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Ecological classification of a set of Mediterranean reservoirs applying the EU Water Framework Directive: A reasonable compromise between science and management

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Abstract

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The Water Framework Directive EU2000/60/EC (WFD) was implemented for reservoirs at a regional scale (northeastern Spain). Twenty-one reservoirs were monitored quarterly over the course of a year. Using principal component analysis, the reservoirs were classified into types according to their geological and morphometric features. The Ecological Quality (EQ) of the reservoirs was assessed by integrating values of total chlorophyll *a*, cyanophyta chlorophyll *a* concentration, fish metrics, Secchi depth, averaged hypolimnetic oxygen concentration and total phosphorus. For each reservoir type, a reference condition of quality was selected. When possible, this reference was the reservoir displaying the best EQ; otherwise expert judgment was used. To allow comparison of quality among reservoirs belonging to different types, thus identifying intrinsic differences, an Ecological Quality Ratio (EQR) was calculated by dividing the EQ value of each reservoir by that of its reference. According to EQR, the majority of the reservoirs accomplished the quality criteria of the WFD. This study identified a number of useful indicators for EQ assessment. Moreover, because the references were chosen among similar reservoirs, low EQR values are indicative of specific problems, such as untreated or wastewater spills or droughts. The results also demonstrate that expert judgment is a reasonable compromise when the low number of water bodies available for the study prevents statistical approaches.

Key words: ecological quality ratio, eutrophication, trophic state, water quality assessment

The European Water Framework Directive (WFD) 2000/60/EC (European Commission 2000) was approved in December 2000 to protect and improve the quality of European waters. Several implementations of the WFD have been published focusing on streams (Oberdorff *et al.* 2002, Munné and Prat 2004), coastal waters (Panayotidis *et al.* 2004) and water management for agriculture (Bazzani *et al.* 2004). There are numerous examples of protocols and applications for lakes and other surface waters (Bernard and Vallee 2003, Moss *et al.* 2003, Schneider *et al.* 2003, White and Irvine 2003, Diekmann *et al.* 2005, Sondergaard *et al.* 2005); however, no implementations have been published specifically for reservoirs, which have ecological properties intermediate between lakes and rivers but different from both.

Eutrophication is the main water quality problem in reservoirs (Vollenweider and Kerekes 1982, Wetzel 2001). They have larger inputs of nutrients and stronger water-level fluctuations than natural lakes, leading to eutrophication and shifts in their biological communities (Vollenweider and

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Kerekes 1982, Wetzel 2001). The attainable ecological potential of a reservoir will greatly depend on (among other factors) the quality of the input water, which will greatly depend on position along the river (Vannote *et al.* 1980). Thus, we propose an approach to classify reservoirs into types depending on position on the river and, therefore, theoretical quality of input water.

Ecological Quality (EQ), mandates establishing five classes (high, good, moderate, poor and bad) for every parameter used in the assessment. The WFD provides extensive guidelines to assess EQ, but only general guidance on how to define the boundaries between classes (Wallin *et al.* 2003). Therefore, according to the proposed approach, the use of nutrient-based indices seems appropriate to define the boundaries between ecological classes. Thus, parameters and boundaries between classes of Trophic State Index (TSI; Carlson 1977) and the Organization for Economic Co-operation and Development, OECD (Vollenweider and Kerekes 1982) classifications were used as a first approach. Fish metrics that link trophic state of waters with abundance and species composition of fish assemblages were also used (Carol *et al.* 2006). Guidelines such as those of the World Health Organization (WHO) for Recreational Waters for cyanophyta (WHO 1993) and the Water Quality Index (WQI; Brown *et al.* 1970) for oxygen conditions were also considered. Some of the boundaries between classes for these indexes were modified using expert criteria. The 10 parameters selected were total chlorophyll *a*, cyanophyta chlorophyll *a* concentration, five different fish metrics, Secchi depth, averaged hypolimnetic oxygen concentration and total phosphorus. This set of parameters was expected to comprehensively reflect the physico-chemical and biological features of the reservoirs and was used to assess the ecological state of the reservoirs.

The obvious lack of unpolluted or pristine reservoirs to be used as references has become one of the emerging problems during the implementation of the WFD (Bennion *et al.* 2004). Reservoirs are one of the most dramatic and irreversible impacts of humans on natural ecosystems due to the concomitant transition from lotic to lentic environment (Nilsson *et al.* 2005) as a result of river damming. Regarding this situation, the choice of a reservoir presenting good EQ as a reference for other reservoirs seems acceptable. Thus, the Ecological Quality Ratio (EQR, calculated by comparing the EQ value of each reservoir with the EQ of the reference) is used to reflect situations where water quality is far from what is expected based only on damming.

The goal of this work is to establish a reliable methodology allowing assessing the Ecological Quality Ratio of reservoirs, following the WFD guidelines, particularly when only a reduced number of water bodies are available, and especially when those bodies are placed in an area of heterogeneous geological settings (e.g., calcareous vs. siliceous watersheds) and human impacts. The specific aims are: (1) the classification of 21 reservoirs (northeastern Spain) into types showing similar hydrological, chemical and geographical features; (2) the assessment of the EQ for every reservoir integrating information from physico-chemical and biological quality elements; (3) the selection of a reference for each type; and (4) the calculation of EQR, comparing the quality of each reservoir with that of the reference.

Material and methods

Sampling of study sites

Reservoirs (Fig. 1) were sampled quarterly (from summer 2002 to spring 2003). In each reservoir, a sampling point was selected near the dam (distances ranged between 200 and 2000 m, depending on reservoir size) and always at the main axis of the reservoir. Temperature, conductivity, percent oxygen saturation and oxygen concentration were measured using a Water Quality Analyzer model T611 from Turo Technology PTY Ltd, Australia. Vertical profiles for all variables were measured (every meter from the surface to the bottom) for each reservoir and showed at what depths strong changes in the water characteristics occurred (usually associated with thermo-, oxi-, or picno-clines), allowing us to characterize epi-, meta- and hypolimnion compartments when present. At representative depths for each of these compartments, and especially before and after clines, chemical samples were collected using a dark, 5-L limnological water sampler from UWITEC, Austria. For nutrient analysis, integrated water samples were collected from the epilimnion using an 8-m tube sampler to avoid small discontinuities (Armengol *et al.* 1999). The Secchi disk depth was also measured.

