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Hydrological modelling in small ungauged catchments

ULISSES B. COMINI, DEMETRIUS DAVID DA SILVA, MICHEL C. MOREIRA & FERNANDO F. PRUSKI

Abstract: The knowledge of the frequency and magnitude of low flow events is necessary to mitigate social, economic and ecological impacts inside the basin. However, the measurement network in Brazil is still restricted to large drainage areas, while basins with less than 300 km^2 remain ungauged. Among different flow estimation methods, we used a rainfall-runoff model designed specifically to estimate flow rates during the dry season in small ungauged basins: the Silveira Method (SM). We tested the model performance for the São Bartolomeu river basin (Minas Gerais, Brazil), a small ungauged basin that experienced severe droughts and water supply shortages in 2014-2016. We tested eleven different scenarios based on the time and duration of drought periods used to estimate the model parameters. In the best scenario, the model underestimated low flow rates by 31% for Q_{95} and was considered suitable to predict local low flow. Finally, the model results suggest that a water volume higher than the river can support has been granted concession during the dry season, which may lead to an unsustainable water supply scenario soon. This result showed the capacity of SM as a complementary tool for the evaluation of water potential in small basins.

Key words: hydrologic modelling, small catchments, ungauged catchments, rainfall-runoff model.

INTRODUCTION

The water availability in a catchment is commonly represented by median and low flows (Uliana et al. 2016, Novaes et al. 2009) and knowledge about its magnitude and frequency is necessary to mitigate social, economic and ecological impacts (Nicolle et al. 2014, Grandry et al. 2013, Novaes et al. 2009). These factors allow adequate planning and reduced conflict among multiple users of water resources (Pruski et al. 2015, Novaes et al. 2009).

In Brazil, precipitation and discharge data are monitored by the Rede Hidrometeorológica Nacional (RHN). Despite the improvements in recent years, the national network is still restricted to large drainage areas at the expense of small basins (Lemos et al. 2015, Beskow et al. 2013), mainly areas larger than 300 km² (Soares et al. 2010) This constitutes a challenge to the proper management of water resources in small basins (Beskow et al. 2013, Li et al. 2010, Silveira et al.1998).

In ungauged sites, flow estimation mechanisms have been widely used (Beskow et al. 2013, Grandry et al. 2013, WMO 2008), such as statistical methods, regional modelling, and rainfall-runoff models (Pruski et al. 2015, GPRH, IGAM 2012).

Although information from regionalization methods is important to decision-making (Lemos et al. 2015), the scope of RHN demands caution when extrapolating the results in small basins (Arsenault & Brissette 2014, Beskow et al. 2013, Silveira et al. 1998), which limits its uses to a small portion of the national hydrography (Pruski et al. 2012).

On the other hand, rainfall-runoff models are an option to estimate runoff in small ungauged basins and are used to the temporal simulation of flow data based on the interaction between physiographic and climatic characteristics of a river basin (Beskow et al. 2013, WMO 2008).

The pursue for models that represent the physical process and spatial variability of characteristics in a basin has made the models more complex and increased their demand for input data. These models are difficult to apply in small ungauged basins due to the lack of hydrological data (Beskow et al. 2013, Novaes et al. 2009) and staff with the technical and computational capacity to use them.

Models such as SWAT (Arnold et al. 1998), widely used in Brazil since 1999 (Bressiani et al. 2015), or LASH model (Beskow 2009), presented like simplified model for ungauged basins, still demand local and technical information unavailable for small basin managers. The lack of local information demands the adoption of input parameters obtained from other regions or countries that may not reflect the local conditions. Besides, the model results should be assessed with caution (Beskow et al. 2009).

Moreover, despite the great diversity in the existing models, it is very difficult to estimate low flow and conduct the comparative evaluation of performance (Nicolle et al. 2014). In addition, the absence of rainfall and runoff historical data for the small basins hinders the assessment of model results (Blöschl 2006).

In this context, Silveira et al. (1998) proposed a simplified methodology for rainfall-runoff modelling in small basins, which is capable of estimating median and minimal flow with three observed flow data in a representative drought period of the hydrological year.

The Silveira Method (SM) was indicated by Eletrobrás (2000) for water potential studies in small hydropower plants. This method considers that the fluvial depletion represents the basin behavior, especially in a small basin with reduced concentration time. In this conception, flows in the drought period are related to the aquifer streamflow (Smakhtin 2001) and the fluvial depletion is supplied and responds to this discharge (Horn 2016).

The structure of the SM is based on the water balance in a watershed, considering two simplifications: the storage on the superficial layer of soil is abstracted and the resulting precipitation (P_r) is the difference between potential evapotranspiration and total precipitation in one day (Silveira et al. 1998). In this approach, only infiltration is an input datum when daily precipitation overcomes the potential evapotranspiration.

Under these conditions, all the characteristics related to the movement of water in the underground reservoir are represented in a concentrated mode from the depletion flow curve in SM. This eliminates the need for parameters such as hydraulic conductivity, hydraulic gradient, soil type, etc., (Silveira et al. 1998) and uses only drainage area, potential evapotranspiration and daily precipitation, which makes SM a simple method that is easy to apply.

SM is an important tool for local small basin managers especially when significantly reduced precipitation is observed in several regions in Brazil (ANA 2015), as well as the lowest flow value in the historical series of several Southern regions (CPRM 2016a, 2016b, 2017a, 2017b). This method allows evaluating water potential or flow rate scale in an agile and simplified way for conflict resolution and emergency planning.

