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Modelling intermittence and river flow in the semi-arid region of Brazil: The Umbuzeiro River, Ceará[1]

Modelagem da intermitência e do escoamento no semiárido brasileiro: rio Umbuzeiro, Ceará

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ABSTRACT - Research shows an increase in the intermittence of rivers of different spatial scales. Exploring intermittence in semi-arid regions, also characterised by a scarcity of data, is important for understanding the process on a global scale. The aim of this study, therefore, was to evaluate the ability of a physically based hydrological model (WASA) to simulate simultaneously the intermittence and flow of the Umbuzeiro River, whose basin is located in Aiuaba, Ceará. The analysis was carried out in three nested basins: the Benguê Reservoir (933 km^2), the Aroeira Reservoir (800 km^2) and the Aiuaba Experimental Basin (AEB, 12 km^2). Eleven simulations were carried out, altering various parameters (saturated hydraulic conductivity of the soil on the slopes and on the riverbed, hydraulic conductivity of the crystalline basement, depth of the riverbed, and the rainfall intensity parameter of the model). The model better represented the larger basins (10^3 km^2) compared to the smaller scale basin (10^1 km^2). The simulations showed a marked improvement once the hydraulic conductivity of the soils as measured *in situ* had been applied, confirming the physical basis of the model. The most sensitive parameter for the generation of flow was the saturated hydraulic conductivity of the soil. This can be explained by the prevalence of Hortonian flow in the basin. It was concluded that none of the parameterisations was successful in simultaneously representing the two processes (intermittence and flow) on the scales of the three basins.

Key words: Water resource. Hydrological modelling. River flow. WASA model.

RESUMO - Pesquisas indicam crescimento da intermitência em rios de diversas escalas espaciais. Nesse sentido, analisar a intermitência em regiões semiáridas, caracterizadas pela escassez também de dados, torna-se relevante para o entendimento desta condição em escala global. A partir disso, o objetivo foi avaliar a capacidade de um modelo hidrológico de base física (WASA) simular, simultaneamente, a intermitência e o escoamento do rio Umbuzeiro. A bacia do rio Umbuzeiro, situa-se em Aiuaba, Ceará. A análise foi realizada em três bacias aninhadas: a do Açude Benguê (933 km²), a de Aroeira (800 km²) e a Bacia Experimental de Aiuaba (AEB, 12 km²). Foram realizadas onze simulações, alterando-se diversos parâmetros (condutividade hidráulica saturada do solo nas encostas e no leito do rio, condutividade hidráulica do embasamento cristalino, profundidade do leito do rio e o parâmetro de ajuste de chuva do modelo). O modelo representou melhor as bacias maiores (10^3 km²) em comparação com a de pequena escala (10^1 km²). As simulações tiveram notável melhora após aplicar a condutividade hidráulica dos solos conforme medição *in situ*, confirmando a base física do modelo. Os parâmetros mais sensíveis na geração de escoamento foram as condutividades hidráulicas saturadas do solo. Isso se explica porque, na bacia, prevalece o escoamento Hortoniano. Conclui-se que nenhuma parametrização teve êxito na representação simultânea dos dois processos (intermitência e escoamento) nas três escalas de bacia.

Palavras-chave: Recurso hídrico. Modelagem hidrológica. Escoamento dos rios. Modelo WASA.

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INTRODUCTION

Water scarcity in the semi-arid region of Brazil has been on the increase due to both a reduction in the water supply (ARAÚJO; BRONSTERT, 2016; FIGUEIREDO *et al*., 2016) and an increase in water demand (MEDEIROS; SIVAPALAN, 2020). In addition, the multiple dams along courses, changes in land use, and climate change influence water availability. Rivers, therefore, undergo changes in their regime, which impacts biodiversity and the control of matter flow (DATRY *et al*., 2018). River intermittence is increasingly common across the globe (MESSAGER *et al*., 2021). Datry, Larned and Tockner (2014) define these rivers as IRES (intermittent rivers and ephemeral streams), making up more than 50% of the global river network, including small-order rivers; similar to Messager *et al*. (2021), who predicted that 51% to 60% of the world's rivers stop flowing at least one day a year. Recurrent episodes of drought make the water available from reservoirs vulnerable and subject to degradation. The basins of perennial rivers register periods of intermittence more frequently (SNELDER *et al*., 2013). It is sought to understand the processes that intervene in intermittence, so as to optimise actions that reduce their impact and/or improve living with the process. The 1000 Intermittent Rivers Project (DATRY *et al*., 2016) was created with the intention of disseminating knowledge on a global scale concerning IRES. As intermittence and ephemerality are common in the semi-arid region of Brazil, now is the time to apply studies in this region to understand the phenomenon, generating scientific support for the adoption of policies that can be applied in watersheds (ALMEIDA; ROEHRIG; WENDLAND, 2014; SOUSA *et al*., 2022).

Cirilo *et al*. (2020) state that in the quest to guarantee future supplies, it becomes necessary to simulate the larger hydrographic basins to verify responses to environmental change and the demand for water, among which can be included the increase in river intermittence. Hydrological models can be used that help our understanding of both the intermittence and flow of rivers. The model for Water Availability in Semi-Arid Environments (WASA) carries out continuous simulations of flow in semi-arid areas (GÜNTNER; BRONSTERT, 2004). Indeed, the WASA model has been successfully used to analyse the hydrology of the semi-arid region in Brazil, with the emphasis on the flow of rivers and, therefore, the water input of the reservoirs (MALVEIRA; ARAÚJO; GÜNTNER, 2012; MAMEDE *et al*., 2018; MEDEIROS *et al*., 2014). The model has also been used to assess the impact of climate change on water availability in the region (KROL *et al*., 2011). However, the literature does not state whether the model is able to reproduce the intermittence and flow of rivers both reliably and simultaneously, and whether there is a restriction on the spatial scale when applying the model. Pending further evaluation, we did not identify in the literature any confirmation of physically based hydrological models being able to simulate simultaneously the water input of reservoirs and the intermittence of rivers. In this context, the aim is to verify the ability of a physically based model (in this case, the WASA model) to represent simultaneously both intermittence and flow in rivers of the semi-arid region of the north-east of Brazil on different spatial scales.

