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Ecohydrological modeling and environmental flow regime in the Formoso River, Minas Gerais State, Brazil

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ABSTRACT

This paper aimed at determining the environmental flow regime in a 1 km stretch of the Formoso River, MG, using River2D model. To carry out the ecohydrological modeling, the following information was used: bathymetry, physical and hydraulic features, and the Habitat Suitability Index for species of the *Hypostomus auroguttatus*. In the River2D, the Weighted Usable Areas were determined from the average long-term streamflows with percentage from 10% to 100%. Those streamflows were simulated for the later construction of optimization matrices that maximize the habitat area throughout the year. For *H. auroguttatus* Juvenile, higher values of Weighted Usable Area were associated with the percentage of 60% and 70% of the average long-term streamflows in October and September, respectively. For *H. auroguttatus* Adult, the highest value of Weighted Usable Area was associated with the percentage of 100% of the average long-term streamflow in September. The environmental flows found for this stretch of the Formoso River varied over the year. The lowest environmental flow was observed in December (2.85 $m^3 s^{-1}$), while the highest was observed in May (4.13 $m^3 s^{-1}$). This paper shows the importance of ecohydrological studies in forming a basis for water resources management actions.

Key words: ecohydrology, hydrodynamic modeling, River2D, water resources, WUA.

INTRODUCTION

The need for drinking water and the dependency on ecological goods and services sustained by fluvial ecosystems represent a big challenge to water resources managers (Arthington et al. 2010). Nowadays, multiple forms of water use generate conflicts, making pressure on water resources. In order to relieve this pressure, several programs for water resources management are proposed. Those seek to discipline water use, making quantitative and qualitative aspects become compatible with the development of ecosystems and human activities both (Almeida et al. 2014, Castro et al. 2016).

Permit for using water resources is an important management tool that helps public entities to

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promote the balance between multiple uses of water, granting the right to use water resources. The permit allows the entity that manages water resources to determine the amount of water that can be available in a stream as well as the streamflow that keeps the integrity of aquatic communities. This streamflow is known as remaining streamflow (Castro et al. 2016). Although having a characteristic of preservation, the remaining streamflow does not demonstrate the real situation of a stream. It does not consider the necessities of aquatic species according to streamflow variations that rule food availability, reproduction and the physical features of the habitat (Huckstorf et al. 2008, Guedes et al. 2014, Kolden et al. 2016).

Through the analysis of hydrological and ecological variables ecohydrological studies try to establish an environmental flow regime that considers the natural hydrological variations of a river. Since aquatic species are adapted to them and depend on them to carry out their vital functions (Zalewski 2002, 2015, Arthington et al. 2006).

Environmental flow is a term proposed to conciliate water resources forms of use with the need of conservation of an aquatic ecosystem, a necessary process in order to maintain sustainable fluvial ecosystems (Wang et al. 2013). Thus, the environmental flow must be analysed according to its seasonal variability. It is necessary to determine the monthly flow regime to be kept in the stream so as to guarantee the aquatic biodiversity (Souza et al. 2008a).

Habitat classification method is the most complete to evaluate the environmental flow. They contemplate several steps, such as physical and environmental features, study plan elaborated by a multidisciplinary team, and different types of analysis (Benetti et al. 2003). This method may consider economic aspects, evaluating the willing to pay for the environmental preservation and the benefits generated by water permit, pursuing the best quantification for an environmental flow (Souza et al. 2008a).

Increasing expansion of demands makes the water resources management associated with the ecological integrity maintenance become more and more complex, since the environmental flows must attend to anthropic and ecological demands simultaneously (Richter et al. 2003). Due to the complexity of applying the knowledge acquired along these years, mathematical models are an important tool for supporting decision making systems. They allow to test alternative scenarios and to implement ecohydrological methodologies aiming at the management of sustainable water and ecosystems uses (Zalewski 2010).

Advances in environmental modeling provide tools to represent the complex interactions between fish populations and their habitats, pursuing to relate several features of a river stretch, such as velocity, depth, and substrate to habitat preferences of certain species or groups of species (Boavida et al. 2011). According to Govind et al. (2009), coupling ecosystem models with hydrological models is a research direction for future ecohydrological studies.

In those studies, unidimensional models that only describe spatial variations along a direction are frequently used. Differently from unidimensional models, hydrodynamic modeling in two dimensions shows a better final result, since it represents with accuracy spatial and timing variations (Jowett and Duncan 2012).