Nutrients and chlorophyll a

Total reactive phosphorus (TP) was measured directly from nonfiltered water (Grasshoff *et al.* 1983). Chloride was analyzed in a liquid chromatograph model KNK 500-A (KONIK-TECH, Barcelona), supplied with two sensors: a conductivity sensor (Wescan Instruments Inc, Deerfield, USA) and a UV/V sensor (Kontron AG, Munich, Deutschland model 332). A measure of the degree of eutrophication was also gauged from the Carlson's TSI (Carlson 1977). The chlorophyll *a* content in phytoplankton (total and from cyanophyta) was measured using a Fluoroprobe (BBE Moldaenke GmbH, Kiel-Kronshagen, Germany). The sampling was carried out to the bottom of the reservoir or to a maximum depth of 50 m. Measurements were made at

Figure 1.-Study reservoirs in northeast Spain.

short intervals, never more than 50 cm, and the average of the water column was calculated (mg/m^3).

Fish sampling

Fish were sampled from the 14 reservoirs from 19 February to 6 May 2003 by daylight boat electrofishing in the littoral zone and multi-mesh gillnets in the limnetic zone. The electrofishing boat was equipped with a 5.0-GPP Smith-Root engine (providing up to 1000 V and 16 A), and two to nine transects about 500–1000 m in distance were sampled in each reservoir depending on its size. Catch per unit effort (CPUE) of electrofishing transects was computed as the number of fish caught per electrofishing time (provided by the engine in seconds) divided by 100 (to avoid leading zeros). Multi-mesh gillnets were 50 × 1.5 m with 10 panels 5 m in length and meshes ranging from 31 to 260 mm (stretched mesh). Meshes were interspersed within the net (to avoid confusion of the mesh size with environmental gradients) and followed a geometric progression (to optimize efficiency). Depending on the reservoir surface, four to seven multi-mesh gillnets were set in each reservoir overnight at 10 m depth in the water column or at the bottom. The CPUE of gillnets was computed as the number of fish caught per net. We captured 3618 fishes from 19 different species; most were released (for further details on the same fish data see Carol *et al.* 2006, Carol and García-Berthou 2007).

Data analysis

To group similar reservoirs, data were analyzed with ordination techniques (principal component analysis) with most variables log-transformed. The goodness of fit of the cyanophyta pigment data to a Gamma distribution was tested with a Chi-square test. Differences between types of reservoirs were tested with one-way ANOVA, followed by Fisher LSD post-hoc test when significant differences were found ($p < 0.05$). In the results, variation is expressed as standard deviation. All statistical analyses were performed using Statistica 6.0 (Statsoft Inc, USA). Data on reservoir characteristics were provided by the Catalan Water Agency.

Calculation of EQ and EQR

We selected 10 parameters to calculate EQ: total chlorophyll *a* (mg m^{-3}), cyanophyta chlorophyll *a* (mg/m^3), total

Table 1.-Parameters and scores selected to calculate the Ecological Quality. These ranges were adjusted to the different reservoir types. According to the observed value of the parameter, a value ranging between 5 (high quality) and 1 (bad quality) is assigned: High = 5, Good = 4, Moderate = 3, Poor = 2, Bad = 1; in the case of fish metrics High and Good = 5, Moderate = 3, Poor and Bad = 1.

Types	Parameters	High	Good	Moderate	Poor	Bad
I, II, III and IV	Chlorophyll-*a* (mg/m^3)	0–1	1–2.5	2.5–8	8–25	>25
	Cyanophyta chlorophyll (mg/m^3)	0–0.5	0.5–1	1–5	5–20	>20
	% anomalies	<2%		2–5%	>5%	
	CPUE of littoral carp	<0.005		0.005–0.009	>0.009	
	CPUE of limnetic carp	<0.261		0.261–0.522	>0.522	
	% of littoral carp	<32%		32–64%	>64%	
	% of limnetic carp	<27%		27–53%	>53%	
	Secchi disk (m)	>12	12–6	6–3	3–1.5	<1.5
	% hypolimnetic oxygen	100–80	80–60	60–40	40–20	20–0
	Total phosphorus (mg/m^3)	0–4	4–10	10–35	35–100	>100
V	Chlorophyll-*a* (mg/m^3)	0–2.5	2.5–10	10–15	15–25	>25
	Cyanophyta chlorophyll (mg/m^3)	0–0.5	0.5–1	1–5	5–20	>20
	% anomalies	<2%		2–5%	>5%	
	CPUE of littoral carp	<0.005		0.005–0.009	>0.009	
	CPUE of limnetic carp	<0.261		0.261–0.522	>0.522	
	% of littoral carp	<32%		32–64%	>64%	
	% of limnetic carp	<27%		27–53%	>53%	
	Secchi disk (m)	>8	8–4	4–2	2–1	<1
	% hypolimnetic oxygen	100–75	75–50	50–35	35–20	20–0
	Total phosphorus (mg/m^3)	0–15	15–25	25–35	35–70	>70
VI	Chlorophyll-*a* (mg/m^3)	0–5	5–15	15–25	25–50	>50
	Cyanophyta chlorophyll (mg/m^3)	0–0.5	0.5–1	1–5	5–20	>20
	% anomalies	<2%		5–2%	>5%	
	CPUE of littoral carp	<0.005		0.009–0.005	>0.009	
	CPUE of limnetic carp	<0.261		0.522–0.261	>0.522	
	% of littoral carp	<32%		64–32%	>64%	
	% of limnetic carp	<27%		53–27%	>53%	
	Secchi disk (m)	>6	6–3	3–2	2–1	<1
	% hypolimnetic oxygen	100–60	60–30	30–15	15–5	5–0
	Total phosphorus (mg/m^3)	0–16	16–32	32–64	64–128	>128

