# Assessing Ecological Integrity in Large Reservoirs According to the Water Framework Directive

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**Abstract** In this chapter we review the implementation of the Water Framework Directive in Catalan large reservoirs and the impact of the first Program of Measures on the ecological quality of these water bodies. In this case, the implementation faced a big challenge, resulting from combining a reduced number of water bodies located on highly heterogeneous geological setting and suffering from different and contrasting human impacts. This chapter introduces the proposed methodology, later assesses how it was implemented in a simplified assessment, and finally makes some suggestions for future improvements. In our opinion, a simplified protocol firstly used in Catalan reservoirs for the assessment of ecological potential is a sound, scientific-based methodology that delivers useful information for tailoring the Program of Measures to realistic and achievable objectives. As potential improvements we suggest: (1) the protocol to assess ecological potential should consider the one-out all-out rule for combining the biological and physicochemical quality elements; (2) definition of water body-specific Maximum Ecological Potential situations, using the *Alternative Prague* approach; (3) update the boundaries between levels of ecological potential inside each typology using the best knowledge available from reservoir limnology studies, particularly those published during the last decade; and (4) including the presence of invasive species in the assessment of biological quality.

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**Contents**



## 1 Reservoirs in the WFD

The European Water Framework Directive (WFD) 2000/60/EC [1] was approved in December 2000 to protect and improve the quality of European waters. Reservoirs are characterized as *artificial* or *modified* water bodies in this Directive, and pointing to that they were created for economic activities after profound physical modification of the river network and thus have restoration targets different from those defined for the unmodified water bodies [2].

According to the WFD, member states may define surface water bodies as *heavily modified* (HMWB) in the process of drafting river basin management plans. This category was defined to include those water bodies that have been physically altered so that they are substantially changed in character. Alternatively, some water bodies may also be defined as *artificial water bodies* (AWB) if they have been created by human activity [3]. Within this context, physical alterations mean changes to the hydromorphological characteristics of a water body, and a water body that is substantially changed in character is one that has been subject to major long-term changes in its hydromorphology.

The environmental objective for HMWB and for AWB is good ecological potential (GEP), which has to be firstly achieved by 2015, or subsequently by 2021 or 2027. This is in contrast with the more meaningful "good ecological status" objective for the other water body typologies. Nevertheless, GEP is an ecological objective which may be difficult to achieve [4]. However, there is an intrinsic challenge in achieving GEP: establishing an appropriate Maximum Ecological Potential (MEP) for a particular HMWB or AWB. The MEP is considered as the reference conditions for HMWB and is intended to describe the best approximation to a natural aquatic ecosystem that could be achieved given the hydromorphological characteristics that cannot be changed without significant adverse effects on the specified use or the wider environment. There is a controversy about the appropriate criteria to derive MEP, and although the working groups implementing the WFD have tried to give guidance on this, at present little has advanced in terms of understanding what does MEP mean, especially in an ecological context [4].

The Common Implementation Process (CIS) of the WFD has suggested two options to define MEP and GEP that rely on scenario modeling: one based on biological quality elements and the other based on identification of mitigation measures [5]. In the first approach, MEP relates to the values of biological quality elements after all mitigation measures have been implemented that do not have a significant adverse effect on the use of water stored in the HMWB. GEP is defined as only slight changes from those values at MEP. The second alternative, the so-called *Alternative Prague* approach, starts excluding those measures that, in combination, are predicted to deliver only slight ecological improvement. GEP is then defined as the biological values that are expected from implementing the remaining identified (and relevant) mitigation measures. It is argued that the *Prague* approach leads to comparable results as the approach based on biological quality elements, while in the same time, it leaves less room for errors due to predictive modeling [5].

However, there is little guidance based on scientific knowledge on what has to be done with the samples of biological elements. Hence, differences in interpretation, methods, and approaches are common across different European countries [6]. In the best scenario, MEP can be defined using the ecological properties of the closest natural comparable water type, i.e., a natural lake. An alternative is to use an AWB or HMWB of the same type. That would eventually allow for considering “others” than the impacts caused by the hydromorphological changes intrinsically linked to the transformation of a river into a reservoir. However, finding such reference situations in reservoirs is unfeasible in most situations. This particularity of reservoirs should be stressed: although they can be defined as HMWBs, being the river as the parent system, it is evident that using a river as a reference to build MEP would be no sense. However, it is not that obvious that the suggested procedure of using a closest lake to define MEP for a reservoir is equally unreasonable. From an ecological point of view, any comparison between lakes and reservoirs is compromised by the deep differences of ecological functioning between these systems [7].

