

A Water Quality Index Applied to an International Shared River Basin: The Case of the Douro River

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Abstract A Water Quality Index (WQI) is a numeric expression used to evaluate the quality of a given water body and to be easily understood by managers. In this study, a modified nine-parameter Scottish WQI was used to assess the monthly water quality of the Douro River during a 10-year period (1992–2001), scaled from zero (lowest) to 100% (highest). The 98,000 km² of the Douro River international watershed is the largest in the Iberian Peninsula, split between upstream Spain (80%) and downstream Portugal (20%). Three locations were surveyed: at the Portuguese–Spanish border, 350 km from the river mouth; 180 km from the mouth, where the river becomes exclusively Portuguese; and 21 km from the mouth. The water received by Portugal from Spain showed the poorest quality (WQI $47.3 \pm 0.7\%$); quality increased steadily downstream, up to $61.7 \pm 0.7\%$. In general, the water quality at all three sites was medium to poor. Seasonally, water quality decreased from winter to summer, but no statistical relationship between quality and discharge rate could be established. Depending on the location, different parameters were responsible for the episodic

decline of quality: high conductivity and low oxygen content in the uppermost reservoir, and fecal coliform contamination downstream. This study shows the need to enforce the existing international bilateral agreements and to implement the European Water Quality Directive in order to improve the water quantity and quality received by the downstream country of a shared watershed, especially because two million inhabitants use the water from the last river location as their only source of drinking water.

Keywords Water quality index · Discharge · Residence time · Reservoir · Dam · Douro River

Introduction

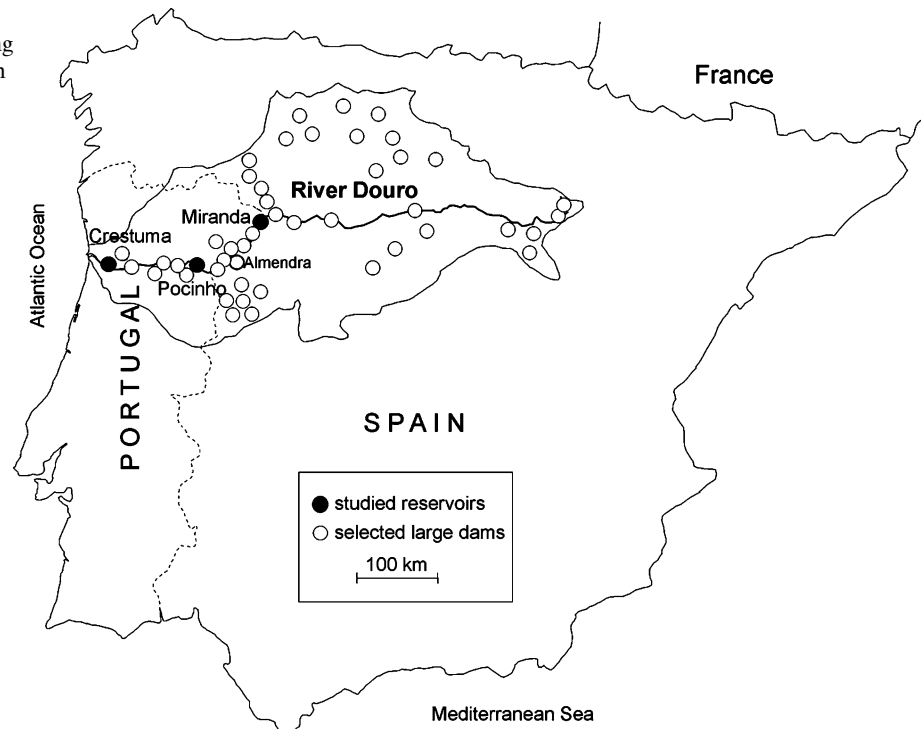
The Douro River flows within the largest watershed in the Iberian Peninsula, draining 98,000 km² or 17% of this territory. The Douro is an international watershed, shared between Spain (80%) and Portugal (20%). Within the watershed, 51 large dams regulate the flow, allowing, presently, about 15 km³ of freshwater per year to be discharged into the Atlantic Ocean at 41°08'N; 08°41'W, an equivalent to 455 m³s⁻¹. However, because the flow regime depends not only on climatic conditions but also is controlled for hydroelectric power generation needs in both countries, as well as by irrigation needs in Spain, the daily discharge rate into the ocean ranges between zero and >13,000 m³s⁻¹ (Vieira and Bordalo 2000). The first dam on the watershed was built in 1920, but most large dams (>15 m wall height) started operating in the late 1950s. The concentration of dams is particularly heavy in the last 350 km of the river main course, with a hydroelectric

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Fig. 1 The Douro River watershed and location of the three sampling sites along the international and Portuguese stretch of Douro River



power dam about every 30 km. Altogether, the large dams retain up to 1100 hm³ (13%) of water in Portuguese reservoirs and 7500 hm³ (87%) on the Spanish side of the watershed.

The scientific evaluation of the water quality, and its temporal trends, is an important task for risk assessment. This is particularly critical when dealing with an international river, i.e., a shared watershed, because the management goals of the different countries may not coincide. One evaluation approach has been to develop water quality indices of multiple parameters, to provide a simple and comprehensible tool for managers and decision makers on the quality of a given water body and its possible uses. A water quality index (WQI) attempts to provide a mechanism for presenting a cumulatively derived numerical expression defining a certain level of water quality (Miller and others 1986), and is useful for comparative purposes and when general questions are addressed (Hallock 2002). The WQI approach has many variants in the literature, and comparative evaluations have been undertaken (e.g., SDD 1976; Ott 1978; Dunnette 1979; Miller and others 1986; Smith 1990; Cude 2001). In this study, a slightly modified SDD WQI was used for reasons discussed in the next section.