Among the different bidimensional softwares used in ecohydrological modeling, River2D (Steffler and Blackburn 2002) stands out due to its use in studies to determine environmental flows and to establish the ecological hydrogram (Sanz and Martínez 2008, Polo and Torres 2009), to revitalize rivers (Jalón and Gortázar 2007, Boavida et al. 2011), and to study the habitat with a view to protecting endangered species (Parasiewicz et al. 2012), among others.

However, few researches about the determination of environmental flow regime using bidimensional modeling are carried out in Brazil (Guedes et al. 2014, Castro et al. 2016). Having this in mind, this paper aimed at determining the environmental flow regime in the Formoso River, MG, using the bidimensional model River2D.

MATERIALS AND METHODS

STUDY SITE

This study was carried out in the Formoso River, tributary on the right bank of the Pomba River, located in the West part of the Paraíba do Sul River basin, Brazil Southeast region (Figure 1), which is 76.7 km long. The Formoso River basin has an area of approximately 398 km². The studied stretch is located at the lower part of the basin, corresponding to a degraded area, since its native vegetation was suppressed due to intensive use for pasture. Withdraw of this vegetation accelerated the erosion process on the banks of the river, increasing the concentration of sediments in the stream. Besides, there is the throwing of sanitary effluents without treatment coming from the population that lives near the river, deeply degrading the fluvial system.

Physical, hydraulic, and habitat characterizations were done in a stretch of 1 km long of the Formoso River. Three equidistant transversal sections of 500 meters from one border to the other were delimited and information about velocity, depth, discharge, fishes and substrate was collected.

PHYSICAL AND HYDRAULIC CHARACTERIZATION

The physical characterization of the river stretch was done based on the bathymetry survey, which employed geodetic GPS Promark II and a Total Station Topcon GTS 212. Exactly 1879 points were tracked by the geodetic GPS, allowing the work's georeferencing.

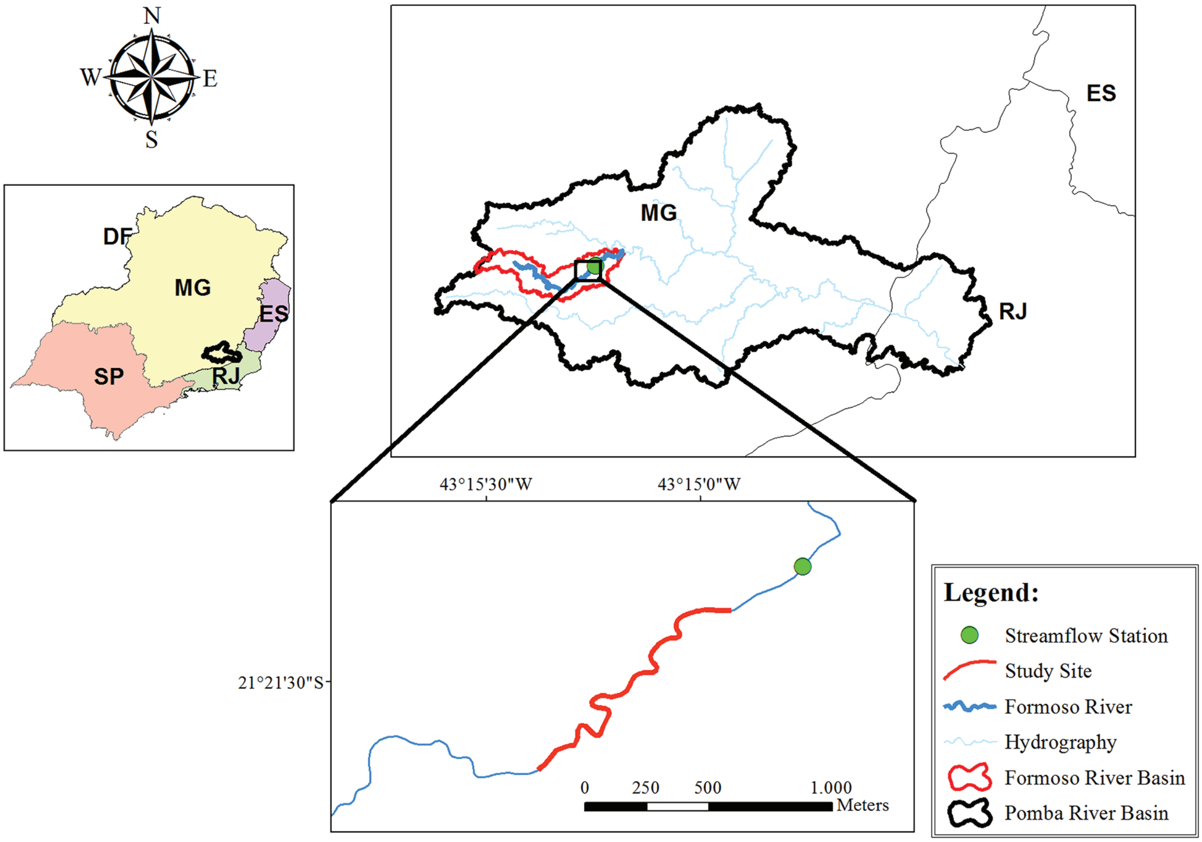

Figure 1 - Location of the Formoso River Basin.

