TOTAL PHOSPHORUS AS AN INDICATOR OF TROPHIC STATE OF PORTUGUESE RESERVOIRS

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ABSTRACT

Total phosphorus was determined for the 44 most important reservoirs all over the country. The objectives were to map phosphorus in Portuguese reservoirs and to determine their trophic state. Total phosphorus, dissolved oxygen concentration, and pH were measured in the fall of 1992 in reservoirs ranging from North to South of Portugal, covering the rivers Lima, Cávado, Ave, Douro, Mondego, Tejo, Sado, Morgável, Mira, Odiáxere, Arade and Guadiana watersheds. Factors such as geographical location, morphometry, geology, surrounding land use, climate, and position in the river continuum influenced water quality of the reservoirs. Of the reservoirs sampled, 40 % were classified as eutrophic, the remaining as mesotrophic. There is an urge to recover the most productive of the studied reservoirs, as well as to prevent further degradation of those still considered as mesotrophic.

Palabras clave: Fósforo total, Estado trbfico, Embalses, Portugal.
Keywords: Total Phosphorus, Trophic State, Reservoirs, Portugal

INTRODUCTION

Portugal is a country with very few natural lakes and therefore where reservoirs fulfill the function of retaining water for the most diversified uses. There are circa 100 operational reservoirs in the country. Mainly built for drinking water supply, irrigation, and electric power generation, these artificial lakes arc also utilized for fishing and recreational purposes.

Freshwater resources in Portugal are scarce. Rainfall is irregular and not abundant, especially in the inland areas where the influence of the sea does not ameliorate the harsh caracter of the climate. With the exception of the 2000 m altitude mountain in the central part of the country, it is frequent to have several (up to three or four) years in a row with practically no rainfall. The few rain events usually take place during winter. Even rivers of appreciable dimension (third or fourth order streams) are characterized by very irregular flow; there are cases, e.g. the River Guadiana, a fourth order river in the south, where totally dry portions of the river bed can be seen in summer, alternating with pools where some stagnant water is left. Cases such as this just described illustrate the dryness of the country climate.

Similarly to what happens at a global level, water quality in the majority of Portuguese reservoirs is threatened by increasing eutrophication. The key role played by phosphorus loads in eutrophication has been object of special attention for long (VOLLENWEIDER, 1968; WETZEL, 1983). Empirical relationships between phosphorus loading and algal biomass are often based on total phosphorus concentrations (VOLLENWEIDER, 1976). Total phosphorus concentrations are, therefore, commonly used to assess the degree of eutrophication as a result of nutrient enrichment of lakes.

There is often a good correlation between total phosphorus concentrations and algal standing crop in a great variety of lakes.

According to WETZEL (1990) reservoirs and natural lakes are functionally alike, being the basic ecological processes occurring in them and their controlling factors the same; the differences are often found in the rates at which those processes take place (usually higher rates in reservoirs than in natural lakes).

The purposes of this research were (1) to determine the total phosphorus concentrations of Portuguese reservoirs, from north to south, so that concentrations could be shown pictorially on a map, and (2) based on total phosphorus concentrations, to determine the trophic state of the reservoirs. There is a lack of this type of studies in Portugal, where reservoirs have so far been studied on an individual basis (one at a time). This study was intended to be integrated both at watershed and country levels. Since lake (or reservoir) ecosystems cannot be viewed independently of their drainage baisins, or watersheds, total phosphorus concentrations were thus related to other factors such as geology, soil composition, land use, precipitation, humidity, insolation, air temperature, surface area and volume of the reservoirs, dissolved oxygen concentrations of the water, and alkalinity of the soil. The ultimate goal of this research was to provide data for correct, integrated management of the Portuguese reservoirs.

MATERIALS AND METHODS

This study was undertaken at a period following a 2-year drought in the country. For this reason, of the *circa* 100 reservoirs in use, only 44 (the largest) were sampled. Most of the remaining are relatively small and were almost dry at the

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time of sampling, therefore were disregarded. A few others were not sampled because of logistic dificulties.

Each of the 44 reservoirs was sampled once, between mid September and beginning of October of 1992. These 44 water bodies belong to 12 river watersheds (Fig. 1) and are distributed among them as follows: 6 to R. Cávado, 2 to R. Ave, 5 to R. Douro, 3 to R. Mondego, 11 to R. Tejo, 5 to R. Guadiana, 7 to R. Sado, and 1 to each of rivers Lima, Mira, Arade, Odiáxere, and Morgável.