The difficulties for finding appropriate reference conditions for reservoirs and the ambiguities related to MEP and GEP definition have resulted in undesired side effects during the implementation of the WFD in reservoirs. Most problems stem from the fact that *expert judgment*, in the WFD indicated as a last resort, is frequently the prime mechanism to establish MEP and GEP values. This can be also the result of a lack of sensibility versus the particular ecology of reservoirs and its strong alteration of the river dynamics [8]. As a result, the usefulness of the implementation of the WFD in reservoirs (i.e., the achievement of GEP) is compromised by either its strong dependence on subjective criteria or the use of unreliable metrics developed from natural lake research.

In this chapter we review the implementation of the WFD in Catalan large reservoirs and the impact of this implementation on the first Program of Measures. Several other implementations have been published focusing on streams [9, 10] and coastal waters [11] and water management for agriculture [12]. There are numerous examples of protocols and applications for lakes and other surface waters [13–18]. Nevertheless, implementations published specifically for reservoirs are becoming more frequent [19–23]. In our case, we faced the challenge that only a reduced number of water bodies were available, and those bodies were located in a heterogeneous geological setting and suffered highly contrasting human impacts. The chapter introduces the proposed methodology, how this proposal was implemented in a first simplified version, and suggestions for future improvements.

## 2 Reservoir Typology in Catalonia

Eutrophication is the main water quality problem in reservoirs due to the larger inputs of nutrients and stronger water-level fluctuations than natural lakes [24, 25]. The MEP of a reservoir will depend to a great extent on the water quality of inflowing river, and in its turn the water quality will depend on the position along the river [26]. Consequently, we suggested an approach that classifies reservoirs into types depending on their position along the river network [27].

The implementation of the WFD for reservoirs in the Catalan River Basin District was based on a specific sampling campaign on 21 large reservoirs located in Catalonia (Fig. 1; Table 1). They were sampled quarterly from summer 2002 to spring 2003. In each reservoir, a sampling point was selected near the dam. Sampling included a wide range of physical, chemical, and biological measurements (temperature, conductivity, dissolved oxygen concentration, nutrient analysis, fish community, phytoplankton and zooplankton communities, etc.). See [27] for further details.

Reservoir typology was established using a collection of variables from system *B* of the WFD: altitude, distance to the sea, volume and the reservoir's catchment area, and geology (using chloride concentration as a convenient proxy). A principal component analysis (PCA) showed that most variables were interdependent. The first PCA axis summarized these correlations displaying a geographical gradient related to altitude and distance to the sea, from lowland reservoirs with high chloride concentration to higher-altitude reservoirs with low chloride. The second PCA axis distinguished two reservoirs of the Ebro River from the rest because of their large basin surface and chloride concentration. Santa Fe, the smallest reservoir, was situated on the opposite side; see [28].

After analyzing the variability along the selected descriptors, we established the boundaries between types by expert judgment, allowing classification of the reservoirs into six types using a dichotomic key (Fig. 2). Escales reservoir was the only member of Type I (large high-altitude reservoirs), whereas Santa Fe was the only one classified as Type II (small high-altitude reservoirs). Discrimination of the two


**Fig. 1** Large reservoirs in Catalonia and main rivers. Source: Catalan Water Agency

high-altitude types from the others was accomplished defining a threshold placed at 815 m. Siurana, Foix, and Riudecanyes reservoirs composed Type III, containing small coastal reservoirs (Fig. 2). Type IV was composed by all reservoirs without extreme characteristics along the axes defined by descriptors (i.e., medium-altitude and lowland reservoirs located at least 25 km away from the coast). Chloride concentration over 40 ppm served as a discriminating characteristic between Type IV and the last two types. A threshold value for catchment area of 1,000 km$^2$ discriminated between Type V (Flix and Ribarroja reservoirs, located in the Ebro River) and Type VI (Sau and Susqueda reservoirs, in the Ter River). All in all, the final classification reflected both the diverse typology of the reservoirs and subjective criteria about the ecological functioning of the systems based on the extensive knowledge available from these systems by the research teams involved in the characterization.

