Definition of ecological flows for rivers located in the north and center of Portugal

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1. Objective

Ecological flow is a relatively new issue in the water sector. Generally, there is a lack of awareness throughout that sector and the general public of the concept and its application.

However, due to the intense agricultural development that is expected in Alentejo (South of Portugal) as a result of the construction of the Alqueva dam, in Guadiana river, several studies have been conducted with the goal of establishing the ecological flow to be implemented downstream each dam. As a result of the research and studies, a hydrologic-hydraulic method was developed to establish an ecological regime that has since proven to be well adjusted to the hydrological regime that occurs in the South of Portugal. More information about these studies can be found in [3].

The good results achieved with the application of the hydrologic-hydraulic method led to the expectation that the adaptation/adjustment of the same method to the hydrological regime of the North of Portugal, being substantially different from the South hydrological regime, should be done and trialed.

The purpose of the investigation project that is summarized in this paper was to test different proposals of adjustments to the hydrologic-hydraulic method, while keeping in mind the formulation of a new method to define an ecological flow regime for the specific hydrological regime of the North of Portugal.

2. Concepts

The aim of ecological flows is to provide a minimum flow regime that is adequate for sustaining the health of the rivers and other natural aquatic ecosystems, the production of species with sport or commercial interest, as well as the maintenance and conservation of the riparian ecosystems, of the esthetic features of the landscape and other features with scientific and cultural interest [1].

The need to predict ecological flows is related to the impacts of actions that are held on the natural fluvial corridor that in some way modify the natural hydrological regime and therefore the ecosystem balance.

Infrastructures such as dams which function is to store, regulate and/or provide water, are often the most significant and direct modifiers of the natural river flow and are a starting point for improving ecological flows studies.

The prediction of the ecological flow regime is aiming to achieve the flowing:

- Conserve and protect the ecosystem by ensuring that rivers are "in good health", protecting their biodiversity, ensuring that the sediment motion and channel morphology maintain the characteristics exhibited in the past.

- Enforce a transparent and legitimate water allocation method that minimizes conflicts and protests from those dependent on the water managed by a dam, either up or down stream, Such method is not to be seen as an environmental "bonus", but rather a serious effort to address problems arisen from situations where the river regulation has gone well beyond the optimum long term point.

Every country expects to improve their economy which, as it is happening in Portugal, often passes for an increase in hydroelectric production. However, a harmonized balance between the development of a country/region, management of its basins and river ecosystem maintenance should be encountered, in order to ensure that communities downstream depending on the environment and related activities such as fishing, farming, cattle raising, tourism, etc are not disrupted and if possible, have such activities enhanced. Meeting these criteria requires a deep analysis that must consider a wide range of aspects, if is to effectively quantify an ecological flow. This variety results from the different types of methods that are used to define a minimum acceptable flow, as a consequence it is considered that a technical team for an ecological flows assessment should be specialized in:

- Hydrology
- Hydraulics
- Marine biology
- Botany
- Zoology
- Ecology
- Agronomy
- Hydro-geology
- Water resource planning and management
- Damn control and operation
- Water quality
- Economy

It is now widely accepted that new thinking on water infrastructure, set within a broader framework of integrated water resource management, is needed to manage water resources sustainably and equitably. The goal is to produce electric energy and the highest the ecological flow is, the smaller is the volume available for the energy production. The fact that the advantage of one "use" is a disadvantage for the other (ecosystem *versus* energy production), has transformed hydroelectricity in an topic of great interest due to the economical and social aspects involved.

Nowadays, and due to the aspects referred above, the developments of methodologies to quantify the ecological flow requirements have become an important issue for the scientific/technical community.

Jowett (1997) recognized three relatively discrete types of ecological flow methodology:

- Hydrological rating method, based in historical monthly or daily flow records;
- Hydraulic rating method, based in simply hydraulic variables, such as perimeter or maximum depth.
- Environmental rating methodologies – based in the relationship between habitat and flow.

The selection of appropriated methods for evaluation of ecological flows depends on the purpose and scale of the study. The limitations of the existing methodologies with regard to many factors imply that quantitative estimates are likely to have wide error.