However, it is necessary to evaluate the results of SM application in other regions with edaphoclimatic conditions different from those used by Silveira et al. (1998) and Horn (2016). Thus, the application and evaluation of SM is justified and necessary for São Bartolomeu river basin, located in Minas Gerais State, Brazil. This is a small and ungauged basin which faced severe droughts in 2014, 2015 and 2016. SM is used to assist local managers in emergency decisions and water resource planning in an ungauged site where traditional modelling methods are not applicable.

MATERIALS AND METHODS

Study area

The basin of São Bartolomeu river is located in Viçosa county in Minas Gerais State, being part of the Doce river basin (Figure 1). The basin has an area of 50 km² (Bezerra 2011), which accounts for 18% of the county area (Silva 2010).

São Bartolomeu river supplies two water treatment plants in Viçosa. One supplies the county (WTP-I) and the other supplies the Universidade Federal de Viçosa (WTP-UFV). These water treatment plants catch a total of 105 L/s in the dry season. The point of water abstraction is in a series of four reservoirs. There are several users upstream the reservoirs, most of which are unregistered and using small flows.

Until 2014, there was some runoff information about flow behavior. Daker (1983) registered flows of 200 L/s in the dry season in the 60's and 70's. Valente (2008) and Bezerra (2011) verified 50% of reduction in water productivity in the 2000s, and considered flows about 100 L/s, unsatisfactory for region.

Data used for the Silveira Method application

Although the SM requests only three flow data in the drought period, in this paper, we used a database with 351 daily flow measurements, measured between October 2014 and December 2016. According to these data, 58% were obtained in the dry season, between April and October.

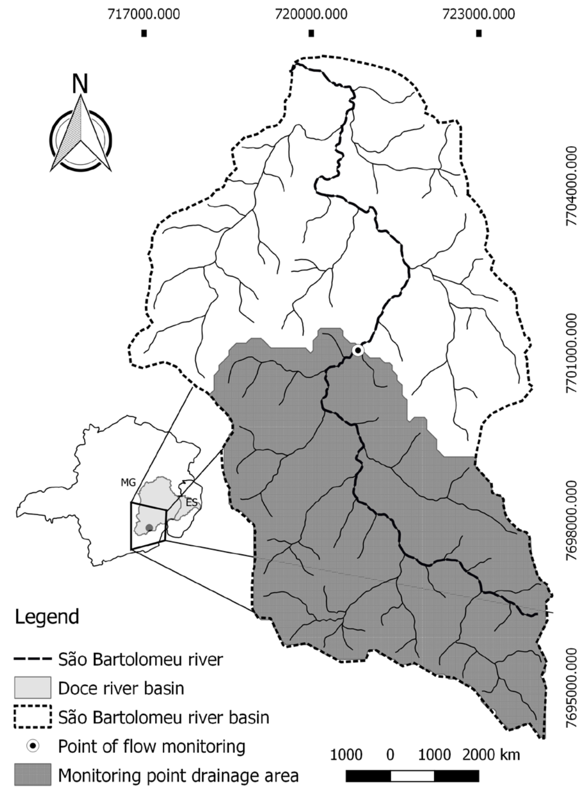

Figure 1. Location of São Bartolomeu river basin and gauge point.

The monitoring point is upstream of the reservoirs, with a drainage area of 25 km². The SEBA Hydrometrie current meter M1 was used for flows above 35 L/s and the rectangular spillway, for lower flows.

The climatic data used was obtained from a weather station of the Instituto Nacional de Meteorologia (INMET), code OMM 83642. The Penman-Monteith FAO method (Allen et al. 1998) was used to calculate the daily potential evapotranspiration and obtain the resulting precipitation (P_r).

The Silveira Method application

The application of SM was conducted in three steps: (i) identification of drought periods in the monitoring period; (ii) obtainment of two parameters; one parameter regards the water balance, the infiltration coefficient (C_{inf}), and the other was called river depletion coefficient, K_{b}. The K_b value represents the coefficient of depletion for the drought period; (iii) daily flows simulations.

The drought period was identified according to two different criteria proposed by Silveira et al. (1998) to enable the evaluation of as many drought periods as possible. The first criterion considered the absence of precipitation for at least 12 consecutive days as a drought period (C1). The second criterion considered the accumulated precipitation up to 15 mm in 12 consecutive days (C2), provided that the rainfall did not affect the behavior of the river depletion curve in the drought period.

The parameter K_b was obtained in two steps. First, we defined two intermediate values of depletion (K_{sub}), which refer to the observed reduction between two sequential flow measurements in pairs (Equation 1). Two by two (Equation 1). Second, to obtain K_b, we summed the two K_{sub} values and divided the result by the time (Δt, days) between the two flow values considered (Equation 2). When the time interval between two observed flow data was different, we adopted the mean of days between sequential flows as Δt.

$$k_{sub} = \Delta t \times \ln\left(\frac{Q_n}{Q_{n+1}}\right) \tag{1}$$

$$k_b = \frac{k_{sub(n)} + k_{sub(n+1)}}{\Delta t} \tag{2}$$

where, Δt refers to the time interval, in days, between two measurement flows (Q_n and Q_{n+1}); Q_n and Q_{n+1} refer to flow measurement in sequential days, in L/s; K_{sub} refer to the intermediate depletion coefficient, in days, and; K_b is the average depletion flow for a specific drought period, in days.

The flow measurements were performed in working days, without a standard frequency, which prevented the adoption of the initial criteria proposed by Silveira et al. (1998) to select observed flows on the 8th, 10th and 12th days in some drought period. Whenever possible, this interval between observed flows (standard interval, SI) was considered to obtain K_b.

Since it was not feasible to use the standard interval proposed by Silveira et al. (1998), we used an alternative interval (AI) for each selection criterion for drought periods (C1 and C2). The AI considers an observed flow data close to the 8th day of the period, an intermediate value close to the middle of the period and the last value available in a drought period. Thus, in AI, the entire duration of the drought period was represented in the coefficient K_b.