MATERIAL AND METHODS

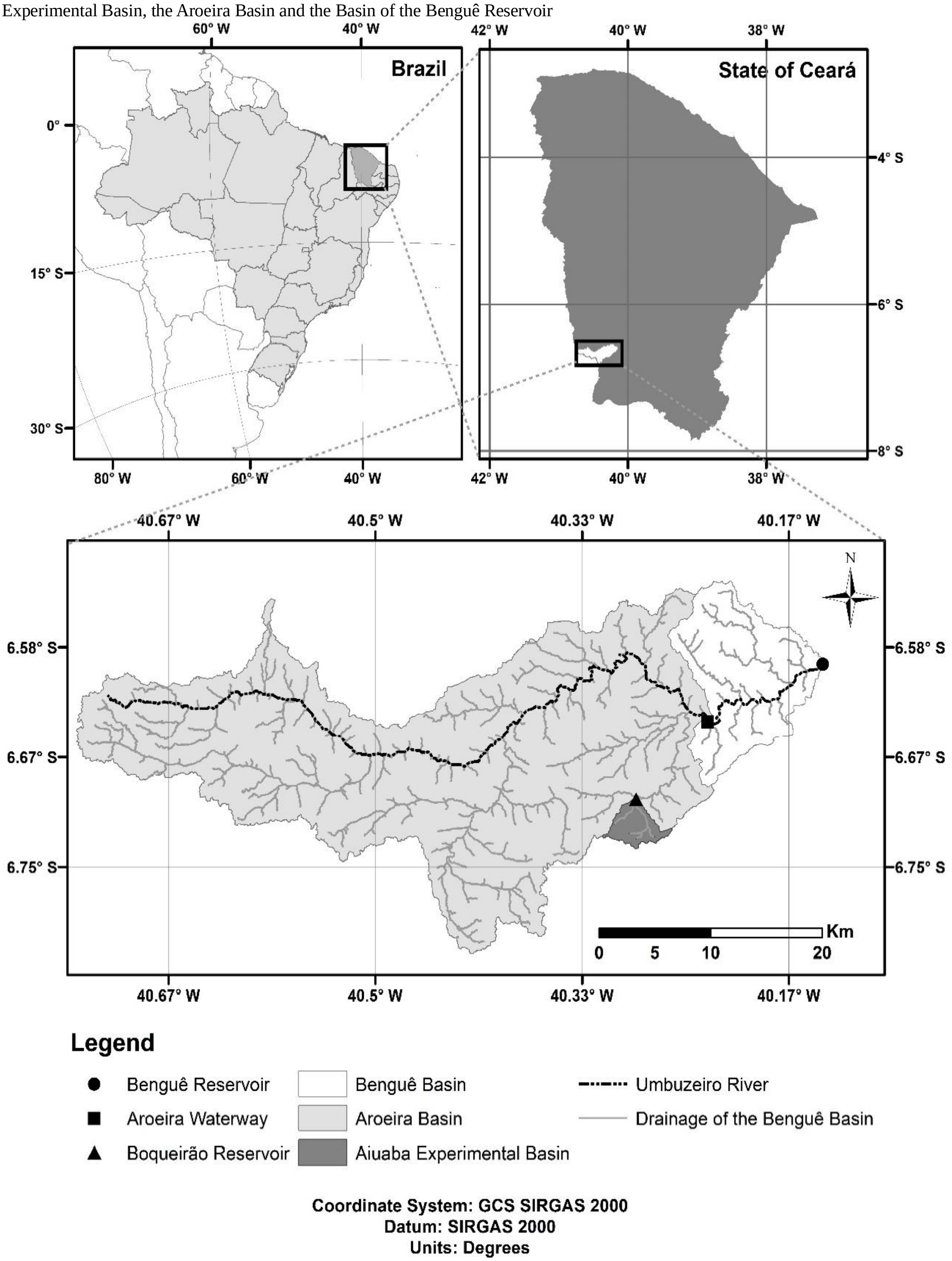
Study Area

This research was carried out in the Umbuzeiro River (78 km) Basin, in the semi-arid region of Ceará, fully inserted in the Caatinga biome. We examined three nested basins: the Benguê Basin (933 km^2), which contains the Aroeira Basin (800 km^2) and the Aiuaba Experimental Basin (AEB, 12 km^2) (Figure 1). Surveys of nested basins use at least two spatial scales, so as to draw more-robust conclusions (GRIFFITHS; WALES, 2019). The difference in scales, therefore, contributes to an understanding of the hydrological behaviour of the basins and their connectivity. The hydrographic basin of the Umbuzeiro River is inserted in the Upper Jaguaribe Basin. The Benguê Reservoir (18 hm³), which dams the Umbuzeiro River, was built in 2000 to supply part of the district of Aiuaba. The Water Resources Management Company of Ceará (COGERH) has been monitoring the Benguê Dam since its construction, with the data available on the Ceará hydrological website since 2004. The outlet from the Aroeira Basin is also a section of the Umbuzeiro River, located 3 km upstream of the Benguê Reservoir. The outlet from the Aroeira Basin comprises a control section (waterway) with a well-established key curve (flow depth versus net flow), monitored daily since 2011. The section, which also has a rain gauge, is relevant to this study as the flow occurring in the river can be measured directly, while in the two other basins flow occurs indirectly by means of the water balance. Hydrological and sedimentological variables in the Aiuaba Experimental Basin (AEB) have been monitored since January 2003. The AEB is located entirely within the Aiuaba Ecological Station (ESEC) and is controlled by the Boqueirão Reservoir, with a capacity of 60,000 m^3 (MEDEIROS *et al*., 2014).