Substrate collection was done in each transversal section using a vertical penetration Petersen dredge with collecting capacity of 3.20 liters. Materials collected were analysed at the Laboratório de Propriedades Físicas do Solo, of the Departamento de Solos, of the Universidade Federal de Viçosa. Their granulometry and their mean particle diameter were measured (Jalón and Gortázar 2007).

Depth (m), width (m), velocity (m s^{-1}) and streamflow (m^3 s^{-1}) were measure during four periods, twice in the dry period (June, 2011 and July, 2012) and twice in the rainy period (March, 2011 and February, 2012). Streamflow measured in the beginning stretch of the river were: 7.52 m^3 s^{-1} (03/26/2011), 5.97 m^3 s^{-1} (06/18/2011), 10.25 m^3 s^{-1} (02/11/2012) and 5.75 m^3 s^{-1} (07/07/2012). Velocity was monitored during the two first periods using a very small hydraulic windlass M1 by SEBA Hydrometrie®. On the third period, due to a bigger magnitude of streamflow, velocity was monitored by a Newton fluviometric windlass by Hidromec®. On the fourth period the ADCP – Acoustic Doppler Current Profiler, model M9 RiverSurveyor by Sontek® was used. The depth was measured from the bathymetry of the transversal sections.

HISTORICAL SERIES OF STREAMFLOW

The historical series of streamflow gauging station (Tabuleiro, code 58720000), with 23 years of daily streamflow data, was used to obtain the daily streamflow. The average long-term streamflows were obtained by software SIsCAH (Sousa et al. 2009), allowing the analysis of the runoff regime in the basin.

HABITAT SUITABILITY INDEX

The Habitat Suitability Index (HSI) is represented as a function of the curves for the Habitat Suitability Criteria (HSC). It represents the level of preference that a fish has in relation to the abiotic variables of depth, velocity, and substrate (Lee et al. 2010, Chou and Chuang 2011).

This study analysed the species *Hypostomus auroguttatus* Kner, 1854 (Pisces, Loricariidae), for they are representative of the Formoso River (Guedes et al. 2014). They prefer habitats with fast (velocity faster than 0.8 m s^{-1}) and coarse substrate (rugosity bigger than 0.35 m) (Casatti et al. 2005).

The HSI preference curves were obtained according to the methodology proposed by Chou and Chuang (2011), performed by Castro et al. (2016), considering the frequency and the preferences of the species studied for depth, velocity, and substrate. The weighted frequency of the preference curve was determined from the relationship between the number of individuals collected in each class of variables observed (velocity, depth, and substrate) and the total number of individuals collected during the monitoring. The frequencies of the variables were divided according to the greatest frequency obtained, making HSI a weighted index.

The substrate was analysed considering the features of the channel and it was used in the modeling to determine the habitat preference among the bioindicator species. The following information was considered: silt (code 1), sand (code 2), granule (code 3), pebble (code 4), cobble (code 5 or 6), boulder (code 7 or 8), rocky bed (code 9), and bank with vegetation (code 10) (Bovee 1982).

The HSI preference curves were elaborated according to the development stage (adult and juvenile) taking into account each variable as well as the area use by the species. Thus, they permitted to determine the species habitat preference (Chou and Chuang 2011), which ranged from 0 (inappropriate) to 1 (optimal) (Bovee 1982).

MODEL RIVER2D

The model River2D was chosen to this study because it is the most efficient model in terms of simulations of spatially distributed phenomena, such as habitat quality for fishes, compared to unidimensional models (Brown and Pasternarck 2009, Lee et al. 2010).

River2D consists in a bidimensional model, developed specifically to be used for rivers or natural streams, based on the Finite Element Method and on the conservative formulation by Petrov-Galerkin (Steffler and Blackburn 2002).

In the computational modeling the model River2D and its modules: RiverBed (R2D_Bed), RiverMesh (R2D_Mesh) as well as the hydrodynamic component River2D were used. The topographical editing was carried out in R2D_Bed, in which the bathymetric data were annotated; these were processed in the computer programs AutoCAD 2011. The post-processing of bathymetric data, such as the geographical correction of points obtained in field, took place in the program ESRI ArcGis 10. Later, bathymetric data were interpolated into every studied stretch using the module R2D_Bed.