and percent CPUE of limnetic and littoral common carp *Cyprinus carpio* (Carol *et al.* 2006), percentage of fish with anomalies, Secchi disk depth (m), average percentage of hypolimnetic oxygen concentration, and total phosphorus (mg/m^3) concentration in the water column (see Table 1). The ranges in ecological status according to the WFD were adjusted to the different reservoir types to take into account variations resulting from reservoir type. According to the observed values of the parameters, values ranging between 5 (high quality) and 1 (bad quality) were assigned. Thus, EQ was assessed following the WFD guidelines (Table 2). Finally, EQR was calculated by dividing the EQ value of each water body by its reference EQ value, which was the EQ assigned to high quality for the reservoir type being considered. According to their EQR values, reservoirs were assigned to one of four categories: good and above, moderate, poor, or bad (Table 3).

Results

Reservoir typology

Reservoir typology was established using some of the descriptors proposed in system *B* of the WFD (physical and chemical factors): altitude, latitude and longitude (using distance to the sea), size (using reservoir volume and catchment area), and geology (using chloride concentration). The indirect gradient analysis performed, a PCA (Fig. 4), showed that many of the variables were interdependent, and the first two axes of the PCA explained 45.3 and 40.3% of the total variation, respectively. The first PCA axis summarized these correlations displaying a geographical gradient, in part related to altitude and distance to the sea, from lowland reservoirs with high chloride concentration (Foix, Flix, Riudecanyes and Riba-roja) to higher altitude reservoirs with low chloride, (Escales and Canelles). The second PCA axis

Table 2.-Calculation of Ecological Quality. The first step is to assess the ecological status (S) of each parameter using Table 1. The second step is to average the status values of the parameters of algae and fish. The third step is to select the worst value from the biological parameters (algae and fishes) and average the status of the physical and chemical parameters. Under the "one-out, all-out" WFD procedure, the worst value among the biological and physico-chemical parameters is selected as Ecological Quality.

First step	Second step	Third step	Fourth step
Chlorophyll-*a* (mg/m^3)	$\frac{\sum S \text{ algae}}{2}$	The worst value will represent the biological state	The worst value will represent the Ecological Quality
Cyanophyta chlorophyll (mg/m^3)			
% anomalies	$\frac{\sum S \text{ fish}}{5}$		
CPUE of littoral carp			
CPUE of limnetic carp			
% of littoral carp			
% of limnetic carp			
Averaged % oxygen saturation		$\frac{\sum S \text{ Phys-Chem}}{3}$	
Total phosphorus (mg/m^3)			
Averaged % oxygen saturation			

distinguished the two last reservoirs of the Ebro River (Ribaroja and Flix) from the rest because of their large basin surface and chloride concentration. Santa Fe, the smallest reservoir with the smallest catchment area, was situated on the opposite side. Significant correlations ($p < 0.05$) were found between chloride and altitude (−0.67); distance to the sea and volume (0.65) and chloride (−0.44); and catchment area and volume (0.49), altitude (−0.55), and distance to the sea (0.45). The subsequent establishment of the boundaries between types was made by expert decision (Fig. 2 and 3) and allowed classification of the reservoirs into six types (Fig. 2) using a dichotomical key (Fig. 3).

Table 3.-Results for Ecological Quality (EQ) and Ecological Quality Ratio (calculated dividing each reservoir's EQ by the EQ of the referent; reservoirs classified according to the following EQR ranges: 1–0.9 High, 0.9–0.7 good, 0.7–0.5 moderate, 0.5–0.3 poor, 0.3–0 bad). The final results were: 6 reservoirs showed high, 10 good, 4 moderate and 1 regular EQR. Reservoirs in bold are the referents. Two letter codes used in Fig. 4 are also included.

Type	Reservoir	EQ	EQR	
I	Escales (ES)	4.00	1.00	High
II	Santa Fe (FE)	2.00	1.00	High
III	Siurana (SI)	2.67	1.00	High
	Foix (FO)	1.00	0.38	Poor
	Riudecanyes (RC)	2.00	0.75	Good
IV	Canelles (CN)	4.67	1.00	High
	Camarasa (CM)	3.33	0.71	Good
	Boadella (BO)	3.00	0.64	Moderate
	La Baells (BA)	3.33	0.71	Good
	La Llossa del Cavall (LL)	3.67	0.79	Good
	Oliana (OL)	2.67	0.57	Moderate
	Rialb (RI)	2.33	0.50	Moderate
	Sant Llorenç (LM)	3.33	0.71	Good
	Sant Ponç (PO)	3.33	0.71	Good
	Santa Ana (AN)	3.67	0.79	Good
	Talarn (TA)	4.00	0.86	Good
	Terradets (TR)	3.00	0.64	Moderate
V	Expert model	4.33	1.00	High
	Flix (FL)	4.33	1.00	High
	Riba-Roja (RR)	4.00	0.92	High
VI	Expert model	3.00	1.00	High
	Sau (SA)	2.67	0.89	Good
	Susqueda (SU)	2.67	0.89	Good

Escales was the only member of Type I (high-altitude large reservoirs), whereas Santa Fe was classified as Type II (high-altitude small reservoirs with deciduous forested catchment). A threshold placed at 815 m allowed discrimination of the two high altitude types from the others (Fig. 4). Secondarily, a volume of 20 hm^3 discriminated between Type I and Type II. Siurana, Foix and Riudecanyes composed Type III, containing small coastal reservoirs with distance to the sea being the factor allowing discrimination of these reservoirs (Fig. 4). Type IV was formed by all reservoirs without extreme characteristics (i.e., at medium-altitude and lowland and being >25 km away from the coast): Canelles, Camarasa, Boadella, La Baells, La Llossa del Cavall, Oliana, Rialb, Sant Llorenç de Montgai, Sant Ponç, Santa Ana, Talarn and Terradets. Chloride concentration values of >40 ppm served as a discriminating characteristic between Type IV and the last two types, those with huge catchment areas. A threshold value of 1000 km^2 discriminated between Type V (Flix and Ribarroja, with >1000 km^2) and Type VI (Sau and Susqueda, with <1000 km^2).