The impetus for this study came from the new Water Framework Directive (WFD 2000) and the Portuguese–Spanish agreement on shared rivers signed in

November 1999. Although a few limited studies dealing with water quality of the Douro River reservoirs have been published (e.g., Barros and others 1995; Gil and Fernandes 1997; Trancoso and others 2001), the recent availability by the Portuguese Ministry of Environment of environmental data on a web site (INAG 2003) for the decade 1992–2001 allows an integrated multiparameter assessment of water quality over the past decade. As the European Union strives through the WFD to stimulate better water quality within the European territory, it is important to examine the past and present water quality status in order to formulate plans for proper management initiatives.

In this study, the water quality status as well as the spatial and temporal trends over a 10-year period were assessed by means of a score describing a general water quality index applied to three different locations of the international Douro River: (i) where the river enters the shared border between Portugal and Spain; (ii) where the river is first entirely in Portuguese territory; and (iii) close to the estuary (Figure 1).

Material and Methods

The locations of the three reservoirs of the Douro River under examination are presented in Figure 1,

Table 1 General characteristics of the reservoirs in the Douro River covered by the present study

Reservoir	Units	Miranda	Pocinho	Crestuma
Top water level	M	528	126	13
Length	Km	14	40	44
Submerged area	Km ²	1.2	8.3	13.0
Total capacity	Hm ³	28	83	110

and their general characteristics are shown in Table 1. The most upstream reservoir, Miranda (MRD), was created when the dam entered operation in 1960 and is located at the border between Portugal and Spain. The second reservoir, Pocinho (PCI), was formed in 1983, resulting in the first reservoir entirely within the Portuguese side of the watershed, about 30 km downstream of the border. Between the Miranda and Pocinho reservoirs, the Douro River provides the boundary separating Portugal and Spain. The last reservoir, Crestuma (CRT), resulted from the impoundment of the Douro River in 1985 at 21.6 km from its mouth. This reservoir serves as the only intake for the production of potable water for approximately two million inhabitants of the Greater Oporto region, or 20% of the Portuguese population.

The raw water flow data consist of averaged daily discharges, obtained from the Electric Authority of Portugal (EDP, personal communication) for the Crestuma reservoir and total monthly discharges from the Portuguese Water Institute (INAG 2003) for the Pocinho and Miranda reservoirs.

Hydraulic residence time (RT) was calculated according to the following equation:

$$RT = V/Q$$

where V is the volume of the reservoir and Q the flow rate out of the reservoir.

The raw environmental data were obtained from the INAG web site (INAG 2003) and refer to water column surface samples collected on a monthly basis from January 1992 to December 2001. A total of 345 data sets were available for the construction of the modified Scottish water quality index (SDD 1976). Thus, particular care was taken to check data quality and assurance. Whenever needed, interpolations were calculated to overcome missing values. Interpolation was done as the average for a particular month in each reservoir if at least 8 years out of 10 years of data were available. Nevertheless, a total of 15 monthly data sets were discarded because of the amount of missing information.

Raw data for each individual parameter, namely, temperature, conductivity, dissolved oxygen, pH, ammonia, suspended solids, biological oxygen demand (BOD₅), chemical oxygen demand (COD), and fecal coliforms were automatically compared to standard curves in order to generate a water quality rating (SDD 1976, Tyson and House 1989).

The reason that the SDD index was selected for this study is that it contains a flexible WQI that, with specific adaptations, has been applied to a wide range of environments, from temperate to tropical (e.g., House and Ellis 1981; Couillard and Lefebvre 1985; Barros and others 1995; Bordalo and others 2001; Curcic and Comic 2002). In this study, the original cold-water version was retained, with the following modification: the number of parameters was reduced from the original 10 to 9; nitrate was excluded because of the large amount of missing data. Thus, the modified SDD index consisted of the aggregation of three groups of parameters, namely, physical (temperature, conductivity, suspended solids), chemical (pH, ammonia, dissolved oxygen), and organic/microbiological (fecal coliforms, biological oxygen demand, chemical oxygen demand). The fecal coliform subindex is in line with EU standards (EEC 1976). The chosen method for subindices aggregation (weighted arithmetic average) is particularly suitable for the indexation of the general water quality, as stated by House (1989). The weight allocated to each individual parameter is presented in Table 2.

The final, modified, arithmetic, weighted index is the result of squaring the sum of the products of water quality ratings (q_i) and weighting each individual parameter (w_i) divided by 100, according to the following equation:

$$WQI = 1/100 \left(\sum_{i=1}^9 q_i w_i \right)^2$$

Because the original index included 10 parameters, the weight of each parameter was scaled up in proportion calculations, in order to give a final parameter weight of 1.00 (SDD 1976). Although the original WQI was developed for lotic systems, due to the short residence time of the impounded water (see Results), the system can be considered fluvial, thus allowing the application of the index approach. In the SDD WQI, 0% represents the poorest and 100% the highest water quality. In this study, the House and Ellis (1987) class rating was adopted: 10–25% badly polluted; 26–50% polluted; 51–70% reasonable; 71–90% good; 91–100% very good.