Measuring intermittence and accumulated volume dynamics in the reservoirs

In the Benguê Basin, flows are evaluated by means of the water balance. From the daily data for the level of the Benguê Reservoir (2004 to 2020) and knowing: (i) the morphology of the reservoir, (ii) the rates of evaporation

Figure 1 - Location of the Umbuzeiro River Basin, which contains the three nested basins, the objects of this research: the Aiuaba Experimental Basin, the Aroeira Basin and the Basin of the Benguê Reservoir



(measured in a class A pan at the AEB, therefore, in the basin itself), (iii) the derived flow of the reservoir, and (iv) the spill, we can estimate the flow added to the reservoir by the river. In the Aroeira Basin, the flow is measured directly in the control section (coinciding with the outlet) using its rating curve (ARAÚJO *et al*., 2017). The measurements were carried out from 2011 to 2020, with eventual breaks during 2013, 2014 and 2017. In the Aiuaba Experimental Basin, the flow in the river was estimated using the water balance of the Boqueirão Reservoir (FIGUEIREDO *et al*., 2016) from 2005 to 2014. In this study, the number of days with flow is considered a metric of river intermittence, since zero flow predominates in the rivers of the study area, which allows the days without flow to be assessed (COSTIGAN *et al*., 2017). For the purpose of comparing the responses for flow and water input during dry years, these will be considered years having a value for rainfall depth lower than the difference between the mean and half the standard deviation for the period under consideration (2004 to 2020). The WASA model gives the daily flow in the principal rivers of the basin as the output, allowing this to be compared with the measured data. To validate the model, two variables are analysed: the number of days with flow in the main river, which indicates the degree of intermittence in the basin; and the volume of the Benguê and Boqueirão Reservoirs, which indicates the degree of flow in the rivers of the basin.

Simulating the intermittence and water input of the reservoirs

When modelling the Umbuzeiro River Basin, the study area is divided into 30 sub-basins which, in turn, are divided into homogeneous landscape units, in which the pedological, topographical and vegetational characteristics are identified (GÜNTNER; BRONSTERT, 2004). We used available information to proceed with the parameterisation: Güntner and Bronstert (2004) parameterised the WASA model for the entire state of Ceará; Creutzfeldt (2006) characterised the vegetation and the use and occupation of the land in the Basin of the Benguê Reservoir; and Medeiros *et al*. (2010) presented a more detailed parameterisation of the WASA model than that of Güntner and Bronstert (2004) for the Umbuzeiro River Basin. Furthermore, Medeiros *et al*. (2010) and Mamede *et al*. (2018) analysed the parameterisation of the basin, but focused on flow generation and water-stock dynamics in the reservoirs, without considering the intermittence of the rivers. Additionally, the study by Figueiredo *et al.* (2016) presents 179 values for saturated hydraulic conductivity, measured in the Aiuaba Experimental Basin and which are used for refining the parameterisation. Due to the scarcity of data, Güntner and Bronstert (2004) used pedotransfer functions to characterise the soils of Ceará. These authors used the equation proposed by Tomasella and Hodnett (1997) to obtain the saturated hydraulic conductivity ($mm.h^{-1}$). The values for saturated conductivity they obtained were high, greater than 180 $mm.h^{-1}$ in the surface layer of the soils in the Benguê Basin, seen as class 1 permeability (> 60 $mm.h^{-1}$) (HAAN; BARFIELD; HAYES, 1994). To compensate for the reduction in rainfall intensity due to daily rainfall measurements, Güntner and Bronstert (2004) adjusted one scale parameter. Medeiros *et al.* (2010) excluded the adjustment parameter, using the Rosetta model (SCHAAP; LEIJ; VAN GENUCHTEN, 2001) to estimate the hydraulic properties of the soil.

Of the 30 sub-basins into which the Benguê Basin was divided, 11 have a reservoir at their outlet (MAMEDE *et al*., 2018). The daily flow rate is calculated in the model for each sub-basin. Climate data were obtained from the Ceará Meteorology and Water Resources Foundation (FUNCEME) for the period from 2004 to 2020; records of the water volume in the Benguê Reservoir were made available by COGERH, again for the period from 2004 to 2020. The primary data from the AEB are rainfall and the water-stock dynamics of the Boqueirão Reservoir (2005-2014). The primary data for the Aroeira Basin are the outlet flow and the rainfall at the site (2011-2020).

The water flow was simulated for the entire Umbuzeiro River Basin over 6,149 days between 2004 and 2020. The AEB was analysed from 2005 to 2014, and the Aroeira Basin from 2011 to 2020 (the years for which measured data are available). The analysed parameters were 'Ksat1' - saturated hydraulic conductivity of the soil on the riverbed, 'Ksat2' - saturated hydraulic conductivity of the soil on the slopes, 'Kfsu' - saturated hydraulic conductivity of the crystalline basement, 'Kf' - adjustment parameter for daily to sub-daily rainfall, and 'Hs' - the soil depth that contributes to subsurface flow. The parameters of conductivity were chosen as they express water infiltration in the soil profile. The Kf parameter is sensitive, and compensates for the effect of the reduction in rainfall due to the daily steps of the simulation, allowing the Hortonian flow to be more-accurately calculated on a daily scale (MAMEDE *et al*., 2018; MEDEIROS *et al*., 2010). The Hs parameter was chosen to verify the response of the model in generating flow by modifying the depth of soil that contributes to the surface runoff. In the simulations, the rainfall data were taken from the daily rainfall. The values for Ksat1 were applied across the entire Benguê Basin. Ksat2 values were applied in Simulation 6 for all the soils in the basin, and in Simulation 7 for the Luvissol and Red-Yellow Argisol only. The hydraulic conductivity of the soil in the experimental basin (Table 1) was analysed using an amoozimeter (FIGUEIREDO *et al*., 2016).

Figure 2 - Division of the Benguê Basin into 30 sub-basins, highlighting the outlets of the sub-basins of the Benguê Reservoir, the Aroeira Basin and the Aiuaba Experimental Basin (AEB)