EQ of reservoirs and EQR

The only Type I reservoir (Escales) showed a good EQ (Table 3), and it was assigned as a reference condition (EQR = 1). In

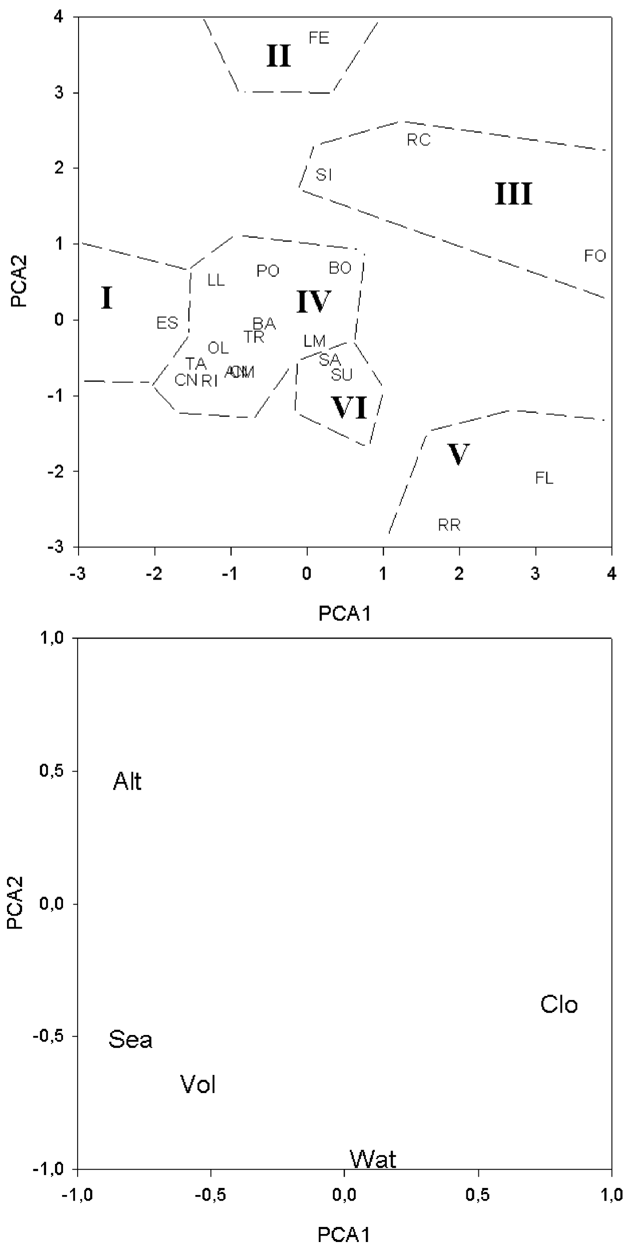

Figure 2.-Principal component analysis of the physical and chemical variables of reservoirs. (A) Factor scores of the reservoirs for the first two principal components (see Table 3 for reservoir codes). Types I to VI shown. (B) Factor loadings of the variables. The typology was established using hydrological, chemical and geographical variables: (altitude-Alt), latitude and longitude (distance to the sea = Sea), size (using the volume = Vol and the reservoir's catchment area = Wat) and geology (using chloride concentration as parameter = Clo).

spite of its headwater position and relatively low chlorophyll values in the oligotrophic range (4–12 mg/m^3), the amount of phosphorus released from hypolimnion and sediments (13 mg/m^3) during the mixing period produced mesotrophic conditions during the entire year.

Santa Fe, the only Type II reservoir, showed high values of both phosphorus (17–35 mg/m^3) and chlorophyll (43–110 mg/m^3) because of its natural dystrophic conditions. Cyanophyta were present in high concentrations (7–11 mg/m^3 of chlorophyll), mainly consisting of *Microcystis* sp. and *Gomphospheria* sp. (unpublished data). Although Santa Fe's value was 2 (poor Ecological Quality), its EQR was 1 because it was its own reference.

Type III reservoirs showed the worst EQ of all groups, averaging 1.8 (between bad and poor). Foix reservoir showed the highest phosphorus values of all the reservoirs (250–350 mg/m^3) and concomitant extreme values of chlorophyll (78–823 mg/m^3), and high concentrations of cyanobacteria (Caputo *et al.* 2008). The other two reservoirs, despite showing mesotrophic values of phosphorus (4–50 mg/m^3), had eutrophic conditions with high values of chlorophyll (17–80 mg/m^3) resulting from small size and critical changes in their water levels due to use for irrigation purposes. Using Siurana as a reference, Foix and Riudecanyes scored 0.38 (moderate) and 0.75 (good) EQRs, respectively. Thus, according to the WFD, Foix will need to implement programs to improve quality.

Type IV reservoirs represented the largest group with 12 reservoirs placed on medium-sized rivers, most (eight) located on adjacent tributaries of the Ebro River (the river with the highest water flow of the Iberian Peninsula; Fig. 1). These reservoirs averaged an EQ of 3.36 (between moderate and good), but their average EQR (using Canelles as reference) was 0.72, indicating a good state. Most of these reservoirs showed mesotrophic conditions during the entire year, and only four presented eutrophic conditions during some part of the year. Consequently, these four reservoirs showed a moderate state and need to be improved: Rialb because it is a new reservoir in the filling process; Boadella, Oliana and Terradets because of eventual inputs of poor quality water.

