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# Rule curve for seasonal increasing of water concessions in reservoirs with low regularized discharges

## *Curva-guia para incremento sazonal da outorga em reservatórios com baixas vazões de regularização*

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## ABSTRACT

Regions with high hydrological variability are usually supplied by reservoirs that regularize discharges inter-annually, with low discharge of regularization, seasonally subject to large overflow and evaporation losses in their periods of high water levels. The Brazilian semiarid is one of such regions. This work looks at the possibility of using water that would be evaporated and/or spilled, in regions with such characteristics, to supply demands that would not be otherwise provided by the maximum legally allowed withdrawal discharge. The proposed method was applied to the operation of a large reservoir, located in the semiarid region of Brazil. Through simulation of the water budget and optimization, a rule curve was developed for reservoir operation for achieving the maximum exploitable reservoir withdrawal in rainy periods. The results show that it is possible to use the excess water in periods of large inflows with no damage to water supply during dry periods.

**Keywords:** Concession discharge; Reservoir operation; Rule curve.

## RESUMO

Regiões com alta variabilidade hidrológica são, geralmente, abastecidas por reservatórios plurianuais com baixas vazões de regularização, sujeitos, sazonalmente, a grandes vertimentos e a perdas por evaporação em seus períodos de cotas altas. O semiárido brasileiro é uma dessas regiões. Este trabalho levanta a hipótese do aproveitamento da água vertida e/ou evaporada, em regiões com estas características, para suprir demandas não atendidas pela vazão outorgável dos reservatórios, utilizando uma vazão máxima excedente para incrementar a vazão outorgável. Como caso de estudo, foi efetuada a operação de um reservatório de grande porte, localizado no semiárido brasileiro. Por meio de simulação do balanço hídrico e otimização, foi desenvolvida uma curva-guia para operação do reservatório e encontrada a vazão excedente máxima explorável em períodos de cheia. Com os resultados encontrados, pode-se concluir que há a possibilidade de utilizar uma vazão excedente em períodos de grandes afluências sem que o abastecimento em períodos secos seja prejudicado.

**Palavras-chave:** Vazão outorgável; Operação de reservatórios; Curva-guia.

## INTRODUCTION

Water demands in river basins with high hydrologic variability, when supplied by surface waters, require reservoirs with inter-annual regularization. Such reservoirs are built with large storage capacity, however their regularization flows and, consequently, their grantable flows tend to be low when compared to values of reservoirs located in basins with lower variability. These reservoirs have regular refills every year and, thus, have their water use planning made for the year of recharge (intra-annual regularization). Due to the small grantable flows, inter-annual reservoirs seasonally suffer major spills and evaporation losses in their periods of full and high storage levels. Question is then whether spilled and evaporated volumes during these periods could be wholly or partially used to meet demands unmet by the grantable flow (MACHADO; GALVÃO; SOUZA FILHO, 2012; LIMA et al., 2005; SILVA; MONTEIRO, 2004; RIBEIRO; LANNA, 2003).

The Brazilian semiarid region is one of those regions presenting significant inter-annual hydrologic variability. The management of water resources is extremely complex, especially due to the extreme weather conditions, like high evaporation rates and irregular rainfall in time and space. This region usually has cycles characterized by successive years of water scarcity, interspersed with successive years of high rainfall, which brings uncertainties regarding refills in upcoming years, so that the manager is induced to remain cautious when granting the use of reservoir water (STUDART; CAMPOS, 2001). Such peculiarities commonly generate mismatch between supply and demand and, consequently, conflicts of use/interest between its multiple users or uses (urban supply, animal consumption, irrigation, fish farming, etc.).

The operation of a reservoir, when properly performed, accordingly conciliating supply (availability) and demand for water, prevents or mitigates conflicts. One of the most commonly used tool to aid reservoir operation is the rule curve, which is the reservoir useful volume division in zones with different strategies for water supply for different uses (BRAVO et al., 2006).

In general, the rule curve has been used as a limitation in the operation: in flood control, limiting the level of water stored at a maximum height, and to prevent collapse supply, by reducing the amount of water supplied to users.

Thus, this work raises the hypothesis that it is possible to explore some of the water that, in periods of full storage, spills from a reservoir or that abstracted by evaporation, using, in these periods, a quantity exceeding the grantable flow (defined by the flow regulation). Therefore, the purpose of this paper is not to use the rule curve to reduce, but to increase the release of water in specific situations of abundance. Together with this hypothesis, is the possibility to grant dynamically a new grant, "conditioned" to the reservoir overflow, which would allow the withdrawal of a flow that is higher than the "static" granted one without compromising security during dry periods (MACHADO; GALVÃO; SOUZA FILHO, 2012; RIBEIRO; LANNA, 2003). To demonstrate this hypothesis, a study of the operation of a typical Brazilian semiarid region reservoir, *Açude Epitácio Pessoa*, was made through simulation and optimization, based on rule curve. The reservoir is an inter-annual regularization reservoir suffering high pressure from users by increasing the granted flow.

## RULE CURVE

### Concept

The rule curve divides the storage volume of a reservoir in zones where different strategies for demand supply will be applied. The limits of each zone may vary seasonally or remain constant during the whole year. Such tool may be used for flood control or water conservation during long dry spells (BRAVO et al., 2006).

Studies using rule curve have been evolving since the 1960s, when this tool began to be applied (e.g., MAASS et al, 1962; REVELLE; JOERES; KIRBY, 1969), incorporating new aspects of modern water management in operational routines of the reservoirs. Among these aspects are, for example, climate change (LEE et al, 2011; ZHOU; GUO, 2013), ecological flows (ZHOU; GUO, 2013) and negotiation of conflicts between users (CHANG; HO; CHEN, 2010). Advances in systems analysis methods have also been incorporated into the determination of rule curves, such as multi-objective approaches (CHANG; HO; CHEN, 2010) and meta-heuristics (TAGHIAN et al., 2014).