Table 2 Scaled individual weighting (w_i) attributed to each parameter for the calculation of the WQIs

Physical	Chemical	Organic/microbiological
Temperature—0.05	pH—0.09	Fecal coliforms—0.12
Conductivity—0.06	Ammonia—0.12	Biological oxygen demand—0.15
Suspended solids—0.07	Dissolved oxygen—0.19	Chemical oxygen demand—0.15

Where appropriate, averaged values are presented with plus or minus standard errors. All original, unadapted algorithms used for WQI computations calculated from the original SDD rating curves were supplied by Mano (1989) and calculated on an Excel spreadsheet. Statistics were performed with the Statgraphics software package. The least square regression approach was used to determine and quantify trends.

Results

Water Discharge

Miranda reservoir

Water discharge rates from the three dams are presented in Figure 2. The influx of water to the Miranda reservoir has its origin within the Spanish portion of the watershed. During the study period, the yearly averaged river flow was $247 \pm 41 \text{ m}^3\text{s}^{-1}$, ranging from a minimum of $105 \pm 16 \text{ m}^3\text{s}^{-1}$ during the extreme drought year of 1992 (Figure 2), to a maximum of $548 \pm 191 \text{ m}^3\text{s}^{-1}$ in 2001, a wet year. Three low discharge years, namely, 1992, 1995, and 1999, could be identified, as well as two wet years, in 1996 and 2001. Although year-to-year variations were significant (ANOVA, $P < 0.05$), seasonal differences were particularly important to note. For example, during the 1995 drought, the monthly averaged flow in August was just $26 \text{ m}^3\text{s}^{-1}$, whereas during 2001, a wet year, the highest discharge month, March, was $1776 \text{ m}^3\text{s}^{-1}$. Nevertheless, for the 10-year study, January through March were the wettest months, with river discharges between 349 ± 164 and $644 \pm 195 \text{ m}^3\text{s}^{-1}$ on average, whereas August was the driest with just $73 \pm 10 \text{ m}^3\text{s}^{-1}$ (Figure 3).

Pocinho reservoir

For the Pocinho reservoir (Figure 2), the influx of water originated not only from the main course of the river but also from both sides of the border (Figure 1). The

10-year averaged river flow was $314 \pm 61 \text{ m}^3\text{s}^{-1}$, representing a 21% increase in volume in relation to the discharge from the Miranda dam, and followed the same temporal trend. However, during the first two drought years (1992 and 1995), the average inflow to the downstream Pocinho reservoir was less than the river discharge received by the Miranda reservoir located 170 km upstream (Figure 2). The yearly averaged values were 87 ± 18 and $105 \pm 16 \text{ m}^3\text{s}^{-1}$ for 1992 and 144 ± 55 and $189 \pm 55 \text{ m}^3\text{s}^{-1}$ for 1995, respectively, for Pocinho and Miranda. This anomalous situation is presumably related to water diversion from the main course of the river for agriculture on the Spanish side of the border (see Discussion section). On average, the highest discharge months were December through February ($454 \pm 121 - 792 \pm 270 \text{ m}^3\text{s}^{-1}$), with January the wettest. August was the driest month, as in the Miranda dam, with $99 \pm 16 \text{ m}^3\text{s}^{-1}$ (Figure 3). Individually, the driest month in the Pocinho reservoir was May 1992, and the wettest month was January 2001 (20 and $2374 \text{ m}^3\text{s}^{-1}$, respectively).

Crestuma reservoir

In the last reservoir, Crestuma, located adjacent to the estuary, the influx of water had its origin from the main course of the river and from the Portuguese side of the watershed. Between 1992 and 2001, the average flow was $546 \pm 100 \text{ m}^3\text{s}^{-1}$, a 55% increase in relation to the Miranda dam water release. Thus, the contribution for the total river flow from the Spanish side of the watershed was 45%; i.e., the Portuguese side of the watershed supplied more than half of the water influx to the estuary. As was seen for the Miranda and Pocinho reservoirs, the lowest yearly average discharge of the Crestuma reservoir occurred in 1992, with $163 \pm 42 \text{ m}^3\text{s}^{-1}$, and the highest in 2001 with $1247 \pm 479 \text{ m}^3\text{s}^{-1}$ (Figure 2). The wettest months were December through February ($902 \pm 480 - 1450 \pm 480 \text{ m}^3\text{s}^{-1}$), with the highest values in January (Figure 3). On average, the driest month was again August, with $106 \pm 18 \text{ m}^3\text{s}^{-1}$, very similar to the discharge rate of the Pocinho dam, located 180 km upstream (see above).