For every K_b calculated, we adjusted the depletion flow curve with the C_{inf} value (Equation 3). The adjustment was performed considering a value between 0 and 1 to obtain the smallest mean percentage error (MPE) between three observed flow data (the same used to obtain the K_b coefficient) and simulated data.

Therefore, we adopted two scenarios to obtain the K_b and C_{inf} values for the simulations:

In Scenario 1 (S 1) we used C1 to select the drought period and two options to obtain K_b and $C_{inf:}$

- Scenario 1.1 (S 1.1) considering SI
- Scenario 1.2 (S 1.2) considering AI
- In Scenario 2 (S 2.0), we used C2 to select the drought period and just AI was an option to obtain K_b and $C_{inf.}$

We performed an extra round of simulation for each of the scenarios (S 1 and S 2.0), considering the average of the parameters obtained in each possible drought season. In these rounds, we used the suffix M for identification.

$$Q_b(t) = \left[Q_b(t-1).e^{-\frac{\Delta t}{k_b}} \right] + \left[\left(C_{\inf} x P_r(t) \right) . \left(1 - e^{-\frac{\Delta t}{k_b}} \right) \right] \quad (3)$$

Once defined every pair of parameters (K_b and C_{inf}) for each proposed scenario, we simulated the daily flow using the Equation 3. Each round of simulation generated average daily flow for three years (2014, 2015 and 2016).

where $Q_b\ (t)$ refers to the total outflow of daily underground runoff, in mm/day; $Q_b\ (t - 1)$ characterizes the total outflow of daily underground runoff on the previous day, in mm/day; $V_i\ (t)$ refers to the total infiltration volume (V_i), in mm/day, and represented by equation $C_{inf}\ x\ P_r\ (t)$; and $P_r\ (t)$ refers to the resultant daily precipitation in mm/day. For conversion of the units into L/s, the result of the Equation 3 was multiplied by the drainage area (25 km²) and divided by the unit conversion factor 0.0864.

The simulated daily flow data allowed obtaining the permanence curve for three years – 2014, 2015 and 2016, through the continuous accumulated frequency, as proposed by Silva et al. (2015). Another curve was obtained using the observed flow data.

As indicated by Silveira et al. (1998) and Horn (2016), only the lower permanence curve range should be assessed, with associated flows only to the frequencies accumulated between 50% and 95%.

SM performance evaluation

SM was evaluated by the difference between the permanence curves. Visual evaluation was the first analysis, followed by other four statistical indexes: mean percentage error (MPE), mean absolute error (MAE), mean quadratic error (MQE) (Uliana et al. 2016) and relative Willmott's index of agreement, d_{rel} (Krause & Boyle 2005).

The Willmott's index of agreement (Willmott 1981) was widely used to evaluate the results from the models. However, several studies have shown that it reduced sensitiveness to evaluate minimum flows. Significant results for model performance were obtained due to sensitiveness to high data variations (Zhang et al. 2015, Krause & Boyle 2005 ASCE 1993). Thus, the relative form was adopted in this paper.

Comparison of the simulated reference flows and concession values in São Bartolomeu river basin

The best simulated scenario was compared to the flow associated with the 95% permanence in time (Q_{95}). Additionally, to expand SM possible uses, we estimated the minimum flow with 7 days of duration and return period of 10 years ($Q_{7,10}$) for the different time interval of simulations. The average long-term flow (Q_{mld}) was also used for comparison. However, for the 3-year simulations and the observed data, the mean flow rate observed in the period was used for comparison with the available reference Q_{mld} values.

Although the minimum reference flow used for granting concessions in the State of Minas Gerais is $Q_{7,10}$, part of the regionalization studies present equations for obtaining Q_{95} and Q_{mld}. In addition, in several Brazilian states, Q_{95} is adopted as a criterion for granting water use.

In this analysis, for the best scenario (defined as the equation with the pair of parameter K_b and C_{inf} that led to the best model performance), a new round of simulations was carried out for the 1975-2005 and 1975-2016 periods. The 1975-2005 simulation interval was chosen because it is the one adopted by GPRH & IGAM (2012), in a regionalization study to improve the process of granting water resources to the State of Minas Gerais. The 1975-2016 simulation interval was used to evaluate the behavior of the reference flows in periods of scarcity, observed in the last three years in several regions of the Minas Gerais state (CPRM 2016a, 2016b, 2017a, 2017b). Indices were well below the historical average of the region The fluviometric station of Porto Firme (code 56075000), the closest station with data for the 1975-2016 period, was used for comparison.

Another comparison considered the reference flows (Q_{mld} and $Q_{7,10}$) presented by Sousa (1993), the methodology adopted by the granting concession for the use of water resources in Minas Gerais state. The Q_{95} was obtained from observed data and the average period flow to be compared with the simulated scenarios. The average period flow was compared with Q_{mld}.

The Sistema Computacional de Análises Hidrológicas – SisCAH 1.0 (Sousa et al. 2009) provided the simulated reference flows $Q_{95,}$ $Q_{7,10}$ and Q_{mld}. The comparison between simulated data, observed data and reference flows of GPRH & IGAM (2012) and (Souza 1993) was performed by the relative difference.

Evaluation of the Silveira Method for planning water uses under water shortage conditions

In order to evaluate the SM results for planning the water uses under shortage conditions, we considered the guidelines presented by the Deliberação Normativa do Conselho Estadual de Recursos Hídricos DN CERH/MG number 49/2015, which defines three possible levels of restrictions in scenarios of water scarcity (Minas Gerais 2015).The attention level occurs when the mean of the daily flows of seven consecutive days (Q_7) is less than 200% of $Q_{7,10}$. The alert level is reached when Q_7 is equal to or less than 100% of $Q_{7,10}$ and the restriction level is defined when Q_7 is less than 50% of $Q_{7,10}$.