**Table 1** Basic morphological characteristics of Catalan reservoirs and ecological potential assessments using the original method proposed by [27] and the simplified implementation

| Reservoir | Dam height (m) | Surface area (ha) | Capacity ($hm^3$) | Ecological potential: original method | Ecological potential: simplified implementation |
|---|---|---|---|---|---|
| Boadella | 63 | 363.3 | 60.2 | Moderate | Moderate |
| Camarasa | 103 | 624 | 163 | Good | Maximum |
| Canelles | 150 | 1,569 | 678 | Maximum | Maximum |
| Cavallers | 70 | 47 | 16 | Not assessed | Maximum |
| El Pasteral | 33 | 34.6 | 2 | Not assessed | Maximum |
| Escales | 125 | 400 | 152 | Maximum | Maximum |
| Flix | 26 | 320 | 11 | Maximum | Maximum |
| Foix | 38 | 67.9 | 3.74 | Poor | Bad |
| El Catllar | 79 | 326.2 | 60.4 | Not assessed | Poor |
| Guiamets | 47 | 62 | 10 | Not assessed | Moderate |
| La Baells | 102.3 | 364.7 | 109.5 | Good | Moderate |
| La Llosa del Cavall | 122.3 | 300 | 79.4 | Good | Maximum |
| Margalef | 33.2 | 31.8 | 3 | Not assessed | Good |
| Oliana | 102 | 443 | 101 | Moderate | Good |
| Rialp | 99 | 430 | 402.8 | Moderate | Good |
| Riba-roja | 60 | 2,152 | 210 | Maximum | Good |
| Riudecanyes | 51 | 40.3 | 5.3 | Good | Good |
| Sallente | 89 | 31 | 6.5 | Not assessed | Maximum |
| Sant Antoni | 86 | 927 | 205 | Good | Maximum |
| Sant Llorenç de Montgai | 25 | 131 | 10 | Good | Maximum |
| Sant Martí de Tous | 34 | 14.9 | 1.3 | Not assessed | Good |
| Sant Ponç | 59.5 | 144.5 | 24.4 | Good | Good |
| Santa Anna | 101 | 768 | 237 | Good | Maximum |
| Santa Fe | 24 | 6.9 | 0.8 | Maximum | Good |
| Sau | 83 | 572.8 | 151.3 | Good | Moderate |
| Siurana | 63 | 85 | 12 | Maximum | Maximum |
| Susqueda | 135 | 466 | 233 | Good | Good |
| Terradets | 47 | 330 | 23 | Moderate | Maximum |
| Vallforners | 62 | 11.4 | 2.3 | Not assessed | Good |

## 3 Assessment of Ecological Potential: Original Proposal

To assess the ecological potential (EP), it is mandatory to establish five classes (maximum, good, moderate, poor, and bad) for all parameters considered in the assessment. The WFD provides extensive guidelines to assess the EP, but only general guidance for defining boundaries between classes [28]. In our case, we used several indexes to define the boundaries between ecological classes. Ten

