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Article

Hydrological guidelines for reservoir operation: application to the Brazilian Semiarid region

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Abstract: The Brazilian water legislation advocates that some uses have priority over others, but this aspect has never been clearly addressed, generating conflicts. Water authorities usually refer to hydrological models to justify their decisions on water allocation. However, a significant group of stakeholders does not feel qualified to discuss these models and is, therefore, excluded from the decision process. We hereby propose a hydrologically robust method to correlate water uses with their respective reservoir alert volumes, which should empower the less formally educated stakeholders. The method consists of: (i) generating the water discharge versus reliability curve, using a stochastic approach; (ii) generating the withdrawal discharge versus alert volume family of curves, using a water-balance approach; (iii) calibrating the key parameter T using field data; and (iv) associating each water use with its alert volume. We have applied the method to four of the largest reservoirs (2.10^3 - 2.10^2 hm^3) in the semi-arid Ceará State. The results indicate that low-priority water uses should be rationalized when the reservoir volume is below 20%; whereas uses with very high priority should start rationalization when it is below 11%. These hydrological guidelines should help enhance water governance among non-specialist stakeholders in water-scarce and reservoir-dependent regions.

Keywords: reservoirs; water allocation; water scarcity; alert volume; governance.

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1. Introduction

The Northeast of Brazil, where the semiarid Caatinga biome prevails, is home to 25 million inhabitants with high water demand. Its rivers, however, are intermittent and groundwater is limited and often salty [1]. To cope with the frequent and severe droughts, the water-supply policy strongly relies on artificial surface reservoirs [2-3], whose eventually-poor management may negatively affect the most vulnerable fraction of the population [4]. During the recurrent water-scarce periods, when societal conflicts arise, efficient operation rules for multiple uses – a requisite for efficient reservoir water allocation – become a great challenge [5-8]. The Brazilian respective water legislation [9] advocates that under scarcity some uses (e.g., human and animal provision) should be prioritized. Although the law is over two decades old, a clear supply prioritization has not yet taken place, and this generates serious conflicts among water users. In 2012, for example, there was the onset of a severe multi-annual drought in the semiarid State of Ceará [10]. During the second year of drought, the irrigation users stopped receiving water from the reservoirs not only for production, but also to maintain trees alive. Contrastingly, industrial users have been uninterruptedly supplied up to the moment [11]. The priority criteria used for these decisions were not clearly justified.

In Brazil, water allocation is a participatory process coordinated by River Basin Committees, which are composed by stakeholders among public authorities, civil society and water users. During water-scarcity periods, the Water Agency is allowed to restrain supply, either partially or totally. In these periods, authorities usually justify their decisions citing the results of operational hydrological

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models. Reservoir operation rules are commonly based on hydrological available information [6] of long-term water storage and are lengthily maintained as once defined [12-13]. Several water allocation models have been developed in the last decades, e.g., AQUATOOL [14], ACQUANET [15], RIVERWARE [16], MODSIM [17], and ILMP [18]. However, among the committee members, there is a significant group that does not feel qualified to discuss such models and, therefore, is excluded from the decision process. Technocracy then defeats democracy, with biased losses for the peasants, who are poorer and less formally educated. They are, nevertheless, able to interpret the degree of water availability – especially during droughts – using the stored water volume in the reservoirs [19]. Thus, in order to guarantee proper governance of water allocation, guidelines based on the reservoir volume, which can be understood by all stakeholders, are certainly preferable to technocratic strategies. We hereby aim at proposing a hydrologically robust method that produces simple outputs, which correlate each water use with its respective alert volume. In this context, the alert volume is the stored volume that triggers water rationalization due to quantitative shortage. The four-step method, which uses the reservoir volume as the key variable, considers water balance in the reservoir, climate and hydrological variability, morphological features of the reservoir and historically released discharges. We have applied the method to four of the largest reservoirs (2 10^2 - 2 10^3 hm^3) of the State of Ceará.