In R2D_Mesh, the mesh of finite elements was created and the boundary conditions were defined, corresponding to the streamflow in the section at the entrance of the stretch of 7.52 $m^3 s^{-1}$. The lateral boundary conditions were defined as without runoff.

Verification of the calibration in the R2D_Mesh module is done considering the Quality Index (QI). This index is defined according to the ratio of the area of each triangle of the mesh to its circumscribed circumference. Satisfactory values of refinement are represented as QI with values between 0.1 and 0.5 (Waddle and Steffler 2002). To reach these values it was necessary to do successive operations of edition and to change the values of roughness of the riverbed. In this study, the integration step used was equal to 1 minute, presenting a time of simulation equal to 2 minutes as well as a mistake associated of 0.00006. Thus, the value found for QI was 0.10. This generated a mesh with mean resolution of 5.0 m.

Validation of the calibration for depth and velocity was done considering the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) between the measured and the simulated values, as proposed by Lacey and Millar (2004) and Chou and Chuang (2011).

After the calibration of the model River2D was concluded and verified, it was used to simulate the different scenarios for the streamflows using the percentage of 10% to 100% of average long-term streamflows. Thus the maximum environmental flow to be reached would be the natural flow regime (Guedes et al. 2014).

HABITAT MODELING

The component habitat of River2D model is based on the Weighted Usable Area – WUA, proposed by Bovee (1982). The WUA is the quantity of physical habitat available, expressed in square meters per kilometer of a stream for the fish species in a streamflow (Eq. 1).

$$WUA = \sum_{i=1}^{n} \left[f\left(V_i, P_i, S_i\right) . A_i \right] \quad (1)$$

where A_i is the area of the stream in each cell i [L^2]; V_i is the velocity in each cell [LT^{-1}]; P_i is the depth in each cell [L]; S_i is the effective roughness (k_s) of the substrate in each cell [L]; and f (V_i, P_i, S_i) is the suitability index combined with the area A_i [L].

The WUA is calculated using the HSI preference curves evaluated in each point of domain (computational nodes of the discretized mesh). And also in each point of the usable surface (Thiessen Polygons) associated to it (Steffler and Blackburn 2002).

The WUA was calculated using *H. auroguttatus* juveniles as well as adults preference curves regarding the variables depth, velocity, and substrate, using the geometric mean between the suitability indexes (Steffler and Blackburn 2002, Guedes et al. 2014). Tables were done for the WUA values associated with the average long-term streamflows used in the simulation, supporting the estimate of the environmental flow regime.

ENVIRONMENTAL FLOW REGIME

Determination of the environmental flow regime must consider the magnitude, the duration and the frequency of streamflows in a stream (Poff and Zimmerman 2010). In this study, the monthly environmental flow was estimated through the optimization matrix proposed by Bovee (1982).

The optimization matrix consists of the construction of a matrix for each month of the year. Columns correspond to the simulated streamflow and lines to the species considered in the study (Bovee 1982). To each simulated streamflow it is calculated a value of WUA using the model River2D. The highest is the value, the highest is the suitability of a species in the studied stretch.

Monthly environmental flow was determined as follows: after calculating the WUA for each simulated streamflow each column was analysed. The minimum value of WUA was selected and registered in the last line of the matrix. The highest level of this line was highlighted. This value corresponds to the poorliest simulated value in the stream in order to guarantee the maintenance of the most vulnerable species in the studied stretch. This streamflow corresponds to the environmental flow. This process was repeated for each month of the year (Bovee 1982, Guedes et al. 2014, Castro et al. 2016).

RESULTS AND DISCUSSION

In the calibration of the River2D, the finite elements mesh presented 9326 nodes, 18182 elements and 68 interactions. Depth and velocity distributions are presented in Figure 2. The streamflow used in the calibration was equal to 7.52 $m^3 s^{-1}$.

Depth ranging from 0.75 m to 1.00 m (Figure 2a) was found in 19% of the studied stretch and values above 2.00 m was found in 9% of it. Depth values lower than 0.75 m were found between monitoring sections 2 and 3. They can be related to the strong degradation and to the conditions of siltation in the stream. According to Faria et al. (2013), erosion processes due to siltation lead to degradation of water resources and diminish the depth of streams.

Regarding velocity (Figure 2b), 61% of the studied stretch showed values ranging from 0.10 m s^{-1} to 0.50 m s^{-1} justified by the flat terrain. Velocity above 2.00 m s^{-1} was found in 11% of the stretch located between the sections 2 and 3, exactly the same stretch with the lowest depth. This indicates the torrential regime in the stream (Mejía 2008). These simulations were frequently observed during the monitoring in field, proving River2D precision in determining the interaction between the streamflows in rivers and the bathymetry of the channel. Similar observations were done by Boavida et al. (2012) and Castro et al. (2016).