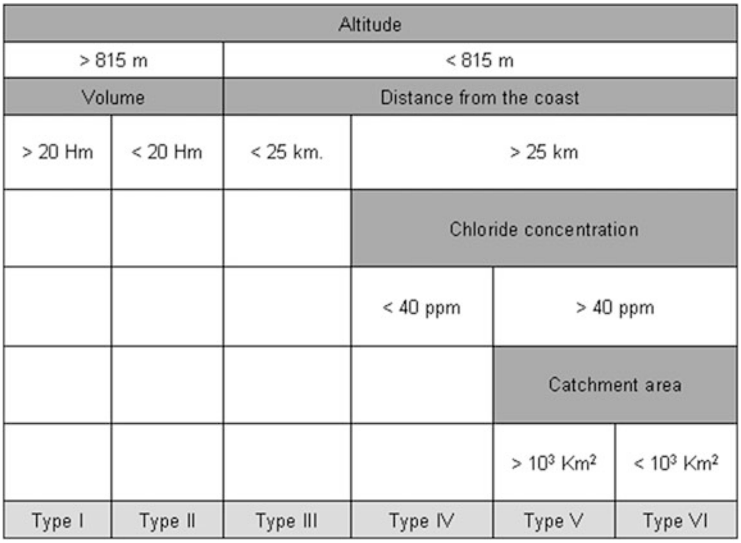


**Fig. 2** Classification of reservoir typology in Catalonia

parameters were selected to calculate EP: total chlorophyll-*a* (mg $m^{-3}$), *Cyanobacteria* chlorophyll-*a* (mg $m^{-3}$), total and percent catch per unit effort (CPUE) of limnetic and littoral common carp *Cyprinus carpio* [29], percentage of fish with anomalies, Secchi disk depth (m), average percentage of hypolimnetic oxygen concentration, and total phosphorus concentration (mg $m^{-3}$) in the water column (see Table 2). This set of parameters was expected to comprehensively reflect the physicochemical and biological features of the reservoirs and was used to assess the ecological state of the reservoirs. In the case of nutrients, parameters and boundaries between classes of the Trophic State Index (TSI) [30] and the Organization for Economic Cooperation and Development (OECD) [24] classifications were used. Fish metrics that link the trophic state of the waters with the abundance and species composition of the fish assemblages were also used [29]. The presence of *Cyanobacteria* was considered using the guidelines from the World Health Organization for recreational waters [31], while the Water Quality Index (WQI [32]) was implemented for oxygen conditions.

The lack of unpolluted or pristine reference systems has become one of the emerging problems during the implementation of the WFD [33, 34]. Since reservoirs are one of the most dramatic and irreversible impacts of humans on rivers, the definition of reference systems is not obvious. As a result, some of the boundaries between classes for the indexes mentioned above were modified using expert judgment. Regarding this situation, the choice of a reservoir presenting MEP as a reference for other reservoirs seems acceptable. However, those reference systems to define MEP were not available for two out of the six types defined in the reservoir typology; because with just 21 systems at play and a highly biased distribution toward impacted systems, we could not identify reference systems for Types V and

**Table 2** Variables used to assess the ecological potential in Catalan reservoirs and thresholds defining EP levels in the different typologies defined (see Fig. 2). Modified from [27]

| Types | Parameters | Maximum | 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 |
| | *Cyanobacteria* chlorophyll-*a* (mg m$^{-3}$) | 0–0.5 | 0.5–1 | 1–5 | 5–20 | >20 |
| | % anomalies in fish | <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 depth (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 |
| | *Cyanobacteria* chlorophyll-*a* (mg m$^{-3}$) | 0–0.5 | 0.5–1 | 1–5 | 5–20 | >20 |
| | % anomalies in fish | <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 depth (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 |
| | *Cyanobacteria* chlorophyll-*a* (mg m$^{-3}$) | 0–0.5 | 0.5–1 | 1–5 | 5–20 | >20 |
| | % anomalies in fish | <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 depth (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 |

VI. Therefore, we defined the boundaries between classes for these types by expert judgment, assigning the MEP to the values defined for the GEP. Table 2 illustrates the quality elements and ranges used to assess the ecological status according to the WFD. Note that when calculating the final EP class merging results from the different elements (biological and physicochemical), we always used the most conservative result, i.e., the worst result in terms of final EP assessment was always considered as the outcome [27].

## 4 Ecological Potential in the Original Sampling

We performed a first evaluation of the ecological potential during year 2003 (i.e., before the period used in the final version of the First Assessment for reporting the EC, 2007–2012). Escales Reservoir, the only Type I reservoir, showed MEP, in correspondence with its definition as a reference system (Table 1). In 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 Reservoir, the only Type II reservoir, showed high values for both phosphorus (17–35 mg $m^{-3}$) and chlorophyll-*a* (43–110 mg $m^{-3}$) because of its dystrophic conditions. *Cyanobacteria* were present in high concentrations (7–11 mg $m^{-3}$ of chlorophyll-*a*), mainly consisting of *Microcystis* sp. and *Gomphosphaeria* sp. However, Santa Fe Reservoir is located in the headwaters of a near-pristine watershed, and those water quality characteristics are typical from dystrophic systems with high inputs from the surrounding deciduous forest. Therefore, Santa Fe was also assigned with a MEP (Table 1).

Type III reservoirs showed the worst EP of all groups, between bad and poor. Foix Reservoir showed the highest values of total phosphorus concentration (250–350 mg $m^{-3}$) and simultaneous extreme values of chlorophyll-*a* (78–823 mg $m^{-3}$) and high concentrations of *Cyanobacteria* [35]. The other two reservoirs showed moderate phosphorus concentration (4–50 mg $m^{-3}$) but eutrophic conditions with high values of chlorophyll-*a* (17–80 mg $m^{-3}$), resulting from their small size and critical changes in their water levels due to their use for irrigation purposes. All in all, Foix and Riudecanyes showed moderate and GEP, respectively. Siurana Reservoir was the reference system for this type, so it showed MEP (Table 1).