2. Materials and Methods

2.1. Study area

The method was applied to four reservoirs, all located in the Caatinga biome (Figure 1), where annual rainfall is moderate (500 – 850 mm.yr-1), potential evaporation is high (2,000 – 2,600 mm.yr-1), groundwater is limited and salty due to a prevailing crystalline basement, rivers are intermittent, runoff is low (10 – 70 mm.yr-1) and droughts are recurrent [10]. The rainy season (January to June) encompasses almost 90% of the annual rainfall and almost 100% of the runoff, whereas the reservoirs suffer depletion in the long dry season (July to December), sometimes drying out completely [20]. The natural hydrological system constantly fails to provide enough water for that densely populated environment, which called for the construction of a reservoir-based water system [2-3]. Due to the considerable meteorological inter– and intra–annual variability, to the high number of reservoirs (one dam every 5 km^2 on average), and to the high residence time of the waters within the reservoirs (which causes low levels of water quality [21]), the Caatinga biome has become a challenging biome for water management [22]. Usually, River Basin Committees decide on water release shortly after the rainy season, the key information being the stored reservoir volume. The committee stakeholders use their empirical knowledge to adjust their demands to the operational water availability, taking into consideration the risk of water scarcity in the coming years. The main hydrological features of the focus reservoirs (Orós, Araras, Pentecoste, and Aracoiaba) are presented in Table 1.

Table 1. Main variables of the four focus reservoirs. Each field data represents a pair, composed of the measured released discharge and the respective reservoir volume on the same day.

Variables	Orós	Araras	Pentecoste	Aracoiaba	Average
Storage capacity (hm^3)	1,940	891	360	162	838
Catchment area (km^2)	24,600	3,520	2,840	533	7,873
Annual rainfall (mm)	529	759	702	828	575[3]
Average inflow ($hm^3.yr^{-1}$)	1,505	608	183	68	1261[3]
Storage capacity/average inflow (yr)	1.29	1.47	1.97	2.38	1.39[3]
Coefficient of variation of inflow (-)	0.9	1.2	1.0	0.6	0.9[3]
Q_{90}/average inflow (-)[1]	0.43	0.38	0.35	0.76	0.42[3]

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Field data sample size	250	147	135	26	140
Field data sampling period (years)	22	20	19	14	19
First sampling year	1996	1996	1996	2003	(-)
Last sampling year	2017	2015	2014	2016	(-)
Optimal drying duration T (months)[2]	5.7	6.0	5.8	6.0	5.9
Number of outliers for T = 6 months	1	0	1	0	(-)

[1] Q_{90} = water yield with 90% annual reliability; [2] obtained by solving Equation (7), assuming that the parameters $Q_i = 0$; and $V_f = 0$; [3] average weighted with respect to the catchment area.

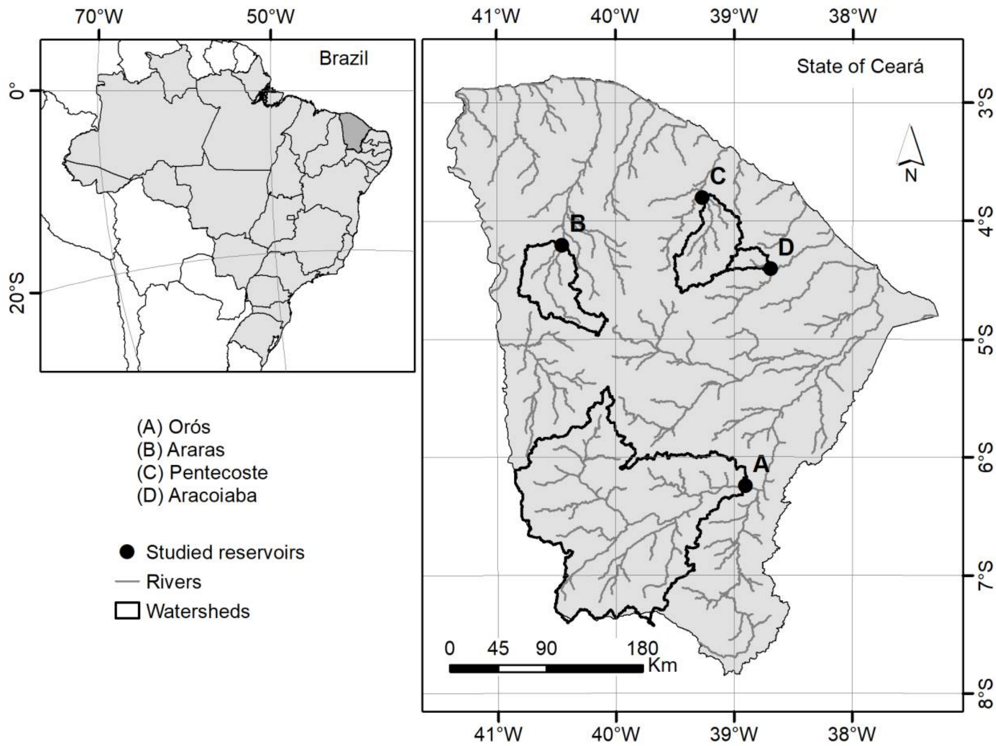

Figure 1. Location of the State of Ceará, Brazil, the study reservoirs, and their respective catchment areas