This evaluation considers the $Q_{7,10}$ of the simulated scenario for the 1975-2016 SM, as presented in item 2.5, considering the likely use of this reference flow as a parameter to define the states observed in the water course and the effectiveness of the available flow allocation, as directed by the DN, for the multiple existing uses. We based this analysis on granting water data provided by IGAM (2017).

RESULTS AND DISCUSSION

Application of the Silveira Method (SM)

Eleven drought periods were considered for the application of SM: one for the Scenario 1.1, six for the Scenario 1.2 and four in Scenario 2. Table I shows the drought periods for each scenario, considering the initial month of occurrence, first flow data (Q_i) and last flow data (Q_f) of the drought period and the duration of drought days.

The preliminary analysis of the scenarios identified a wide variation between K_{sub} and C_{inf}, in some cases, with values physically impossible under natural conditions in a river basin. Therefore, Horn (2016) suggested the exclusion of the scenarios with K_{sub} variation (ΔK_{sub}) greater than 100% or C_{inf} outside the range of 1.0 and 0.6.

Table II presents two intermediate values of the depletion coefficient (K_{sub}), percentage variation in K_{sub}(ΔK_{sub}), river depletion coefficient (K_b) and infiltration coefficient (C_{inf}) obtained for each of the scenarios. The average scenarios (1.2.A and 2.A, Table II) were obtained considering the Horn (2016) recommendations for ΔK_{sub} and C_{inf} applicable values.

The adoption of different criteria for calculating the parameters produced two scenarios (1.1.1 and 1.2.1) for the same drought period, occurred in January 2015, which lasted 21 days. In S 1.2.1, the adoption of the entire period resulted in lower K_{sub} variation and a more consistent C_{inf} value.

K_{sub} values in S 1.1.1 and S 1.2.1 were the lowest observed for all simulations, except for

Table I. **Observed drought periods in Scenarios 1 and 2.**

Scenario		Drought period	Month	Q_i (L/s)	Q_f (L/s)	Duration (days)
1	1.1	1.1.1	Jan/15	168	28	21
	1.2	1.2.1	Jan/15	168	28	21
		1.2.2	Apr/15	66	55	13
		1.2.3	May/15	192	61	15
		1.2.4	Jun/15	52	35	31
		1.2.5	Jul/15	81	33	25
		1.2.6	Jun/16	49	35	59
2	2.0	2.1	May/15	61	35	67
		2.2	Aug/15	38	33	23
		2.3	Sep/15	156	28	30
		2.4	Jun/16	39	35	94

Q_i – first observed flow data in the drought period, in L/s.
Q_f – last observed flow data in the drought period, in L/s.

K_{sub1} in S.1.2.2. This behavior is attributed to the rainy season, against the assumptions of the SM, which represent the behavior of the basin in the dry period when there is no recharge of the underground reservoir by precipitations.

K_{sub} showed great variance for S 1.2.2 and S 1.2.4 (3.133% and 748%, respectively). In S 1.2.2, the high variation was caused by the reduced K_{sub1} value. This low value may be due to the hourly variation of the current in the basin, with reports of sudden falls between the observed floods.

A marked decline of K_{sub1} is observed for S 1.2.4, for the same reason. For the other scenarios, where ΔK_{sub} was greater than 100% (1.1.1, 1.2.6 and 2.4), such discrepancy was not observed between the K_{sub} values obtained.

In general, as expected, K_{sub1} represented the sharpest part of the decay curve. However, variations above that recommended by Horn (2016) for the K_{sub} were generated due to the rapid stabilization of the decay curve at the end of the drought periods. Physically, this fact represents the low storage capacity of the underground reservoir, due to the current stage of degradation of the hydrographic basin.

The C_{inf} values for S 1.1.1, S 1.2.2, S 2.1 and S 2.4 exceed the range recommended by Horn (2016): the first two with values lower than 0.1, while the last values were above 0.6. In these cases, the scenarios were discarded.

The parameter value variation in São Bartolomeu river basin out of the ranges suggested by Silveira et al. (1998) and Horn (2016) is explained by the temporal variability of the precipitation in the region, unlike that observed in the author's original study region (Southern Brazil). Notably, the years 2014, 2015 and 2016 reduced precipitation volumes during the rainy periods and a prolongation of the dry season was observed in our study area.

The alternative criteria (C 2) allowed the use of all selected drought periods between April and September (dry season), which demonstrates the natural decay of the flows, and meets the basic assumptions of the SM.

The standard deviation of K_b and C_{inf} differed significantly from those observed in six basins

Table II. K_{sub}, K_b and C_{inf} obtained per drought periods.

Scenarios	Drought period	K_{sub1}	K_{sub2}	ΔK_{sub} (%)	K_b	C_{inf}
1.1	1.1.1[1]	8.63	17.38	101%	13.00	0.08
1.2	1.2.1	11.53	18.35	59%	5.43	0.23
	1.2.2[1]	5.15	166.50	3.133%	85.82	0.06
	1.2.3	25.95	25.39	2%	17.11	0.14
	1.2.4[1]	35.57	301.48	748%	30.64	0.31
	1.2.5	97.38	152.95	57%	29.44	0.20
	1.2.6[1]	181.46	413.89	128%	17.26	0.15
	1.2.A	-	-	-	17.33	0.19
2.0	2.1[1]	129.81	78.50	65%	7.18	1
	2.2	310.48	201.00	54%	68.20	0.13
	2.3	84.90	89.87	6%	15.89	0.21
	2.4[1]	215.81	106.02	104%	8.97	0.85
	2.A	-	-	-	42.05	0.17

