A hydrologic-hydraulic method to define of ecological flows downstream dams located in South European semi-arid regions

MARIA MANUELA PORTELA
Department of Civil Engineering and Architecture
IST, Instituto Superior Técnico
Av. Rovisco Pais, 1049-001 Lisboa
PORTUGAL

Abstract: - A new method supported by hydrologic and hydraulic criteria and aiming at the definition of ecological flows downstream dams located semi-arid regions, like those of the South of Portugal, was developed. The hydrologic criteria account for the water scarcity and for the temporal irregularity of the natural hydrologic regime and the hydraulic criteria, for the geometry of the cross sections and of the river reaches. The method is briefly described and the ecological flows achieved for 13 case studies are presented. The method seams to be applicable to regions similar, from a hydrologic point of view, to the one analyzed, namely located around the Mediterranean Sea.

Key-Words: - Ecological flows, hydrologic-hydraulic method, hydrologic regime, hydraulic characteristics, cross section, mean flow velocity

1 Introduction

In 2004 the multi-purpose Alqueva system started its exploitation. The main component of that system is the Alqueva dam, located in Guadiana River, in the South of Portugal and providing the largest artificial lake in Europe, with a gross and a net storage capacity of 4500 and 3150 million cubic meters, respectively. Alqueva dam is the "heart" of an irrigation system that will supply water to 115 thousand hectares, by means of 15 dams spread over the region (existing and new ones), more than 300 km of open channels and more than 2000 km of buried conduits [3].

One the environmental issues related with Alqueva irrigation system is the definition of the ecological flows to be implemented downstream each dam. In fact, Alentejo has very specific hydrological constraints being the driest region of Portugal, with a mean annual rainfall of about 500 mm and a mean annual flow below 150 mm, these hydrological variables also being characterized by a very pronounced temporal irregularity: about 75 to 80% of the rainfall and 90 to 95% of the runoff occur during the wet season (from October to March).

The availability of water that became possible by the Alqueva system may suggest that more water could be launched into the rivers during the dry season, by means of artificial ecological flows. This perspective may not be the more correct one as the local river ecosystems are naturally adapted to extreme water scarcity. Also due to the semi-arid characteristics of Alentejo, a wise and tight management of the water is crucial.

In the previous scope several methods were tested and compared aiming at defining the ecological flows downstream 13 dams (either existing or new ones) of the Alqueva system.

In a broad sense, the ecological flow for a given river reach can be considered as the minimum flow that ensures the conservation and maintenance of the natural aquatic ecosystems, including their biodiversity, the production of species with sporting or commercial interest, as well as the conservation and the maintenance of the riparian ecosystems, of the esthetic features of the landscape or of other features with scientific and cultural interest [2]. An ecological flow regime is a temporal sequence of ecological flows, generally defined in a monthly basis. Any flow or sequence of flows able to preserve the "dynamics" (performance, composition and structure) of the "fluvial-related" ecosystems in natural conditions can be therefore considered an ecological one. This implies that for each river reach there is not such thing as "the ecological flow" but instead a range of ecological flows, varying from minimum ones to maximum ones. Being water a resource progressively scarce, the minimum ecological flows are generally the envisaged ones.

The physical organization of each natural fluvial corridor as well as the biologic "performance" of the ecosystems connected with it are deeply dependent on the flow regime as this regime determines the morphologic, the hydraulic, and by extension, the biologic parameters of such corridor. Consequently, several methodologies and criteria aiming at defining ecological flows utilize the characteristics of the natural river flows, with emphasis on the values of the flows themselves as well as on their temporal variability (along the year and among years). Also, the river flows are most of the time the only easily available hydrologic data when the definition of a given ecological flow regime is envisaged.

In the previous understanding, three methods of the hydrologic type were applied to 13 dams of Alqueva system and the ecological flows thus achieved compared. The methods under consideration were the wet perimeter method (**WP method**) [1], a method specifically conceived for Portugal (**INAG method**) [3], and the basic flow method developed by Palau and Alcázar (**QB method**) [5] and [6]. The application of the INAG and QB methods requires only flow series and the one of the WP method also cross sections of the river reaches under consideration.