Water samples for total phosphorus (TP) deterinination were collected from the upper 0 2 m stratum into acid rinsed polyethylene bottles Water temperature and dissolved oxygen concentrations were recorded in ***situ*** with a YSI model 57 thermometer-oxymeter. Indicator pH paper (Johnsons of Hedon, Ltd.) was utilized in the field for approximate pH determinations.

Total phosphorus was determined after acid hydrolysis with persulfate for 60 minutes under high temperature and pressure followed by the MURPHY & RILEY (1962) spectrophotornetric method on 5 replicates. Carlson's Trophic State Index (CARLSON, 1977) was the criterion for trophic classification of the reservoirs.

RESULT

TP and age of the reservoirs: Portuguese reservoirs are all relatively recent; of those studied, Póvoa (built in 1927, R. Tejo) was the oldest and Lindoso (built in 1992, R. Lima) had been filled up for the first time about six months before sampling for this research was undertaken. A significant positive correlation ($P<0.05$, $n=44$) was found between TP and the yeas of construction of the reservoirs

TP and surface area of the reservoirs: Sampled reservoirs were divided into four classes according to their surface area (class A > 1900 ha; class B from 600 ha up to 1900 ha; class C from 100 ha up to 500 ha; class D < 100 ha). The largest reservoirs were located in rivers Douro, Tejo, and Sado watersheds (Table I). Regarding the above classification 36.4 % of the studied reservoirs belong to class B and 40.9 % belong to class C, being both very large and very small reservoirs relatively few. A significant correlation was not found between TP and surface area of the reservoirs.

TP and trophic state of the reservoirs: In figures 2, 3 and 4 the 44 reservoirs are depicted in their respective watersheds (2 - rivers Lima, Cávado, Ave, and Douro; 3 - rivers Mondego and Tejo; 4 - rivers Sado, Guadiana, Morgável, Mira, Odiaxere, and Arade) with indication of relative magnitudes of TP, dissolved oxygen (DO) and pH. Absolute values for all of these parameters are indicated on Table 1 TP was used to compute Carlson's Trophic State lndex (CARLSON, 1977) Based on this index (phosphorus component only) the reservoirs were classified according to trophic stale. Twenty seven reservoirs were considered as mesotrophic and seventeen were considered as eutrophic. The watershed with

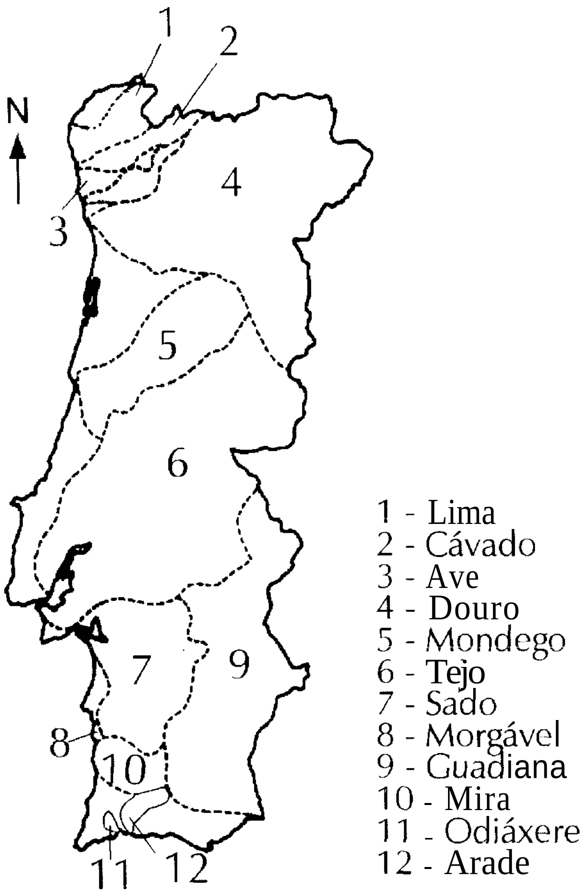

Figure 1. Location in the map of Portugal of the 12 drainage basins sampled
Figura 1. Locnlizacion de las 12 cuencas muestreadas en Portugal.

the lowest percentage of eutrophic reservoirs was that of R. Sado (15 %). The highest percentage of eutrophic reservoirs was concentrated on R. Tejo watershed (64 %).