2.2. Synthesis of the proposed method and data sources

Figure 2 presents a synthesis of the proposed method. Initially, there is the preparatory phase, in which the users collect respective data and associate each water use with a priority level associated with a certain degree of reliability. The preparatory phase is supposed to be outlined within the River Basin Committee, using a participatory approach. In Phase I, the main goal is to establish the relation between the withdrawal discharge from the reservoir and its respective reliability. In Phase II, reservoir depletion during the dry season is simulated, generating a family of curves rationally based in relation to the parameter T (depletion duration). The objective of Phase III is to calibrate the parameter T, establishing the function between a possible maximum withdrawal discharge and the effectively stored volume. The last step, Phase IV, is meant to associate each water use (and, therefore, its degree of reliability) to the respective alert volume and its withdrawal discharge. The output table generates reference values, which are to be validated or modified by the committees. The hydrological data were obtained in [23] and the specific dam data were retrieved from [24] and [10].

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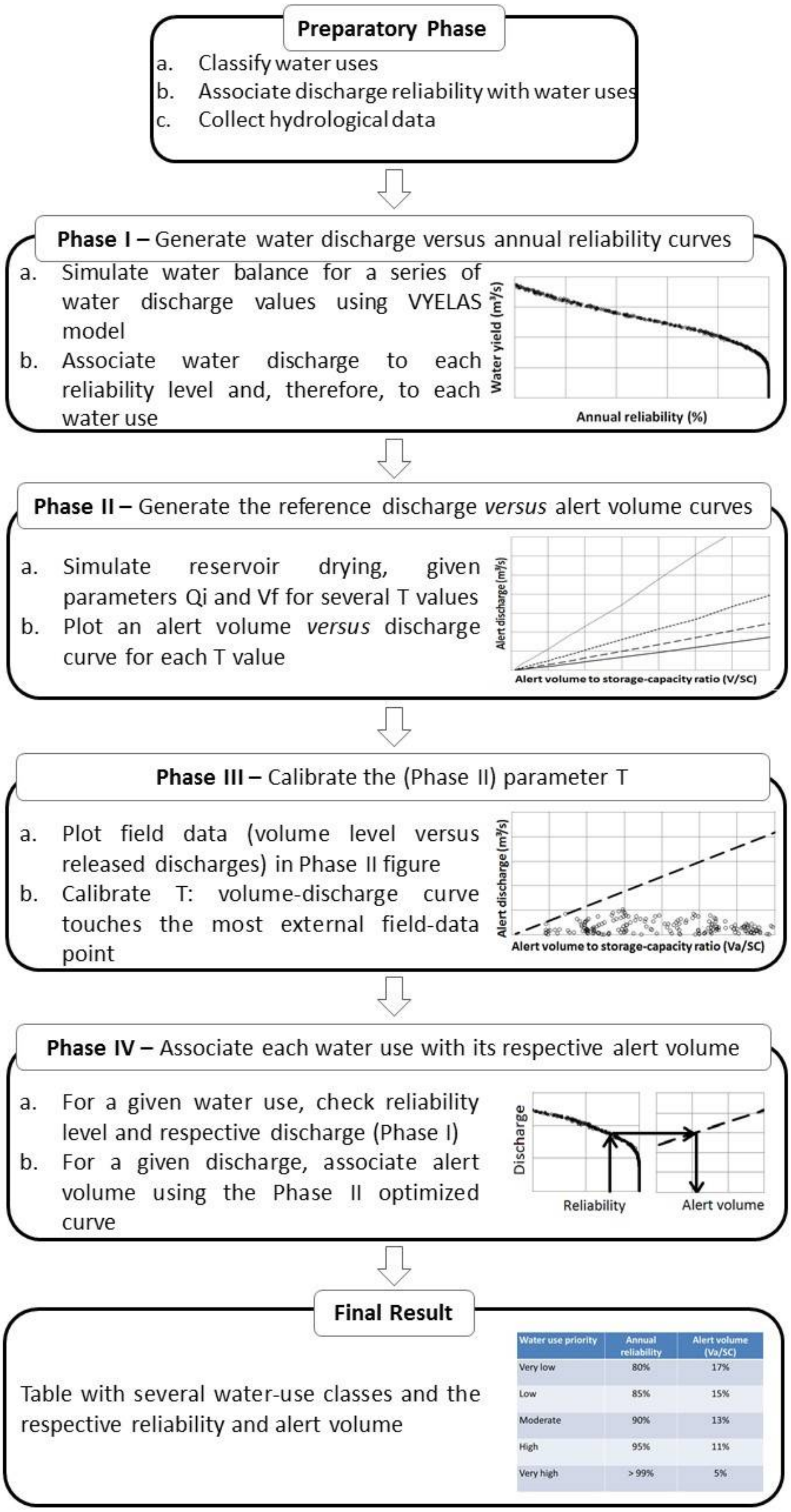