An incorrect evaluation of the ecological flow needs has two potentially large societal consequences. Either the ecosystem will not get what it needs and degrade – whit the associated loss of socially valued ecosystems services – or other potential water uses will be unnecessarily curtailed or limited, whit attendant social and economical disruption [6].

Therefore, the process of defining ecological flow should be viewed as an iterative process, in which each water management action such as flow restoration is viewed as an experiment that must be monitored and evaluated carefully, enabling scientific refinement of ecological flow recommendations over time. This process of deliberate learning through testing, evaluation and modifying management actions is called *adaptive management*, [4], [5] and [11]. The selection of appropriate methods for quantification should be ideally considered an action of *adaptive management*.

In Portugal there are only some "pointers" in legislation about the subject. However, different methods have already been used to define ecological flows for several damns.

One of those methods is the hydrological-hydraulic method developed by [8]. This method is able to provide comparable ecological flow rates under similar hydrological constraints. The method is supported by hydrological and hydraulic criteria. The hydrological criteria account for water scarcity and for temporal irregularity (along the year and between years) of the natural hydrologic regime and the hydraulic criteria, as well as the geometry of the cross sections and the river reaches.

The goal of this method is to define a monthly ecological flow regime for cross-sections of rivers located in the South of Portugal, specifically Alentejo that is considered one of the driest if not the driest region of Portugal, whit a mean annual flow bellow 150mm associated to a very pronounced temporal irregularity.

3. The hydrologic-hydraulic method. General description.

The application of the hydrologic-hydraulic method requires:

- Cross-sections, representative of the river, with detailed geometry;
- Long series of mean daily flows.

By considering only a part of the mean daily flows (in accordance with the criteria shortly presented), the flow heights and the flow velocities are computed, as well as the mean values of those hydraulic parameters. The mean ecological flow is such that its velocity is equal to the mean velocity previously achieved. [8] Based on that flow, a month-by-month regime is established by applying a kind of "monthly rotation", in accordance with the following equation, which accounts for the temporal variability of the flow regime throughout the year.

$$Q_i = Q_{eco} \times \frac{Q_{ave\ i}}{Q_{mod}}$$

In the previous equation Q_{eco} is the mean monthly ecological flow, Q_i is the ecological flow in month I, $Q_{ave\ i}$ the average of the mean daily flows in month I and Q_{mod} the modulus (all variables expressed in the same units, commonly m^3/s).

The selection of the range of mean daily flows that supports the computation of Q_{eco} takes into account the particular hydrologic features of the hydrologic regime in the region in what concerns the extreme flows.

In fact, most of the time the rivers present extremely small flows and often, for two months or even more, no flows at all. Under these constraints the floods, though rare and restricted to few days per year, may contribute significantly for the total runoff, as they may present exceptionally large flood discharge, with maximum values often several set of tens bigger than the modulus. As those floods do not really represent the flow regime in terms of water availability along the year, it was decided to discard part of the maximum mean daily flows namely those flows with a mean annual duration smaller than 5 days (criterion for the extreme large flows). On the other hand, the irregularity of the hydrologic regime combined with the extremely dry conditions that may occur during a significant part of the year, could justify ecological flows very small as those issues suggest that local ecosystem are adapted to water scarcity. To prevent, somehow, ecological flows essentially influenced by the water scarcity, part of the flows with mean annual durations $\overline{D}$ (days) computed by the following equation (criterion for extremely small flows) $D' \geq 365 - (100 - \overline{D})$, where $\overline{D}$ (days) is the mean annual duration of the modulus estimated as a function of the mean annual flow depth $\overline{H}$ (mm) by applying the following equation $\overline{D} = 0.2108\,\overline{H} + 15.101$ that is supported by the extensive hydrological regionalization studies developed by [9] and [10]. The upper and lower limits of the part of mean daily flows considered will be referred as D_{up}, upper limit and D_{low}, lower limit.

The method above described is exemplified in **Figure 1**.