Type IV gathers 12 reservoirs placed on medium-sized rivers, most of them located on adjacent tributaries of the Ebro River. These reservoirs showed moderate and GEP. Most of these reservoirs showed mesotrophic conditions during the year, and only four reservoirs presented eutrophic conditions during part of the year. These four reservoirs showed a moderate EP and should have been the target for restoration measures: Rialb Reservoir, in its initial phases of first filling, and Boadella, Oliana, and Terradets reservoirs because of the poor quality of the inflowing water from tributaries.

Type V systems (Flix and Riba-roja reservoirs) are located at the lower reaches of the Ebro River. The presence of an upstream reservoir (Mequinenza Reservoir, not included in this study, with a volume of 1,533.8 $hm^3$ and a residence time of 72.5 days) significantly reduces the amount of nutrients. Both reservoirs presented

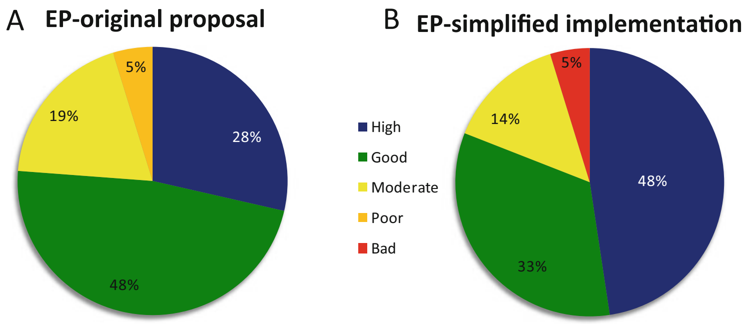


**Fig. 3** Ecological potential calculated for the original set of reservoirs using (**a**) the original criteria suggested by [27] and (**b**) the results from a simplified assessment delivered in 2012, considering the same set of reservoirs

mesotrophic conditions during the entire year, with some episodic eutrophic conditions. 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 (i.e., we applied a rather subjective expert judgment). Thus, EP values were between GEP and MEP (Table 1).

Type VI reservoirs are associated with a relatively large river (Ter River). Its watershed suffers from intense human pressures, particularly agriculture and farming, which produce a large amount of diffuse inputs that reach the reservoirs and accumulate in the sediments. Despite the implementation of a sanitation plan that has greatly reduced the nutrient inputs, they are eutrophic or hypereutrophic ($78 \pm 80$ and $62 \pm 33$ mg $m^{-3}$ total phosphorus). Expert judgment was applied in choosing reference values, with the values of the parameters being quite close to those observed in the reservoirs.

Because of the toxicological relevance of cyanotoxins, chlorophyll-*a* from *Cyanobacteria* was analyzed (81 data from 21 reservoirs) to assess the risk of exceeding 1 μg $L^{-1}$, the maximum value allowed for GEP. 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.

Overall, 28% of the reservoirs were identified as having MEP and 48% as having GEP. The rest of the reservoirs (24%) were below the GEP target (Fig. 3a; Table 1).

## 5 From Proposal to Simplified Implementation: Ecological Potential Outcomes

The Catalan Water Agency issued a protocol for the assessment of the EP in reservoirs of the Catalan River Basin District, following suggestions contained in [27] and summarized above. This first simplified implementation procedure contained several modifications to tailor it to available monitoring resources and also to test cheaper and quicker procedures. Outcomes from the original and this simplified proposal were compared here; however, it is worth mentioning that the current final implementation (year 2015) is a more complete methodology than the simplified version compared here.

First, the simplified protocol did not include total phosphorus concentration, Secchi disk depth, and parameters related to the fish community. Only total chlorophyll-*a* concentration, chlorophyll-*a* concentration from *Cyanobacteria*, and hypolimnetic dissolved oxygen concentration were considered in the simplified monitoring analysis for reservoirs in Catalonia. Note that the possibility of excluding quality elements from the EP calculation was already considered in early CIS guidance documents and therefore should not be considered as bad practice. Second, the simplified EP value was not equaled to the worst EP value from the different elements (the one-out all-out principle) but computed using the average. The potential impacts of those changes in the protocol on the final EP assessment are discussed later in this section.

The EP was assessed for 30 reservoirs in the simplified assessment, including additional reservoirs beyond the set used to develop the method (Table 1). The simplified assessment identified 46% of the reservoirs in MEP and 32% in GEP (Fig. 4c). This implies that 22% of the reservoirs in Catalonia do not fulfill the target quality requirements (i.e., GEP). Most of the reservoirs identified with moderate EP or less were relatively small reservoirs located near the coast. Remarkably, a large reservoir currently used as one of the main sources for water supply was also identified as having moderate EP (Sau Reservoir), as well as two large reservoirs (Boadella and La Baells reservoirs) used to deal with the seasonal variability of water available for water supply and irrigation in downstream locations (Table 1).