Figure 2. Flow chart of the proposed methodology. Q_i means input discharge, V_f the final reservoir volume after depletion, and T the depletion duration.

2.3. Phase I - Withdrawal discharge as a function of annual reliability

We used the VYELAS (Volume-Yield Elasticity) model to calculate the annual reliability of a given withdrawal discharge (Q_W, or water yield) of surface reservoirs [25]. It establishes the water

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balance (Equations 1 and 2) at monthly time steps using long synthetic series to compute the annual reliability (G, Equation 3) of a given withdrawal discharge [26]. The model considers the operational rules as executed by the River Basin Committees in the Semi-arid [10]; and implicitly solves the simultaneous processes of evaporation, infiltration and withdrawal during the dry season.

$$\frac{dV(t)}{dt} = (Q_H + Q_R + Q_G + Q_{imp}) - (Q_W + Q_E + Q_{inf} + Q_O + Q_{exp}) = \Delta Q(t). \quad (1)$$

In Equation (1), V(t) is the effectively stored reservoir volume at time t; Q_H is the discharge of the direct precipitation over the lake; Q_R is the inflow discharge from the rivers; Q_G is the inflow discharge from the groundwater; Q_{imp} is the eventual import discharge from another basin by transfer structures; Q_W is the withdrawal discharge; Q_E is the evaporation discharge; Q_{inf} is the infiltration discharge; Q_O is the overflow discharge through the outlet; and Q_{exp} is the eventual export discharge to another basin by transfer structures. Field measurements in the Brazilian Semi-arid region have shown that, in most cases, the difference ($Q_H + Q_G$) - ($Q_{EW} + Q_{inf}$) is negligible on a monthly time scale [25-26]. The term Q_{EW} represents the evaporation discharge of the wet season, and the annual evaporation discharge is constituted by $Q_E = Q_{EW} + Q_{ED}$, where Q_{ED} is the evaporation in the dry season. Equation (1) turns into Equation (2), which is used in the VYELAS model. For the reservoirs of this research, note that $Q_{imp} = Q_{exp} = 0$.

$$\frac{dV(t)}{dt} \approx (Q_R + Q_{imp}) - (Q_W + Q_{ED} + Q_O + Q_{exp}), \quad (2)$$

$$G = \frac{N_S}{N_S + N_{NS}}. \quad (3)$$

In Equation (3), G is the annual reliability for long series (we used 10,000 simulations), N_S is the number of successful years, whereas N_{NS} is the number of unsuccessful years in the simulation. In this context, a successful year is one in which the planned water demand can be integrally met without constraint, i.e., not leading to the reservoir level be below alert volume.

2.4. Phase II - Reference discharge versus alert volume family of curves

The joint application of Equations (4), (5), and (6) yields Equation (7).

$$\int_{V_0}^{V_f} dV = \int_0^T \Delta Q(t).dt, \quad (4)$$

$$Q_i = Q_H + Q_R, \quad (5)$$

$$\delta Q = Q_{inf} - Q_G = \varphi.E_A.A, \quad (6)$$

$$V_f = V_0 + \int_0^T [Q_i + Q_{imp} - (Q_W + Q_E + Q_O + \delta Q + Q_{exp})].dt. \quad (7)$$