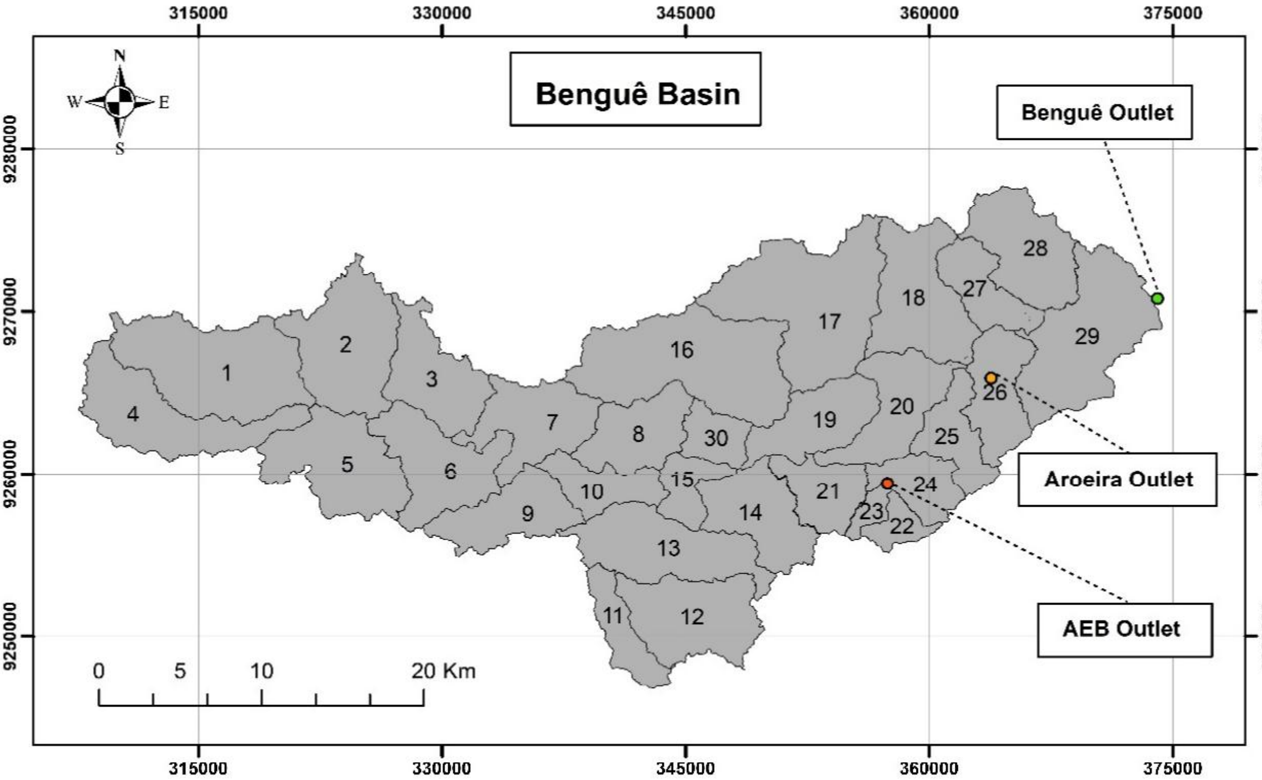


Table 1 - Characteristics of the parameterisation phases for five parameters of the WASA model: Ksat1 (saturated hydraulic conductivity of the soil on the riverbed – $mm.h^{-1}$), Ksat2 (saturated hydraulic conductivity of the soil on the slopes – $mm.d^{-1}$), Kfsu (saturated hydraulic conductivity of the crystalline basement – $mm.d^{-1}$), Kf (daily rainfall adjustment parameter for sub-daily rainfall), and Hs (depth of soil that contributes to subsurface flow - mm)

n	Parameter				
	Ksat1[1]	Kf	Hs	Ksat2[2]	Kfsu
1	1000	122.6	100	Rosetta	10.0
2	7	122.6	100	Rosetta	10.0
3	7	1.0	100	Rosetta	10.0
4	7	1.0	1000	Rosetta	10.0
5	7	1.0	10	Rosetta	10.0
6	7	1.0	100	Amoozimeter[3]	10.0
7	7	1.0	100	Amoozimeter[4]	10.0
8	7	1.0	100	Rosetta	0.1
9	7	1.0	100	Rosetta	0.01
10	7	40.0	100	Rosetta	10.0
11	7	70.0	100	Rosetta	10.0

[1] Saturated hydraulic conductivity of the soil in the riverbed ranging from 1000 $mm.h^{-1}$ to 7 $mm.h^{-1}$, with 1000 $mm.h^{-1}$ being the value used by Medeiros *et al.*, (2010) and 7 $mm.h^{-1}$ the mean value obtained in the field by Figueiredo *et al.* (2016). **[2]** Saturated hydraulic conductivity of the soil on the slopes obtained by either the Rosetta model or amoozimeter. **[3]** Mean value for ksat2 obtained by amoozimeter (FIGUEIREDO *et al.*, 2016) applied to all the soils in the Benguê Basin. **[4]** Mean value for ksat2 obtained by amoozimeter applied to the Luvissol and Red-Yellow Argisol, which were the soils analysed in the basin (FIGUEIREDO *et al.*, 2016)

The validation procedures were applied in the sub-basins, comparing the days with observed flow to the days with flow simulated by the WASA model. To assess the validity of the model, the Nash-Sutcliffe statistical coefficient (NSE) was used as an objective function, a metric widely used in hydrological models (FELIX; PAZ, 2016; MAMEDE *et al*., 2018; PINHEIRO *et al*., 2016; YU *et al*., 2018).

RESULTS AND DISCUSSION

Measuring intermittence and accumulated volume dynamics in the reservoirs

In 2011, a year with above-average rainfall (708 mm), the Benguê and Boqueirão Reservoirs reached their maximum capacity, 18 hm^3 and 0.57 hm^3, respectively. During the following years, characterised by multi-annual drought (2012-2017), the water stock of the reservoirs reduced to zero in the Boqueirão Reservoir and 2.5 hm^3 in the Benguê Reservoir, with a respective reduction of 100% and 86% compared to the volume reached in 2011 (Table 2). It can also be seen that, due to being a smaller reservoir (0.57 hm^3) than the Benguê Reservoir (18 hm^3), Boqueirão dries up almost every year. In approximately 90% of the analysed data, the minimum water stock of the Boqueirão Reservoir was less than the dead volume (10% of maximum capacity), which can be explained by its open morphology and the high losses to evaporation in the region, which exceed the rainfall by three to five times (KROL *et al*., 2011).