TP and dissolved oxygen in the water of the reservoirs: The highest values of DO concentration in lake water were recorded for R. Sado watershed reservoirs, the lowest for R. Tejo watershed reservoirs (Figs. 3 and 4). There was a significant negative correlation between surface DO and TP in the 44 reservoirs.

TP and pH of the water of the reservoirs: Water pH varied between 5 and 5.5 in R. Cávado watershed, was 5.5 for all reservoirs of rivers Lima, Ave, and Mondego, varied beteen 5.5 and 6.7 in R. Tejo watershed. between 5.8 and 6.7 in R. Guadiana watershed, and between 5.5 and 6.4 in R. Sado watershed (Table 1). There was no correlation between water pH and TP of the reservoirs.

Table I. Some morphometric and chemical characteristics of the sampled reservoirs. Y.C. = year of construction; volume in $m^3 x 10^6$; area in surface area, in ha, followed by a letter representing the area class: TP in µg/l; O_2 in mg/l.

Tabla I. Características morfométricas y químicas de los embalses estudiados. Y. C. -año de construcción; volumen en $m^3 x 10^6$; área (corresponde a área superficial) en ha, seguida de una letra que indica la clase; TP en µg/l; O_2 en mg/l.

RESERVOIR	WATERSHED	Y. C.	VOLUME	AREA	TP	O_2	pH
Lindoso	Lima	1992	348	1072 B	81.37	4.5	5.5
A. Rabagão	Cávado	1964	569	2200 A	29.76	5	5.2
V. Nova	Cávado	1951	97	400 C	29.1	5.5	5.2
Salamonde	Cávado	1953	63	242 C	48.94	4.8	5.5
Caniçada	Cávado	1955	153	689 B	83.28	4.8	5.5
V. Furnas	Cávado	1972	118	346 C	80.03	9.3	5
Penide	Cávado	1951	0.5	69 D	56.95	10.3	5.5
Guilhofrei	Ave	1938	22	1630 B	101.49	4	5.5
Andorinhas	Ave	1945	1.2	21 D	48.52	3.8	5.5
Pocinho	Douro	1982	81	830 B	84.46	7.5	6.7
Vilar	Douro	1965	100	670 B	58.78	6.2	6.7
Carrapatelo	Douro	1972	140	952 B	52.3	5	6.7
Torrão	Douro	1988	124	651 B	28.99	3.4	6.4
C. Lever	Douro	1985	106	420 C	57.41	5.5	6.7
Fagilde	Mondego	1984	2.8	7.5 D	12.94	5.8	5.5
Aguieira	Mondego	1981	450	2000 A	47.31	5.7	5.5
Raiva	Mondego	1981	21	300 C	103.85	3.3	5.5
Idanha	Tejo	1949	78	678 B	81.19	3.7	5.5
Póvoa	Tejo	1928	22	236 C	83.5	4.3	5.5
Fratel	Tejo	1973	93	750 B	110.95	4	6.7
Marateca	Tejo	1991	37	634 B	80.62	3.8	5.5
Belver	Tejo	1952	13	286 C	108.58	5	6.7
S.ta Luzia	Tejo	1942	54	246 C	45.73	5.5	5.5
Cabril	Tejo	1954	719	2033 A	57.27	5.2	5.5
C. Bode	Tejo	1951	1100	3291 A	56	5.2	5.5
Maranhão	Tejo	1957	220	1960 A	110.01	3.2	6.1
Montargil	Tejo	1958	180	1646 B	86.33	4.5	6.1
Divor	Tejo	1965	12	239 C	39.98	6.9	6.1
Gaia	Guadiana	1967	203	1970 A	77.61	6.4	6.1
Vigia	Guadiana	1981	17	262 C	26.22	5.2	6.1
M. Novo	Guadiana	1982	15	277 C	35.97	6.6	6.7
T. Grande	Guadiana	1984	10	150 C	33.98	5.8	5.8
Beliche	Guadiana	1986	48	292 C	27.15	8.1	5.8
M. Rocha	Sado	1972	105	1100 B	34.38	5.5	6.1
Campilhas	Sado	1954	22	333 C	70.06	7.2	5.8
F. Serne	Sado	1977	5.2	105 C	45.91	7.5	5.8
Roxo	Sado	1968	96	1378 B	37.6	9.3	6.1
Alvito	Sado	1977	133	1480 B	25.73	8.3	6.4
Odivelas	Sado	1972	96	973 B	26.22	11.6	6.4
P. Altar	Sado	1949	94	876 B	62.25	5.2	6.4
Morgável	Morgável	1980	33	340 C	26.62	8.1	6.7
S.ta Clara	Mira	1968	485	1986 A	20.57	6.4	6.1
Bravura	Odiáxere	1958	35	285 C	80.36	8	5.8
Arade	Arade	1955	28	182 C	103.76	4.5	6.4