In Equations (4) – (7), t is time; V_0 is the reservoir volume in the beginning of the dry season; V_f is the reservoir volume after the simulated depletion; T is the simulated depletion duration; Q_i is the input discharge; δQ is the difference between infiltration and groundwater discharges; E_A is the evaporation rate; A is the effectively flooded area of the reservoir; and ϕ is a parameter. According to [2], ϕ equals 0.30 for a long-term balance in the Brazilian Semiarid. In the dry season, for a given reservoir volume (V_0), there is a withdrawal discharge (Q_W) that depletes the reservoir to volume V_f at duration T, given the input discharge Q_i. The withdrawal discharge Q_W is calibrated regarding the objective function (ψ: Equation 8), which should yield a value as close to zero as possible when solving Equation (7). The same procedure is repeated for varying initial volumes V_0 and T, delivering a family of curves of $Q_W(V_0, T)$, for the given parameters Q_i and V_f.

$$\psi = V(V_0, T, Q_W, Q_i) - V_f. \quad (8)$$

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The three parameters (Q_i, V_f, and T) must be established. The model user elects two of them (Q_i and V_f, for example) and calibrate the third (T, in this case) during Phase III. In the study region, the water drawdown during the dry season is caused by simultaneous evaporation, infiltration and withdrawal; whereas the rainfall and runoff contribution is negligible [3, 23]. Therefore, in the simulations of the present research, we assumed that no input discharge occurred ($Q_i = 0$) and that the reservoir dried out ($V_f = 0$) after the duration T. Since no inflow was assumed, no overflow discharge through the outlet was expected either ($Q_O = 0$).

2.5. Phase III - Calibration of the parameter T

The curves generated by Equation (7) were confronted with the field data, which consisted of pairs of actually released discharges [$Q_W(t)$], associated with the reservoir volumes [V(t)] on the same day that Q_W was first released. The calibrated T value is the one with a curve that is tangent to the most external field-data point. The most external field-data point represents the highest-risk water release, i.e., the highest withdrawal discharge calculated for the reservoir level. It is important to observe that field data are only meaningful if the decision on water release is based on a valid criterion (a collective decision of the basin committee, for example), i.e., if the reservoir operation is acceptable to society. Otherwise, the data are not representative of the legitimate will of the users and should be discarded. The key output of Phase III is, thus, one curve that relates reference discharge to alert volume.

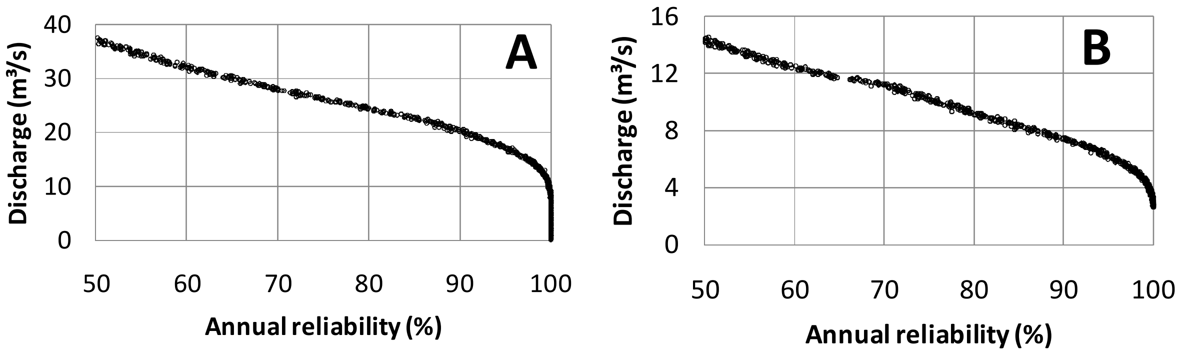
2.6. Phase IV - Association of each water use with its respective alert volume

For the water committee, each water use must be associated with a priority category (e.g., very low, low, moderate, high and very high) and, therefore, with the respective reliability level. Based on the result of Phase I, the users can compute the withdrawal discharge as a function of its respective reliability level. Subsequently, based on the result of Phases II and III, they can assess the alert volume as a function of the withdrawal discharge. At the end of Phase IV, there is a direct association between each water use and its respective alert volume. This means that, when the reservoir reaches alert volume, the respective users must start rationing water. This output, although based on a robust hydrological analysis, is simple and refers directly to the key decision variable of the stakeholders: the effective reservoir volume.

3. Results

3.1. Discharges as a function of the annual reliability level

Figure 3 depicts the monotonically-decreasing relation among withdrawal discharges with their respective annual reliability for the investigated reservoirs. It is also noteworthy that model sensitivity increases particularly in a region of high reliability (90% – 100%). The derivative dQ_W/d_G in the vicinity of G = 100%, for example, is almost five times higher than that of the G = 80% vicinity.