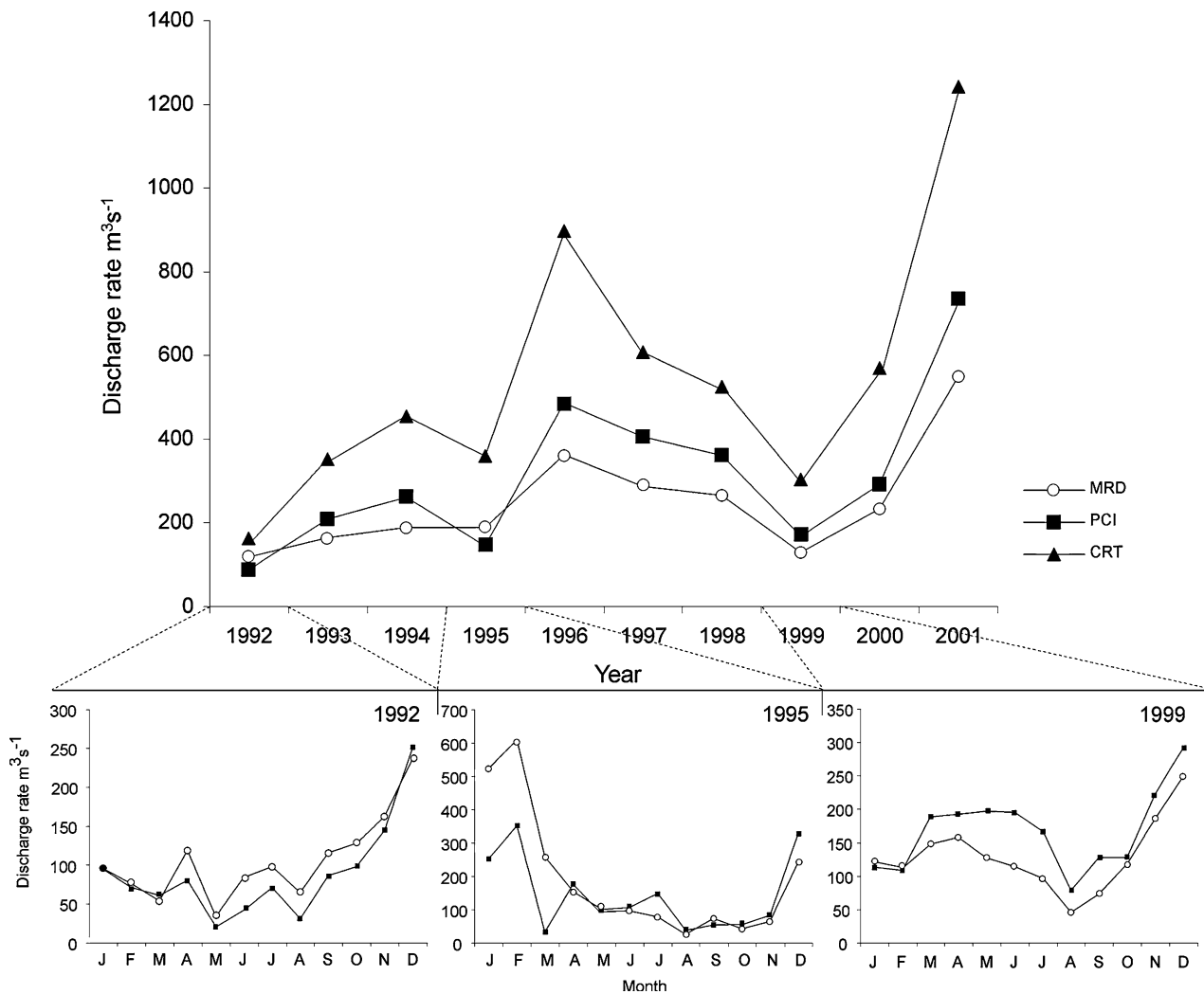


Fig. 2 Yearly averaged discharge rates at the three sampling sites along the international and Portuguese stretch of Douro River. MRD, Miranda; PCI, Pocinho; CRT, Crestuma. Inserts of monthly discharge rates for three drought years: 1992, 1995, 1999 (N.B. Note scale changes for the data in inserts)

Residence Time

In the Miranda reservoir, the 10-year average residence time (RT) was 2.7 ± 0.2 d. In the downstream reservoirs, RTs were significantly greater ($p < 0.05$) than in the Miranda. The 10-year average reached 6.7 ± 1.4 and 5.8 ± 1.1 d, respectively, for Pocinho and Crestuma reservoirs. Values were particularly high during the 1992 drought year, up to 16.9 ± 3.6 d in the Pocinho and 14.6 ± 4.5 d in the Crestuma reservoirs (Figure 4). However, the increase in the second drought year of 1995 was smaller (11.9 ± 2.6 and 8.5 ± 2.5 d, respectively, for Pocinho and Crestuma) and, finally in the last drought year of 1999, the increases were modest. Although RTs were largest during drought periods, a significant decreasing trend over the decade was

noticed ($r^2 = 0.42$, $p < 0.05$ for Pocinho and Crestuma, $r^2 = 0.51$, $p < 0.01$ for Miranda). On a monthly basis, January 2001 presented the shortest RTs, when all three reservoirs were flushed in less than 10 h. In contrast, the 1992 and 1995 drought years showed the largest RTs: Miranda in May 1995, with 12.4 d; Pocinho in May 1992 with 45.0 d; and finally, Crestuma in August of the same year, with an astonishing 61.3 d.