[1]Drought periods excluded considering Horn (2016) recommendations.
K_{sub1} – depletion coefficient between the first and second observed flow data in a total of three measurements used to characterize the depletion in a drought period.
K_{sub2} – depletion coefficient between the second and third observed flow data in a total of three measurements used to characterize the depletion in a drought period.
ΔK_{sub} (%) percentage variation between K_{sub1} and K_{sub2}.
K_b – depletion coefficient for a specific drought period.
C_{inf} - infiltration coefficient.

analyzed by Silveira et al. (1998) and ranged from 0.77 to 1.86 for K_b and from 0.04 to 0.08 for C_{inf}. For this study, the standard deviation for K_b and C_{inf} parameters ranged from 12.01 to 0.05 for the S 1.2 and from 36.99 to 0.06 for the S 2.0 (Table III).

Table III shows that the removal of the scenarios with percentage variation of K_{sub} above 100%, as proposed by Horn (2016), is not enough to reach the range obtained by Silveira et al. (1998). On the other hand, the removal of the C_{inf} values outside the proposed range reduced the standard deviation to the range presented by Silveira et al. (1998).

This high variation of the K_b values requires special attention to the selection of the drought period to be adopted for the application of the method, since its use in river basins without any preliminary flow information will require an even greater knowledge of the scale of flow rates from the technical team.

The variation obtained in the results is probably due to the following factors: (i) the precipitation regimes in the study areas are different. In São Bartolomeu basin, the climate is characterized by rainy summers and dry winters, especially after 2014, in which pluviometric indices were well below the historical average of the region (CPRM 2016a, 2016b, 2017b), while Silveira et al. (1998) developed their study in a region with well-distributed rainfall amounts throughout the year; and (ii) the flows in São Bartolomeu basin present great hourly variation caused by multiple upstream uses- , as verified by the new automatic fluviometric station installed in 2016.

Table III. Mean and standard deviation for K_b and C_{inf} obtained for S 1.2 and S 2.0: (a) in compliance with the exclusion criteria suggested by Horn (2016); and (b) including all preselected periods.

Condition	Scenario	Mean K_b	Deviation K_b	Mean C_{inf}	Deviation C_{inf}
a	1.2	17.33	12.01	0.19	0.05
	2.0	42.05	36.99	0.17	0.06
b	1.2	30.95	28.44	0.18	0.09
	2.0	25.06	29.00	0.55	0.44

Considering the simulation possibilities, seven scenarios could be used for the 2014-2016 period and their respective permanence curves. Table IV shows the observed and simulated flows for the 50% to 95% range of time permanence.

Figure 2 shows the behavior of the curve of permanence for the observed and simulated data in the seven scenarios. The highlight shows the permanence range of 80% to 95%. As observed, the underestimation of the lower range flows for all simulated scenarios from permanence time is above 80%.

The visual evaluation suggested by ASCE (1993), demonstrates that the slope of the simulated curves is higher than the observed. However, the observed permanence curve was constructed with only 44% of the days throughout the monitoring period, with emphasis on the recession flows. This datum shows a pattern tending to a flatter shape in the transition between the upper (0 – 50%) and the lower (50 – 100%) range, since the peak flows were not represented.

Figure 2 shows the underestimation of the lower range flows for all simulated scenarios from permanence time above 80%.

The sudden drop in the lower range of the permanence curve for S 1.2.1 can be explained by the value of K_b (5.43), which is the lowest among the others. This behavior is also observed in S 1.2.3, which has a higher K_b value, (17.11) but reduced C_{inf} value (0.14).

The S 1.2.5, S 1.2.A and S 2.3 presented accentuated decay, although smaller than S 1.2.1 and S 1.2.3. The intermediate values of K_b for these scenarios were 29.44, 17.33 and 15.89, respectively. For S 2.2 and S 2.A from 75% of permanence, all the simulated curves show smaller underestimation for the observed flows.

MPE for the 50 to 95% curves ranged from – 69% to -5% for the S S 1 scenarios; for the S 2 scenarios, the MPE values ranged from – 32% to 12 %; and for the S 1 scenarios, the S 1.2.A did not present the best result, as expected. For the S 2 scenarios, S 2.A and S 2.2 presented similar performance. Table V presents the MPE results for all scenarios.

Considering the flows for 50% and 95% of permanence, the MPE ranged from -7% to 2% for the Q_{50} in S 1 scenarios and ranged from 50% to 65% in S 2 scenarios. For $Q_{95,}$ MPE ranged from -100% to -90% for S 1 scenarios and ranged from -86% to -31% for S 2 scenarios.

Horn (2016) presented values ranging from 22% to 65% for Q_{50} and -28% and 121% for Q_{95}. For S 1.2.1 and S 1.2.3, the results for Q_{50} were close to the expected, with MPE of -7% and 2%, respectively. For $Q_{95,}$ all scenarios have been outside the range presented by Horn (2016), with clear tendency to underestimation.

The underestimated flows in a higher permanence time can be explained by the heterogeneous rainfall distribution throughout the year in the study area, which concentrates a well-defined rainy period and long dry season,

Table IV. Observed and simulated flows associated for a difference time permanence (presented in L/s).