TP and climatic and soil characteristics affecting the reservoirs: Data for rainfall, alkalinity of the soil, drainage, annual variation of air humidity, hours of insolation, evapotranspiration, and air temperature of the areas where reservoirs are located were collected from an Environment Atlas (ATLAS DO AMBIENTE, 1975, 1978, 1980) or kindly supplied by the Institute of Meteorology (Instituto Nacional de Meteorologia, Lisboa, Portugal) and used in the regressions. All data of the Environment Atlas and specially those for rainfall must be faced in a general way, since the last editions of the Atlas refer to a decade earlier. However, more recent data for rainfall were obtained from the Institute of Meteorology. Even so, since in the two years previous to this study there was practically no rainfall in the whole country, the conclusions of the respective regressions should be taken as the usual tendency. The reservoir affected by the highest values of precipitation was V. Furnas (> 2800 mm/year) in R. Cávado watershed. The lowest recorded values for annual precipitation corresponded to T. Grande and Beliche, two reservoirs of the R. Guadiana watershed (400-500 mm/year). Soil pH was Sound to be quite acid (between 4.5 and 5.5) in rivers Cávado, Lima, Ave and Mondego watersheds, less acid (between 5.5 and 6.5) in rivers Douro and Tejo watersheds, and around neutral (between 6.5 and 7.4) in rivers Guadiana and Sado watersheds. A significant negative correlation was found between rainfall and the pH of the surrounding soils for all 44 reservoirs sampled. A significant negative correlation was also found both between rainfall and alkalinity of the soil and between rainfall and runoff. A significant positive correlation was found between runoff and alkalinity of the soil. Runoff is more intense into the northern reservoirs of rivers CBvado and Ave watersheds. The reservoir V. Furnas, in R. Cávado watershed, is subjected to more than 2200 mm precipitation, therefore it is probably one of the reservoirs affected by very high runoff from the surrounding land. In the south of the country, the reservoirs least affected by runoff are mainly those of the rivers Guadiana and Sado watersheds; the lowest values for precipitation (50-100 mm) corresponded to T. Grande (R. Guadiana) and F. Serne (R. Sado). Humidity is highest in rivers Cávado and Sado watersheds (75-85 %) and lowest in R. Tejo watershed; the lowest found value for humidity was recorded for Marateca Reservoir (R. Tejo). Nevertheless there is not a large variation in humidity throughout the country at a watershed scale. Conversely, annual insolation is highest for the reservoirs in the R. Guadiana watershed (Vigia, M. Novo, and T. Grande exhibited the highest values: 300-3100 hours per year). The highest evapotranspiration values (700-800 mm per year) were attributed to the reservoirs in the rivers CBvado and Ave watersheds, in the north of the country. Lowest mean annual air temperature was recorded for some of the reservoirs in the R. Cávado watershed (A. Rabagão, V. Nova, and V. Furnas, 7.5-10 "C). Highest mean annual air temperature was recorded for the rivers Guadiana and Sado watersheds reservoirs (T. Grande, R. Guadiana, more than 17.5 "C). Regarding the geology, soil composition, and land use around the reservoirs throughout the country: Almost all reservoirs in rivers CBvado and Ave watersheds were constructed on calcium-alkaline granitic soils, with the exception of A. Rabagão and V. Nova reservoirs (R. Cávado). The latter are located on soils which also contain some schist. The reservoirs in the rivers Douro, Mondego, and Tejo watersheds are located either on soils mainly composed of calcium-alkaline granites or on predominantly schistous soils. It was not found a relationship between TP and any of the above described characteristics.