The outlets of the Benguê and Aroeira Basins are in the same river (Umbuzeiro) and are close to each other (3 km). It should be noted that in the control section of the Aroeira Basin, days with flow are evaluated by direct measurement in the field, while in the Benguê Basin this is achieved by means of the water balance in the reservoir. It can be seen that for dry years, there is relative disparity in the number of days with flow in the two basins, while for rainy years the similarity is greater, with the exception of 2020 (Table 2). From 2012 to 2017, which were dry years, the number of days with flow in the Benguê section ranged from 7 to 21, while in the Aroeira section this number ranged from 8 to 29 (Table 2). It was expected that, due to the proximity of the sections, the number of days with flow in both sections would be more similar. One explanation for this difference is that during dry years, small streams gain importance in generating flow due to localised convective rainfall (MORIN; YAKIR, 2014). In addition, losses during transit are more important in

Table 2 - Annual measured data: minimum and maximum volumes of the reservoirs; number of days with flow and number of accumulated days with flow in the Benguê (Beng), Aroeira (Aro) and AEB Basins. A dash indicates no measured data; NC means measured data that was not considered due to being outside the period of analysis. Outflow weir height: Benguê (20.1 m), Boqueirão (4.5 m). Average annual rainfall in the district of Aiuaba – 568.3 mm, highlighting (*) the rainfall during the multiannual drought

Year	Minimum volume of the reservoir (1000 m^3)		Maximum volume of the reservoir (1000 m^3)		Number of days with no flow			Number of days with outflow		Average rainfall (mm)
	Beng	AEB	Beng	AEB	Beng	Aro	AEB	Beng	AEB	Aiuaba
2004	1330 (74%)	-	18000 (100%)	59.7 (100%)	42	-	NC	4	114	879
2005	9510 (53%)	6.71 (11%)	12800 (71%)	49.29 (82%)	13	-	5	0	0	550
2006	7110 (39%)	0 (0%)	9510 (53%)	15.10 (25%)	27	-	3	0	0	486
2007	7000 (39%)	2.18 (4%)	11980 (67%)	28.04 (47%)	33	-	8	0	0	655
2008	8080 (45%)	1.67 (3%)	17800 (99%)	37.77 (63%)	29	-	6	0	0	486
2009	12430 (69%)	0 (0%)	18000 (100%)	10.70 (18%)	98	-	5	60	0	631
2010	10670 (59%)	0 (0%)	14100 (78%)	50.9 (85%)	31	-	4	0	0	671
2011	10650 (59%)	0.89 (1%)	18000 (100%)	59.7 (100%)	100	99	4	93	89	708
2012	9100 (51%)	0 (0%)	13510 (75%)	20.90 (35%)	16	19	1	0	0	359*
2013	5310 (29%)	0 (0%)	9120 (51%)	2.82 (5%)	17	-	4	0	0	350*
2014	3050 (17%)	0 (0%)	5930 (33%)	21.86 (37%)	21	-	2	0	0	380*
2015	2790 (15%)	-	5530 (31%)	-	14	29	-	0	NC	424*
2016	2680 (15%)	-	5460 (30%)	-	21	8	-	0	NC	394*
2017	2510 (14%)	NC	4370 (24%)	NC	7	-	NC	0	NC	419*
2018	1340 (59%)	-	2590 (14%)	-	17	15	-	0	NC	578
2019	1020 (6%)	NC	2650 (15%)	-	27	33	-	0	NC	509
2020	1620 (9%)	NC	10280 (57%)	NC	47	76	NC	0	NC	770

dry years, altering the flow between the two sections (DATRY *et al*., 2018). In contrast, for years with above-average rainfall, as in 2011, the number of days with flow was practically the same in both sections (100 days for Benguê and 99 for Aroeira). The reason is that the greatest hydraulic conductor in this case is the Umbuzeiro River, for which the relative losses during transit are smaller, given the high flow in the river channel (DATRY *et al*., 2016).

Messager *et al*. (2021) correctly identified that rivers in the semi-arid region of Brazil are not perennial. However, these authors identified a predominance of intermittent rivers whereas, according to metrics available in the literature, the data point to a prevalence of ephemeral rivers, (COSTIGAN *et al*., 2017; DATRY; LARNED; TOCKNER, 2014). Annual data measured on the scales of the three basins show the high frequency of zero flow. Flow only occurs during the rainy season with negligible baseflow on the working scales of the present research, as observed by Figueiredo *et al*. (2016) and by Sousa *et al*. (2022).

Simulating the intermittence and water input of the reservoirs

The difficulty of adequately representing the number of days with flow on the three spatial scales simultaneously can be seen (Table 3). Among the 11 simulations, no parameterisation was able to satisfactorily simulate (observing the NSE statistical parameter) intermittence on the three spatial scales. It is believed that this difficulty is related to the different hydrological scales. Srinivasan *et al*. (2021) state that the size, land use and surface cover of hydrographic basins play a significant role in generating flow, affecting the response of the basins and model simulations.

For example, for the AEB (the smallest basin), the NSE was positive for two parameterisations only. It can be seen that the simulations do not well represent the flow (visible in the volume dynamics of the reservoirs) and the intermittence of the rivers simultaneously. Additionally, new parameterisations improve the performance of one variable, but worsen that of the other. Only when the values for the hydraulic conductivity of the crystalline basement were changed, did the number of accumulated days with flow to the AEB show a positive NSE. This confirms the findings of Figueiredo *et al*. (2016), who say that the saturated hydraulic conductivity represents a key parameter in analysing the infiltration, and, consequently, in evaluating surface runoff. The model gave a good representation of the intermittence of the rivers for the two largest basins in Parameterisation 2 only, which considers the adjustment parameter for rainfall intensity (MAMEDE *et al*., 2018); in the three simulations in which an NSE > 0.5 was obtained for the Benguê and Aroeira basins, the Kf parameter is greater than 1.