The analysis of the ecological flows thus predicted showed that the QB method is not applicable whenever the flow regime may present periods with very low or even nonexistent flows as it results in mean monthly ecological flows close to zero. The INAG method also revealed to be unsuitable, though due to opposite reasons: it resulted in mean monthly ecological flows basically comprehended between 16 and 24% of the mean daily flows or modulus, that is to say, to high and therefore incompatible with the economical value of the water in the region.

The WP method led to unpredictable and uncorrelated ecological flows, both for a given river reach and for different river reaches, those flows being either very high or very low.

The sort of "anachronism" among ecological flows provided by the WP method seemed even more abnormal as the region under consideration presents a very uniform hydrologic regime, characterized, as previously mentioned, by a very small mean annual flow depth, with almost the same value in the whole region, and by a very pronounced temporal irregularity. Notwithstanding the differences among locations related with the geometry of the cross sections and with the area of the watersheds, it was expected to achieve ecological flows of the same order of magnitude when expressed as percentage of the modulus, Q_{mod}[(1)].

[(1)] The modulus is the average of the mean daily flows. It can be expressed in terms of either a flow rate or a flow depth uniformly distributed over the horizontal projection of the watershed – mean annual flow depth.

Besides the values of the ecological flows, some hydraulic features of the flow regimes were also compared namely the flow heights and the mean flow velocities, v[(2)]. This comparison showed that pronounced differences among ecological flows did not necessarily mean differences equally pronounced among the previous hydraulic parameters. In fact, the flow heights and especially the flow velocities were much closer than the differences among ecological flows could indicate. These results suggested that to recommend an ecological regime based only on the values of the natural flows may not be the most correct decision as only part of the features of the flow regime are taken into account.

In the previous scope, a research was carried out in order to develop a method able to provide comparable ecological flows under similar hydrologic constraints. The method thus achieved is supported by hydrologic and hydraulic criteria [7] and [10] and was named hydrologic-hydraulic method (**HH method**). The hydrologic criteria account for the water scarcity and for the temporal irregularity (along the year and among years) of the natural hydrologic regime and the hydraulic criteria, for the geometry of the cross sections and of the river reaches.

2 The hydrologic-hydraulic method

In each cross section and besides its detailed geometry, the application of the HH method requires a long series of mean daily flows which, for Portugal, does not represent an obstacle as that kind of series can be easily established by applying the procedures developed by [8], [9] and [11] and widely proved.

By considering only 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 monthly ecological flow** is such that its velocity is equal to the mean velocity previously achieved, [7] and [10]. Based on that flow, a month-by-month regime is established by applying a "monthly rotation", in accordance with the following equation, which accounts for the temporal variability of the flow regime throughout the year:

$$Q_i = Q_{eco} \times Q_{ave_i} / Q_{mod} \quad (1)$$

where Q_{eco} is the mean monthly ecological flow; Q_i the ecological flow in month i; Q_{ave_i} the average of the mean daily flows in month i; and Q_{mod} the

[(2)] To simplify the presentation, the mean flow velocity in a given cross section will be referred as flow velocity.

modulus (all variables expressed in the same units, usually 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 Alentejo 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 a few days per year, may contribute significantly for the total runoff, as they may present flood discharge exceptionally large, 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(3) 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 the local ecosystems are adapted to water scarcity. To prevent, somehow, ecological flows essentially influenced by the water scarcity, part of the flows during the dry season were discarded, namely the flows with mean annual durations D' (days) computed by the following equation (**criterion for the extreme small flows**):

$$D' \geq 365 - (100 - \overline{D}) \quad (2)$$

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:

$$\overline{D} = 0.2108\,\overline{H} + 15.101 \quad (3)$$

The latter equation is supported by the extensive hydrologic regionalization studies developed by [8] and [9]. Those studies proved that the mean annual flow depth is a regional parameter capable of "describing" the hydrologic regime and of providing a powerful tool that enables the establishment of flows series at ungauged river sections.
According to the criteria established for extreme large and extreme small flows the average of the velocities at each cross sections were computed based on the daily flows with a mean annual duration comprehended between 5 and $D' \geq 365 - (100 - \overline{D})$ days.

