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Estimated Ecological Flow of the Preto River by the Wetted Perimeter Method

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Abstract- The ecological flow is the minimum flow of a river necessary to maintain its aquatic fauna. In the present study, this flow was estimated for the Preto River, which belongs to the Piabanha River Basin, located in the state of Rio de Janeiro, Brazil. Because the Preto River's entire length is within the state, its management is under the responsibility of the Rio de Janeiro State Environmental Institute (INEA). The INEA adopts the value of 50% of $Q_{7,10}$as the minimum ecological flow for rivers in the state. Hydrological data were obtained from a stage gauge located on the river, allowing estimation of the ecological flow. The results were satisfactory, because the two ecological flow values calculated were lower than the lowest flow observed during the historic discharge series of the river.

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I. Introduction

The rational use and preservation of water resources are vital elements of public policy. In Brazil, Law 9,433/1997 established the National Water Resource Policy, which includes a series of measures regarding the use of water resources for various purposes and preservation of the quantity and quality of water. In rivers, a minimum flow, called the ecological flow, is necessary to maintain the aquatic fauna. Although there is no consensus on the method to calculate this metric, it can be estimated by hydraulic methods that relate characteristics of the current and channel, considering reference flow values and including holistic methods based on economic values and habitat classification techniques to identify physical and environmental traits of the water course in question [1]. This article presents the ecological flow, estimated by two equations, to be considered for the Preto River, located in the Piabanha River Basin.

II. Piabanha River Basin

The Piabanha River Basin is located in the state of Rio de Janeiro (Figure 1). It covers approximately 4,484 km^2 and contains about 700 thousand inhabitants, in ten municipalities, of which six lie totally within the basin. The Piabanha River extends 80 km and passes through the municipalities of Petrópolis, Areal and Três Rios. The Preto River, with extension of 54 km, is its main tributary [2].

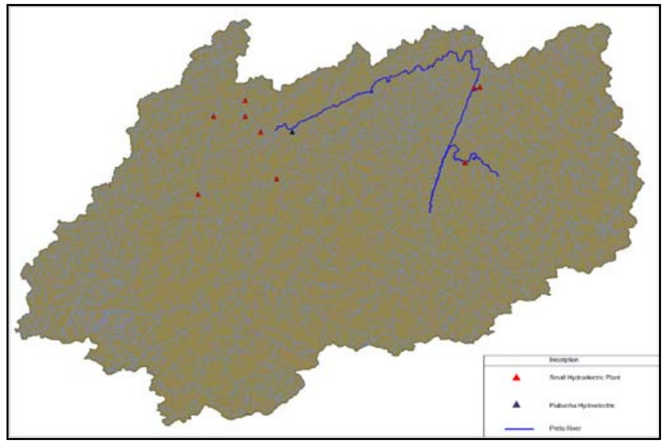

Figure 1 : Piabanha River Basin

III. Water Availability, Maximum Surface Water Withdrawal and Ecological Flow

The Preto River lies completely within the state of Rio de Janeiro, so according to Federal Law 9,433/1997, it is under state domain, with the Rio de Janeiro State Environmental Institute (INEA) having responsibility for its management. To grant water use rights, it is necessary to evaluate the water availability. This evaluation considers, among other factors, the maximum surface water withdrawal (MSW), which represents the maximum flow that can be taken from the river, or granted for use. The water availability is calculated by equation (1).

$$WA = MSW - \sum Q_{granted} - Q_{eco} \qquad (1)$$

Where WA is the water availability; MSW is the maximum surface water withdrawal; $\sum Q_{granted}$ is the sum of the flows granted for use upstream of the point studied and Q_{eco} is the ecological flow, defined as 50% of $Q_{7,10}$. $Q_{7,10}$ is defined as the smallest average flow occurring during a period of 7 consecutive days in a period of 10 years of recurrence.

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IV. Wetted Perimeter Method and Premises Adopted

The wetted perimeter method is based on the existence of a direct relation between the wetted perimeter and the availability of habitats for ichthyofauna [1]. This method assumes there is a relation between the wetted perimeter and the habitat availability [3].

To apply this method, we relied on data from the Fazenda Sobradinho stage gauge (code 58420000), located on the Preto River. These data are stored in the HidroWeb database [4]. Table 1 presents the descriptive information on this post.

Table 1: Descriptive information on the Fazenda Sobradinho stage gauge

Code	58420000
Name	FAZENDA SOBRADINHO
Sub-basin	PARAÍBA DO SUL RIVER (58)
River	PRETO RIVER
State	RIO DE JANEIRO
Municipality	TERESÓPOLIS
Latitude	-22:12:1
Longitude	-42:54:4
Altitude (m)	700
Drainage Area (km^2)	719

Source : ANA (2013)

The lowest flow value measured at the Fazenda Sobradinho stage gauge occurred on September 23, 1955. This flow and the associated hydraulic variables are reported in Table 2.