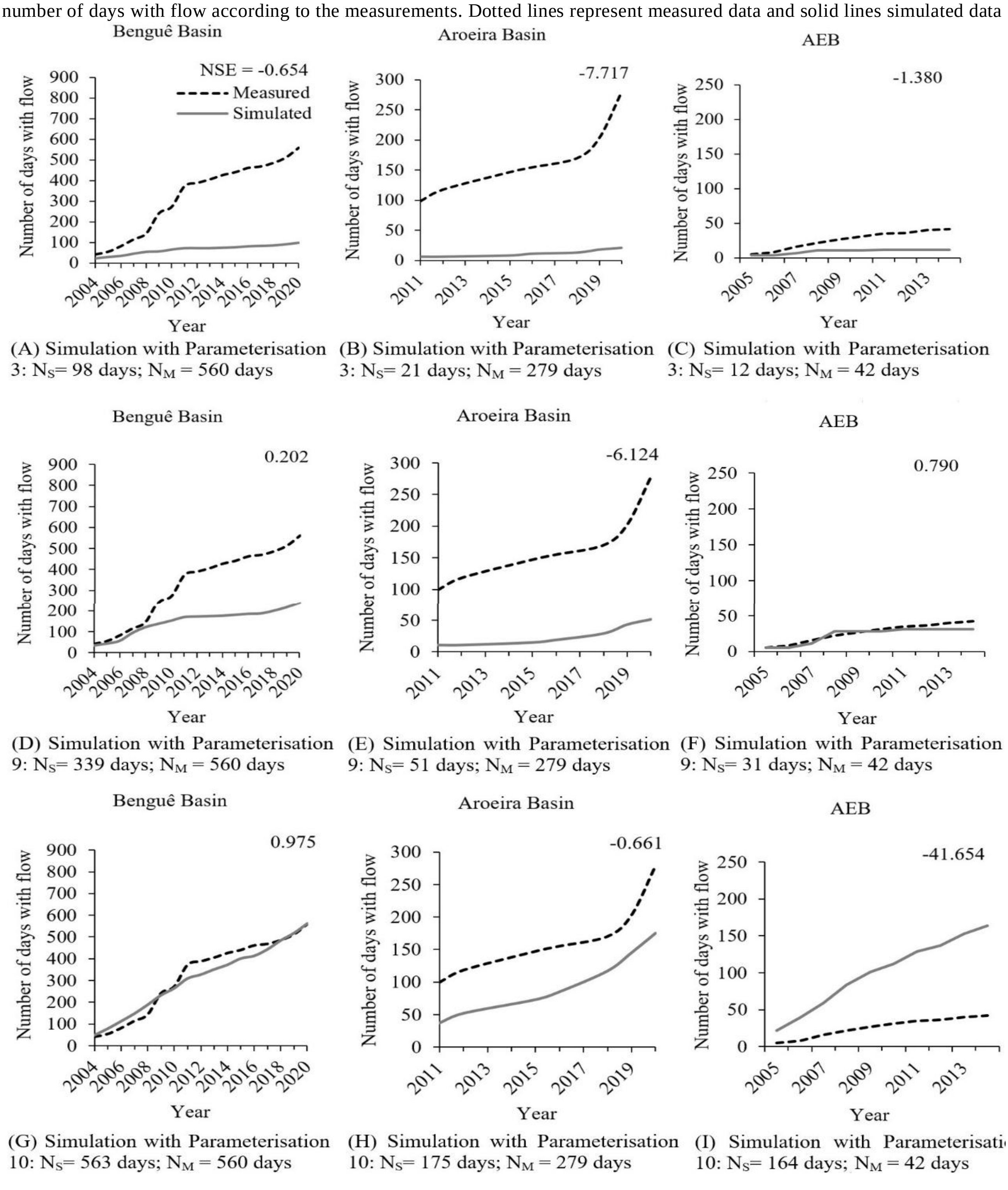
Parameterisation 3 (saturated hydraulic conductivity of the river equal to the measured value, and the Kf parameter equal to 1) stands out due to the excellent performance of the model for the Benguê Basin. Parameterisation 7 generated satisfactory model performance for the input to the Boqueirão Basin due to applying measured data to two soils in the basin. Figueiredo *et al*. (2016) carried out a soil conductivity analysis in the AEB, a basin of the Boqueirão Reservoir, and from this it is believed that the application of measured data favoured the response of the model to the water input of the reservoir of the basin under analysis. The simulation with Parameterisation 10 came the closest to the intermittence of the Benguê Basin during the period of analysis, differing by just three days.

Table 3 - Performance of the WASA model for the volume dynamics of the reservoirs (a function of the water input of the rivers) and for the annual number of days with flow (intermittence indicator). NSE coefficients with a positive value are highlighted in bold

n	NSE volume reservoirs		NSE days with flow			Days with flow (modelled)		
	Benguê	Boqueirão	Benguê	Aroeira	AEB	Benguê	Aroeira	AEB
1	0.44	-0.56	-0.77	-9.15	-3.36	96	0	4
2	-2.72	-4.49	0.66	0.60	-109.83	811	259	241
3	0.92	-0.07	-0.65	-7.72	-1.38	98	21	12
4	0.92	-0.07	-0.66	-7.72	-1.38	97	21	12
5	0.92	-0.07	-0.67	-7.72	-1.38	96	21	12
6	0.04	0.38	-0.29	-6.85	-0.70	157	37	16
7	0.67	0.36	-0.60	-7.72	-0.70	104	21	16
8	0.38	-0.01	0.17	-6.22	0.79	232	50	31
9	0.34	0.10	0.20	-6.12	0.79	239	51	31
10	-2.52	-3.99	0.97	-0.66	-41.65	563	175	164
11	-2.64	-4.21	0.94	0.19	-68.76	670	220	200

Figure 3 represents the accumulated days with flow during the period of analysis, it shows three of the best parameterisations (3, 9 and 10). In Parameterisation 3, a change can be seen in the value of the Kf rainfall parameter, which did not achieve satisfactory performance for the flow of any of the three basins under analysis. A Kf value greater

Figure 3 - Number of measured days (accumulated) with flow for the period of analysis in the Benguê Basin (2004-2020), in the Aroeira basin (2011-2020, except for 2013, 2014 and 2017), and in the Aiuaba Experimental Basin – AEB (2005-2014). The Nash-Sutcliffe statistical coefficients (NSE) are shown. N_S = number of days with flow according to the simulations. N_M = number of days with flow according to the measurements. Dotted lines represent measured data and solid lines simulated data



than one (1) (the case of parameterisations 9 and 10) allows better representation of the temporal variability of the rainfall (high intensity) in the semi-arid region (CIRILO *et al*., 2020). These authors emphasise the importance of establishing procedures in order to consider the rainfall pattern in the design of rainfall-flow models in semi-arid regions. In turn, Parameterisation 9 showed satisfactory statistical performance for the AEB: the number of accumulated days with flow for the period of analysis was 31 days, compared to 42 when measured. The simulation with Parameterisation 10 gave a good representation of the intermittence of the Benguê Basin. In this parameterisation, 563 days with flow were simulated, a value close to the 560 days with flow that were measured.

In the parameterisations that were carried out, the intermittence in the three basins (represented by the number of accumulated days with flow), showed that the most sensitive parameter was the saturated hydraulic conductivity (Table 3). The adjustment factor for rainfall intensity (Kf) had to be used for the simulated intermittence to approach the data measured in the largest basins. Use of the adjustment parameter corroborates the proposals by Güntner and Bronstert (2004) and by Mamede *et al*. (2018), which aim to adapt the model to represent a primarily Hortonian flow in the basin. It can be seen that the parameters that most influenced the number of days with flow are those that are directly involved with saturated hydraulic conductivity.