(3) For a given set of n years, the duration, D, of a given flow/discharge, Q, is the number of days with flows equal or larger than that one. The mean annual duration, $\overline{D}$, is the average number of days per year with flows equal or larger than Q ($\overline{D} = D/n$).

In general terms, in each cross section of a given river reach the application of the HH method is accomplished according with the following steps:

i) establishment of the mean daily flows series at that section for a period of n years, n being as large as possible (15 or more years);
ii) for each mean daily flow with mean annual duration comprehended between 5 and $D' \geq 365 - (100 - \overline{D})$ days, computation of its velocity;
iii) for the whole period, computation of the average of the velocities achieved in the previous step;
iv) computation of the mean daily flow which flow velocity is equal the previous average;
v) establishment of the mean monthly ecological flow by assigning it to the flow evaluated in step iv).

It should be stressed that the computation of the flow velocities as well as of the flow with a given velocity was carried out based on the assumption of uniform flow, by applying the Manning equation.

3 Results

Table 1 presents some features of the 13 case studies (watershed areas, mean annual flow depths and modulus) along with number of cross sections analyzed for each case and with the mean monthly ecological flows (expressed in a non-dimensional form, as percentage of the modulus, Q_{mod}) predicted by the WP and the HH methods applied to those sections. Both methods utilized the same cross sections. Fig. 1 contains the schematic location of the case studies. Photos from 12 of those 13 case studies are presented in Fig. 2.
Conceptually, the WP method provides only one flow for each cross section: the smallest flow for which the curve that relates the wet perimeter with the flow (curve WP-F) denotes an inflexion. However, some of the WP-F curves had more than one inflexion, the smallest flows represented by those inflexions being often too small and therefore unsuitable for ecological purposes. Under these circumstances, more than one flow was adopted for the WP method, as represented in Fig. 3 for case study 11. On the other hand, the WP-F curve may not have any inflexion at all, as it happen in one of the cross sections of case study 9, thus not allowing the identification of an ecological flow.
According to the conception of the HH method, for each cross section only one ecological flow can be defined.

Table 1 – Case studies. General features and ecological flows.

Case study	Watershed area (km²)	Mean annual flow depth (mm)	Modulus Q_{mod} (m3/s)	Mean monthly ecological flow (% of Q_{mod})				
				Section number	WP method		HH method	
					Value	Range	Value	Range
1	13.1	83.7	0.035	1	30.1	3 to 52	10.8	9 to 12
				2	2.9		9.0	
					5.7			
				3	7.2		11.3	
				4	51.6		11.7	
2	60.5	89.6	0.172	1	29.4	3 to 29	10.1	10
				2	2.9		10.2	
3	101.8	90.7	0.293	1	7.9	8 to 22	7.5	8 to 12
				2	13.0		12.3	
				3	21.7		9.0	
				4	71.4		9.5	
4	6.3	94.5	0.019	1	7.8	8 to 137	12.6	12 to 13
					88.2			
				2	24.1		11.6	
				2	137.4			
5	176.2	95.5	0.534	1	1.9	2 to 11	9.9	9 to 12
					9.7			
				2	6.0		8.8	
					6.6			
				3	11.4		12.4	
				4	3.9		11.1	
6	37.6	95.7	0.114	1	180.8	5 to 285	9.7	7 to 11
				2	285.3		7.0	
				3	52.7		7.6	
				4	70.8		11.2	
				5	5.4		11.4	
7	351.0	124.2	1.395	1	1.8	less than 1 to 21	10.6	7 to 11
				2	0.5		9.0	
				3	0.5		7.1	
					1.3			
					20.6			
8	509.0	143.8	2.321	1	2.0	less than 1 to 4	11.5	7 a 12
					4.2			
				2	0.4		7.4	
					2.4			
9	38.9	152.0	0.188	1	1.9	2 to 56	11.6	11 to 12
					55.7			
				2	--		10.7	
10	15.4	153.0	0.076	1	36.9	5 to 37	11.0	11 to 16
				2	5.3		15.9	
11	48.0	155.3	0.237	1	3.6	4 to 7	6.6	7 to 9
					7.0			
				2	5.1		9.3	
12	212.0	161.0	1.081	1	6.5	7 to 12	11.9	7 to 12
				2	12.0		7.2	
13	218.0	178.4	2.432	1	2.2	2 to 3	4.6	4 to 5
				2	3.2		4.0	