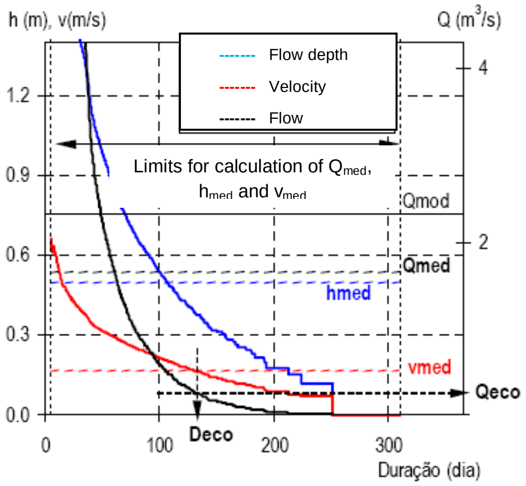
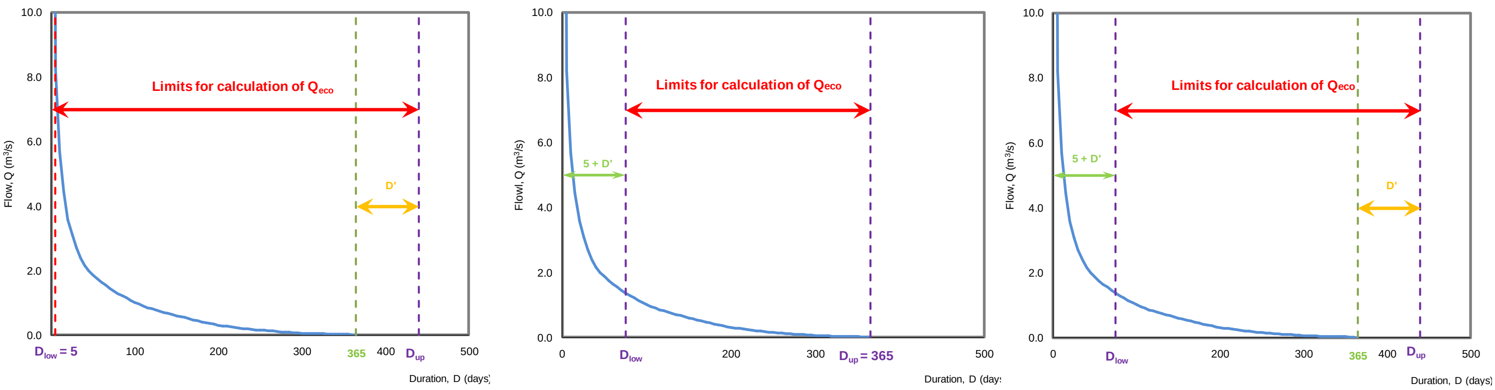


Figure 1 – Hydrologic-hydraulic method exemplification of the procedure used to identify the mean monthly ecological flow, Q_{eco} and the correspondent duration, D_{eco}. Adapted from [8].

4. Investigation work

This chapter presents the adjustments that were introduced in the hydrologic-hydraulic method keeping in mind the hydrological regime that occurs in the North of Portugal, characterized by mean annual flows above 400mm. The variations were made only on the upper and lower limits of the mean daily flows considered for the calculation of flow heights and velocities.

The three adjustment proposals are presented on **Figure 2**, along with the limits taken in account to compute Q_{eco}. D' represents the number of days with flow equal to 0m^3/s that should be added to the series, $D' = [\bar{D} - 100]$.



$D_{up} = 5$ days $\quad$ $D_{up} =$ 5 days + $[\bar{D} - 100]$ $\quad$ $D_{up} =$ 5 days + $[\bar{D} - 100]$

$D_{low} =$ 365 days + $[\bar{D} - 100]$ $\quad$ $D_{low} = 365$ days $\quad$ $D_{low} =$ 365 days + $[\bar{D} - 100]$

Figure 2 – Hydrological-hydraulic method. Exemplification of the procedure used to identify the mean monthly ecological flow, Q_{eco} and the correspondent duration, D_{eco}. Proposals of adaptation for the hydrological flow in the North of Portugal.

From the three proposals, only the <u>second</u> one led to ecological flows comparables among the different cross sections, from the same river stream and even between different rivers with similar mean annual flows. However, apart from the fact that the results obtained for the different case studies were very consistent they still represent an extremely high percentage of the Q_{mod}, when compared to the percentages that are acknowledged as acceptable for ecological purposes.