Figure 4 - Daily rainfall, and measured and modelled daily flow in the Benguê Basin (2004-2020), in the Aroeira basin (2011-2020, except for 2013, 2014 and 2017), and in the Aiuaba Experimental Basin – AEB (2005-2014)

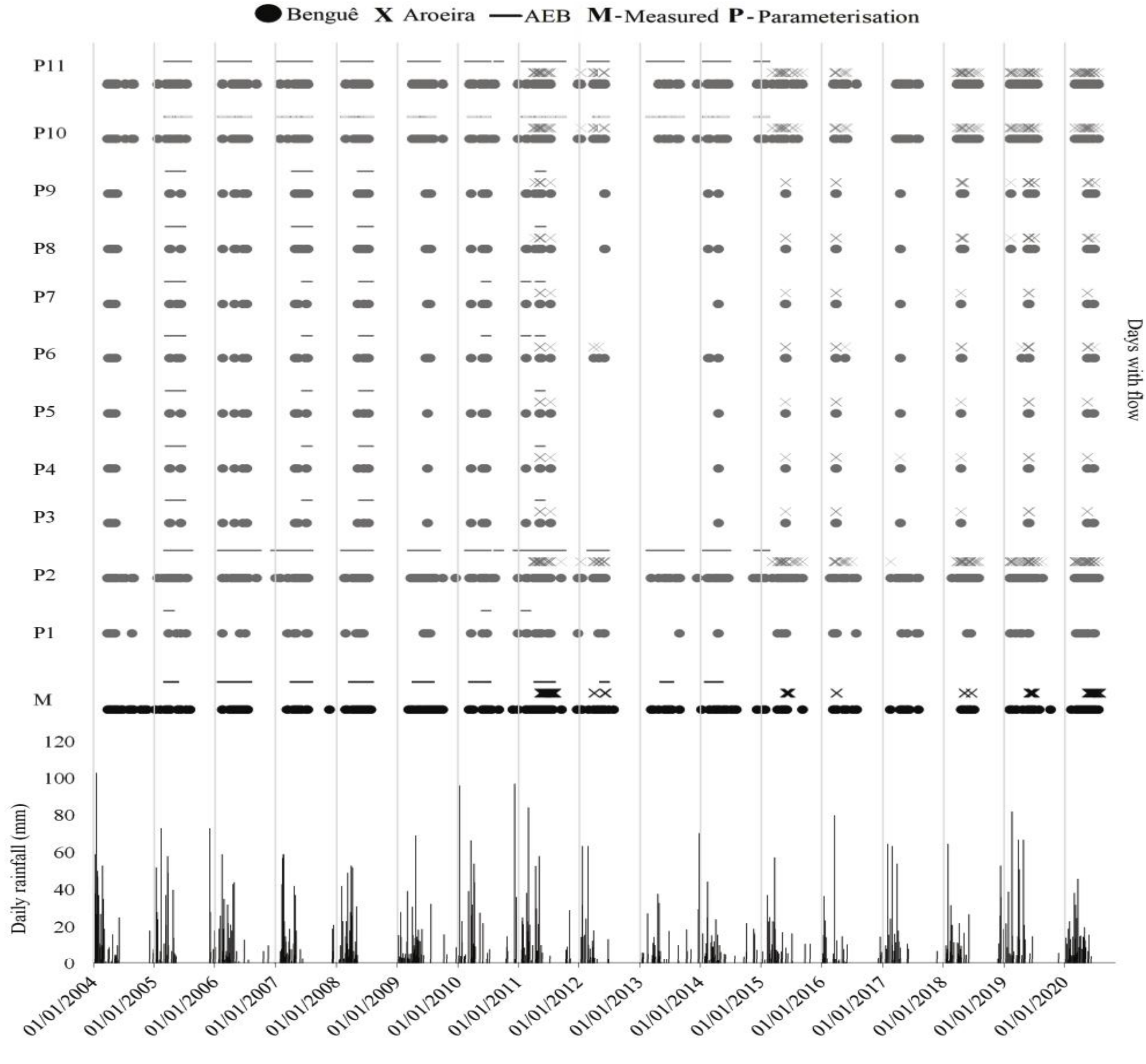
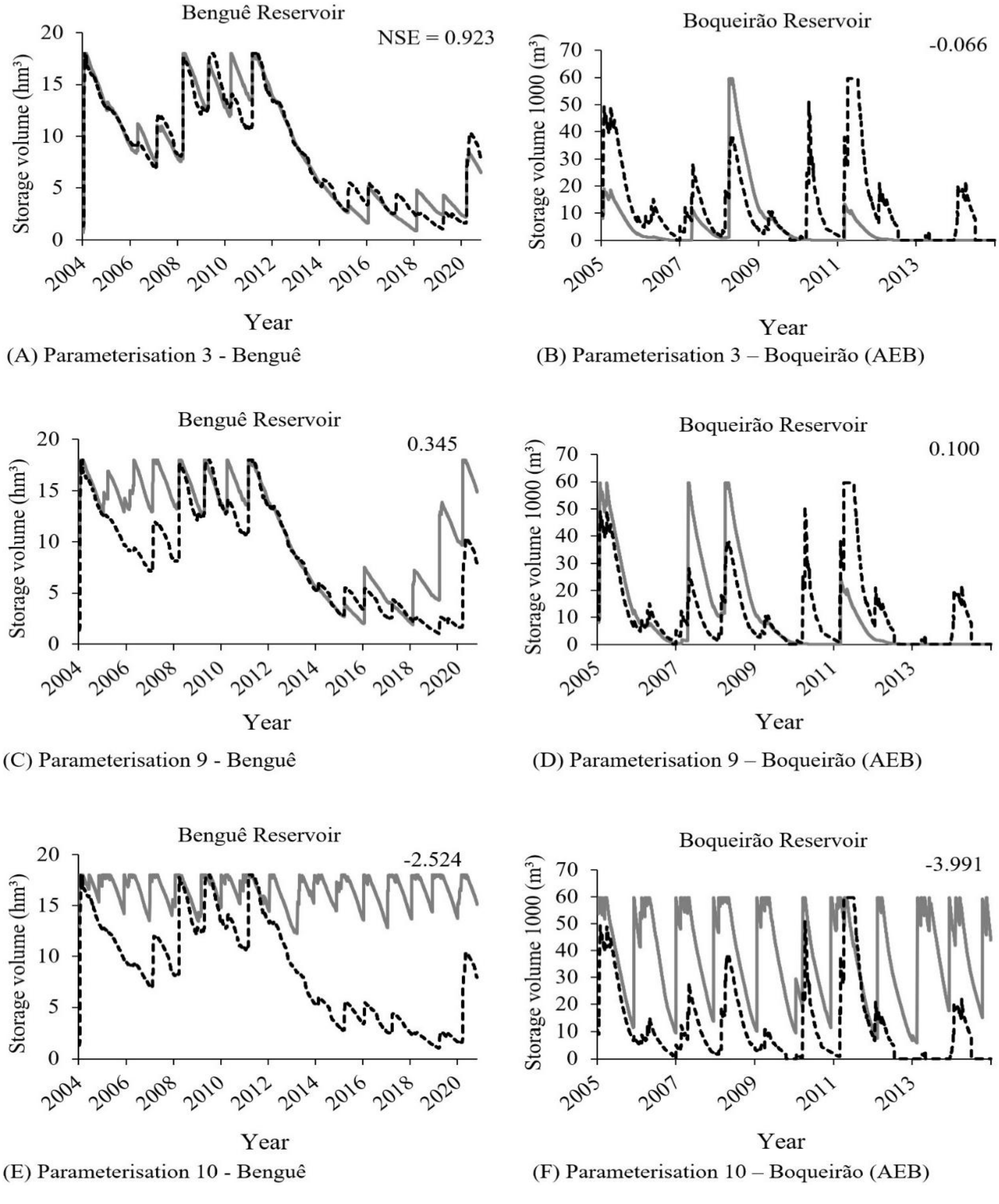