Permanence (%)	Observed flows (L/s)	Simulated flows (L/s) for each scenario						
		1.2.1	**1.2.3**	**1.2.5**	**1.2.M**	**2.2**	**2.3**	**2.A**
50	46	43	47	75	76	73	69	88
55	43	31	37	63	59	63	53	70
60	40	21	27	54	46	54	39	59
65	38	14	21	47	34	47	30	50
70	36	9	17	38	26	42	24	45
75	35	6	14	27	21	37	20	38
80	35	3	10	21	16	34	14	30
85	33	1	7	18	11	31	10	23
90	31	0	5	14	7	24	7	18
95	29	0	3	10	5	20	4	14

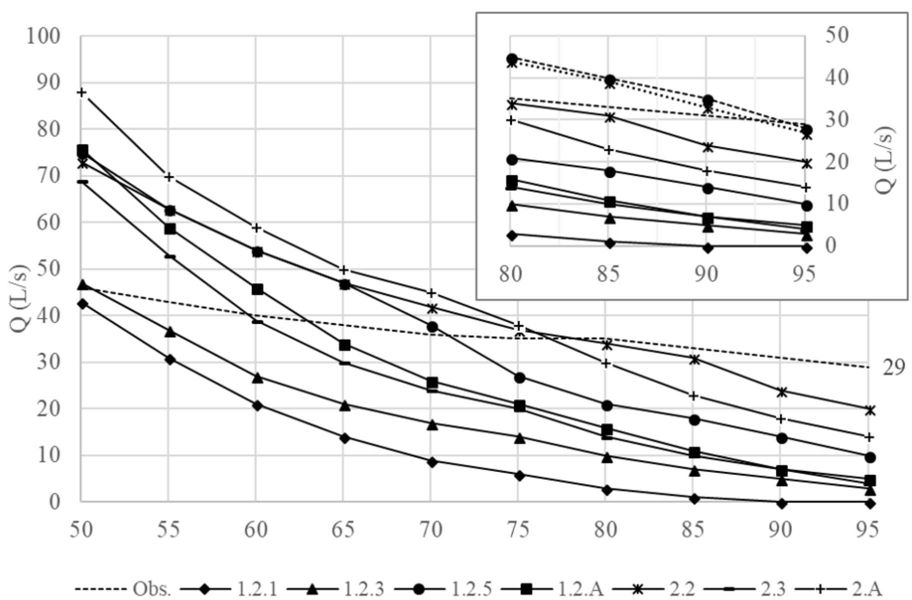

Figure 2. Behavior of the curve of permanence of the observed and simulated data for the different scenarios.

the latter accentuated during the monitoring time. This precipitation pattern contributes to reduced simulated flows along the drought period, since the decay is represented by an exponential equation, and the natural flows during a recession period tend to stabilize.

The S 1.2.A and S 2.A scenarios did not present the best results, as expected from the considerations of Silveira et al. (1998). In both scenarios, the use of several periods to construct an average period was enough to improve the results, however insufficient to achieve best results. However, MPE results were better, compared to the periods with K_b values less than 18 (S 1.2.1, S 1.2.3 and S 2.3), although the high standard deviation of parameter values has affected the average scenario with low values of K_b and C_{inf}.

Table V shows that the S 2.2 scenario is considered the best among the seven simulated scenarios, as it presented the second smallest

Table V. Mean Percentage Error for 50% to 95 % range of the permanence curves, for 50% (Q_{50}) and 95% (Q_{95}).

Permanence (%)	Scenario 1				Scenario 2		
	1.2.1	1.2.3	1.2.5	1.2.M	2.2	2.3	2.M
50 to 95	-69%	-53%	-5%	-24%	12%	-32%	13%
50	-7%	2%	63%	65%	59%	50%	91%
95	-100%	-90%	-66%	-83%	-31%	-86%	-52%

value for MPE (12%) and smaller MPE for Q_{95} (-31%).

MAE ranged from 0.39 to 0.95 L/s.km² for the 50% to 95% range permanence curves; from 0.04 to 1.68 L/s.km^2 for Q_{50}; and from 0.36 to 1.16 L/s.km^2 for Q_{95}. For the S 2.2 scenario, MAE was 1.08 and 0.36 for Q_{50} and Q_{95}, respectively. Horn (2016) obtained mean error ranging from 4.78 to 0.63 L/s.km² for Q_{50} and Q_{95}, respectively. Thus, the SM errors for the São Bartolomeu river basin were lower, compared to Horn (2016) results. Table VI presents MAE values for each scenario.

Table VII presents the MQE and the relative Willmott's index of agreement. These evaluation indexes were not used by Silveira et al. (1998) and Horn (2016), however, were used in this study because they are normally found in the literature to evaluate the quality of the results obtained from such simulations. MQE values ranged from 0.50 to 1.02 L/s.km² and the Willmott relative index values ranged from 0.23 to 0.77. S 2.2 satisfactorily obtained the best results for both indexes.

The SM application was generally able to produce at least one scenario with acceptable results, which represented well the current deficit regime of the flows in São Bartolomeu river basin. However, the tendency to underestimate the flow, which does not exclude the potentialities of SM, reveals the need for careful evaluation of the drought period selected, especially when applied in regions with a long and well-defined dry season.

Comparison between the simulated reference flows (Q_{95} and $Q_{7,10}$) and the concession values adopted in Minas Gerais state

For the São Bartolomeu river basin, the criteria for the granting of concession to water use by the Minas Gerais State is based on $Q_{7,10}$. In addition, Q_{95} was used in this analysis because it is a criterion frequently adopted by other Brazilian states and is present in several regionalization studies. Therefore, these two reference values were considered for comparison with reference values simulated by SM for the S 2.2 scenario.

Table VIII shows the simulated reference flows adopted by IGAM & GPRH (2012), from 1975 to 2005 time interval, considering K_b and C_{inf} parameters from S 2.2. It also presents the values of Q_{mld} and $Q_{7,10}$ obtained by Souza (1993) and currently used for granting concession to water use in the region. The simulated values in Table VIII correspond to Q_{mld}, Q_{95} and $Q_{7,10}$ for the period from 1975 to 2005, which is the same period used by IGAM & GPRH (2012), and an alternative period from 1975 to 2016 for more updated estimates.