As it was already mentioned, six different case studies were considered in the North of Portugal, all with mean annual flows above 400mm.

Apart from the adjustment proposals for the hydrological-hydraulic method presented in **Figure 2,** other methods where taken in consideration: wet perimeter method [1], a method specifically designed for Portugal, focused on the characteristics of the monthly flow series [1], and the basic flow method [7], these methods will be further referred to as WP method, INAG method and QB method, respectively. Their application to each location/dam requires only monthly flow series (INAG and QB method) and cross section of the river reach downstream of the dam (WP method).

The application of these methodologies was intended to gather information for further comparison.

The WP method resulted in such dissimilar results for cross sections in the same river that those results were not considered for the comparison

It should be said that none of the cross sections used in this project was coincident with the hydrometric stations available which, for Portugal, does not represent an obstacle once that series can be easily established by applying two procedures developed by [9] and [10].

5. Results

The characteristics of each case study and the results obtained are presented on the following tables and figure.

Table 1 – Data referring to the six case studies located in the North of Portugal.

Projects		**1**	**2**	**3**	**4**	**5**	**6**
Location		**Norte**					
Hydrometric station		Santa Marta de Alvão	Fábrica da Matrena	Murça	Cabriz	Vale Giestoso	Vale Giestoso
Recording period		45 years	13 years	27 years	33 years	40 years	40 years
		1955/56 to 1999/2000	1976/77 to 1988/89	1970/71 to 2003/04	1966/67 to 1999/2000	1957/58 to 1996/97	1957/58 to 1996/97
Water course		Avelames River	Sertã River	Tinhela River	Ovil River	Covas River	Couto River
Main watershed		Tâmega River	Tejo River	Tâmega River	Douro River	Tâmega River	Tâmega River
Watershed area (km^2)		78.8	301.5	87.0	53.7	21.3	58.9
Mean annual flow	**Volume** (hm^3)	40.4	174.9	53.1	37.6	28.3	78.3
	Flow depth (mm)	512.7	580.1	610.0	700.2	1328.6	1329.4
	Modulus (m^3/s)	1.28	5.55	1.68	1.19	0.90	2.48
Mean annual duration (day)		101	88	86	107	91	91
Cross sections		S1.1, S1.2 e S1.3	S2.1, S2.2 e S2.3	S3.1, S3.2, S3.3 e S3.4	S4.1 e S4.2	S5.1, S5.2 e S5.3	S6.1 e S6.2
Mean slope		1.2%	0.8%	4.5%	0.8%	9.0%	4.3%
Mean monthly flow (l/s)	October	577.75	1824.90	581.80	552.46	306.43	847.84
	November	1363.32	3606.65	1220.16	1125.52	736.76	2038.45
	December	2421.62	8496.43	3338.39	1992.26	1497.44	4143.10
	January	2672.99	10132.11	3725.05	2560.09	1891.67	5233.84
	February	2581.87	16667.85	3992.69	2421.85	2061.46	5703.63
	March	2031.65	8178.88	2699.21	1675.70	1461.11	4042.58
	April	1510.22	6061.19	1717.56	1429.06	1033.16	2858.53
	May	1041.51	4557.43	1262.30	1294.82	702.30	1943.11
	June	520.71	2521.88	671.15	629.97	423.96	1173.00
	July	193.94	1451.40	310.35	177.47	213.40	590.43
	August	72.34	907.39	145.04	83.73	116.91	323.46
	September	95.72	894.06	150.37	95.31	121.41	335.92

In **tables 2** and **3**, Q_{mod} is the modulus, Q_{eco} is the mean monthly ecological flow, $\overline{H}$ (mm) is the mean annual flow depth, D_{up}, is the upper limit and D_{low}, the lower limit of mean annual duration that is presented as D. The symbol SX.i identifies the cross section I (with i=1,…,4) of the case study X (with X=1,…,6).

Table 2 – Results from the application of the INAG and QB methods.