A closer look on the quality elements used to calculate EP gave interesting conclusions. Actually, the physicochemical quality of many samples was identified as bad, while the other half was classified as good (Fig. 4b). However, the biological quality was high in 75% of the reservoirs, and those with moderate or less quality were just 25% of them (Fig. 4a). It becomes clear that the overall EP assignments are more influenced by the biological quality elements than by the physicochemical elements in the simplified implementation.

Unfortunately, we cannot make judgments about non-measured variables, so we can only speculate about the potential impact of the discarded variables in the simplified implementation (Secchi disk depth, total phosphorus concentration, and fish community indexes) on the final EP assignments. However, we can easily check the effect of the criterion to aggregate the biological and physicochemical

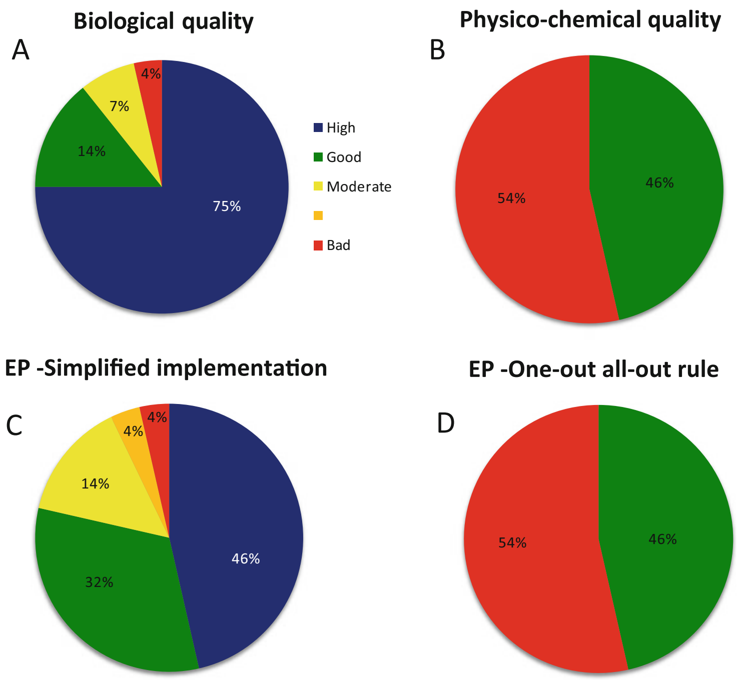


**Fig. 4** Results from the simplified assessment for (**a**) the distribution of biological quality scores, (**b**) the physicochemical quality scores, and (**c**) the final ecological potential assignments resulting from the combination of the previous two elements. Additionally, we calculated (**d**) the ecological potential for the same dataset but applying the one-out all-out rule when combining the physico-chemical and the biological quality scores

elements into a single EP class. We compared the EP assignments in the simplified assessment with EP classes computed using the one-out all-out rule when aggregating the biological and physicochemical quality (i.e., we picked the worst result as the final EP). The comparison between the EP assignments in the simplified assessment and using the one-out all-out rule could not be more contrasting (Fig. 4c, d; Table 1). While 46% of the reservoirs still comply with the GEP using the new rule, the rest of them (54%) were classified as having bad EP.

These results stress the fact that choosing the procedures to calculate EP is paramount for the implementation of the WFD in HMWBs and by extension in all water bodies. The suggested procedure by the CIS is to use one-out all-out rules to compute the EP and ecological status (ES), but this is particularly prone to misclassification when a large number of quality elements are included in the assessment. This is not our case, because the number of elements included in the assessment is rather low. Therefore, we have to focus on the ecological meaningfulness of the elements included in the analysis and the appropriate reference conditions established for the different types. The next section is a critical evaluation of the simplified implementation.

## 6 Critical Evaluation of the Simplified Implementation

In our opinion, the weakest point of the simplified implementation is the fact that it does not consider the one-out all-out rule when combining the biological and physicochemical quality elements to assess the EP. This may imply an overly optimistic assessment (see Figs. 3 and 4). We acknowledge that assuming the one-out all-out rule may in its turn imply an overly pessimistic result, and this fact points to potential problems in the variables selected for the calculation of the biological and physicochemical quality.