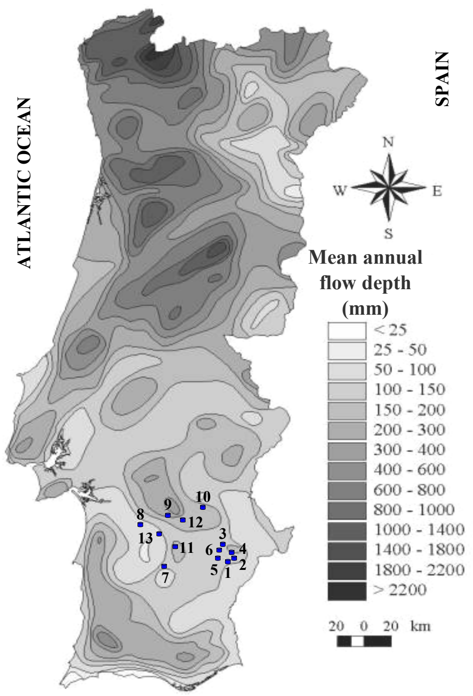

Fig. 1 – Schematic location of the 12 case studies (basis: map of the mean annual flow depth).

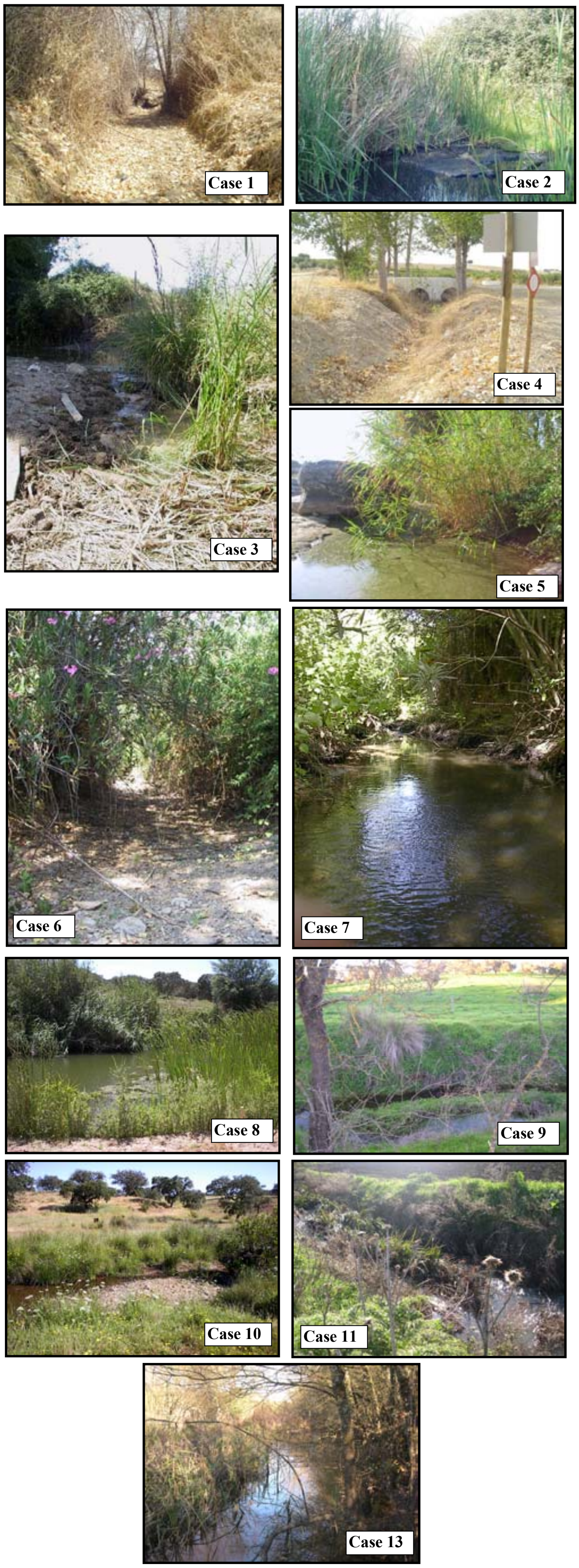

Fig. 2 – Photos of some of the case studies.