			INAG/DSP		QB	
			Q_{eco}			
Case studies	**Q_{mod}** **m^3/s**	**H** **mm**	**Value** m^3/s	**Percentage** %	**Value** m^3/s	**Percentage** %
1	1.281	512.7	0.2880	**22.5**	0.1211	**9.4**
2	5.546	580.1	0.1124	**2.0**	0.5762	**10.4**
3	1.683	610.0	0.0419	**2.5**	0.2155	**12.8**
4	1.192	700.2	0.2817	**23.6**	0.0399	**3.3**
5	0.897	1328.6	0.2309	**25.7**	0.0696	**7.8**
6	2.483	1329.4	0.6390	**25.7**	0.1925	**7.8**

Table 3 – Results from the application of the second proposal of adjustment of the hydrological-hydraulic method.

					SX.1			SX.2		
					D	**Q_{eco}**		**D**	**Q_{eco}**	
	Case studies	**H** mm	**D_{inf}** days	**D_{sup}** days	dias	Value m^3/s	Percentage %	days	value m^3/s	Percentage %
North	**1**	512.7	28	365	193	0.4419	**34.5**	191	0.4564	**35.6**
	2	580.1	42		208	1.6754	**30.2**	179	2.2231	**40.1**
	3	610.0	49		193	0.5084	**30.2**	192	0.5105	**30.3**
	4	700.2	68		227	0.2656	**22.3**	220	0.3076	**25.8**
	5	1328.6	200		291	0.1425	**15.9**	306	0.1254	**14.0**
	6	1329.4	200		291	0.3943	**15.9**	291	0.3942	**15.9**

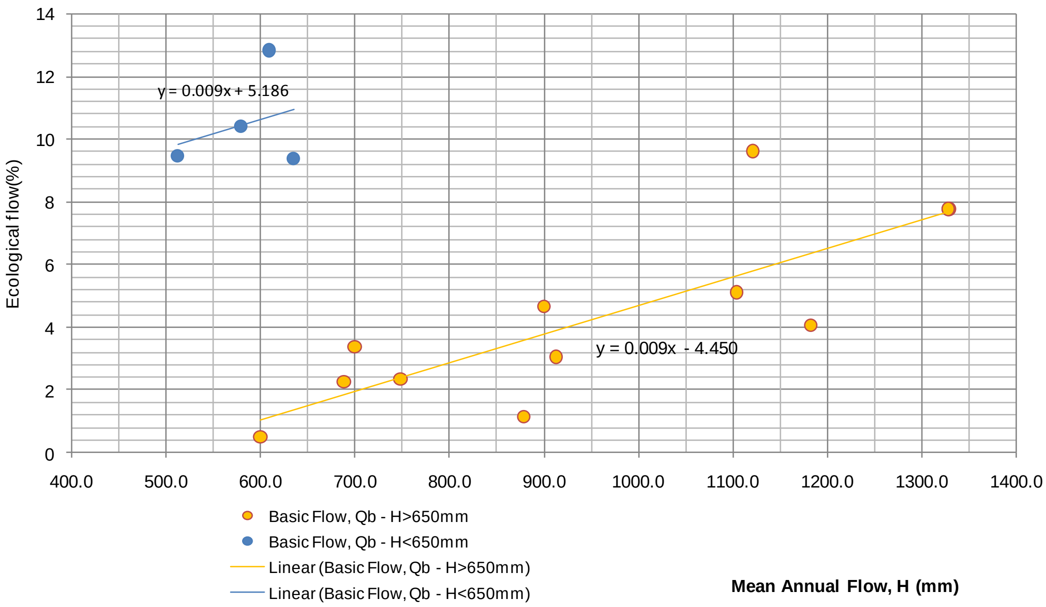
					SX.3			SX.4		
					D	**Q_{eco}**		**D**	**Q_{eco}**	
	Case studies	**H** mm	**D_{inf}** days	**D_{sup}** days	days	Value m^3/s	Percentage %	days	Value m^3/s	Percentage %
North	**1**	512.7	28	365	180	0.5252	**41.0**	-	-	**-**
	2	580.1	42		188	2.0008	**36.1**	-	-	**-**
	3	610.0	49		194	0.5009	**29.8**	209	0.4406	**26.2**
	4	700.2	68		-	-	**-**	-	-	**-**
	5	1328.6	200		316	0.1122	**12.5**	-	-	**-**
	6	1329.4	200		-	-	**-**	-	-	**-**

Apart from the data presented on **Table 2,** data related to the application of the QB method was available, used and can be consulted in [2]. The results can be analyzed on **Table 4** and **Figure 3**.