In regions with high hydrologic variability, the rule curve, when used for water conservation, is based on restrictions of use/supply of resource during periods in which the reservoir reaches certain low levels of storage, so there is water to be used during a prolonged drought. This reduction in the supply takes place gradually, in order to prevent users from getting no water (CHANG; HO; CHEN, 2010).

The rule curve developed here points to the opposite side. Instead of decreasing supply during dry periods, it objectively aims to increasingly meet the demands in flooding periods, when the reservoir has high storage, suffering spills and/or high evaporation rates. The increased release, controlled by the rule curve, is named, here, as Maximum Exploitable Withdrawal (Qem). Figure 1 illustrates a hypothetical rule curve, seasonal or monthly variable. The curve defines two zones for water release. When storage is in Zone 1, operation with grantable water discharge occurs (Qout). If the storage is high enough and reaches Zone 2, the release can be higher and reaches the maximum withdrawal (Qem). Several rule curves can be established by setting various operating zones and gradual transitions between the magnitudes of withdrawals.

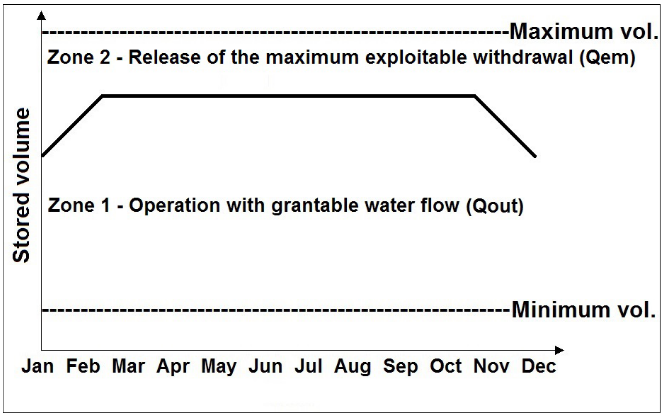

**Figure 1.** Rule curve for surplus discharge.

It is worth noting that the rule curve is a tool that should be used for planning the operation of a reservoir (strategic operational level). When the operation is implemented (tactical operational level), if extreme events occur – like very long cycles of drought or structural problems – this rule can be broken or adapted.

## The establishment of rule curve

Considering the case of a unique rule curve, their monthly levels and maximum withdrawal (Qem) can be established by simulating the water balance of the reservoir, under historical/synthetic series of rainfall and inflow discharge, optimizing an objective function. As a more suitable goal, Equation 1 proposes minimizing spills and evaporated volumes, storing more water and allowing a withdrawal beyond the granted one when the storage is at high levels.

$$\boldsymbol{FO} = \boldsymbol{min}\left\{ \sum_{t=1}^{n} \boldsymbol{Ev}_t + \sum_{t=1}^{n} \boldsymbol{Ve.}_t \right\} \tag{1}$$

where $\boldsymbol{FO}$ is the objective function; $\boldsymbol{n}$ is the number of months of simulation; $\boldsymbol{t}$ is the simulation interval (month); $\boldsymbol{Ev}_t$ is the evaporation in every month $\boldsymbol{t}$; and $\boldsymbol{Ve.}_t$ is the volume spilled in every month $\boldsymbol{t}$.

Monthly values of the rule curve will be limited between the minimum operating volume and the capacity of the reservoir. On the other hand, a necessary restriction is the minimum withdrawal that cannot be lower than the grantable discharge (Equation 2).

$$\boldsymbol{Q}_{em} \geq \boldsymbol{Q}_{out} \tag{2}$$

where $\boldsymbol{Q}_{out}$ is the grantable discharge; and $\boldsymbol{Q}_{em}$ is the maximum withdrawal discharge.

Although, in Figure 1, the grantable discharge is constant throughout the year, it may, of course, be variable. Other restrictions may be adopted, to meet various operational objectives.

The monthly simulation of sequential water balance of the reservoir and the calculating of the rule curve were performed on a spreadsheet implemented in Excel, called Hidro (SILVA, 1997; GALVÃO; MEDEIROS; OLIVEIRA, 2004). The Hidro spreadsheet in its original form has warning levels, which have been adapted as rule curves for the modeling adopted here.

Equation 3 shows the formulation of the water balance sheet adopted in Hidro.

$$\boldsymbol{S}_{t+1} = \boldsymbol{S}_t + \boldsymbol{Q}_t - \boldsymbol{E}_t - \boldsymbol{R}_t - \boldsymbol{V}_t \tag{3}$$

where $\boldsymbol{t}$ is the present simulation interval and $\boldsymbol{t}$ + 1 is the next simulation interval; $\boldsymbol{S}_t$ is the volume stored in the reservoir; $\boldsymbol{Q}_t$ is the inflow discharge to the reservoir; $\boldsymbol{E}_t$ is the water volume lost by evaporation; $\boldsymbol{R}_t$ is the volume withdrawn from the reservoir, for consumption; and $\boldsymbol{V}_t$ is the volume of water spilled from the reservoir.

For optimization, the Evolver tool was used, implemented as add-in for Microsoft Excel (PALISADE CORPORATION, 2013). Evolver uses linear programming, when the identified problem is linear. For non-linear problems, a genetic algorithm method and an algorithm called OptQuest are used. This is an algorithm that makes use of a set of meta-heuristics: Tabu search, scatter search, integer programming and neural networks. To solve the problem that is the object of this article, the optimization engine used was *OptQuest*.