Figure 4 shows the days with measured flow and the flow from the eleven simulations during the period of analysis in the three basins; the daily rainfall distributed in the basin can also be seen.

Figure 4 shows the direct association between rainfall and flow, snce in the basin the baseflow is negligible. For the Benguê Basin, the best representations of measured flow occurred in parameterisations where

Figure 5 - Measured and modelled volumes for the simulation periods in the Benguê (2004-2020) and Boqueirão (located at AEB, 2005-2014) reservoirs. The Nash-Sutcliffe statistical coefficients (NSE) for the volume dynamics of the reservoirs are also shown



the rainfall adjustment parameter Kf was greater than 1 (P2, P10 and P11), highlighting the importance of the parameter (GÜNTNER; BRONSTERT, 2004; MAMEDE *et al*., 2018). In the Aroeira section, the data show flows on days that are closer to each other, while in the simulations the temporal spacing is greater; in this basin, the best performance was obtained with Parameterisation 2, applying a Kf of 122.6, with 259 simulated and 279 measured days. For the AEB, the best parameterisations for the number of accumulated days with flow were P8 and P9, in which we applied data for the hydraulic conductivity of the crystalline basement close to the reference values for the state, resulting in 31 days of simulated flow compared to the 42 days that were measured. From this, it can be seen that for the basins with a larger catchment area, the number of accumulated days with flow was only reached after the application of a rainfall adjustment parameter. For the smaller basin, the number of days with flow approached the value observed in the field after applying the hydraulic conductivity of the crystalline basement calculated for the state of Ceará (GÜNTNER; BRONSTERT, 2004). In general, evaluating the three basins in the 11 simulations, the simulation with Parameterisation 10 was considered the best to represent intermittence, i.e. the number of days with flow, since it came closest to the values measured during the period of analysis.

Figure 5 shows the response of the models in terms of the volume dynamics of the reservoirs in the three above-mentioned parameterisations.

It can be seen from Figure 5A that the Benguê reservoir (NSE = 0.923) was well represented by the model in relation to water stock in Parameterisation 3, with Kf equal to 1 and the saturated hydraulic conductivity of the river equal to that measured by Figueiredo *et al*. (2016). However, the volume of the Boqueirão Reservoir was not well represented in Parameterisation 9, although the inermittence was adequately portrayed (Figure 4-F). In Parameterisation 10, the model generated a large water input for both reservoirs due to the increase in the value of Kf (Figures 5-E and 5-F).

In research modelling the volume of the Benguê Reservoir, good performances have been obtained from the WASA model (MAMEDE *et al*., 2018; MEDEIROS *et al*., 2010). Representing the volumes of reservoirs of different scales in a single parameterisation is not a simple task, which indicates the complexity of dealing with the question of scale in Hydrology. Medeiros *et al*. (2010) found that the performance of the WASA model in representing the volume dynamics of the Benguê Reservoir was superior to that for the Boqueirão Reservoir, whose catchment area is smaller. Mendiondo and Tucci (1997) also noted the difficulty in representing hydrological processes on different spatial scales. In this study, it could be seen that, among the simulations carried out, generating a better performance for the simulated volume of the Boqueirão Reservoir resulted in a worsening of the performance in relation to the volume dynamics of the Benguê Reservoir. It was also seen that for most of the simulations the performance was worse for the hydraulic modelling of the reservoirs during years of drought, suggesting that the model has difficulties in modelling flow under summer conditions. Medeiros *et al*. (2010) managed a good representation of the water input and, therefore, the volume dynamics of the Boqueirão and Benguê Reservoirs in some of their parameterisations; however, the authors used a shorter period of analysis. In applying the WASA model to the Alto Jaguaribe Basin, Malveira, Araújo and Güntner (2012) obtained different performances for different spatial scales, suggesting the possibility of the model not always giving a good representation of the volume of the reservoirs on different scales.

CONCLUSIONS

1. We were unsuccessful in simultaneously representing the intermittence and water input of the reservoirs of the Umbuzeiro River on the three spatial scales using the WASA model. Despite this, the two dependent hydrological variables (intermittence and water input to the reservoirs) were well represented on the three scales, albeit not simultaneously;
2. The parameterisations that used field data improved the simulated results, demonstrating the physical robustness of the WASA model to simultaneously simulate the flow and intermittence of the rivers;
3. The physical WASA model shows high sensitivity to the parameters of saturated hydraulic conductivity and the adjustment parameter for rainfall intensity for both the intermittence and the water input of the reservoirs. This corroborates the fact that Hortonian flow prevails in the basin, as these parameters have a direct influence on the two variables of this process, namely, infiltration and rainfall intensity.

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