The MAE calculated for depth in the transversal sections was 5.4%, while the MAE for velocity was 13.4%. The RMSE obtained for depth in the transversal sections was 0.079 m, and the RMSE for velocity was 0.159 m s^{-1}. The difference between the transversal sections considered in the Rive2D can influence the adjustment between the simulated and the observed values of the hydraulic variables, since the composition of the area by finite elements method generates softer surfaces than the ones measured in field (Boavida et al. 2013).

Jowett and Duncan (2012) found MAE of 22% and 34% for depth and velocity, respectively. According to these authors, River2D tends to underestimate the depth values, and depending on the flow conditions, it may underestimate or overestimate velocity values. The authors state that these discrepancies may be associated with the imprecision in water surface elevation values used in the modeling and also with the fact that a bathymetry survey does not represent all

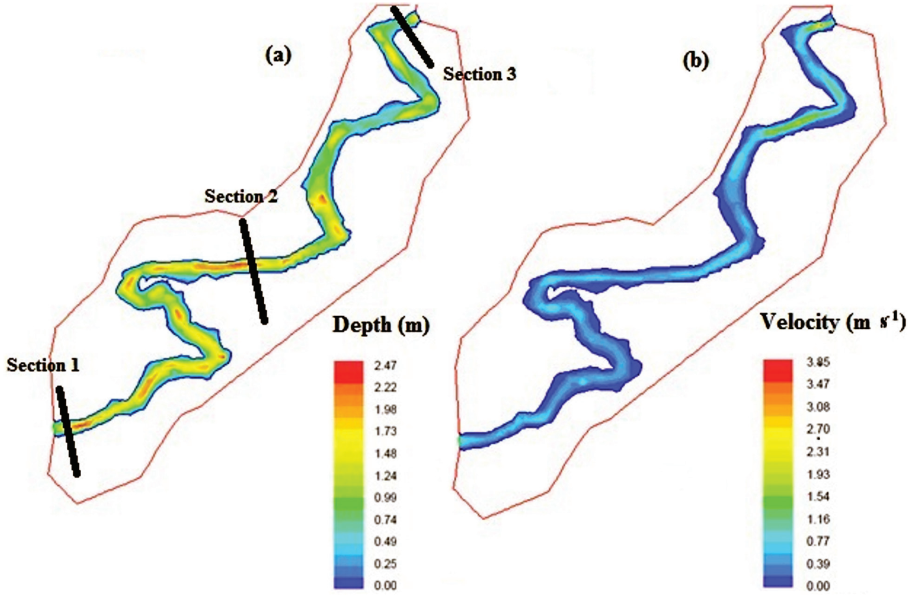

Figure 2 - Formoso River stretch studied. **a.** Depth. – **b.** Velocity.

riverbed features. Despite these discrepancies, the authors highlighted the importance of River2D in simulating the physical environment conditions.

The table for simulated WUA and average long-term streamflows associated with the percentage from 10% to 100% in the studied stretch are presented in Table I. An analysis of Table I shows that the WUA values varied between life stages and among the different months according to the average long-term streamflows. A similar result was found by Guedes et al. (2014) and Castro et al. (2016).

TABLE I

WUA, $m^2\ km^{-1}$, and the average long-term streamflows associated with the percentage of 10 to 100% in the Formoso River stretch studied.

H. auroguttatus	**JANUARY (Q_{mean} = 17.25 $m^3\ s^{-1}$)**									
	Percentage of 10 to 100% of the average long-term streamflow x WUA ($m^2\ km^{-1}$)									
	10	20	30	40	50	60	70	80	90	100
Juvenile	14.16	23.39	19.79	7.78	4.18	2.22	4.16	3.98	4.36	6.41
Adult	44.16	102.15	107.88	67.95	44.63	33.13	53.63	46.58	48.78	50.85
Minimum of the column	14.16	**23.39**	19.79	7.78	4.18	2.22	4.16	3.98	4.36	6.41
Maximum of the minima	**WUA: 23.39 $m^2\ km^{-1}$**				**Environmental flow: 3.45 $m^3\ s^{-1}$**					
	FEBRUARY (Q_{mean} = 12.75 $m^3\ s^{-1}$)									
Juvenile	7.72	16.43	23.25	12.27	9.71	6.04	3.13	2.94	2.42	8.22
Adult	19.81	67.18	101.88	87.84	78.71	56.94	38.98	35.24	31.28	57.70
Minimum of the column	7.72	16.43	**23.25**	12.27	9.71	6.04	3.13	2.94	2.42	8.22
Maximum of the minima	**WUA: 23.25 $m^2\ km^{-1}$**				**Environmental flow: 3.83 $m^3\ s^{-1}$**					
	MARCH (Q_{mean} = 12.06 $m^3\ s^{-1}$)									
Juvenile	9.06	16.01	24.28	14.78	10.70	6.91	4.11	2.77	2.80	4.73
Adult	23.93	64.98	102.15	93.33	84.43	62.4	44.73	36.08	34.21	40.41
Minimum of the column	9.06	16.01	**24.28**	14.78	10.70	6.91	4.11	2.77	2.80	4.73
Maximum of the minima	**WUA: 24.28 $m^2\ km^{-1}$**				**Environmental flow: 3.62 $m^3\ s^{-1}$**					