Optimized results of the rule curve levels are often conceptually inconsistent with hydrologic and operational reality. In order to make the rule curve have conceptual consistency and be more easily understandable by the operator, it is usual to smooth results found in optimization (e.g., SARGENT, 1979). In this work, the smoothing is done by using the average values or closer multiples of million, to soften the month-to-month level changes, to replace values considered inconsistent and, hence, to make the rule curve more understandable.

## CASE STUDY

### Boqueirão reservoir

Epitácio Pessoa Reservoir, known as Boqueirão, is the second largest surface water reservoir in the State of Paraiba. The fact that it supplies water to nearly half a million people, in a region that is polarized by Campina Grande, the biggest city in the interior of Paraiba and educational, economical and industrial center, raises concern with the management of the water resources of the reservoir, not only in the crisis periods, like the one that has occurred since 2012 (RÊGO; GALVÃO; ALBUQUERQUE, 2012; RÊGO et al., 2014).

The reservoir is inserted in the Paraiba River basin, in the boundary between the Upper and Middle River Course at an altitude of 420 m, between the coordinates 07° 28’ 04” and 07° 33’ 32” south latitude, 36° 08’ 23” and 36° 16’ 51” west longitude (Figure 2). The climate is hot semiarid according to Köppen classification, with its dry season covering eight to ten months of the year.

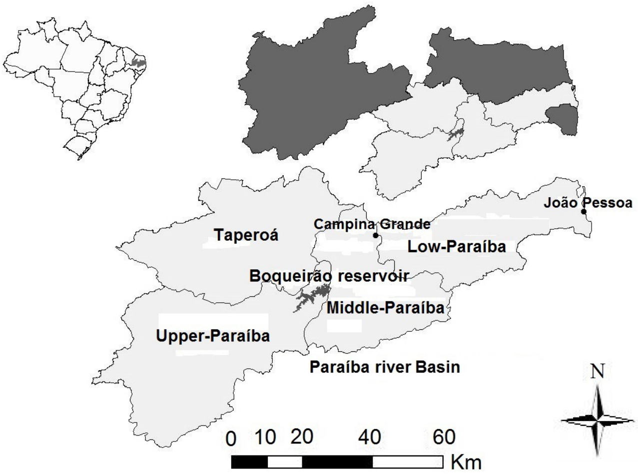

**Figure 2.** Boqueirão Reservoir location.

Boqueirão was built by the National Department Against Droughts – DNOCS, between the years 1953 and 1956 (DNOCS, 2015), and its main purpose was to solve the water supply problems in Campina Grande. Also, the reservoir aimed to regularize the middle course of Paraiba River, allow fish farming, irrigation, leisure and even hydropower.

The reservoir was designed for a storage capacity of 536 $m^3$. However, in a bathymetric survey in 2004 it was attested that its capacity was reduced to 411,686,287 $m^3$. In 2013, a new bathymetric survey was carried out by the National Water Agency (ANA, 2014), which confirmed the first one.

Figure 3 shows Boqueirão's crisis and abundance periods through stored levels in every month, since 1998. The first crisis of the reservoir occurred between 1998 and 2003, with three episodes of urban supply rationing and irrigation suspension, among other consequences. After the first crisis, the Boqueirão Reservoir had an abundance period lasted from 2004 to 2011. In the last raining year of that period, the spilling of the reservoir lasted until September, which is rare, once periods of inflows in the basin usually happen no later than June. During those eight years, the management of the reservoir was inefficient. Without adequate monitoring and supervision, withdrawals from Boqueirão were much more than the regularized discharge and, logically, the granted one, in a situation that lasted during 2012, the beginning of the dry period in the basin, until mid 2013. Interventions by the management agency, ANA, occurred too late (second half of 2013) and the actions taken were, for a long time, minor, causing the reservoir storage, then with very few refills, to reach 100 million $m^3$ in 2014. After reaching such level, a rationing of urban water supply was initiated in December 2014, which would be intensified six months later, in June 2015.

The crisis in the reservoir could be minimized and drastic measures, such as rationing, could be prevented through a continuous management of its water resources, in particular through a controlled and efficient operation of the reservoir (RÊGO; GALVÃO; ALBUQUERQUE, 2012; RÊGO et al., 2014).

The main reservoir water users are the Water and Sewerage Company of Paraiba - CAGEPA (urban water supply) and about 400 irrigators (agriculture) (RÊGO et al., 2015.). The latter ones would have the biggest benefit – even if seasonal only – from the increasing of the grantable discharge, since they are of lower priority (and not-granted) and with relative flexibility in the temporal allocation of water. It would not be possible to cope with their needs if the withdrawal is limited to the fixed grantable discharge.

## Inflow discharges

Two series of inflow discharges to the reservoir were used in this study. The first was obtained from the Paraíba State Water Resources Plan (UFPB, 1994) and covers twenty-one years of monthly data between 1963 and 1983 (Figure 4). The values of inflow discharge of this series were reduced by the method of trial and error, since the regularized discharge obtained from them (by Hidro spreadsheet) equaled the current value in the 2006's Paraíba State Water Resources Plan (AESA, 2006). This procedure was necessary to consider the influence of several small and medium-sized reservoirs built within the basin, which reduce its area with effective contribution to the reservoir.

Also used herein, another series of flows, 2004-2015 (Figure 5), was calculated by water balance, based on daily measurements of the remaining volumes in the reservoir, provided by the State of Paraiba Water Agency – AESA.

## Evaporation

In the absence of evaporation measurements in the reservoir, average monthly data of Class A pan evaporation tank were used, collected from São João do Cariri School Basin of the Federal University of Campina Grande, from 1987 to 2008 (Figure 6). These data can be considered representative due to the proximity of the reservoir and due to the similar climate, vegetation and terrain characteristics. For the correction of the measured values in the Class A tank, coefficients were used (Kp), calculated by Oliveira et al. (2005) for the Boqueirão reservoir.