TP and population density in the reservoirs area: Almost all studied reservoirs are located in areas of relatively low population densities, The reservoirs of R. Douro watershed are located in the most densely populated areas (100-250 ind./Km^2) among those sampled, with the only exception of Pocinho (<20 ind./Km^2). R. Sado reservoirs are affected by the lowest population density of all the reservoirs sampled (<20 ind./Km^2). There was not a significant correlation between TP and population densities in the reservoirs catchment areas when the whole set of reservoirs was analysed i.e. at country level.

Correlations were also tried at the drainage basin level, between several environmental variables and the parameters intrinsic to the limnology of the reservoirs, TP included, for all reservoirs of the same watershed. For R. Cávado watershed only one significant positive correlation was found between water pH and volume of the reservoirs. For R. Douro watershed five significant negative correlations were found: TP and rainfall, TP and population density, TP and evapotranspiration, dissolved oxygen and volume of the reservoirs, water pH and volume of the reservoirs. For R. Guadiana watershed there were two significant negative correlations (dissolved oxygen and evapotranspiration, and volume of the reservoirs and cvapotranspiration) and two significant positive correlations (TP and surface area of the reservoirs, and TP and soil pH).

Principal Components Analysis (PCA) was applied to the data of five of the watersheds sampled: those of rivers Cávado, Douro, Tejo, Guadiana, and Sado. These watersheds were chosen because they were the most representative in terms of number of reservoirs sampled. TP exhibited the best absolute score in the first axis for all but R. Guadiana watershed. The first factor accounted for respectively 64 % of the variance in R. Cávado watershed, 75 % in R. Douro watershed, 76 % in R. Tejo watershed. and 70 % in R. Sado watershed.

PCA was also run for the whole set of 44 reservoirs (country level analysis). The measure of sampling adequacy (Kaiser-Meyer-Olkin) was mediocre, therefore those results are not presented here.

DISCUSSION

The purposes of this study –to map TP concentrations ot the Portuguese reservoirs and to classify them according to trophic state– assume greater relevance as cultural eutrophication

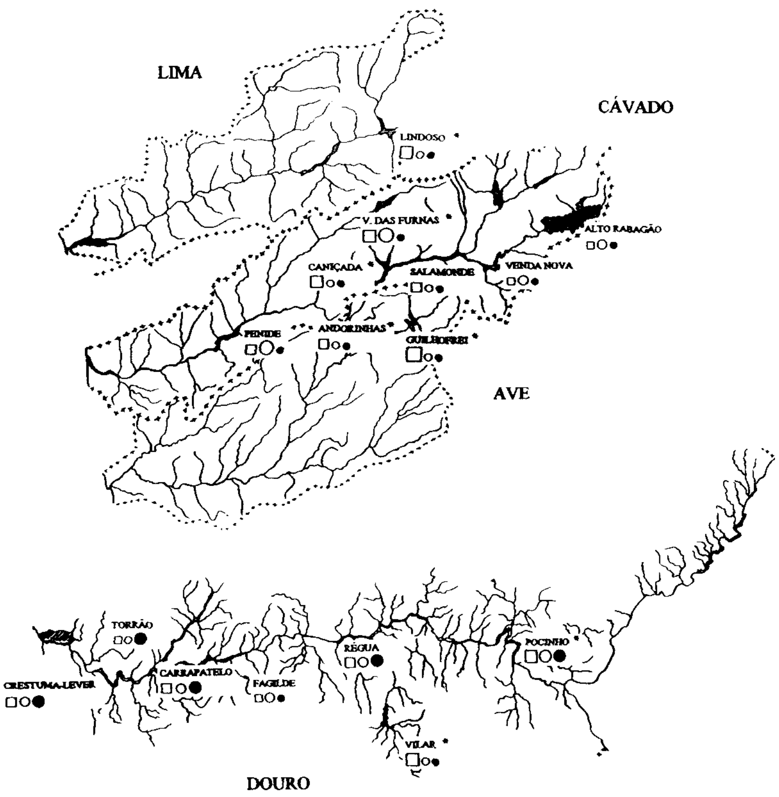

Figure 2. Location of the reservoirs in rivers Lima, Cávado, Ave, and Douro watersheds. Relative magnitudes of TP (❒), DO (0), and water pH (•) are provided, incl-easing quantitites corresponding to increasing sızaes of the respective symbols. Eutrophic reservoirs are marked with an asterisc.
Figura 2. Localización de los embalses en las cuencas de los rios Lima, Cávado, Ave y Duero. Se incluyen las magnitudes relativas de TP (❒), DO (O), y pH (•) del agua, a través del tamaño creciente de los símbolos respectivos. Los embalses eutróficos se señalan con un asterisco.