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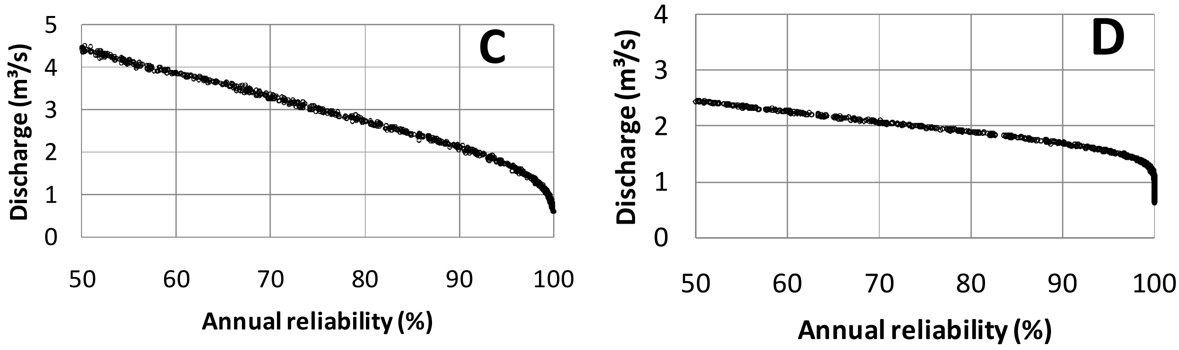

Figure 3. Withdrawal discharge as a function of the annual reliability level for the focus reservoirs: (A) Orós; (B) Araras; (C) Pentecoste; and (D) Aracoiaba.

3.2. Released discharges as a function of the reservoir volumes

The field data (Figure 4) evince that there is a declining-demand trend when the stored volume is high. At the other extreme, when the stored volume decreases below 25% of the reservoir capacity, the withdrawal discharges also decrease. From Figure 4 and Table 1, it is clear that the optimal T value (for null Qi and Vf) for the focus reservoirs lies close to six months for all cases (ranging from 5.7 to 6.0 months). The boxes inside the plots (Figure 4) show that the highest-risk discharges (i.e., those of the most external points) are usually released when the reservoir volumes lie between 5% and 25% of the storage capacity.

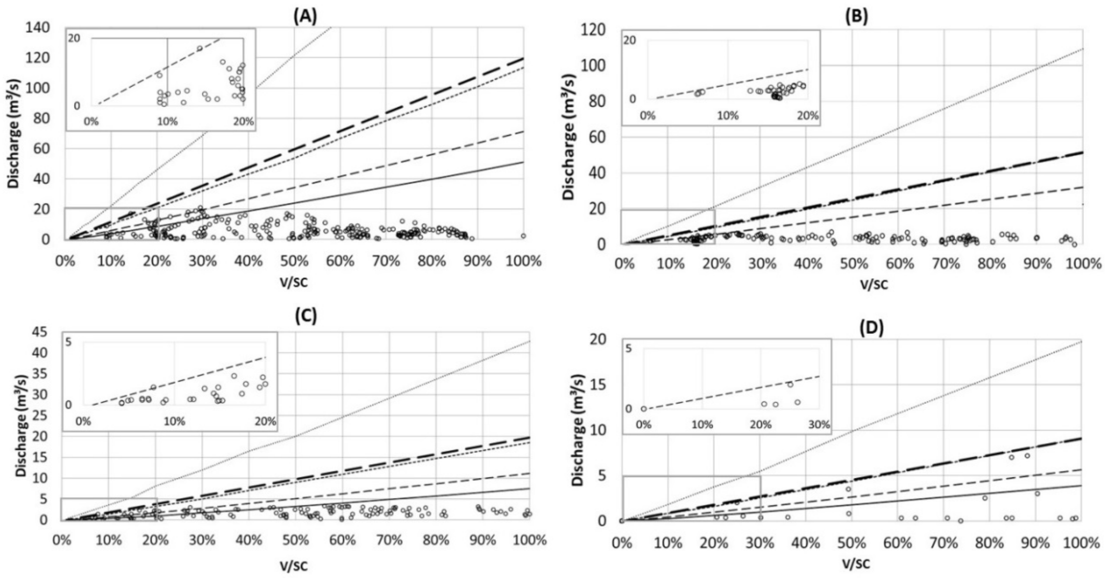

Figure 4. Field data (dots) and simulation (lines) of released discharges as a function of the reservoir volumes (V) divided by the storage capacities (SC) for several depletion periods (T). The continuous black line refers to T = 12 months; the dashed line to 9 months; the dotted line to 6 months; and the continuous grey line to 3 months. The bold dashed line refers to the optimal drying period. The small box on the top right zooms the optimal curve and the field data near the most external point: (A) Orós; (B) Araras; (C) Pentecoste; and (D) Aracoiaba.