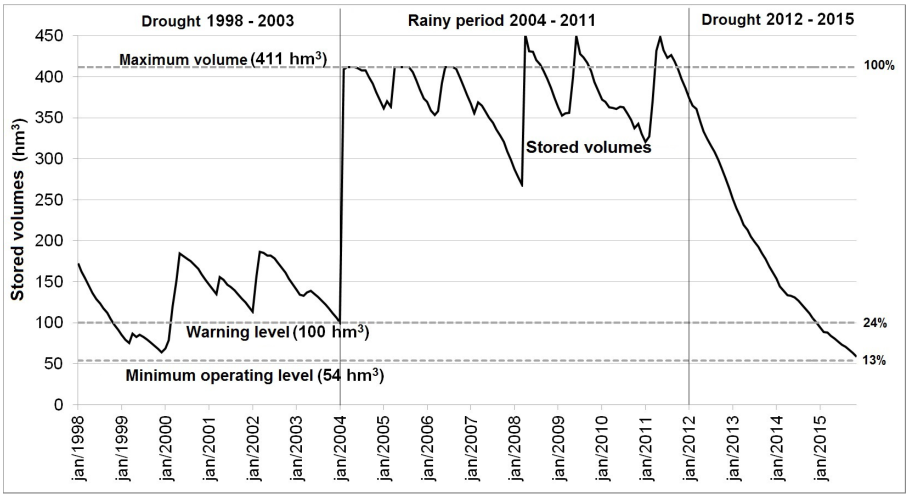

**Figure 3.** Actual volumes stored in Boqueirão from 1998 to 2015. Source: AESA (2015).

## Definition and application of rule curve

Rule Curve and maximum exploitable withdrawal (Qem) were calculated by using the 1963-1983 inflow series, smoothing the curve to correct the inconsistencies. Then, the established curve was applied using the 2004-2015 inflows, to verify its performance in contrasting situations: a sequence of relatively rainy years (2004-2011) followed by a series of dry years (2012-2015). Thus, the curve is tested in a period that was not used for its building. For this study, 1,230 L/s, that is equal to the reservoir regularized discharge, was assumed as the granted flow of the reservoir.

To estimate the water volume that would, without the application of the rule curve, be withdrawn by evaporation and spilling, a reservoir operation simulation was done without the application of the rule curve, with the withdrawals limited by the granted flow. Comparing the results to the ones obtained with the use of the rule curve, it was possible to estimate the amount of water that would be evaporated and/or spilled (in the operation without the use of the rule curve) and, thus, be used to lower priority uses. Naturally, evaporation would continue in the two operations. However, once more water is used (applying the operation with the rule curve), a reduction of the lake area would occur and, consequently, a reduction in the evaporation would take place.

## RESULTS AND DISCUSSION

Figure 7 shows the established rule curve in the optimization and after smoothing. The result is satisfactory, since the shape of the curve is consistent with the hydrologic situation of the basin. The curve shows lower levels in the first months of the year, when it is expected that there are inflows to the reservoir and, therefore, larger withdrawals. On the other hand, in May, June and July, by the end of the rainy season, these levels are higher, once it is expected that the reservoir has received recharge and that the stored volume is higher. In the following months, once the inflow period in the region is over, there are no entries. Thus, the curve shows a gradual decline in levels and it is time to use the water that was stored during the rainy season. The most inconsistent value occurred in June, between two peaks in May and July, and can be attributed to the optimization numerical process.

According to the results found in the rule curve establishment, Boqueirão Reservoir can provide in times of abundance (when the stored volume is above the rule curve) up to 1,802 L/s (Qem),