TABLE I (continuation)

	APRIL (Q_{mean} = 8.58 m^3 s^{-1})									
Juvenile	2.10	14.16	16.98	24.79	20.47	12.20	10.72	8.16	5.64	4.29
Adult	4.79	44.16	69.47	100.54	102.73	87.61	84.57	70.16	54.28	45.81
Minimum of the column	2.10	14.16	16.98	**24.79**	20.47	12.20	10.72	8.16	5.64	4.29
Maximum of the minima	**WUA: 24.79 m^2 km^{-1}**			**Environmental flow: 3.43 m^3 s^{-1}**						
	MAY (Q_{mean} = 6.89 m^3 s^{-1})									
Juvenile	0.49	9.58	13.00	18.13	17.04	21.57	14.78	10.89	10.43	9.28
Adult	0.83	25.34	49.13	74.22	68.61	103.78	93.33	85.61	82.69	76.49
Minimum of the column	0.49	9.58	13.00	18.13	17.04	**21.57**	14.78	10.89	10.43	9.28
Maximum of the minima	**WUA: 21.57 m^2 km^{-1}**			**Environmental flow: 4.13 m^3 s^{-1}**						
	JUNE (Q_{mean} = 5.42 m^3 s^{-1})									
Juvenile	0.16	3.77	11.89	13.32	18.56	22.56	23.44	19.17	14.38	14.09
Adult	0.12	9.15	35.55	51.20	75.64	91.65	101.88	100.49	92.63	90.77
Minimum of the column	0.12	3.77	11.89	13.32	18.56	22.56	**23.44**	19.17	14.38	14.09
Maximum of the minima	**WUA: 23.44 m^2 km^{-1}**			**Environmental flow: 3.79 m^3 s^{-1}**						
	JULY (Q_{mean} = 5.10 m^3 s^{-1})									
Juvenile	0.16	4.88	11.74	13.09	16.43	23.29	24.69	22.39	16.32	12.27
Adult	0.12	12.19	33.77	49.84	66.54	93.33	102.61	104.03	95.22	87.84
Minimum of the column	0.12	4.88	11.74	13.09	16.43	23.29	**24.69**	22.39	16.32	12.27
Maximum of the minima	**WUA: 24.69 m^2 km^{-1}**			**Environmental flow: 3.57 m^3 s^{-1}**						
	AUGUST (Q_{mean} = 4.66 m^3 s^{-1})									
Juvenile	1.71	1.91	10.28	12.36	15.98	20.06	18.11	23.74	21.17	17.50
Adult	1.62	3.96	28.25	42.23	64.69	81.27	76.30	99.88	103.41	94.44
Minimum of the column	1.62	1.91	10.28	12.36	15.98	20.06	18.11	**23.74**	21.17	17.50
Maximum of the minima	**WUA: 23.74 m^2 km^{-1}**			**Environmental flow: 3.73 m^3 s^{-1}**						
	SEPTEMBER (Q_{mean} = 5.06 m^3 s^{-1})									
Juvenile	0.16	4.88	11.74	13.07	16.47	23.28	25.42	22.38	16.99	21.24
Adult	0.12	12.19	33.78	49.76	67.38	93.31	103.78	104.30	96.08	113.09
Minimum of the column	0.12	4.88	11.74	13.07	16.47	23.28	**25.42**	22.38	16.99	21.24
Maximum of the minima	**WUA: 25.42 m^2 km^{-1}**			**Environmental flow: 3.54 m^3 s^{-1}**						
	OCTOBER (Q_{mean} = 5.91 m^3 s^{-1})									
Juvenile	0.16	7.79	12.18	16.00	21.64	25.42	21.30	15.50	11.00	13.19
Adult	0.12	20.04	39.73	64.86	87.34	103.78	103.51	94.02	85.56	81.81
Minimum of the column	0.12	7.79	12.18	16.00	21.64	**25.42**	21.30	15.50	11.00	13.19
Maximum of the minima	**WUA: 25.42 m^2 km^{-1}**			**Environmental flow: 3.55 m^3 s^{-1}**						
	NOVEMBER (Q_{mean} = 9.63 m^3 s^{-1})									
Juvenile	2.46	12.54	20.78	23.13	14.78	10.64	8.44	5.64	3.60	4.19
Adult	5.68	44.43	84.07	102.17	93.33	85.13	71.66	54.27	41.82	39.61
Minimum of the column	2.46	12.54	20.78	**23.13**	14.78	10.64	8.44	5.64	3.60	4.19
Maximum of the minima	**WUA: 23.13 m^2 km^{-1}**			**Environmental flow: 3.85 m^3 s^{-1}**						
	DECEMBER (Q_{mean} = 14.26 m^3 s^{-1})									
Juvenile	10.53	20.88	20.47	10.72	7.35	4.32	2.81	2.42	8.22	3.94
Adult	28.47	84.35	102.73	85.42	65.31	45.85	35.59	33.98	57.70	47.42
Minimum of the column	10.53	**20.88**	20.47	10.72	7.35	4.32	2.81	2.42	8.22	3.94
Maximum of the minima	**WUA: 20.88 m^2 km^{-1}**			**Environmental flow: 2.85 m^3 s^{-1}**						