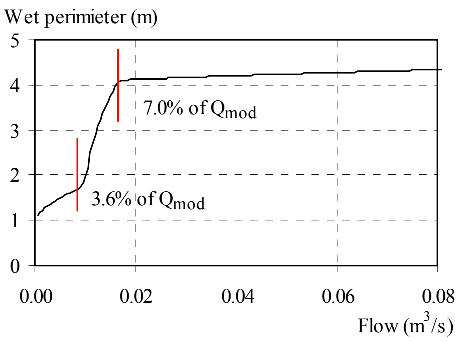

Fig. 3 – Case study 11. WP-F curve with two inflexions.

Fig. 4 completes Table 1, by representing the ecological flows as a function of the number of the case study. For each case the figure also includes the average of the ecological flows predicted based on the different cross sections.

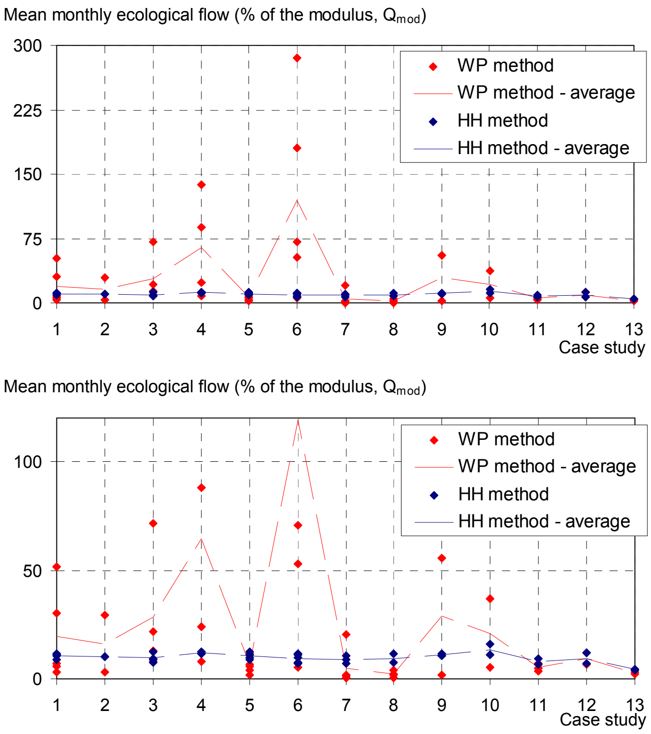

Fig. 4 – WP and HH methods. For each case study: mean monthly ecological flows obtained for the different cross sections and corresponding average. The figure bellows only enlarges the vertical axis of the first figure.

Table 1 and Figure 4 clearly show that:

i) despite the differences among watershed areas and among mean annual flows depths, the HH method applied to the different cross sections of each river reach always resulted in a narrow range of non-dimensional mean monthly ecological flows in clear opposition to the wet perimeter method. This circumstance is even more remarkable as both methods utilized the same cross sections;

ii) with the exception of case 13, the ranges of non-dimensional mean monthly ecological flows provided by the HH method are quite similar; in fact, for the others 12 cases, mean monthly ecological flows around 10% the modulus seam to be justifiable, as shown in Fig. 5.

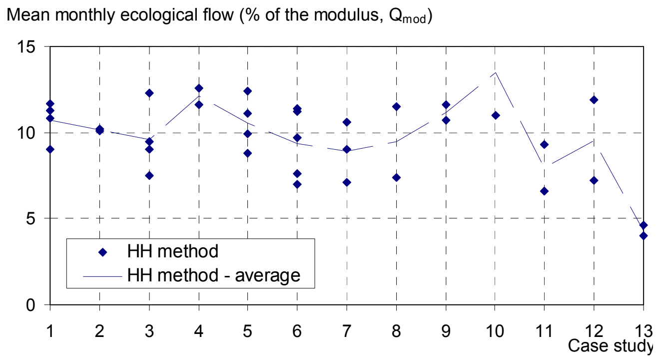

Fig. 4 – Mean monthly ecological flows predicted by the HH method and corresponding averages for the 13 case studies.