increases. First of all it is necessary to know these values to effectively manage the reservoirs. Often in these latitudes and because of the dryness of the weather TP values in August September (time of the year samples were taken) are below annual maxima. However, it is best to take as reference for this kind of study values lower than maxima to avoid interpretations based on extreme measurements. On the other hand, it is only with ecosystems perspectives that an efficient management can be achieved. As WETZEL (1996) pointed out, limnological expertise is required to understand the mechanisms regulating the operation of freshwater ecosystems; because limnology is an integrative discipline, it offers the only possible, encompassing way of facing, and eventually solving, eutrophication.

Among the relationships found for Portuguese reservoirs, the significant positive correlation between TP and the age of the reservoirs may reflect the procedure generalized up until about a decade ago: After the dam was built, only large, tall trees would be removed from the prospective lake basin, all other vegetation left in place; as a consequence of inundation, many nutrients (phosphorus surely included) would be released into the water over a relatively short time. In addition, 30-40 years ago it was a common procedure to release domestic sewage of small towns and villages to the reservoirs almost with no treatment (most of the small towns would go no further than secondary treatment at the time).

As contradictory as it seems, it was not observed a significant correlation between TP and population density at country level. This might be because population densities are in general low in the catchment areas and especially because sewage and industrial effluents treatment has been being emphasized during the last decade. The relationship between TP and population density would have been better studied if the area of land draining into each reservoir was also considered. This was not done because such areas were not known with precision for most of the studied reservoirs. It was thought, however, that population density per se would somehow reflect that.

It could be argued that, because of the way pH was estimated in the field (with indicator paper), there was no point in trying to find a correlation between this water parameter and TP. It is true that pH values for the water of the reservoirs could have been underestimated as a result of the method used. However, it was estimated in the same way for all the reservoirs, this rendering the values comparable. On the other hand, soil pH was acid (data obtained from the Environment Atlas) for most of the watersheds studied, except those of the rivers Guadiana and Sado. This may be an indication that water pH might not have been underestimated.

Although some of the obtained correlations (e.g. DO/volume of the reservoir, DO/evapotranspiration, TP/soil pH) were statistically significant, they have no ecological meaning. PCA was performed considering those variables with ecological meaning since the objective of this analysis is to group sampling units according to their ecological resemblances.

TP exhibited the best absolute score in the first axis for PCA on all but one of the five most representative watersheds. TP was the variable used to compute Trophic State Index. In spite of the recommendation of the author of the Index that chlorophyll is the best indicator when one component of the index is used alone, TP coming next (CARLSON. 1977), PCA results reinforce the argument that TP gives a good estimate of trophic state, at least in Portuguese reservoirs. According to