The SM (1975-2005) Q_{mld}, Q_{95} and $Q_{7,10}$ presented values lower than IGAM & GPRH (2012), with underestimation of 74%, 87% and 91%, respectively. In relation to the values obtained from the methodology proposed by Souza (1993), the underestimation for Q_{mld} and $Q_{7,10}$ were 70% and 84%, respectively. The simulated scenario SM (1975-2005) and SM (1975-2016) presented similar results.

It must be highlighted that the Q_{mld} and Q_{95} from the observed data are lower than the values

Table VI. Absolute errors, in L/s.km², for the 50% to 95% range, 50% (Q_{50}) and 95% (Q_{95}).

Permanence (%)	Scenario 1				Scenario 2		
	1.2.1	1.2.3	1.2.5	1.2.M	2.2	2.3	2.M
50 to 95	0.95	0.72	0.59	0.68	0.39	0.65	0.62
Q_{50}	0.12	0.04	1.16	1.2	1.08	0.92	1.68
Q_{95}	1.16	1.04	0.76	0.96	0.36	1.00	0.60

presented by other methods adopted, 68 L/s and 29 L/s, respectively. Among all the results, only those obtained by the SM were close to the scenario observed in the São Bartolomeu river basin. This is corroborated by recent flows observed in the basin, which corresponded to only 16 L/s on September 25, 2017 the lowest value observed until then.

Despite having similar results, SM (1975-2016) presented Q_{mld}, Q_{95} and $Q_{7,10}$ smaller than SM (1975-2005), namely, 4%, 7%, 6%, respectively. Decreased reference flows were observed in recent years in several counties of the Southeastern Brazil (CPRM 2017a, 2017b).

The hydrological behavior in the region was assessed by comparing our results to those of the Estação Fluviométrica de Porto Firme (code 56075000), the closest to our study area with available data. These data showed Q_{mld}, Q_{95} and $Q_{7,10}$ reduced values, around 6%, 23% and 18% in comparison between the 1957 to 2005 and 1975 to 2016 periods. The observed behavior for the analyzed station shows reduced values for the three reference flows evaluated.

This behavior was also observed for the SM simulations. For the SM (1975-2005) and SM (1975-2016), Q_{95} decays from 29 L/s to 27 L/s, respectively, was similar the observed in the station analyzed and in accordance with the positive SM evaluation.

In general, SM presented more suitable results with the data currently observed in the basin, mainly in comparison with Q_{95}. Sousa (1993) and IGAM & GPRH (2012) methodologies overestimated the reference flows.

Though Q_{mld} presented no significant results, it is worth mentioning that the observed values of the permanence curve underestimate the mean values of permanence for the period, as already discussed. Thus, it was not possible to perform a thorough evaluation of the SM capacity for the SM (1975-2005) and SM (1975-2016) for Q_{50} and Q_{mld} for the observed period, though the simulated results are closer to the current scenario of the basin.

This analysis reveals that the use of current methods generates an unreal expectation of water availability, which leads to the catchment of water in quantities not available during periods of extreme drought or extreme events. Again, the importance of complementary evaluation tools is evident, and the SM is indicated for this purpose.

Using SM for planning the multiple uses of water under water scarcity conditions

In the absence of a database for use of traditional methods, the use of SM in the São Bartolomeu river basin proved to be sufficient to represent more accurately the current water availability, in which the values granted do not correspond to the water availability of the basin. During the most part of the monitoring period, the observed flows were below 50% of the $Q_{7,10}$ reference value presented by GPRH & IGAM (2012) or by Souza (1993), as shown in Figure 3.

Table VII. Mean Quadratic Error (MQE), in L/s.km², and Willmott relative coefficient (d_{rel}) for the different scenarios assessed.

	Scenario 1				Scenario 2		
	1.2.1	1.2.3	1.2.5	1.2.M	2.2	2.3	2.M
MQE	1.02	0.81	0.65	0.77	0.50	0.74	0.75
d_{rel}	0.23	0.32	0.64	0.52	0.77	0.48	0.67

Table VIII. Comparison between Q_{mld}, Q_{95} and $Q_{7,10}$, in L/s, observed flow and other methodologies.

Flows	Observed flow	Souza[1] (1993)	IGAM and GPRH (2012)	MS (1975-2005)	MS (1975-2016)
Q_{mld}	69[2]	452	507	134	128
Q_{95}	29	-	225	29	27
$Q_{7,10}$	-	113	185	17	16

[1]the method presented by Souza (1993) does not allow for the Q_{95} estimate.
[2]Although treated as Q_{mld}, this value should be considered as the mean of the observed values over the available data period.
MS (1975-2005): Application of the SM for the 1975-2005 period, considering the pair of parameters used for Scenario 2.2.
MS (1975-2016): Application of the SM for the 1975-2016 period, considering the pair of parameters used for Scenario 2.2.

The analysis of the database over the monitoring period allowed to define that, at least 60% of the time, Q_7 was below 50% of the $Q_{7,10}$ (the maximum value granted in Minas Gerais State) presented by GPRH & IGAM (2012). Using Sousa (1993) methodology, Q_7 below 50% of the $Q_{7,10}$ was observed in at least 50% of the time.

According to DN CERH/MG number 49/2015, this scenario determines that, in at least of 50% of the year, the flow grants should have been reduced, in order to ensure the necessary residual flow. From the available data of user registries, the sum of the values granted and insignificant uses registered upstream of the flow measurements is approximately 4 L/s of surface abstractions, according to IGAM (2017).