Water Quality Index

Average decade values for the nine parameters used for the WQI calculations are presented in Table 3. Conductivity decreased downstream, as well as water turbidity. On average, the water at the end-member reservoirs had appreciable levels of fecal contamina-

Fig. 3 Monthly averaged discharge rates at the three sampling sites along the international and Portuguese stretch of Douro River for the period 1992–2001. MRD, Miranda; PCI, Pocinho; CRT, Crestuma

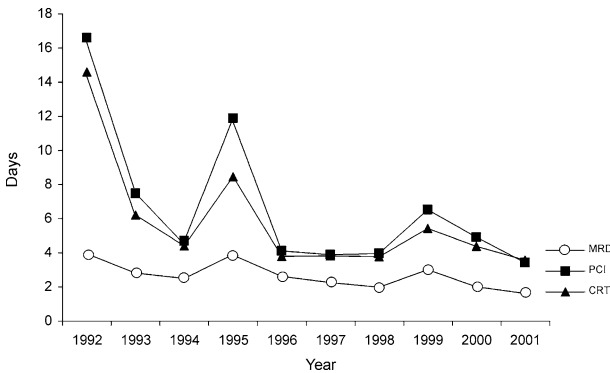
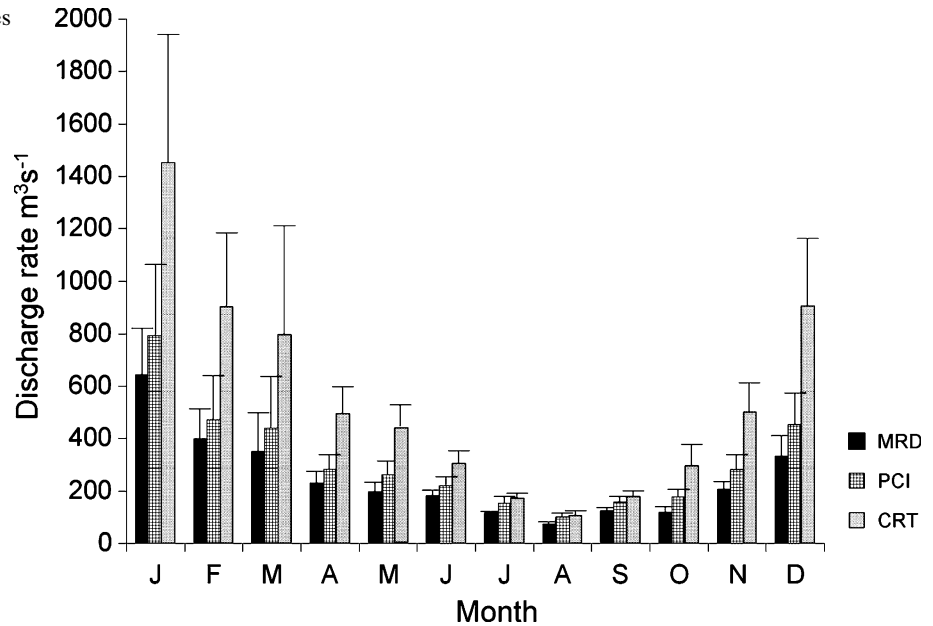


Fig. 4 Yearly averaged residence times at the three sampling sites along the international and Portuguese stretch of Douro River. MRD, Miranda; PCI, Pocinho; CRT, Crestuma

tion, whereas the Pocinho reservoir showed the lowest ammonia concentration and the highest oxygen saturation.

On average, the WQI increased downstream, ranging from “polluted” $47.3 \pm 0.7\%$ in Miranda to “reasonable” $55.4 \pm 0.8\%$ in Pocinho and $61.7 \pm 0.7\%$ in Crestuma. In the Pocinho reservoir, 41.9% of the water quality value was explained by variations in the Miranda reservoir ($p < 0.1$), whereas in Crestuma the explanation level increased up to 60.8% ($p < 0.05$).

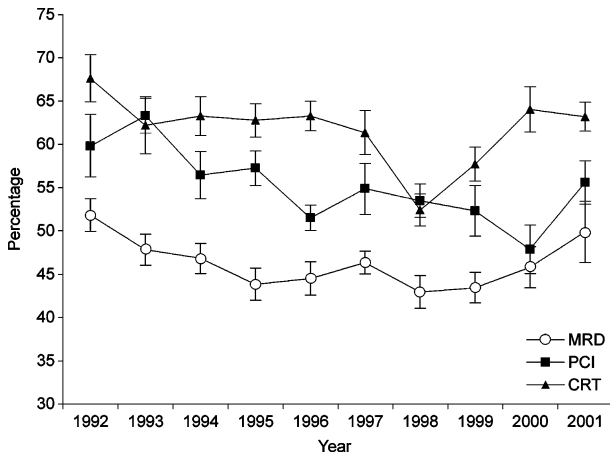
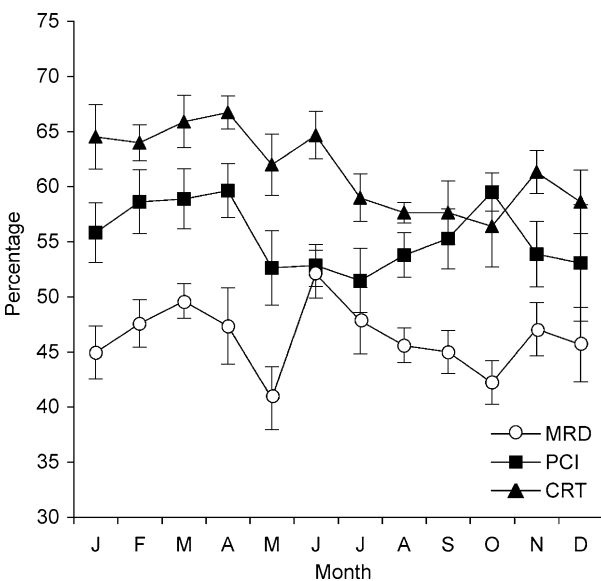
Over the decade, the yearly averaged water quality at Miranda decreased monotonically and significantly until 1995 ($r^2 = 0.954$, $p < 0.05$, $n = 4$), mainly due to a sharp decrease in oxygen content. After 1998, WQI scores rose towards 2001 ($r^2 = 0.894$, $p < 0.05$, $n = 4$), concurrent with the decrease of conductivity and ammonia concentrations and the increase in dissolved