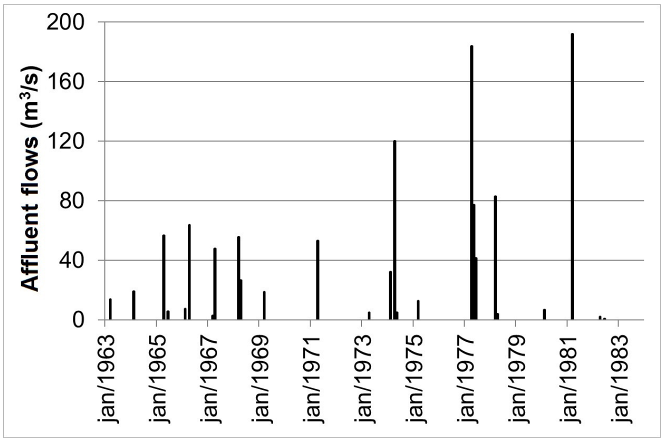

**Figure 4.** Historical series of inflow discharge to Boqueirão Reservoir (1963-1983). Source: UFPB (1994).

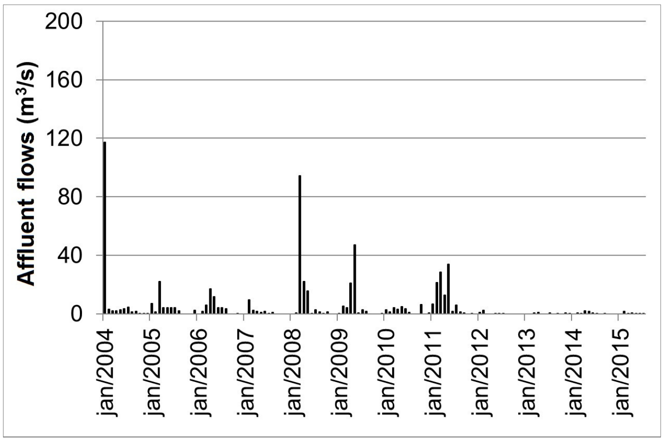

**Figure 5.** Historical series of inflow discharge to Boqueirão Reservoir (2004-2015).

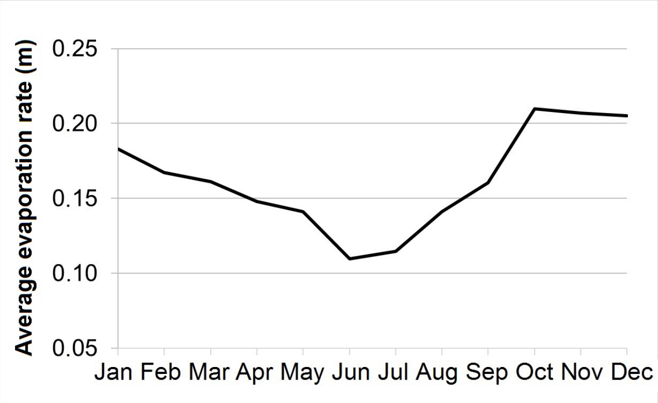

**Figure 6.** Average monthly evaporation.

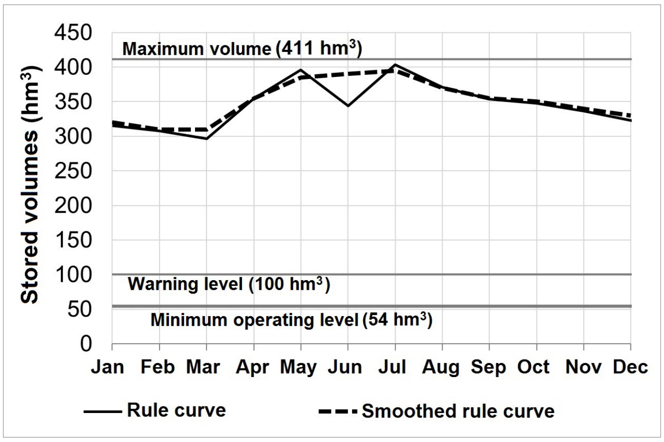

**Figure 7.** Calculated rule curve and smoothed rule curve used in Boqueirão.

about 46.5% more than the grantable flow. In periods when the storage is below the curve, the amount to be available for withdrawals must be equal to 1,230 L/s (Qout).

Figures 8 and 9 show the simulation results after applying the smoothed rule curve to the series of years used in its establishment (1963-1983). In this series, there were basically two moments with great inflows: 1977 to 1979 and 1981, both with a short interruption. During 27 months (11% of the series) the withdrawals equal to Qem (1.80 m$^3$/s), equivalent to approximately 40 million m$^3$ withdrawn beyond the grantable flow.

Aiming to test the rule curve in a period that is different from the one applied to its establishment, a series of inflows from 2004 to 2015 was considered. As shown in Figure 3, in the initial phase of that period (2004-2011) there was a predominance of great inflows to the reservoir. In the last four years, a sequence of uninterrupted low inflows occurred.

Figure 10 shows the reservoir operation simulation, using the rule curve in the 2004-2015 period. It can be seen that from 2004 to 2011, in 72% of the months, the withdrawal was over the granted one. During that time, great inflows took place every year, and the storage level was usually over the rule curve. Thus, a great part of the water was either spilled in the actual operation (Figure 3) or lost in evaporation could be completely or partly used for other uses. However, it is important to observe that there were moments when the granted flow had to be limited (28% of the months), until the level went up again.

The total benefit of the use of the maximum exploitable withdrawal – Qem (1.80 m$^3$/s) can be observed in Figure 11. This additional available volume would total, between 2004 and early 2012, approximately 108 million m$^3$, distributed in basically three episodes, without interruptions.

Another simulation was performed, this time using the crisis period only, from September 2011, when the reservoir was filled to capacity (the last month spilled occurred), to August 2015 (Figures 12 and 13). The initial volume of the simulation was assumed as the observed, i.e., full reservoir. It is worth noting that this crisis has been the most serious of all the history of the reservoir, since there has never been, nor in the 1963-1983 series, a period of four consecutive years with such low inflows. This different simulated scenario presents results that are very similar to the ones found with the operation for the whole period (2004-2015), shown in Figure 10. This similarity is due to the fact that 2011 had exceptional inflows, which resulted in spilling until the second half of September. The operation in this scenario (September 2011 to August 2015) was not impaired by the use of excess water that occurred in the prior months and years. Figures 12 and 13 show the use of Qem in the last months of

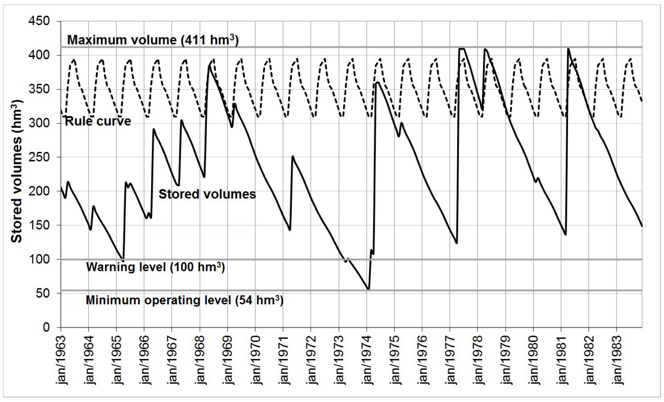

**Figure 8.** Smoothed rule curve applied to the 1963-1983 series: stored levels and volumes.

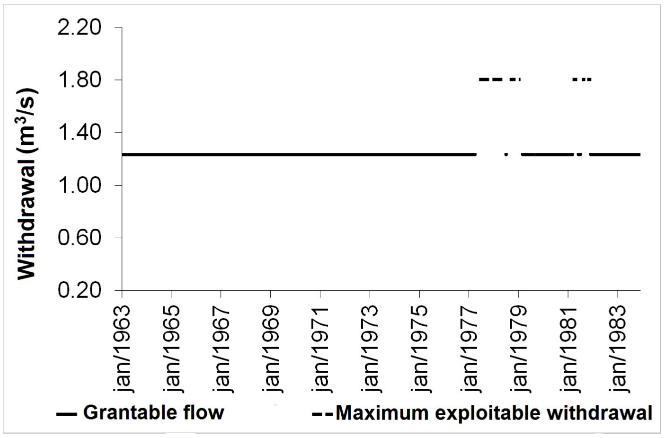

**Figure 9.** Granted flow and maximum withdrawal resulted from the application of the rule curve to the 1963-1983 series.