For *H. auroguttatus* Juvenile, WUA higher values are associated with the percentage of 60% and 70% of the average long-term streamflows in October and September, respectively. For *H. auroguttatus* Adult, WUA highest value is associated with the percentage of 100% of the average long-term streamflow in September. October and September correspond to the dry season end in the Formoso River. This shows a preference of *H. auroguttatus* for lower streamflows, confirming the results found by Castro et al. (2016). According to Leal et al. (2013) individuals tend to occupy the habitats where they are most adapted to. So, the relation between species and certain environmental variables, such as velocity, depth, discharge and substrate is usually intense.

But WUA higher values only do not guarantee greater abundance of *H. auroguttatus* individuals, since the permanence in the stream depends on other factors, such as food availability (Condini et al. 2011). According to Dunham et al. (2003) although River2D disregards other ecological factors that have a significant impact on *Hypostomus* population, such as the presence of pre-existent or exotic species, habitat connectivity, and food availability, it reflects this species' population dynamics.

According to Ferreira and Casatti (2006), among the factors that affect the icthyofauna distribution in lotic environments, loss and transformation of internal habitat stand out. They are usually associated with the riparian forest suppression and to the consequent rise of the solar incidence as well as the absence of certain food items, like fruits, seed and allocthone insects (King and Warburton 2007, Mouton et al. 2012). These features are found all along the studied stretch of the Formoso River, justifying lower WUA values compared to the study done by Castro et al. (2016).

Figure 3 shows the environmental flow regime for the studied stretch of the Formoso River, as well as the remaining streamflow. It corresponds to 50% of the seven days long minimum streamflow with a return period of ten years – $Q_{7,10}$, the same scenario considered by the Instituto Mineiro de Gestão das Águas (IGAM) in this part of Minas Gerais state for analyses of water right permits.