oxygen. Maximum values were found in 1992 and 2001, $51.8 \pm 1.9\%$ and $49.9 \pm 3.6\%$, respectively (Figure 5). In the Pocinho reservoir, quality decreased linearly from 1992 until 2000 ($r^2 = 0.770$, $p < 0.001$, $n = 10$). Increased conductivity and suspended solids as well as lower oxygen content contributed most to the declining WQI scores. Water quality rose slightly in 2001, although the highest yearly averaged score was found in 1993 ($63.3 \pm 2.0\%$). In the Crestuma reservoir, quality was slightly above 60% through 1997, then rose from a minimum of $52.4 \pm 1.8\%$ in 1998 until 2001 ($r^2 = 0.856$, $p < 0.05$, $n = 4$), due to a 10-fold decrease in fecal contamination and ammonia concentrations that was followed by an increase in dissolved oxygen. No overall statistical relationship between discharge rate (Figure 2), and consequently residence time (Figure 3), to WQI scores could be established. Even during the three low discharge periods of 1992, 1995, and 1999, no signal was evident although quality slightly increased in all reservoirs in 2001, a particularly wet year.

The winter months of January to March had the highest WQIs 10-year averages in all reservoirs (Figure 6). Subsequently, in the Miranda reservoir, the WQI decreased sharply between April and May, coinciding with the beginning of the irrigation season in Spain. After a recovery in June, the WQI values decreased monotonically until October, overlapping the lowest seasonal discharge period (Figure 3). In the Crestuma reservoir, a similar trend was observed, although averaged monthly WQI values were significantly higher (ANOVA, $p < 0.05$). On the other hand, in the Pocinho reservoir, located roughly halfway between the others, water quality declined only from

Table 3 Averaged values \pm SE for the nine water parameters included for the calculation of the WQIs for the reservoirs of the Douro River covered by the present study during the 1992–2001 period

Reservoir	Temperature (°C)	pH	Conductivity ($\mu\text{S cm}^{-1}$)	Oxygen saturation (%)	Suspended solids (mg l^{-1})	BOD ₅ (mg l^{-1})	COD (mg l^{-1})	Ammonium ($\text{mg NH}_4 \text{l}^{-1}$)	Fecal coliforms ($\text{cfu } 100 \text{ ml}^{-1}$)
Miranda	14.32 \pm 0.49	7.80 \pm 0.03	374 \pm 9	75.63 \pm 2.01	12.77 \pm 1.19	2.35 \pm 0.11	10.61 \pm 0.39	0.34 \pm 0.03	2614 \pm 1603
Pocinho	16.26 \pm 0.49	7.91 \pm 0.04	280 \pm 9	94.05 \pm 2.34	14.13 \pm 2.56	2.44 \pm 0.12	10.65 \pm 0.43	0.17 \pm 0.01	316 \pm 154
Crestuma	16.26 \pm 0.42	7.44 \pm 0.03	209 \pm 7	91.50 \pm 0.99	10.55 \pm 1.34	1.30 \pm 0.08	8.01 \pm 0.35	0.20 \pm 0.06	4914 \pm 1571

**Fig. 5** Yearly averaged water quality index \pm SE at the three sampling sites along the international and Portuguese stretch of Douro River. MRD, Miranda; PCI, Pocinho; CRT, Crestuma**Fig. 6** Monthly averaged water quality index \pm SE at the three sampling sites along the international and Portuguese stretch of Douro River for the period 1992–2001. MRD, Miranda; PCI, Pocinho; CRT, Crestuma

May through July, followed by an increase until October.

Taking into account the total number of water quality data sets (345), it should be stressed that not a single one yielded a WQI value considered excellent, i.e., $>91\%$ according to the adopted definition (Table 4). In Miranda, with the lowest average score, 71.3% of the data sets were considered polluted and only 25.2% of the samples showed reasonable water quality. In the Pocinho reservoir, the medium category rose to include 64% of the sets, whereas 30.7% of the scores were considered polluted. In the Crestuma reservoir, reasonable water quality was found in 79.3% sets, whereas only 7.8% of the samples were considered polluted and 12.9% showed good water quality scores. Furthermore, different parameters were responsible for the sharp decline in monthly WQIs (Figure 7). In the Miranda reservoir, increased BOD values and conductivity as well as low oxygen saturation were often the key constituents responsible for the monthly decline of water quality. Downstream, in the Pocinho reservoir, fecal coliforms and oxygen saturation were the more frequent parameters related to the monthly decrease of WQI values. In the Crestuma reservoir, fecal coliform contamination emerged as the major constituent responsible for the worsening of water quality.