Table 4 – Results from the application of the QB method, Source: FERREIRA (2004).

Hydrometric station		**Watershed ared**	**Recording period**	**Mean annual flow**			**QB method**	
code	**name**	km²	years	**Volume** hm^3	**Modulus** m^3/s	**Flow depth** mm	**Value** m^3/s	**Percentage** %
09G/01	Pte. Vale Maior	188	15	222.5	7.055	1183.4	0.2860	**4.1**
17F/02	Pte. Nova	102	10	114.5	3.630	1122.3	0.3482	**9.6**
09F/01	Pte. Minhoteira	114	14	126.0	3.994	1104.9	0.2033	**5.1**
11M/01	Pai Diz	50	17	45.7	1.449	914.1	0.0441	**3.0**
05K/01	S. Marta do Alvão	52	13	46.9	1.486	901.1	0.0689	**4.6**
06K/01	Ermida-Corgo	291	20	256.0	8.117	879.6	0.0927	**1.1**
10M/03	Videmonte	121	15	90.6	2.873	748.7	0.0670	**2.3**
08J/01	Castro d'Aire	291	18	200.5	6.358	689.0	0.1436	**2.3**
03K/01	Vale Giestoso	77	20	48.9	1.551	635.2	0.1450	**9.3**

Figure 3 – Results from the application of the QB method to the six case studies located in the North of Portugal (**Table 2**) and case studies presented in FERREIRA (**Table 4**).



6. Discussion

Initially, it was considered that, for small hydropower stations, ecological flows around 3% of the modulus were suitable. This percentage was later increased to 5%. Such stations are located mainly in the North of Portugal, and are characterized by water availability and a regular temporal variability (along the year and between years).

The analysis based on dams located on the South of Portugal, Alqueva system in particular, suggested the adoption of higher values due to the scarcity of water and to the high temporal irregularity that characterizes the region. Values around 10% of the modulus were proposed in [8]. Analysis of this information suggests that mean monthly ecological flows from 5 to 10% of the modulus are the most appropriate for the hydrological regimes that occur in Portugal.

The ecological flows that were obtained with the application of the second method presented in point 4 of this document, revealed to be higher than expected (and for that reason economically, unjustifiable), although they proved to be consistent and able to denote the characteristics of the hydrological regime.

One of the reasons that can explain the unsatisfactory results that were obtained is the lack of detail on the cross sections that were used.

Looking closely to the results obtained, it is clear that the higher the mean annual flow, the lower is the percentage of the modulus that should be considered as ecological flow. Case studies that have mean annual flows above 1000mm have ecological flows around 12% and 15%, which may imply the possible application of the method to case studies with mean annual flows above 1000mm.

The results obtained with the application of the INAG method show higher but consistent values due to the hydrological features of the method. The case studies **2** and **3** resulted in unusual values that might be explained by the small number of years for which data in the hydrometric stations considered to establish the series of flows is available, 13 and 27 years, respectively.

According to the initial considerations of the value of ecological flow that should be safeguarded for ecological purpose, the results obtained with the QB method turned out to be the most satisfactory ones. Apart from the case study **4** the ecological flows ranged from 8 to 13% of the modulus, percentages that points towards the possibility of using that method to established ecological flows. For that purpose, a different understanding of the procedure is necessary, for instance, by considering each basic flow as a monthly average ecological. The data presented in **Figure 3** suggests that this percentage decreases as the mean annual flow increases, partly explained by the regularity of the hydrological regime in the North.

Due to the good performance of the QB method, the results achieved by [2] by applying the same method to river sections located in the North of Portugal were also analyzed. Those results combined whit the ones from the 6 case studies (**Figure 3**) show a clear difference among river sections with mean annual flows between 400mm and 650mm and above 650mm. In general terms it can be stated that for basins having mean annual flows above 650mm, the QB method seems to be satisfactory, conclusion that should be evaluated on future studies.

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