Type V reservoirs (Flix and Riba-Roja) were located at the lower reaches of the Ebro River. Presence of an upstream reservoir (Mequinenza, not included in this study, with a volume of 1533.8 hm^3 and a residence time of 72.5 days) significantly reduces the amount of nutrients. Both reservoirs presented mesotrophic conditions during the entire year, with some episodic eutrophic conditions; the zebra mussel is present in both reservoirs (Navarro *et al.* 2006). Expert judgment was applied for this type. Reference values were chosen to be in the range of values shown by both reservoirs, considering that their present ecological status is of good quality. Thus, EQ values were between 4 and 4.33, between good and high, thus displaying high EQR values.

Type VI reservoirs, similar to Type IV, were associated with a relatively large river (the Ter). Its watershed suffers from

<table>
<tr><td colspan="6">Altitude</td></tr>
<tr><td colspan="2">> 815 m.</td><td colspan="4">< 815 m.</td></tr>
<tr><td colspan="2">Volume</td><td colspan="4">Distance from the coast</td></tr>
<tr><td>> 20 hm.</td><td>< 20 hm.</td><td>< 25 km.</td><td colspan="3">> 25 km.</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">Chloride concentration</td></tr>
<tr><td></td><td></td><td></td><td>< 40 ppm</td><td colspan="2">> 40 ppm</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">Catchment area</td></tr>
<tr><td></td><td></td><td></td><td></td><td>> 10^3 Km^2</td><td>< 10^3 Km^2</td></tr>
<tr><td>Type I</td><td>Type II</td><td>Type III</td><td>Type IV</td><td>Type V</td><td>Type VI</td></tr>
</table>

Figure 3.-Classification of reservoir typology.

intense human pressure, especially intensive agriculture and farming facilities, which produce a large amount of diffuse nutrient input stored in the sediment over the course of decades. Despite the implementation of a sanitation plan that has greatly reduced the nutrient inputs, these reservoirs will continue to be in the eutrophic or hypereutrophic range for a number of years (78 ± 80 mg/m^3 and 62 ± 33 mg/m^3 phosphorus). Expert judgment was applied in choosing reference values, with the values of the parameters being quite close to those observed in the reservoirs.

Using the annual average values of chlorophyll, Secchi disk and TP, differences between types were analyzed (Table 4). The results show that types II and III clearly differed from the rest because of their high chlorophyll concentrations (total and from cyanophyta), and types III and VI because of their lower percent oxygen. The Secchi disk values did not show any difference between types. The fish data have been previously analyzed in detail elsewhere (Carol *et al.* 2006), and the five fish metrics applied in this paper (absolute and relative abundances of littoral and limnetic carp and percentage of fish with anomalies) were shown to be well correlated with the trophic state (phosphorus or chlorophyll concentration) and shown not to depend on reservoir or river basin size or altitude.

Because of the toxicological relevance of cyanotoxins, cyanophyta chlorophyll *a* was analyzed (81 data points from 21 reservoirs) to assess the risk of exceeding 1 μg L^{-1}, the maximum value allowed for good EQ. No significant

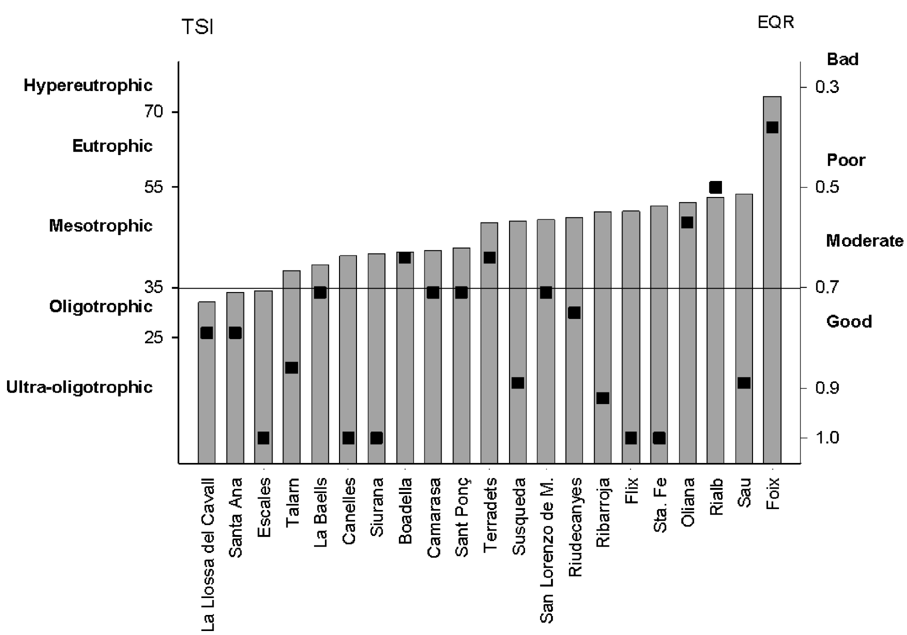

Figure 4.-Comparison of the trophic state index (TSI) and the EQR values obtained. The threshold proposed to establish the limit of the "good and above" EQR class is the TSI oligotrophic limit (35).

Table 4.-Top: annual averaged results of every reservoir type for: total chlorophyll *a* (Chl-*a*), chlorophyll *a* from cyanophyta (Chl-*a* Cyan.), total phosphorus (TP), Secchi depth (SD), and % oxygen saturation (%Ox). Bottom: differences between types for the variable are indicated as Chl = total chlorophyll *a*, Cya = chlorophyll *a* from cyanophyta, TP = total phosphorus, Ox = % oxygen (Fisher LSD test).