Discussion

The Douro River watershed is the largest on the Iberian Peninsula, draining 17% of its territory into the Atlantic Ocean. The watershed is shared between Portugal (20%) and Spain (80%). The river is the only source for the production of potable water for approximately two million inhabitants in the Portuguese territory, and is intensively used for irrigation on the Spanish side of the border. In Portugal and along the shared border (Figure 1), most of the dams are located on the main course of the river and were built for hydroelectric power generation purposes (PBHD

Table 4 Class ratings in percentage for Water Quality Index values in the Douro River for the period 1992–2001^a

Reservoir	Data sets	Badly polluted (10–25%)	Polluted (26–50%)	Reasonable (51–70%)	Good (71–90%)	Excellent (91–100%)
Miranda	115	3.5	71.3	25.2	0	0
Pocinho	114	0.9	30.7	64.0	4.4	0
Crestuma	116	0	7.8	79.3	12.9	0

^a Rating scale according to House and Ellis (1987)

1999). In Spain, most of the dams were built in the tributaries and, besides hydroelectricity, they are heavily used for irrigation (CHD 1993).

Although the river is heavily regulated, the seasonality of river flow is still evident (Figure 3). The highest discharges coincide with the wettest period, between December and March in Portugal, and January through March in Spain.

Located on a Spanish tributary close to the shared border and downstream of the Miranda dam (Figure 1), the Almendra dam contains the largest reservoir of the Douro watershed, impounding more than 2600 hm³ of water. An unspecified amount of water is used for irrigation from April to September, and the water used to generate hydroelectricity during the daytime is eventually returned to the reservoir during the nighttime from the main course of the Douro River. Thus, during the severe drought years of 1992 and 1995, the water from the Douro was partially intercepted, and the amount of flow downstream to the Pocinho reservoir was less on average than the amount that entered into the river at the Miranda reservoir (Figure 2). On a monthly basis, the situation is even clearer. During the drought of 1992, the Pocinho reservoir received less water 10 out of 12 months than the Miranda reservoir did. In 1995, the number of months dropped to 8, and in 1999 only between January and February did such events occur.

The relatively small volume of impounded water and the appreciable, but variable, water flow produce rather short residence water times. In an earlier report, Gil and Fernandes (1997) calculated the hydraulic residence time for the period 1990–1996 in the three reservoirs between 1.4 and 6.2 d, which is in agreement with the data presented here (Figure 4). Because of the flow pattern of the river, dependent not only on the precipitation regime but also on the requirements for hydroelectricity generation and irrigation, RT values increased dramatically during the driest years and within each year, during the summer months.

The water quality status and the spatial and temporal trends along the Douro River were assessed

through the application of a nine-parameter WQI derived from the Scottish Development Department index (SDD 1976) to a 10-year public database of environmental data. Barros and others (1995) applied another modification of the SDD index with 11 parameters to the same reservoirs, for a limited period (January through June 1993) with similar results (see below). In our case, it should be stated that the index is not adapted to a specific use, such as bathing water or fish spawning, but rather produces a general index to characterize the overall water quality of the Douro River. It can, however, provide an important, simple, and concise method for expressing the significance of those public data gathered from monitoring programs. Moreover, the index includes subindexes for such parameters as temperature and dissolved oxygen, particularly important for fish, as well as fecal coliforms, which can adversely affect humans (Cude 2001).

Along the 350-km stretch of the river, the water quality increased modestly but steadily downstream, as flow increased. Thus, the water received from the Spanish watershed showed the lowest quality. Such a trend was also noticed in sediments by Gonçalves and others (1987). Those authors found that the increased metal contamination in the Miranda reservoir was related to upstream industrial discharges. Although water quality improved in the Pocinho and Crestuma reservoirs, the highest values were just above 60%, denoting generally reasonable water quality. Since the Crestuma reservoir is the only source of freshwater for 20% of the Portuguese population, the potential health risk is evident, especially during the driest months of July to October (Figure 6). This study shows a clear decrease in water quality during the summer period, although not as dramatic as the drop in river flow. Similar findings were obtained by Barros and others (1995) for a single year.

As stated above, the influx of water to the Miranda reservoir originates entirely from the Spanish portion of the watershed. Because of the type of soil and farming practices, soil erosion and salinity tend to increase, leading to the increase of water mineraliza-