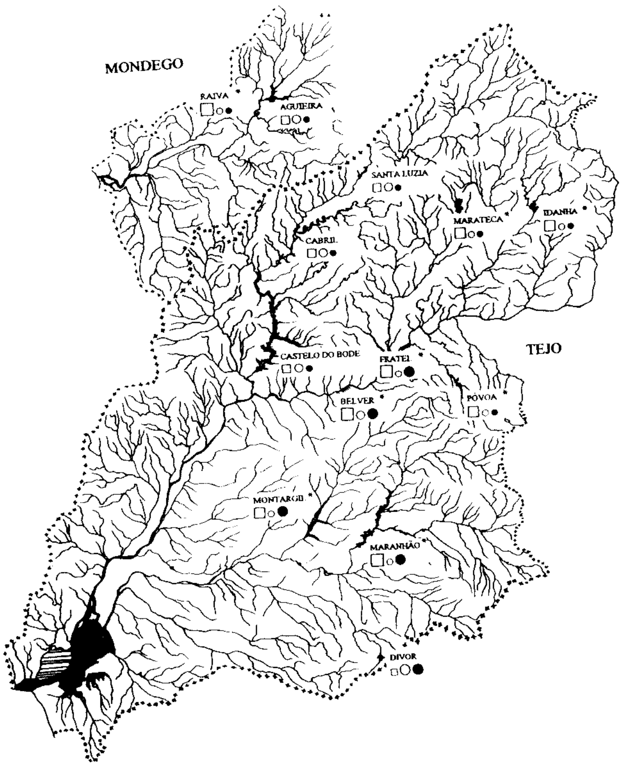

Figure 3. Location of reservoirs in rivers Mondego and Tejo watersheds. Relative magnitudes of TP (□), DO (O), and water pH (•) are provided, increasing quantities corresponding to increasings sizes of the respective symbols. Eutrophic reservoirs are marked with an asterisc.
Figura 3. Localización de los embalses en las cuencas de los ríos Mondego y Tajo. Se incluyen las magnitudes relativas de TP (□), DO (O), y pH (•) del agua, a través del tamaño creciente de los símbolos respectivos. Los embalses eutróficos se señalan con un asterisco.

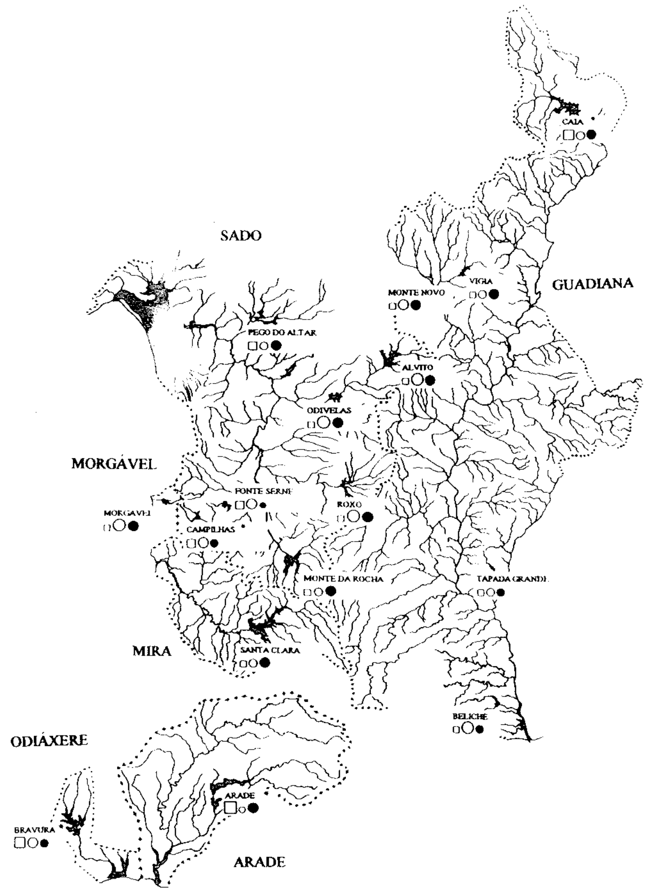

Figure 4. Location of reservoirs in rivers Guadiana, Sado, Morgável, Mira, Odiáxere, and Arade watersheds. Relative magnitudes of TP (□), DO (O), and water pH (•) are provided, increasing quantities corresponding to increasing sizes of the respective symbols. Eutrophic reservoirs are marked with an asterisc.
Figura 4. Localización de los embalses en las cuencas de los ríos Guadiana, Sado Morgável, Mira, Odiáxere y Arade. Se incluyen las magnitudes relativas de TP (□), DO (O) y pH (•) del agua, a través del tamaño creciente de los símbolos eutróficos se señalan con un asterisco.

Carlson's index the drainage basin of R. Sado contained the smallest percentage of eutrophic reservoirs, that of R. Tejo contained the largest percentage of eutrophic reservoirs: 15 % and 64 % respectively. R. Sado watershed is totally located in Portuguese territory, and in an area where rainfall is scarse, thus where recurrent drought years constitute the rule. Less rainfall implies less nutrients brought to the reservoirs by runoff. R. Tejo drainage basin, on the other hand, is very large and extended over the territories of the two Iberian countries (Spain and Portugal) - there might be an accumulation effect in the Portuguese reservoirs, downhill with respect to a much larger area of the drainage basin, thereby also receiving materials from the neighbouring country area of the watershed.

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