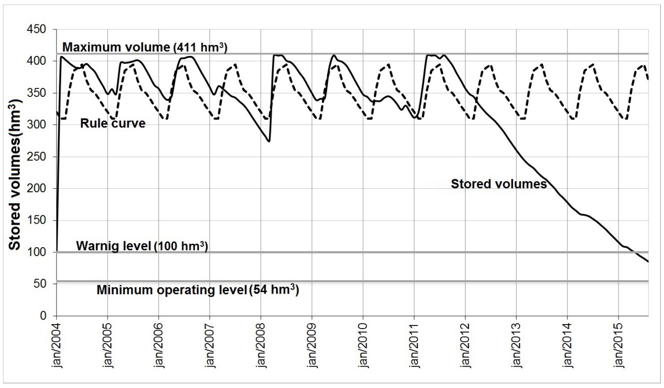

**Figure 10.** Smooth rule curve applied to 2004-2015 series: stored levels and volumes.

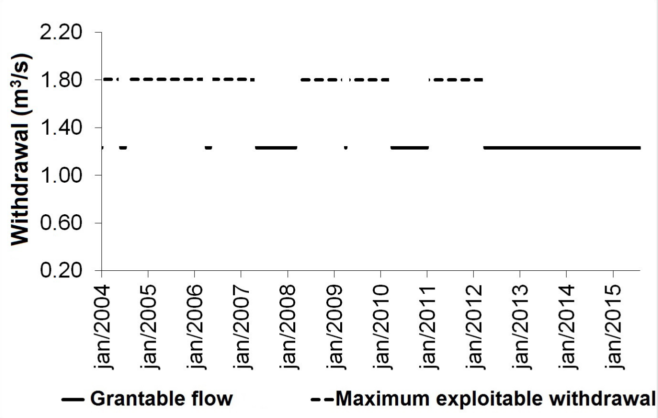

**Figure 11.** Granted flows and maximum exploitable withdrawal resulting from the application of rule curve to the 2004-2015 series.

2011 and early 2012 and, since then, limited availability to grantable flow, since there was no recovery of the stored volume.

In order to quantify the use of spilled and evaporated volumes, the operation of the reservoir was also simulated without using the rule curve, i.e., with restriction only to the grantable discharge – Qout (1.23 $m^3/s$). Figure 14 shows the two simulations. In the graph, the curve indicated by "stored volume 1" represents the levels reached in the reservoir with the use of the rule curve, while "stored volume 2" are those without using the rule curve. It may be noted that, in several years, the spills that occurred when the use was limited to Qout, would no longer happen with the application of the rule curve (possible use of Qem), showing greater use of water. The monthly numerical results from each component of the water balance, used in the simulations, showed that there would be, with the temporary grant of Qem, a reduction of more than 88 million $m^3$ of spilled water and over 13 million $m^3$ of evaporated water, totaling approximately 102 million $m^3$. This proves that the amount of additional water used came predominantly (96%) of these reductions in spillage and evaporation, causing no harm to the granted discharge availability in the dry seasons.

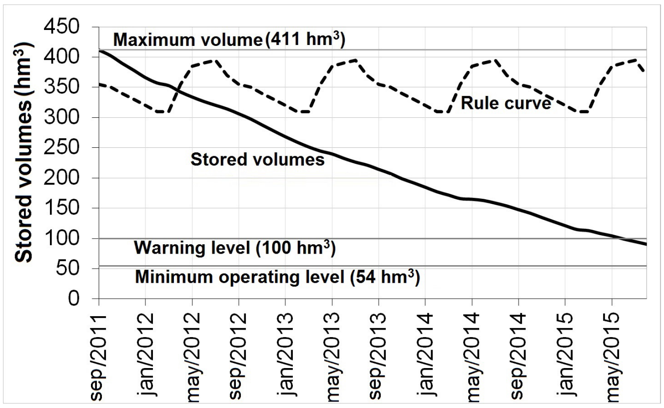

**Figure 12.** Smoothed rule curve applied to the 2011-2015 series: stored levels and volumes.

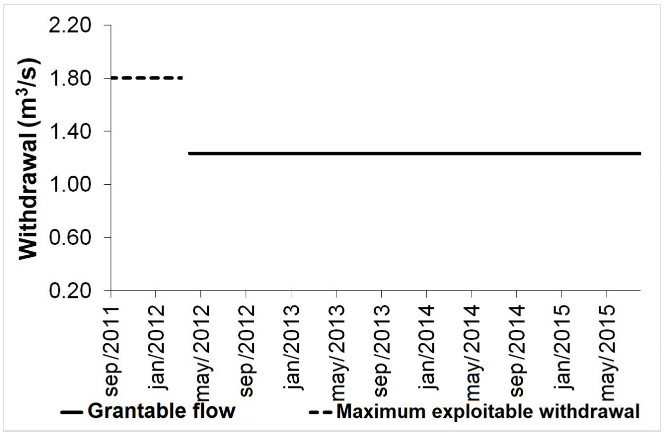

**Figure 13.** Granted and maximum exploitable withdrawal resulting from the application of the rule curve to the 2011-2015 series.