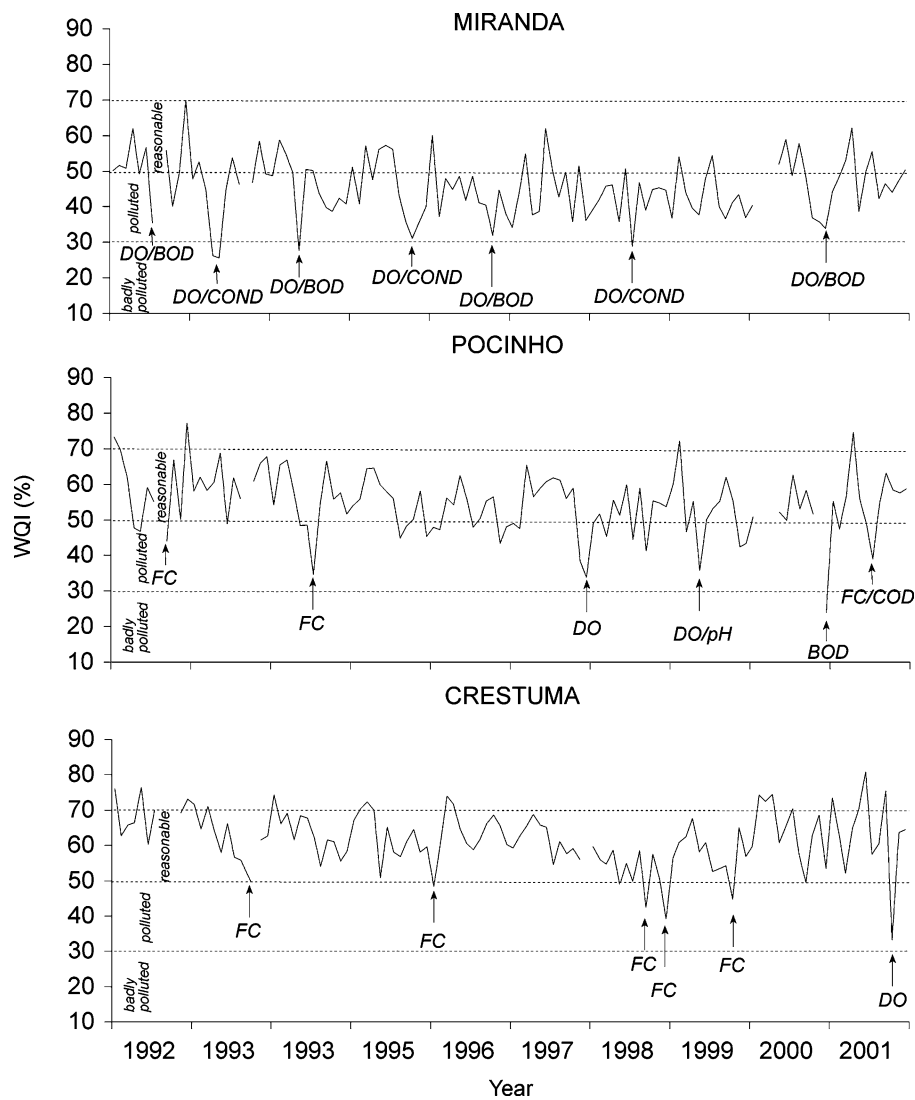


Fig. 7 Monthly variability of WQIs in the Douro River. Parameters contributing the most to particularly low scores are shown. BOD, biological oxygen demand; COD, chemical oxygen demand; COND, conductivity; DO, dissolved oxygen (saturation); FC, fecal coliforms. Water quality class ratings according to Table 4r

tion (Limnos 2000). Thus, high conductivity as well as BOD values and low oxygen content were the parameters most responsible for the episodic worsening of water quality (Figure 7). On a yearly basis, the land use effect was clearer (Figure 5). The decline of WQI scores between 1992 and 1996 was mainly due to increased conductivity values and decreases in dissolved oxygen. Downstream, in the Pocinho reservoir, the increase in conductivity and suspended solids between 1992 and 2000, resulting from heavy dredging and the construction of a large dam in one of the tributaries during the first half of the decade, as well as a decrease in oxygen content, were the main parameters associated with the decline in water quality. In the Crestuma reservoir, increased fecal coliform

numbers were usually related to episodic worsening of monthly water quality (Figure 7). When a sharp decline of fecal contamination occurred during the period 1998 to 2001, because of improvements in the sewage system in the vicinity of the reservoir, WQI scores rose significantly (Figure 5).

According to Hallock (2002), water quality is frequently correlated with flow, increasing with the rise of water discharge (Al-Ani and others 1987), but in this study no statistical relationship could be established between flow and WQIs on a year-to-year basis. Moreover, during low flow years, averaged water quality showed no noticeable decrease or even increased as in the Miranda and Crestuma reservoirs in 1992 (Figure 2). Taking into account the three

reservoirs, the increase in freshwater flow along the 350-km stretch of the Douro River under examination, which hypothetically could foster a higher dilution capacity, and thus improved water quality does not promote a dramatic increase in water quality values. This is particularly evident in the Crestuma reservoir where the flow is 2.2× higher than in Miranda, but averaged water quality increased only 1.3×, probably due to the doubtful quality of the water drained by the Portuguese side of the watershed. In other words, the spatial recovery of the system was modest. On the other hand, only in the particularly wet year of 2001 was an important increase in WQI scores noticed, although the increase was restricted to Miranda and Pocinho reservoirs, where average water quality was systematically lower than in the Crestuma reservoir.

Using the index scale proposed by House and Ellis (1987), a water quality class of 26–50% that covers almost one third of the scores obtained for the three reservoirs in the present study, illustrates that the water requires advanced treatment to produce potable water and for most industrial uses, can be used for indirect, noncontact recreational activities, although the quality is still reasonable for fish and wildlife.

In conclusion, this study highlights the importance of applying a WQI that reflects the collective influence of various criteria and allows easy interpretation of data from monitoring networks that, otherwise, are checked individually against European recommended and mandatory values, with an evident loss of effectiveness. Additionally, the results presented here show that the water entering the shared and Portuguese stretches of the Douro River exhibited, overall, polluted quality. This study confirms the need to enforce the existing bilateral agreements between Portugal and Spain and to design a large international study covering the entire watershed in order to ascertain land uses, identify and quantify point and diffuse pollution sources; to quantify present water uses and define future utilization of water resources; and to develop ecological sound management strategies in the same vein as stated in the Water Framework Directive (WFD 2000). Although the doubtful water quality in the Douro River clearly affects the recreational and commercial uses of the fluvial water, including production of drinking water, there may also be serious consequences to the estuary into which the river flows from the Crestuma reservoir on its passage to the Atlantic Ocean. The Douro River water flow and water quality problems must be viewed not only as a continental river issue but also must be seen as important for the estuary and even

the coastal ocean, as emphasized by the Water Framework Directive (WFD 2000).

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