse leakage from rural septic tank systems. In particular, the results suggest that a strategy based on transferring earlier published findings for North Temperate catchments to semi-arid Mediterranean catchments could lead to inefficient management of the reservoir resource, and only a slow improvement or maintenance of the current ecological status in the studied reservoirs. Any management strategy targeting P export from agricultural sources in semi-arid regions similar to those reported here would need to adopt alternative techniques that identify source areas of high P loss and offer the possibility of the proactive management of P loss at the farm and catchment scale. Overall, however, reduction of P loading on semi-arid region water resources will require improved control of P export from domestic effluents, including point source discharges from both small rural STWs and diffuse septic tank systems, if eutrophication problems are to be brought under control and good ecological status is to be supported.

The present study showed the ability of the ECM to estimate point and diffuse inputs as well as future trends in four semi-arid catchments ranging from 211 km^2 to 351 km^2 in area, which could provide a valuable and versatile tool to catchment managers for determining optimal mitigation options to reduce phosphorus concentrations in such regions, and thereby aiding decision making for the WFD. Nevertheless, further studies using the ECM approach in a wider range of semi-arid catchments need to be conducted to enable wider validation of this approach as a tool to support the development of integrated water resource management in semi-arid regions.

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