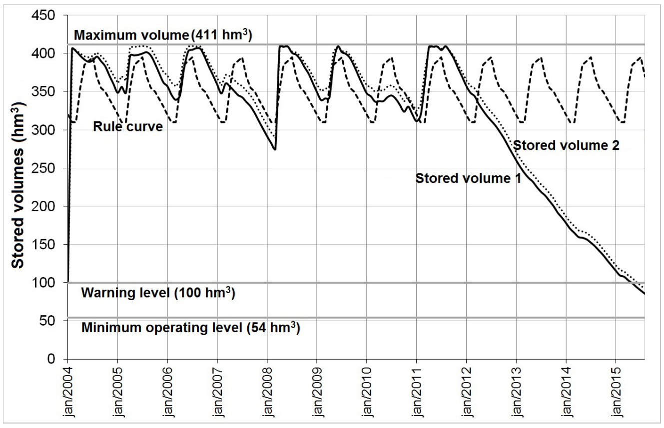

**Figure 14.** 2004-2015 series: stored levels and volumeswith (vol. 1) and without (vol. 2) the use of rule curve.

However, after a long period of drought, the operation with the rule curve can take the remaining volume in the reservoir slightly below those that would be achieved without its use, as shown in Figure 14, for 2012-2015. This situation can be reversed or at least strongly attenuated, through a management that incorporates, as tactical element, seasonal climate forecasting. In the exemplified case, rainfall forecast below average for February to April 2012 (CPTEC, 2012) would lead to tactical abandonment of the rule curve indication and the adoption, in early 2012, of the grantable flow as limit for withdrawn from the reservoir, which, in turn, would provide higher remaining levels.

It is possible to evaluate other benefits of using the rule curve comparing the simulated scenario (Figure 10) with the real one (Figure 3). With the use of the rule curve, for example, Boqueirão Reservoir would be, in August 2015, with approximately 15 million $m^3$ above the volume actually observed. It should be noted that the simulation does not include water rationing that has occurred since December 2014.

## CONCLUSIONS

The results confirm the hypothesis that, in regions with high hydrologic variability, which use inter-annual reservoirs with low regulation flows, it is possible to use, in periods of higher inflows, part of the water that would be spilled or lost to evaporation, thus increasing, seasonally, the grantable flow.

The rule curve tool, which has extremely conceptual and operational simplicity, proved to be suitable to be used in reservoir operations for this purpose, showing satisfactory and consistent results.

Withdrawal of the excessive water to supplement the grantable flow does not compromise its compliance at times of water shortage, since the additional withdrawal almost exclusively use the water that would be removed or lost by evaporation.

The rule curve, thus constructed, can be used to assist in the implementation of the water rights instrument through its seasonally variable expansion.

The rule curve is a proposal for the water abundance periods, and it is necessary to develop techniques that improve the operation of the reservoir during the other periods, when the water volume is below the rule curve. A possibility is the search for a rule curve for a drought alert.

The seasonal rainfall forecasting should be incorporated into the use of the rule curve, allowing, with the announcement of a possible water crisis, withdrawals are limited to the grantable flow.

A strategy, like the proposed one, of a change in the limits of granted flows must be discussed and approved by the river basin committee and incorporated to the respective water resources plan.

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## REFERENCES

AESA – AGÊNCIA EXECUTIVA DE GESTÃO DAS ÁGUAS DO ESTADO DA PARAÍBA. *Plano Estadual de Recursos Hídricos do Estado da Paraíba*. João Pessoa, 2006.

AESA – AGÊNCIA EXECUTIVA DE GESTÃO DAS ÁGUAS DO ESTADO DA PARAÍBA. *Volumes armazenados nos reservatórios*. João Pessoa, 2015. Available from; <www.aesa.pb.gov.br>. Access on: 20 july 2015.

ANA – AGÊNCIA NACIONAL DE ÁGUAS. *ANA define regras emergenciais de uso em rios e açudes no semiárido por causa da seca*. Brasília, 2014. Available from; <http://www2.ana.gov.br/Paginas/imprensa/noticia.aspx?id_noticia=12402>. Access on: 11 june 2015.

BRAVO, J. M.; COLLISCHONN, W.; PILAR, J. V.; TUCCI, C. E. M. Otimização de regras de operação de reservatórios utilizando um algoritmo evolutivo. In: SIMPÓSIO DE RECURSOS HÍDRICOS DO SUL-SUDESTE, 1., 2006, Curitiba, PR. *Anais*... Curitiba: ABRH, 2006.

CHANG, L.; HO, C.; CHEN, Y. Applying multiobjective genetic algorithm to analyze the conflict among different water use sectors during drought period. *Journal of Water Resources Planning and Management*, v. 136, n. 5, p. 539-546, 2010. http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000069.

CPTEC – CENTRO DE PREVISÃO DE TEMPO E ESTUDOS CLIMÁTICOS. Previsão de chuvas abaixo da normal no Nordeste e acima da normal no Norte do Brasil. *Infoclima*. v. 19, n. 1, 2012.

DNOCS – DEPARTAMENTO NACIONAL DE OBRAS CONTRA AS SECAS. *Açude Boqueirão de Cabaceiras*. Fortaleza, 2015. Available from; <http://www.dnocs.gov.br/barragens/boqueirao/boqueirao.htm>. Access on: 25 july 2015.

GALVÃO, C. O.; MEDEIROS, P. C. M.; OLIVEIRA, K. F. *Hidro*: versão 2-4. Campina Grande: Departamento de Engenharia Civil, Universidade Federal de Campina Grande, 2004.

LEE, S.; FITZGERALD, C. J.; HAMLET, A. F.; BURGES, S. J. Daily time-step refinement of optimized flood control rule curves for a global warming scenario. *Journal of Water Resources Planning and Management*, v. 137, n. 4, p. 309-317, 2011. http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000125.