4 Conclusions and discussion

A new method to define ecological flows based on hydrologic and hydraulic criteria was developed for Alentejo (South of Portugal) and it is briefly presented.

The hydrologic criteria account for the water scarcity and for the temporal irregularity of the natural hydrologic regime and the hydraulic criteria, for the geometry of the cross sections and of the river reaches. The data required by the application of the method to a given river reach are a series of mean daily flows and, as for the wet perimeter method, cross sections of that reach. In order to ensure that the special features of the flow regime are correctly considered, the previous series must be as long as possible (15 years or more). Also more than one cross section must be considered to attend the spatial variability of the geometry of the fluvial corridor.

The results achieved for 13 dams clearly show that the HH method is able to provide similar non-dimensional ecological flows despite the differences among watershed areas and mean annual flows depths. Mean monthly ecological flows around 10% of the modulus seem to be appropriate to the regional hydrologic constraints. Based on each mean monthly ecological flow a monthly regime is established by applying equation (1).

Despite the fact that the hydrologic-hydraulic method and the wet perimeter method utilized the same cross sections, while the wet perimeter method was unable to provide a general guideline in terms of ecological flows, the hydrologic-hydraulic method resulted (with only one exception) in mean monthly ecological flows very similar.

These circumstance points towards the ability of the method to combine the general features of the hydrologic regime with the particularities of the geometry of the fluvial corridors. These circumstances suggests that the method may be applicable to hydrological regimes similar to the one that occurs in the region where the case studies are located, with emphasis to the semi-arid regions located around the Mediterranean Sea.

References:

[1] Alves, M. H, *Método de determinação do caudal ecológico*, MSc Thesis. IST. Portugal, 1993.

[2] Alves, M. H., "Aproveitamentos hidráulicos, alterações dos regimes naturais e caudal ecológico" *in Caudais ecológicos em Portugal*, INAG, DSP, pp. 2.1-2.18, 2002, Portugal.

[3] Alves, M. H.; Bernardo, J. M., "Determinação de caudais ecológicos" *in Caudais ecológicos em Portugal*, INAG, DSP, pp. 3.1-3.27, 2002, Portugal.

[4] EDIA, Empresa de Desenvolvimento e Infra-Estruras do ALQUEVA, SA, www.edia.pt.

[5] Palau, T.; Alcazar, J., "The basic flow: an alternative approach to calculate minimum environmental instream flows", Procs *2nd Int. Symp. on Habitat Hydraulic*, Vol. A: 547-558, 1996, Canada.

[6] Palau, T.; Alcázar, C.; J. Roi, *El Caudal Básico. Método para la gestión hidrobiológica de rios regulados*, Informe Técnico para CEDEX, 1998, Spain.

[7] Portela, M. M., "Proposta de procedimento hidrológico hidráulico para definir caudais ecológicos em cursos de água do Sul de Portugal Continental", *Recursos Hídricos*, Vol. 26 (1), APRH, 2005, Portugal.

[8] Portela, M. M.; Quintela, A. C., "Regionalization of hydrologic information: establishment of flow series at ungauged watersheds", *Water Resources Management III* (Carvoeiro, Portugal), Wessex Institute, WITPress, ISBN 1-84564-007-1, pp. 11-20. 2005, Southampton, Boston..

[9] Portela, M. M.; Quintela, A. C., "Estimação em Portugal Continental de escoamentos e de capacidades úteis de albufeiras de regularização na ausência de informação". *Recursos Hídricos*, Vol. 27(2), APRH, 2006, Portugal.

[10] Portela, M. M., "A new method to define ecological flows in the South of Portugal", *2nd International Congress. Energy and Environment Engineering and Management*, IICIIEM2007, 2007, Badajoz, Spain.

[11] QUINTELA, A., Recursos de águas superficiais em Portugal Continental. PhD Thesis, IST, 1967, Portugal.