3.3. Simulations for the focus reservoirs

Table 2 presents the final results of the simulations for the focus reservoirs. On average, water rationing should start when the reservoir stores 20% of its capacity for very low priority uses (80%

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annual reliability); 17% for moderate priority uses (90% reliability); and 11% for very high priority uses (99% reliability), such as human and animal supply.

Table 2. Example of simulation. Withdrawal discharges (Q_W, in m³/s) and the ratio between alert volume (Va) and the storage capacity (SC) for the focus reservoirs, considering five water-use priorities and their respective annual supply reliability. Simulation parameters consider reservoir completely dry-out (V_f = 0) and no inflow (Q_i = 0) during six months (T = 6 months).

Water use	Water-use priority	Water-use reliability	Orós		Araras		Pentecoste		Aracoiaba	
			Q_W	Va/SC	Q_W	Va/SC	Q_W	Va/SC	Q_W	Va/SC
Temporary-culture irrigation	Very low	80%	24.35	0.23	9.12	0.19	2.71	0.17	1.89	0.23
Aquaculture and similar	Low	85%	22.74	0.21	8.36	0.17	2.46	0.15	1.81	0.22
Permanent-culture irrigation	Moderate	90%	20.55	0.19	7.35	0.15	2.06	0.13	1.65	0.20
Industries and energy provision	High	95%	17.09	0.16	6.16	0.13	1.72	0.11	1.54	0.19
Human and animal supply	Very high	99%	9.57	0.10	4.61	0.10	1.15	0.08	1.32	0.16

4. Discussion

The fact that the derivative dQ_W/d_G increases with reliability level means that, to obtain small increments of high-reliability levels, the withdrawal discharge must be considerably reduced. This is an important feature for decision making in systems designed to supply for high-reliability demands, such as human provision. In Brazil, the annual reliability discharge of 90% (Q_{90}) is commonly used for water resource planning and can be interpreted as the reference water availability of the reservoir [26]. The largest reservoir, Orós, is capable of yielding Q_{90} over 20 m³/s (Table 2), whereas the smallest dam, Aracoiaba, yields less than 2 m³/s with the same reliability. Figure 3 and Table 1 indicate that Q_{90} is, on average, only 42% of the inflow, which means that 58% of the inflow either evaporates or overflows through the spillway. In fact, hydrological losses are much higher in a semiarid environment than in other climatic zones, including tropical wet basins, due to excessive evaporation and high variation coefficients of the annual inflow to the reservoirs, which leads to considerable outflow during wet years. De Araújo and Piedra [27] compared water availability in two meso-scale basins: one semiarid (in Brazil) and one wet (in Cuba). The results showed that, although the average precipitation in the wet basin was only twice that of the semiarid one, the first had a water availability of 280 mm.yr^{-1} against 20 mm.yr^{-1} in the latter. Another aspect that has to be considered is the effect of the inter-annual hydrological variability [6]. For example, the Q_{90} of the Pentecoste dam is only 20% higher than that of Aracoiaba, although the Pentecoste storage capacity is two-fold and its catchment area is five times as big as the one of Aracoiaba. This occurs because the hydrological variability of the Pentecoste basin (coefficient of variation of annual inflow 1.0) is considerably higher than that of Aracoiaba (0.6). The difference of the hydrological variability between both basins is mainly due to their respective upper basin morphologies. In Pentecoste, located in the dry hinterlands, the upper-basin terrain slopes are mild (typically below 20%), the air is dry and temperatures are high; whereas in the upper Aracoiaba basin, located in higher altitude, the terrain is steeper, air moisture is higher and temperatures are lower. These features determine evaporation losses, as well as the initial runoff conditions, as investigated by [28].