The variables selected in the first proposal by [27] were intended to cover the main threats to water quality in HMWBs. Carlson's Trophic State Index (TSI [30]) and the OECD model [36] are the rationale behind the selection of most variables in the original proposal, since cultural eutrophication was considered the main threat. Actually, eutrophication is the most important environmental problem of dammed water [37–39]. A comparison of the results obtained using the Danish method to assign EP categories [18], which is also based on trophic characteristics, gave very similar results [27]. Therefore, the use of variables related to eutrophication seems a good procedure to assign EP categories.

However, both TSI and the OCDE models were first developed for natural lakes, not reservoirs. Indeed, there are problems applying the TSI in reservoirs [40], mainly related to the fact that turbidity in reservoirs can be related to mineral particles, and not to phytoplankton biomass, as assumed in the original study by [30]. Some authors [30, 41–43] also pointed out to the limitation of Secchi disk depth as a trophic state predictor in turbid water bodies like reservoirs. Therefore, the use of transparency (i.e., Secchi disk depth) to track EP in reservoirs should be applied with care. At this respect, the fact that the final implementation did not consider transparency to assess the EP should be considered opportune. In fact, chlorophyll-*a* levels are already a convenient proxy of eutrophication that largely outcompetes transparency. The removal of total phosphorus from the final implementation is not dramatic either: total phosphorus usually covariates with chlorophyll-*a*.

The implementation of the WFD requires the use of fish fauna as a biological quality element. Fish are one of the biological quality elements used to describe the ecological status because they are present in most water bodies, present several qualities to be used as indicators of water quality, occupy several trophic levels, and are considered essential in restoration and management measures. However, many WFD standards are based on the extensive knowledge of Central and Northern Europe aquatic ecosystems [44], but Mediterranean reservoirs have a significantly different functioning compared to natural lakes from Central Europe. In the case of fish fauna, studies on Spanish reservoirs have proved that these type of water bodies present basically introduced species [29], and the fish richness does not seem to be tightly related to EP. This is why Navarro et al. [27] used the percent abundance of cyprinids and variables related to morphological alterations in the suggested methodology. The feeding habit of grubbing through bottom sediments particularly exposes common carp to pollutants accumulated on that compartment of reservoirs, being thus a good bioindicator for chemical pollution [45–47].

In our opinion, the exclusion of fish as a biological quality element to assess EP in reservoirs is not critical, because fish community indicators usually correlate with total phosphorus and other proxies of eutrophication. However, there are several invasive species actively spreading across Spanish reservoirs (e.g., catfish and *Alburnus*), with measurable and significant impacts on water quality [48]. However, the presence of invasive species is not playing a role in the present quality elements defining EP. This is a substantial limitation, because the presence of invasive species may be regarded as one of the fundamental impacts threatening the uses of water. This applies to fishes introduced during the last decades but not to species almost naturalized in the Iberian Peninsula, like *Cyprinus carpio*. Particularly, other invasive organisms like the zebra mussel should be also considered [49]. We suggest that at least a qualitative or semiquantitative monitoring to control modern invasive species should be included in future versions of the methodology to assess EP, especially for those potentially causing strong modifications on the habitats or food webs.

Another potential improvement to assess ecological potential for reservoirs is the use of "tailored" hypolimnetic oxygen thresholds to define the physicochemical quality element, considering other factors than those related with the human impacts. In fact, the simplified methodology considers different thresholds for different reservoir types. However, even considering this, the hypolimnetic oxygen level in reservoirs is highly dependent on climatologic factors that may dramatically vary from year to year [50, 51]. This implies that a reservoir may show contrasting results concerning this parameter irrespective of the pressures and impacts the system suffers. Also, there are reservoirs that may suffer hypolimnetic anoxia promoted by huge inputs of organic matter from the terrestrial ecosystems (e.g., from an extensive deciduous forest). In those cases, hypolimnetic anoxia is not a good proxy of bad EP, because it would be disconnected from human pressures.

All these points converge in a fundamental problem of the simplified methodology: the lack of site-specific MEP references. 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 [10]. This is particularly relevant in reservoirs, because they are systems with relatively short water residence times which are strongly modulated by all processes occurring in the upstream watershed. Therefore, the so-called *Alternative Prague* approach, in which MEP values are derived after heuristic scenario assessment, seems the best alternative to improve the current implementation. This approach would require defining MEP values system by system, but it does not necessarily ask for complex dynamic simulation models, because robust empirical load-response models requiring minimal information are available for many parameters. For instance, oxygen levels can be predicted during scenario assessments using the empirical formulations in Marcé et al. [50], while formulations for chlorophyll-*a* in reservoirs are a classical topic resolved many years ago [52]. All these approaches are based on linear regression techniques, so they would be easy to apply and flexible enough to be practical and feasible for heuristic scenario assessment.