LIMA, G.; BOLDRIN, R. S.; CASTRO, M. A. S.; SOUZA, M. P.; MAUAD, F. F. Critérios técnicos para outorga de direito de uso de recursos hídricos. In: SIMPÓSIO BRASILEIRO DE RECURSOS HÍDRICOS, 16., 2005, João Pessoa, PB. *Anais*... Porto Alegre: ABRH, 2005.

MAASS, A.; HUFSCHMIDT, M. M.; DORFMAN, R.; THOMAS JUNIOR, H. A.; MARGLIN, S. A.; FAIR, G. M. *Design of water-resource systems*. Cambridge: Harvard University Press, 1962. http://dx.doi.org/10.4159/harvard.9780674421042.

MACHADO, E. C. M. N.; GALVÃO, C. O.; SOUZA FILHO, F. A. Alocação quali-quantitativa de águas em bacias hidrográficas: metodologia multiobjetivo inserida no contexto da gestão dos recursos hídricos. *Revista Brasileira de Recursos Hídricos*, v. 17, n. 2, p. 213-227, 2012. http://dx.doi.org/10.21168/rbrh.v17n2.p213-227.

OLIVEIRA, G. M.; LEITÃO, M. M. V. B. R.; GALVÃO, C. O.; LEITÃO, T. J. V. Estimativa da evaporação e análise do uso do coeficiente (Kp) do Tanque "Classe A" nas regiões do Cariri e Sertão da Paraíba. *Revista Brasileira de Recursos Hídricos*, v. 10, n. 4, p. 73-83, 2005. http://dx.doi.org/10.21168/rbrh.v10n4.p73-83.

PALISADE CORPORATION. *Evolver*: Solver de Algoritmo Genético para Microsoft Excel. Versão 6. Ithaca, 2013. Manual do Usuário.

RÊGO, J. C.; GALVÃO, C. O.; ALBUQUERQUE, J. P. T. Considerações sobre a gestão dos recursos hídricos do açude Epitácio Pessoa – Boqueirão na Bacia Hidrográfica do rio Paraíba em cenário de vindouros anos secos. In: SIMPÓSIO DE RECURSOS HÍDRICOS DO NORDESTE, 11., 2012, João Pessoa, PB. *Anais*... João Pessoa: ABRH, 2012.

RÊGO, J. C.; GALVÃO, C. O.; RIBEIRO, M. M. R.; ALBUQUERQUE, J. P. T.; NUNES, T. H. C. Novas considerações sobre a gestão dos recursos hídricos do açude Epitácio Pessoa - a seca 2012-2014. In: SIMPÓSIO DE RECURSOS HÍDRICOS DO NORDESTE, 12., 2014, Natal, RN. *Anais*... Natal: ABRH, 2014.

RÊGO, J. C.; GALVÃO, C. O.; RIBEIRO, M. M. R.; ALBUQUERQUE, J. P. T.; NUNES, T. H. C. A crise do abastecimento de Campina Grande: atuações dos gestores, usuários, poder público, imprensa e população. In: SIMPÓSIO BRASILEIRO DE RECURSOS HÍDRICOS, 21., 2015, Brasília, DF. *Anais*... Brasília: ABRH, 2015.

REVELLE, C.; JOERES, E.; KIRBY, W. The linear decision rule in reservoir management and design: 1, development of the stochastic model. *Water Resources Research*, v. 5, n. 4, p. 767-777, 1969. http://dx.doi.org/10.1029/WR005i004p00767.

RIBEIRO, M. M. R.; LANNA, A. E. L. A outorga integrada das vazões de captação e diluição. *Revista Brasileira de Recursos Hídricos*, v. 8, n. 3, p. 151-168, 2003. http://dx.doi.org/10.21168/rbrh.v8n3.p151-168.

SARGENT, D. M. Reservoir operating rules for drought conditions. *Hydrological Sciences*, v. 24, n. 1, p. 83-94, 1979. http://dx.doi.org/10.1080/02626667909491836.

SILVA, L. M. C.; MONTEIRO, R. A. Outorga de direito de uso de recursos hídricos: uma das possíveis abordagens. In: MACHADO, C. J. S. (Ed.). *Gestão de águas doces*. 1. ed. Rio de Janeiro: Interciência, 2004. p. 135-178. (v. 1).

SILVA, R. P. *Hidro*. Campina Grande: Laboratório de Meteorologia, Recursos Hídricos e Sensoriamento Remoto da Paraíba da Secretaria Extraordinária do Meio Ambiente, dos Recursos Hídricos e Minerais da Paraíba, 1997.

STUDART, T. M. C.; CAMPOS, J. N. B. Incertezas nas estimativas da vazão regularizada por um reservatório. *Revista Brasileira de Recursos Hídricos*, v. 6, n. 3, p. 81-94, 2001. http://dx.doi.org/10.21168/rbrh.v6n3.p81-94.

TAGHIAN, M.; ROSBJERG, D.; HAGHIGHI, A.; MADSEN, H. Optimization of conventional rule curves coupled with hedging rules for reservoir operation. *Journal of Water Resources Planning and Management*, v. 140, n. 5, p. 693-698, 2014. http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000355.

UFPB – UNIVERSIDADE FEDERAL DA PARAÍBA. ATECEL. *Plano estadual e sistema de gerenciamento de recursos hídricos*: potencialidades hídricas superficiais do Estado da Paraíba. João Pessoa: SEPLAN/PB, 1994. Relatório Conclusivo.

ZHOU, Y.; GUO, S. Incorporating ecological requirement into multipurpose reservoir operating rule curves for adaptation to climate change. *Journal of Hydrology*, v. 498, p. 153-164, 2013. http://dx.doi.org/10.1016/j.jhydrol.2013.06.028.

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