Table 2 : Discharge Measurement on September 23, 1955

Depth (cm)	Flow (m^3/s)	Wetted area (m^2)	Width (m)	Average current speed (m/s)
28	2.76	20.4	19	0.135

Source: ANA (2013)

However, the cross-section data available in the HidroWeb database do not include data for 1955, making it necessary to identify a cross section corresponding to the lowest flow in the historic series, which was September 9, 1997. It is important to stress that the use of the minimum flow values measured is based on the premise that the ecological flow must be present in all natural flows of the river, i.e., it is expected to be lower than or equal to the lowest flow measured/ observed in the river. The information regarding this cross section, measured on September 9, 1997, is shown in Table 3.

Table 3 : Discharge Measurement on September 9, 1997

Depth (cm)	Flow (m^3/s)	Wetted area (m^2)	Width (m)	Average current speed (m/s)
53	6.12	18.8	23	0.326

Source : ANA (2013)

We superimposed the cross sections to note any relevant modification over the years for which data were available. This analysis is important, because if the cross section has undergone a considerable change, it means the cross section used as the baseline will not be an accurate representation to allow correlation with information for previous years. Figure 2 presents the overlapped cross sections avaialable in the database.

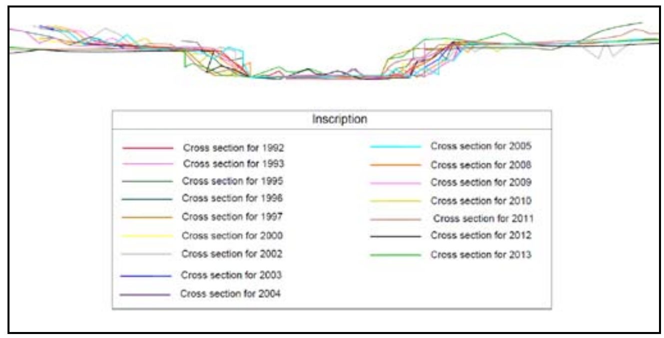

Figure 2 : Superimposed cross sections

Observation of Figure 2 shows the cross section did not undergo any relevant modifications over time. Figure 3 below depicts the cross section for 1997, plotted with Autocad 2013, for which distinct wetted areas, and hence wetted perimeter values, could be extracted based on the water depth.

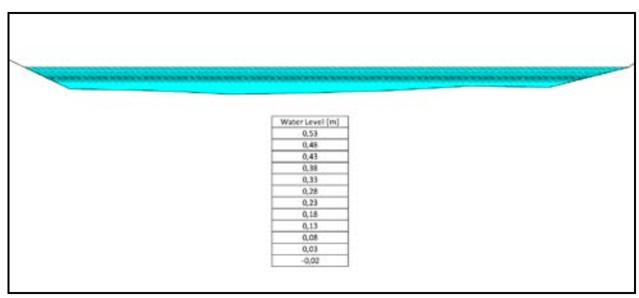

Figure 3 : Detail of the cross section for 1997

To calculate the ecological flow by the wetted perimeter method, we adopted the following premises [5]:

- Permanent and uniform flow, i.e., the flow is equal to the product of the wetted area and the average current speed. The average speed was defined as that corresponding to the lowest flow recorded in the historic series of net discharge measured at the Fazenda Sobradinho stage gauge.

- Definition of the critical point based on the maximum curvature [3].

Table 4 shows the flow results obtained by multiplying the wetted area by the current speed selected.

Table 4 : Flows obtained for each wetted area

Depth (cm)	Flow (m^3/s)	Wetted area (m^2)	Width (m)	Average speed (m/s)	Wetted perimeter (m)
53	2.38	17.65	22.71	0.135	23.00
48	2.23	16.52	22.41	0.135	22.68
43	2.08	15.41	22.11	0.135	22.36
38	1.93	14.31	21.80	0.135	22.04
33	1.79	13.23	21.50	0.135	21.72
28	1.64	12.16	21.20	0.135	21.40
23	1.50	11.11	20.90	0.135	21.09
18	1.36	10.07	20.60	0.135	20.77
13	1.22	9.05	20.30	0.135	20.45
8	1.09	8.04	19.99	0.135	20.13
3	0.95	7.05	19.69	0.135	19.81
-2	0.82	6.07	19.39	0.135	19.41

From the data in Table 4, we plotted a graph relating the flows and the corresponding wetted perimeters. According to [3], the ecological flow is the flow value corresponding to the highest slope present in this curve. To determine this point, [3] suggest using the maximum curvature method, for which purpose it is necessary to define the function that best fits the points on the graph. For this, as in [3] we used Manning's formula:

$$Q = \frac{1}{n} \cdot A \cdot R^{2/3} \cdot S^{1/2} \qquad (2)$$

Where Q is the flow; n is the Manning's roughness coefficient; A is the wetted area of the water course's cross section; R is the hydraulic radius and S is the water surface slope.