Whereas this water is generally used for irrigation and animal consumption, the DN proposes a 25% reduction. For public supply, granted uses are of 30 L/s and 65 L/s (during the dry season) for the local university and county, respectively. With the proposed DN reduction, the uses should be 24 L/s and 48 L/s. Thus, all uses sum 75 L/s in the critical periods of flow.

It is straightforward that the reduction proposed by DN is not enough to solve the problem in water uses during the dry periods. For the periods of water restriction, even considering the reductions, São Bartolomeu river still has uses that amount up to 81% of the $Q_{7,10}$ presented by GPRH & IGAM (2012). For the $Q_{7,10}$ presented by Souza (1993), the uses were still 33% higher than $Q_{7,10}$ itself. In both cases, the limits allowed by the legislation would be exceeded (residual flows should be, at least, of 50% of $Q_{7,10}$).

The SM (1975-2016) simulated $Q_{7,10}$ of 16 L/s, lower than those adopted for water granted in Minas Gerais State, even using the new methodologies that imposed restrictions to minimize the effects of extrapolation of the regionalization on drainage areas different from the intervals of the stations adopted.

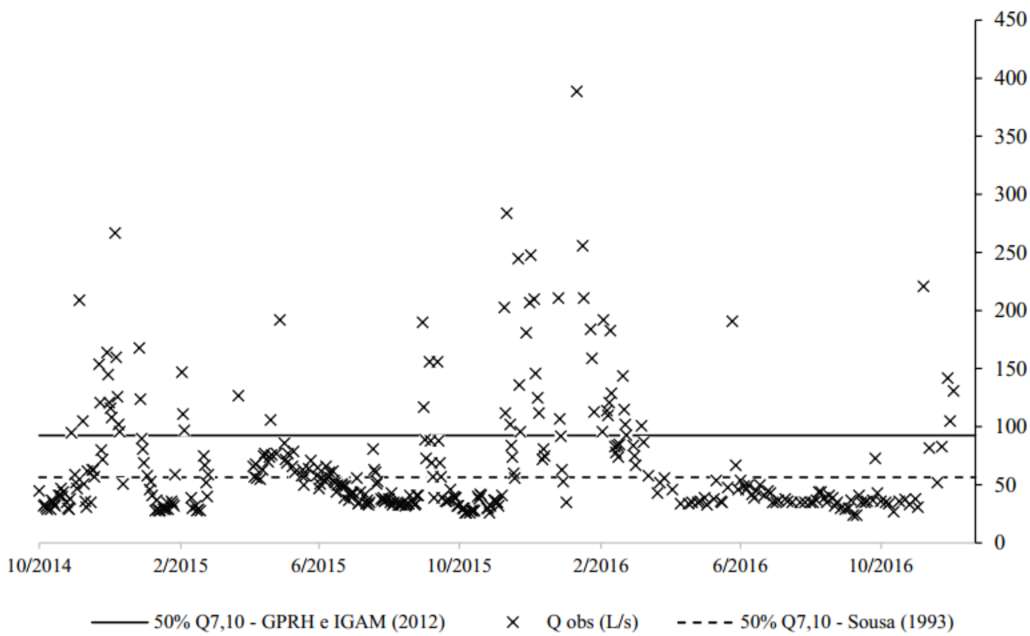

Figure 3. Observed data for the monitoring period and 50% limits of Q7,10 by GPRH & IGAM (2012) and Souza (1993) methodologies.

Therefore, SM can be used as a complementary tool for multiple water use planning. It also allows for the reassessment of the current scenario in periods of scarcity and conflicts over water use. In addition, the restriction imposed by the methodology adopted by DN CERH/MG n 49/2015 may not be an effective solution for critical conditions of deficit in water resource supply.

CONCLUSIONS

Based on the results presented in the previous sections, we can conclude that the selection of the drought period is the key point for the precision of the method. This shows the relevance of the knowledge of the local climate characteristics for the application of the method.

The adoption of three flow data over the entire duration of the drought period (alternative criteria), unlike the one recommended by Silveira et al. (1998), proved to be beneficial, with better results for reference flow estimates.

We observed that the higher values of K_b for watersheds inserted in regions with long drought periods tend to provide better results for flows associated with longer duration, due to the exponential representation of the decayed flows adopted in the SM.

The comparison between the results of the SM and the values obtained from the available methods to estimate the $Q_{7,10}$ for granting concession of water use, in Minas Gerais State, showed the ability of the method to obtain water availability in the São Bartolomeu river basin, reinforcing the associated limitations of methods of transposition for small river basins.

Thus, SM is recommended as a complementary tool for local planning of water resources under water scarcity conditions. The results allow water agencies to evaluate the status of water availability, improve water allocation and reconsider the water granted for the local users.

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ULISSES B. COMINI[1]
https://orcid.org/0000-0001-6744-2389

DEMETRIUS DAVID DA SILVA[2]
https://orcid.org/0000-0001-9666-7421

MICHEL C. MOREIRA[2]
https://orcid.org/0000-0001-8024-7705

FERNANDO F. PRUSKI[2]
https://orcid.org/0000-0002-7957-6402

[1]Diretoria de Meio Ambiente, Universidade Federal de Viçosa/UFV, Av. P.H. Rolfs, s/n, Campus Universitário, 36570-900 Viçosa, MG, Brazil

[2]Reitoria, Universidade Federal de Viçosa/UFV, Av. P.H. Rolfs s/n, Campus Universitário, 36570-900 Viçosa, MG, Brasil

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Correspondence to: **Ulisses Bifano Comini**
E-mail: ulisses.comini@ufv.br

Author contributions

Comini UB conducted this study by analyzing data, performing the simulations and producing the results and discussion. Silva DD idealized and supervised the research, contributed to methodology development, evaluation of results, discussion and text review. Moreira MC and Pruski FF co-supervised the development of research regarding the methodology and evaluation of results.