Chlorophyll, nutrients, Secchi disk and oxygen					
Type	**Chl-a (mg/m^3)**	**Chl-a Cyan. (mg/m^3)**	**TP (mg/m^3)**	**SD (mg/m^3)**	**%Ox**
I	10 ± 5	0.2 ± 0.4	9 ± 4	5.8 ± 0.9	85 ± 1
II	71 ± 32	7.4 ± 11.2	26 ± 8	2.1 ± 0.6	77 ± 18
III	171 ± 263	8.4 ± 10.9	133 ± 152	9.2 ± 21.9	61 ± 33
IV	14 ± 10	0.6 ± 0.8	36 ± 70	12.2 ± 57.2	91 ± 19
V	16 ± 11	1 ± 1.3	40 ± 26	26.4 ± 54.7	99 ± 58
VI	79 ± 81	0.7 ± 1.4	62 ± 32	4.2 ± 2.5	51 ± 14
Differences between types					
Type	**VI**	**V**	**IV**	**III**	**II**
I				Chl. Cya. TP	Cya.
II	Cya.	Cya.	Cya.	Chl. TP	
III	Chl. Cya. TP	Chl. Cya. TP. Ox	Chl. Cya. TP. Ox		
IV	Ox				
V	Ox				

differences were found between transformed data and a Gamma distribution (10 categories; Chi-Square = 2.71, adjusted df = 2, $p = 0.25$). Using the probability distribution function (shape parameter = 0.42), the probabilities of exceeding the limit values of 1 and 5 μg L^{-1} were 19% and 4%, respectively. The six samples over the 5 μg L^{-1} limit were from Santa Fe, Foix and Riudecanyes reservoirs. During the summer, only Type III reservoirs showed values representing an ecological or human-health risk.

Calculation of EQR

For each of the 10 parameters, we used the summer value (Table 5) to calculate the EQ. To calculate the EQR, real values were first transformed to a value ranging from 5 (high) to 1 (poor) using Table 1. Second, values were integrated to a single score (see procedure in Table 2). Third, EQR were calculated by dividing each reservoir EQ by the EQ of the reference (Table 3), and reservoirs were classified according to the following EQR ranges: 1–0.9 high, 0.9–0.7 good, 0.7–0.5 moderate, 0.5–0.3 poor, 0.3–0 bad. Six reservoirs showed high, 10 good, four moderate and one poor EQR. Therefore, 16 reservoirs are already in the good and above status, and five need to be improved.

Discussion

Trophic State of the reservoirs

Only reservoirs placed in upstream reaches of low-impacted watershed streams showed oligotrophic conditions (Fig. 2) because of the relatively small catchment areas and the low nutrient load of water incomes (Allan 1996). This was the case for Escales (oligotrophic), but not for Santa Fe, which showed a TSI of 51, similar to eutrophic reservoirs (Armengol *et al.* 1999). The catchment area of Santa Fe is fully covered by deciduous trees (*Fagus sylvatica* and *Castanea sativa*). The large amount of leaf biomass entering the reservoir in autumn and its small size make this reservoir dystrophic (Wetzel 2001). For some dates, this reservoir had 35 μg L^{-1} TP, a value considered within the range of eutrophic systems (Vollenweider and Kerekes 1982) and twice as high as the maximum TP values in Escales. Most of the mesotrophic reservoirs showed the expected quality according to their position in the stream (Vannote *et al.* 1980), which is reflected by the calculated EQR, most of which are good or above. Among the eutrophic reservoirs (during summer), Sau and Susqueda are both located in an intensively farmed and agricultural watershed, resulting in large inflow of nutrients (Marcé *et al.* 2004). Riba-roja and Flix have the largest watersheds (most of that of the Ebro River). Despite the implementation of sanitation plans in both Ter (Armengol *et al.* 1999) and Ebro watersheds (Ibáñez *et al.* 2008) a noticeable quantity of phosphorus from diffuse sources and from resuspended sediments still arrives in these systems (Marcé *et al.* 2004) and promotes algal growth (Feijoó *et al.* 2008). Rialb is a newly built reservoir and thus in the process of being filled, resulting in an active decomposition of flooded organic matter (Baxter and Glaude 1980) and thus eutrophic conditions. Oliana receives untreated wastewaters. The only hypereutrophic reservoir is Foix, which receives untreated wastewater, and, being the shallowest (average depth of 7–12 m),

Table 5.-Values used to calculate the Ecological Quality (Summer values): total chlorophyll *a*, cyanophyta chlorophyll *a*, percentage of fish with anomalies, total and percent catch per unit of effort of limnetic and littoral carp, Secchi disk, % hypolimnetic oxygen saturation, and the total phosphorus concentration in the water column.

Type	Reservoir	Chl-a (mg/m^3)	Cyan. (mg/m^3)	% an	CPUElit	CPUElim	%lito	% lim	DS (m)	%Oxi	TP (mg/m^3)
I	Escales	2	0.0384	0	0	0.0602	0.00	4.68	6.77	87	17
II	Sta. Fe	5.4	0.0000	0	0.0003	0.0000	1.89	0.00	2.57	32	35
III	Siurana	1.5	0.0132						5.51	39	10
	Foix	22.2	31.0939	82.93	0.0155	0.8714	83.47	65.03	0.75	6	297
	Riudecanyes	10.8	15.2709	0	0.0015	0.4133	39.59	44.28	1.11	71	4
IV	Canelles	0.9	0.0912						7.46	103	2
	Camarasa	2.8	0.1334	0	0.0079	0.1505	16.07	24.31	4	72	13
	Boadella	3.4	0.0000	0	0.0012	0.0000	12.09	0.00	3	61	17
	La Baells	2	0.1099	0	0.0005	0.0000	0.40	0.00	4.34	62	10
	La Llossa	2.6	0.1710						4.78	62	7
	Oliana	4.9	1.7783						4.76	52	42
	Rialb	7.8	0.0776						1.69	53	38
	Sant Llorenç	2.6	0.1127						1.52	104	23
	Sant Ponç	1.3	0.0136	0	0.0047	0.0602	4.00	13.50	1.6	86	12
	Santa Ana	1.3	0.0880	0	0.0007	0.4686	17.62	45.89	4	86	12
	Talarn	1.4	0.0400						7.35	83	15
	Terradets	1.8	1.7869	0	0.0068	0.0000	63.63	0.00	0.78	91	27
V	Model	2.5	1.0000	2.18	0.0019	0.0000	4.42	0.00	6	75	15
	Flix	2.35	0.0000	2.18	0.0019	0.0000	4.42	0.00	5.85	56	0
	Ribarroja	4.33	0.0513	0	0.0051	0.1003	3.03	8.42	5.35	43	4
VI	Model	15	1	2.18	0.0019	0.0000	4.42	0.00	3	30	32
	Sau	25.2	0.0158	0	0.0005	0.5170	100.00	34.52	1.34	22	32
	Susqueda	22.6	0.0000	0	0.0003	0.3022	11.64	84.47	1.62	27	32