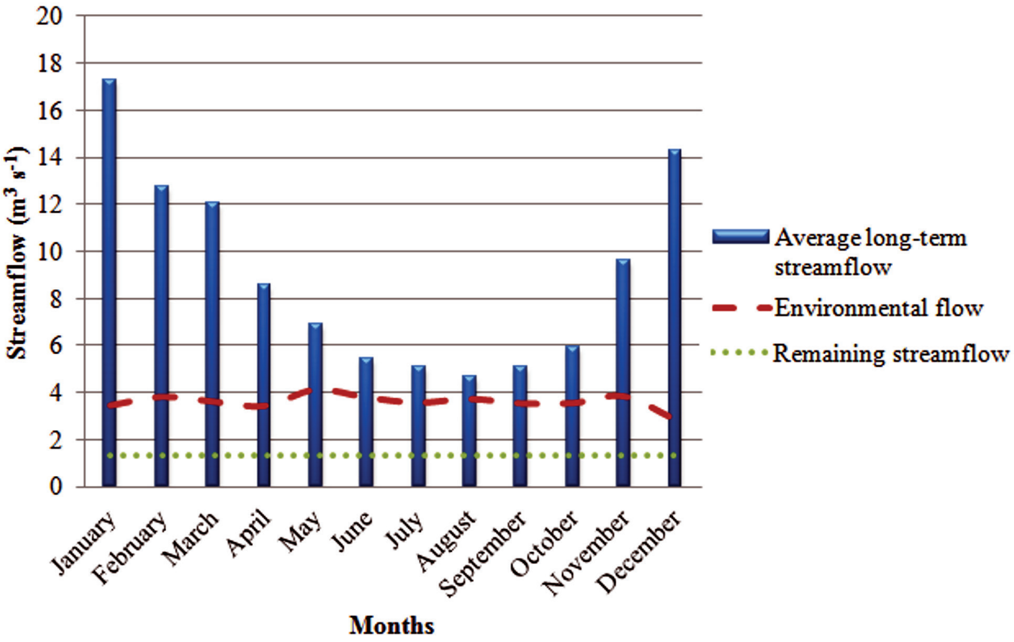

Figure 3 - Environmental flow regime, average long-term streamflows, and remaining streamflow for the Formoso River stretch studied.

The environmental flows found for the Formoso River stretch varied along the year. The lowest environmental flow was observed in December (2.85 m^3 s^{-1}), while the highest was observed in May (4.13 m^3 s^{-1}). In May, a characteristic month of the dry period in the Formoso River basin, the environmental flow tends to be higher due to the need of maintenance of the ecological integrity of the stream. December, a characteristic month of the rainy period that naturally presents the streamflows more elevated in the river basin has a water supply that keeps the physical habitat of the species. So it is not necessary to maintain a higher level of environmental flow. Note that this is a preliminary analysis and that the definition of the monthly environmental flow should be done considering the necessities of use of water resources in the river basin (Souza et al. 2008b).

H. auroguttatus Juvenile was the most sensitive to streamflow variation, since it presented the lowest value of WUA. Thus, this species limited the environmental flow definition in the Formoso River degraded stretch. Therefore, the environmental flow regime established guarantees the sustainability and the minimum environmental condition in order to maintain the species in the studied stretch.

The streamflows represent the main force behind freshwater ecosystems, determining the distribution, the abundance, and the river organisms' diversity (Poff et al. 1997, Santos et al. 2010). Streamflow reduction to a lower rate than a value considered minimum to the environmental flow in a stream does not necessarily extinguish certain species. However, it can cause the individuals moving to other sites of the river or even to tributaries with similar suitability features, since there is aquatic ecosystems interrelation. These species can come back to their original stream when conditions become favorable again.

Comparing the current criterion of water use permits in Minas Gerais state with remaining streamflow (Figure 3) and with the environmental flow in December (most critical month) it can be concluded that the species would probably move to other river stretches, or even to the nearest tributaries that present higher streamflows and better suitability conditions. Thus, this Formoso River stretch can present fish species reduction since environmental flow values are much higher than the remaining streamflow established by the current permit criterion of surface water.

According to Postel and Richter (2003) fixing a value of environmental flow for a stream can damage the aquatic fauna since the environmental flow has space and time variation. Furthermore, environmental effects that happen in the aquatic habitat are associated with the different environment regime levels, not only because of a streamflow minimum value, but also because of the streamflows medium and maximum values, besides the features of the hydrologic regime, such as duration and frequency of extreme events. According to Escobar (2008), the biological productivity and diversity of the fluvial ecosystems are guaranteed if these features are present.

Environmental flow values should not be adopted only based on the results obtained. This paper consists in the initial process of an attempt to find an environmental flow regime effectiveness. So it is necessary several presentations of workshops to agencies and basin committees, to water users and mainly to the civil society before implementing it.

CONCLUSIONS

Environmental flows found for the Formoso River stretch varied all over the year. The lowest environmental flow was observed in December (2.85 m^3 s^{-1}), while the highest was observed in May (4.13 m^3 s^{-1}). Comparing the current criterion of water use permits in Minas Gerais state to the remaining streamflow and to the environmental flow in December (most critical month) it can be concluded that the species would probably move to other river stretches, or even to the nearest tributaries that present higher streamflows and better suitability conditions. This study shows the importance of ecohydrological studies in forming a basis for water resource management actions.

H. auroguttatus Juvenile was the species most sensitive to streamflow variation, since it presented the least values of WUA. Thus, this species limited the environmental flow definition in the Formoso River degraded stretch.

The methodology presented can be applied in any river, without distinction of size and streamflows magnitude. It should be emphasized that the bigger the stream, the more exhaustive will be the field work. The greatest limitation of this methodology refers to the precise determination of fish groups to be considered in the environmental flow regime. Besides, it demands a lot of experience from the experts and a certain subjectivity degree.

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