The geometry of river cross sections normally varies between roughly rectangular and triangular [6]. According to [3], from equation (1), for channels with rectangular and trapezoidal cross sections, the best approximation of the relation between the wetted perimeter and flow is given by a logarithmic function, represented by equation (3).

$$PM = a \cdot \ln(Q) + 1 \qquad (3)$$

According to [3], for channels with triangular cross sections, the best approximation of this relation is given by a power function represented by:

$$PM = Q^b \qquad (4)$$

From observation of Figure 2, it can be perceived that the cross section used to calculate the ecological flow is rectangular, so we used the logarithmic function to approximately fit the points on the graph. However, in Brazil the usual practice is to use a power function to relate the hydraulic characteristics of a cross section with flow, as recommended by [6]. Therefore, we employed both logarithmic and exponential equations to represent the relation between the flow versus wetted perimeter values, allowing comparison of the ecological flow results.

V. Results

We first plotted a graph of flow versus wetted perimeter by fitting a logarithmic trend line (Figure 4).

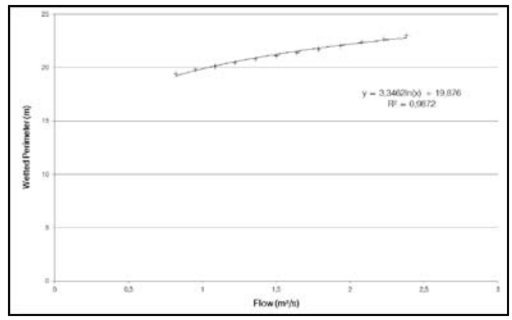

Figure 4 : Flows and wetted perimeters approximated by the logarithmic function

From equation (3) we used a scale factor to normalize the two axes of the graph, so that both ranged from zero to one, as shown in Figure 5.

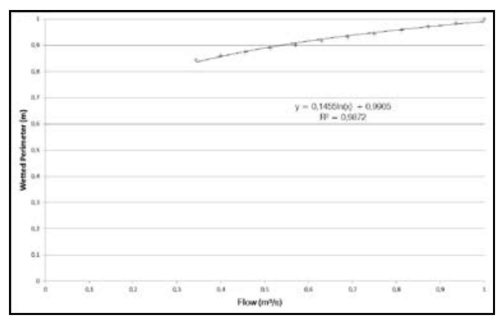

Figure 5 : Flows and wetted perimeters according to the scale factor

We fitted the same points by the power function, for subsequent comparison of the results produced by the two curve-fitting techniques. The resulting graph is shown in Figure 6.

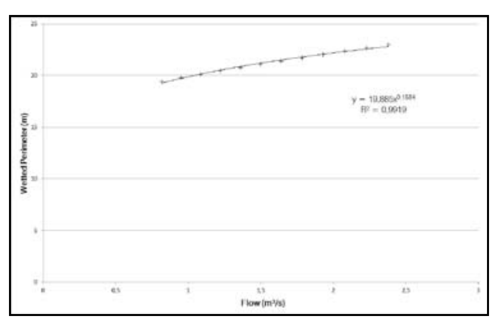

Figure 6 : Flows and wetted perimeters approximated by the power function

The curvature (k) is the rate at which a curve's slope changes. It is a function of the angle formed by the tangent line to the curve with the x-axis and the arc length [3], expressed by equation (5).

$$k = \frac{\frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{3/2}} \quad (5)$$

Where $\frac{d^2y}{dx^2}$ is the second derivative of the wetted perimeter in relation to flow; $\frac{dy}{dx}$ is the first derivative of the wetted perimeter, in m, in relation to flow, in m³/s.

To find the curvature of a logarithmic function, equation (6) is used, while to find the curvature of a power function, equation (7) is used.

$$|k| = \frac{\left|\frac{-a}{Q^2}\right|}{\left[1+\left(\frac{a}{Q}\right)^2\right]^{3/2}} \quad (6)$$

$$|k| = \frac{\left|b \cdot Q^{b-2}\right|}{\left[1+\left(b \cdot Q^{b-1}\right)^2\right]^{3/2}} \quad (7)$$

Where |k| is the absolute value of the curvature; Q is the flow; b is the exponent of equation (4) and a is the number that multiplies ln(Q) in equation (3).

By applying these two equations, we identified the points of greatest curvature, resulting in a flow equal to 0.206 m³/s for the logarithmic approximation and of 0.034 m³/s for the exponential approximation.

To help compare the order of magnitude of the ecological flow values resulting from application of the hydraulic method, we calculated the ecological flow adopted as a criterion by the INEA, namely 50%$Q_{7,10}$ (using the free software avaialable at [4]). Table 5 presents the results obtained.

Table 5 : Ecological flow results

$Q_{7,10}$ (m³/s)	50%$Q_{7,10}$ (m³/s)	Function	
		Logarithmic	Power
3.75	1.88	0.206	0.034

VI. Conclusion

Based on the ecological flow results calculated by the wetted perimeter method, it can be seen that these are lower than the ecological flow value adopted by INEA (50%$Q_{7,10}$). Therefore, the results can be classified as satisfactory. One of the difficulties encountered during this study was the shortage of data on cross sections, since the results would have more closely reflected the real situation of the cross section for September 23, 1955 had been available, when the lowest flow was recorded in the historic series.

In closing, as mentioned earlier, there is still no consensus on the best method to calculate a river's ecological flow, so further research is necessary, given the importance of this subject for environmental studies and water resource management policies.

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