wind easily resuspends highly nutrient-enriched sediments (Kleeberg and Dudel 1997), increasing nutrient concentration in the water column. The remaining reservoirs displayed different degrees of mesotrophy.

Typology

The special characteristics of Santa Fe (discussed previously) led to it being assigned its own type. Because its nutrient status is "natural" and no human activities are involved, it was necessary to separate high mountain reservoirs (>815 m) into two types to achieve quality criteria: Type I for large (>20 hm), high mountain (<815 m) reservoirs and Type II for small ones (<20 hm). Type III reservoirs are located in intensively agricultural areas, and thus their reduced catchment areas support similar human activities that are easily identifiable and controllable. From the various mid-position reservoirs, most of them forming Type IV (Fig. 4), two reservoirs, Sau and Susqueda (previously described), must be emphasized. These and the other two located in the lower reaches of the Ebro River (Riba-roja and Flix) have the same problem: a large catchment area involving a great number of diffuse, difficult to control nutrient sources. To discriminate among these four reservoirs, we used chloride concentration, a tracer and conservative element of the waters (Long *et al.* 1993), which can reveal the type of geology and, more important, the size and sometimes degree of anthropic nature of the catchment area. Finally, it was possible to distinguish among the Ebro (Type V) and Ter reservoirs (Type IV) using catchment area. By classifying the largest reservoirs together and selecting reference conditions by expert judgment, achievement of the water quality objectives will be affordable. The WFD aims at achieving scores of good and above status for all water bodies by 2015. Because this ecological status or potential status is the goal of the WFD implementation, the remaining discussion focuses on how to set limit values for each parameter used for EQ assessment.

Total chlorophyll a

Types II, IV and V showed mesotrophic conditions, and Types III and VI eutrophic. Only Type I (high mountain, big volume reservoirs) showed values in the range of oligotrophic conditions. Thus, the limit value proposed for the good EQ class is 2.5 mg/m^3 chlorophyll *a* for Types I–IV, which corresponds to the TSI and OECD oligotrophic state. The limits among the rest of the EQ classes (high to bad) were adjusted to the OECD limits (Vollenweider and Kerekes 1982) as follows: ultra-oligotrophic = high;

oligotrophic = good; mesotrophic = moderate; eutrophic = poor; and hypereutrophic = bad. For Types V and VI, limits for good EQ and above were placed at 10 and 15 mg/m^3 chlorophyll *a*, respectively, values considered to be eutrophic according to both OECD and TSI, but in accordance with the particular characteristics of these two Types (discussed above).

Cyanophyta chlorophyll a (mg/m^3)

Cyanophyta occur widely in lakes, reservoirs, ponds and slow-flowing rivers. Many species are known to produce toxins, a number of which are health concerns. Monitoring the number of blue-green cells or specific chlorophyll *a* concentration is one of the most widely used management tools to control the risk posed by these bacteria (WHO 1993). According to WHO guidelines, a limit of 2000 cyanophyta cells mL^{-1}, equivalent to 1 $\mu g\ L^{-1}$ cyanophyta chlorophyll *a* and equivalent to 0.4–2 μg microcystin (World Health Organization 2003), for all reservoir types was established between good and moderate classes. A value of 5 (exceeded only in six cases) was placed between moderate and poor. The proposed limit (1 μgL^{-1}) has a security factor of 10 in comparison with the limit for "relatively low probability of adverse health effects" of 20,000 cyanophyta cells mL^{-1} proposed by WHO for recreational waters (WHO 2003), which was derived from epidemiological studies (Pilotto *et al.* 1997). The high values shown by Santa Fe (dystrophic) and Foix (hypereutrophic) are to be expected (Demirkalp *et al.* 2004). Foix reservoir is hypereutrophic, with severe problems of cultural eutrophication owing to human activity in the drainage basin. Riudecanyes, an irrigation reservoir, is sometimes almost empty (under 10% of its capacity), which could explain these episodes (Williams *et al.* 2005). None of these reservoirs is used for drinking water production.

Fish metrics

Richness and other conventional fish metrics were not related to water quality of the reservoirs (Carol *et al.* 2006). In contrast, the total and relative abundance (CPUE) of common carp (*Cyprinus carpio*) in the littoral (electrofishing) and limnetic (gillnet) zones were well correlated with total phosphorus and other trophic state variables (Carol *et al.* 2006). Additionally, the percentage of fish with anomalies was also related to the trophic state. Carp, present in the 14 reservoirs where fish were sampled, are an invasive species widely introduced worldwide with well-known effects on water turbidity, nutrient resuspension (Lougheed *et al.* 1998) and macrophyte declines (Crivelli 1983). For scoring, the metrics of carp were trisected following conventional procedures for reservoir fish (McDounough and Hickman 1999). Note that the absolute abundance scores must be calibrated in each sampling campaign in contrast to the relative (percentage) abundance.