## 7 The Relevance of Reservoir Water Quality on the Program of Measures

A key component of the WFD is the development of river basin management plans which will be reviewed on a six-yearly basis and which set out the actions required within each river basin to achieve set environmental quality objectives. In the case of HMWBs, this is achieving at least GEP. This involves a so-called gap analysis where, for each water body, any discrepancy between its existing status and that required by the Directive is identified. A Program of Measures can then be identified and put in place to achieve the desired goals.

The first Program of Measures for the Catalan River Basin District was delivered on 2010 with the measures to achieve GEP for HMWBs by 2015. A total of 10 out of 30 reservoirs were identified as not compliant with the required objective (GEP) in 2009, and the objective of the Program of Measures is to reduce the number of noncompliant systems to 2 in 2015 (corresponding to El Catllar and Foix reservoirs).

As for the concrete measures present in the Program of Measures that concern reservoirs, most of them refer to management strategies to ensure appropriate environmental flows, downstream reservoirs, and sufficient sediment load to receiving rivers to maintain a correct morpho-sedimentary dynamics. However, the Program of Measures did not include many actions explicitly devoted to improve the ecological potential of those reservoirs which were not compliant with the GEP objective in 2009. The only highlighted measure unequivocally pointing to the ecological potential of a reservoir is the remediation program to remove contaminated sediments from Flix Reservoir. This is a huge remediation program with a budget from the Spanish Government amounting to ca. 155 million euro, and the main goal is to remove from the reservoir industrial-contaminated sediments with several priority substances.

Although we acknowledge that any measure taken to improve the upstream river water bodies will ultimately impact the reservoir as well, this should not be considered as a guaranteed outcome of the Program of Measures. Reservoirs have a strong tendency to keep eutrophication conditions despite remediation measures due to the lasting influence of sediments on water quality.

Another relevant aspect of the Program of Measures as far as it concerns reservoirs is the extensive space devoted to invasive species. Both, zebra mussel (*Dreissena polymorpha*) and fish introductions are considered two of the main threats to the EP in reservoirs along the document, with particular protocols and prevention measures defined. This is reflected by the fact that the Control and

Surveillance Program of the Catalan Water Agency already considers early warning systems for the detection of new invasions by these species. However, this vividly contrasts with the fact that the presence of invasive species is not considered in the current assessment of EP in reservoirs and that all fish community elements have been removed from the biological quality element to assess EP.

## 8 Final Remarks

The implementation of the WFD across Europe has been the magic bullet to put freshwater quality and ecosystem health at the forefront of policy priorities during the last decade. As an ambitious Directive, its implementation is an enormous scientific and policy challenge that has boosted, and will keep pushing, basic and applied research in Europe. This implies that the scientific-based protocols for the assessments and the overall strategy of the concrete policies steaming from DMA implementation have been modified and will continue changing during at least the next decade. Actually, the monitoring programs have already provided enough data to elucidate whether the EP and ES boundaries and water body types proposed in the protocols work in accordance with the spirit of the WFD.

In our opinion, the protocol for the assessment of EP in Catalan reservoirs is a sound, scientific-based methodology that delivers useful information for tailoring the Program of Measures to realistic objectives. However, it is evident that some improvements are still possible. We suggest the following modifications for future revisions of the protocol:

- The protocol to assess EP should consider the one-out all-out rule for combining the biological and physicochemical quality elements.
- Define water body-specific MEP situations, using the *Alternative Prague approach*.
- Update the boundaries between levels of EP inside each typology using the best knowledge available from reservoir limnology studies, particularly those published during the last decade.
- Include the presence of invasive species in the assessment of biological quality.
- The most recent studies disentangling the contribution of both the climatic change and the human-derived impacts on the water quality of reservoirs may allow for a more precise threshold establishment for certain EP metrics (e.g., oxygen levels).

We are confident that these changes would facilitate the definition of concrete actions in forthcoming Program of Measures, because the EP objectives would be tailored to already defined and realistic management options. And last but not the least, it would improve the EP of our water bodies, which is the final aim of the WFD.

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