The declining-demand trend when the stored volume is high means that demand decreases as the stored volume increases above a threshold value (around 50%), and so do the withdrawal discharges, due to the relative abundance of water from other sources in the basin, such as cisterns,

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ponds and wells [10]. However, the demand depletion for low stored volume is due to another reason: in that case, despite water scarcity in the basin, the stakeholders fear the lack of water in the near future. In fact, drought experiences strongly affect people emotionally [29], culturally [30] and socially [32-33]. A possible explanation for the optimal duration to be 6 months is its similarity with the length of the dry season, i.e., the stakeholders try to use the available water as rationally as possible before the next rainy season. Considering the differences in the catchment areas of the reservoirs (size, precipitation, runoff), the constancy of the optimal T value suggests that it is representative of the committees located in the Brazilian Semiarid region. What concerns the highest-risk discharges (see the boxes in Figure 4), we noticed that, in the Araras and Pentecoste reservoirs, this limit is low (below 10% of the storage capacity), showing that their stakeholders are willing to take higher risks concerning the water supply of the following year. In the Orós and Aracoiaba reservoirs, observations differed (15% and 25%, respectively). The more conservative policy in Orós is probably due to the dam's relevance for the regional water supply. In fact, it is a central supplier to other regions in the State within the drought-relief policies [22]. The Orós operation is, therefore, decided not only by direct water users, but rather by the Management Company, which plans the water policy for the State as a whole. The Aracoiaba dam is the least vulnerable reservoir among those investigated in this research: it has the highest (2.38 years) average residence time (i.e., the ratio between the storage capacity and the average inflow), which is 50% higher than the average of the remaining reservoirs. It also counts on the highest precipitation (828 $mm.yr^{-1}$) and the highest (76%) hydrologic efficiency (Q_{90}/average inflow, Table 1; see also [27]). This means that the Aracoiaba reservoir rarely dries out, and its stakeholders fear extreme scarcity already when the stored volume is 25% of its capacity (against 15% in Orós, 7% in Araras, and 8% in Pentecoste). From Table 2, it is noticeable that Aracoiaba presents the highest relative alert volumes.

According to the Brazilian National Water Law (BRAZIL, 1997), some water uses should have priority when it comes to water access during water-scarcity occasions. We assumed, hence, several (five) priority levels among the water uses, and associated an annual reliability to each priority, simulating a possible result from a committee decision meeting (Table 2). After six years of hydrological drought, on 23 January 2018, Orós had 6% of its storage capacity, Araras 7%, Pentecoste less than 1%, and Aracoiaba 15% [23]. Considering the results of Table 2, on this date, all studied reservoirs should rationalize water even for very high priority uses, which has not occurred so far. Another important issue is the decision on how much water should be rationalized for each water use in each situation. The hierarchical water-reliability policy, although necessary and helpful, is also a source of conflicts. Take, for example, the case of Orós reservoir at 20% of its capacity. Very low and low priority users will have to save water, but they will struggle to get as much as possible, whereas higher priority users will try to release as little as possible, so as to delay (or even avoid) having to rationalize water themselves. An even worse scenario is that, in which all users have to suffer supply restriction. By how much should each use be reduced? Should rationalization be linear with the licensed discharge? Another gap – still to be developed within the model framework – is the consideration of water quality [21] as a key parameter in the decision making. These problems are still technically unsolved, but a democratic and representative basin committee seems to be the best forum to decide such matters and provide proper water governance in reservoir-dependent regions [34].

5. Conclusions

We introduce a novel and hydrologically-sound method to provide a simple relation between classes of water uses and their respective alert volumes. The method uses a new approach and considers the input from committee stakeholders to classify water uses and to associate them with the annual reliability level. Hydrological models associate withdrawal discharges with both the reliability level and the alert volume. Our method was applied to four important reservoirs (2.10^2 - 2.10^3 hm^3) of the Brazilian Semiarid region. The results indicate that uses with very low priority should start rationalization when the reservoir volume is, on average, below 20%; whereas uses with very high priority should start rationalization when the reservoir volume is below 11%. It was

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observed that, after six years of hydrological drought, all the users of the focus reservoirs should be under water rationalization, but this has not happened until now. The field data shows that, when the stored reservoir volume is higher than 50%, demand decreases because of the relative abundance of water from other sources in the basin. When the stored volumes are low (typically below 25%), the withdrawal discharges also decrease, most likely due to the fear of water scarcity in the near future. The field data also give evidence that the highest-risk discharges (i.e., those of the most external points) are usually released when the reservoir volumes lie between 5% and 25% of the storage capacity. Despite the water-priority policy's relevance, it is also a source of conflicts, with no technical solution whatsoever. However, a democratic and representative committee seems to be the best forum to decide such matters. The here-derived guidelines are simple and should help to enhance water governance among the less educated stakeholders (in terms of hydrological modeling) in water-scarce and reservoir-dependent regions.

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