Secchi disk

The limit value of the Secchi disk depth for "good and above" EQ is 6 m, which corresponds to oligotrophic or low eutrophic conditions, according to TSI and OECD. Values of 4 and 3 m (both in the mesotrophic range) were chosen for Types V and VI, respectively. Similar to the case of total chlorophyll *a*, standard OECD limits were used for the rest of the EQ classes. Secchi disk measurements showed significantly low and negative correlations with TP (−0.26) and SS (−0.29), but these two variables showed a significant positive correlation of 0.56. These relatively low correlation values are due to the high turbidity of reservoirs caused by the large amount of suspended solids carried by the rivers and by the erosion of the reservoir shores due to changes in water level (Armengol *et al.* 2003). Despite the suspended solids, the positive correlation between total phosphorus and the Secchi disk indicates that both the TSI and OECD models are valid for this set of reservoirs.

Averaged percentage of hypolimnetic oxygen

The averaged oxygen percentages of the water columns of the reservoirs were 72 ± 20 (summer), 74 ± 20 (autumn), 95 ± 38 (winter) and 94 ± 31 (spring). Summer showed the lowest oxygen conditions for all reservoirs, with values of 62 ± 27 in the hypolimnion. Six reservoirs showed oxygen hypolimnetic values under 50%: Foix, Riba Roja, Santa Fe, Siurana, Sau and Susqueda. At low dissolved oxygen concentrations, phosphorus, usually the most limiting nutrient for growth of algae, is released from the sediment into the water (Cooke *et al.* 1986). Therefore, the hypolimnetic oxygen concentration during summer is a good estimator of the capacity of the system to process its nutrient loads (Wetzel 2001). Using the WQI (Brown *et al.* 1970) for oxygen conditions, a value of 80% oxygen saturation was selected as the limit for good EQ. This value is also considered by other national agencies to maintain beneficial use and ecological integrity of water bodies (U.S. Environmental Protection and Region III 2003). Lower oxygen limits of 50 and 30% were set for Types V and VI, respectively, due to their particular conditions.

Total phosphorus concentration in the water column

The phosphorus limit proposed for good EQ (for Types I, II, III and IV) is 10 mg/m^3, the same as the OECD limit between oligotrophic and mesotrophic. Similar to oxygen, limits for

Types V and VI were 25 and 32 mg/m^3, respectively (Table 1).

EQR compared to Trophic State Index

Carlson's TSI index is the rationale behind EQR calculations, so comparison of the two methods (Fig. 2) seems appropriate for assessment of the feasibility of the EQR. According to TSI, only three reservoirs, all situated in the upper reaches of low human impact watersheds, showed oligotrophic conditions; one showed hypereutrophic conditions, and the rest were mesotrophic (Fig. 2). Assuming that mesotrophic conditions are equivalent to moderate EQR, all of these reservoirs should improve in quality (mainly reducing the nutrient input). Considering that many of these reservoirs are placed in middle and low stream reaches (inherently receiving a considerable amount of nutrients), enhancement of the trophic state is not a viable solution.

A more logical question is: does the EQ of the reservoir correspond with its position along the stream? The EQR will indeed allow reservoir-managers to answer this question. Because we used similar systems showing better quality water conditions as reference conditions (to take into account the inherent effect of the construction of the reservoir), the EQR indicates deviations from the "expected" water quality. After applying the EQR calculation, results showed a notable improvement of quality. Some of the reservoirs showed the maximum quality, because they were selected as references and thus achieved a value of 1 for EQR; most of the remaining reservoirs showed good or above conditions when adjusted according to type. Finally, some reservoirs showed important deviations with regard to the good EQR, but these deviations are a result of well-known and identified problems, which have affordable solutions. Some of the reservoirs (the newest) are still in the process of being filled. This process produces an increased trophic level due to the digestion of the entire biomass of the basin; for this reason, Rialb and La Llossa del Cavall showed values of moderate and below EQR, but we can expect a natural process of improvement during the next years. All of these results show that the method applied to calculate EQR allows discrimination of reservoirs into a wide range of quality water conditions.

Comparing different EQRs

Because EQR were not formerly available for these or similar reservoirs, a comparison of the results obtained was achieved using the Danish EQR system (Sondergaard *et al.* 2005). The Danish EQR system uses a wide range of variables (22), but comparison was only possible with the ones shared: total chlorophyll *a*, cyanophyta chlorophyll *a* (measured as biovolume), Secchi disk depth and total phosphorus. Using the Danish method, 13 reservoirs showed good or above conditions, five moderate, two poor and one bad. Compared to our results (Table 3), it is noteworthy that the number of good or above is quite similar possibly because both systems are based on trophic characteristics, so many of the variables are directly or indirectly correlated with total phosphorus.

Seasonality of monitoring and use of reference values

There is widespread agreement that reservoirs in temperate latitudes often show their worst conditions during the summer stratification period, especially because the hypolimnetic oxygen may suffer depletion (Nurnberg 1995). This may reflect a high load of nutrients and the incapacity of the ecosystem to assume them. Oxygen depletion has other negative consequences on water quality: bad odor or taste (for drinking or recreational uses), metal and nutrient resolubilization from sediments, alteration of fish and algal communities, and a favorable period for toxic algal blooms (Heresztyn and Nicholson 1997, Jacoby *et al.* 2000). Furthermore, during summer, the reservoirs showed the highest average value of total chlorophyll *a* (80 ± 178.4 mg/m^3); therefore, yearly sampling is proposed, coinciding with the strongest stratification period. In addition, the values of summer sampling (2002) may serve as a reference to assess the temporal evolution of the EQR during the next years.

In our opinion, and similar to the case of rivers in this region, large classification units are not useful for local management because of the environmental heterogeneity typical of Mediterranean watersheds (Munne and Prat 2004). Future monitoring programs will provide further data needed to elucidate whether the EQR status boundaries and reservoir types proposed in this study work in accordance with the spirit of the WFD.

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