Journal of Urban and Environmental Engineering
E-ISSN: 1982-3932
celso@ct.ufpb.br
Universidade Federal da Paraíba
Brasil

Ráurium Bacalhau, José; Ribeiro Neto, Alfredo; Gico Lima Montenegro, Suzana Maria

WATER SUPPLY RESERVOIR OPERATION IN RELATION TO CLIMATE VARIABILITY: PIRAPAMA RIVER BASIN (PERNAMBUCO-BRAZIL)

Journal of Urban and Environmental Engineering, vol. 10, núm. 2, 2016, pp. 279-287
Universidade Federal da Paraíba
Paraíba, Brasil

Journal of Urban and Environmental Engineering, v.10, n.2, p.279-287

ISSN 1982-3932
doi: 10.4090/juee.2016.v10n2.279287

Journal of Urban and Environmental Engineering

www.journal-uee.org

WATER SUPPLY RESERVOIR OPERATION IN RELATION TO CLIMATE VARIABILITY: PIRAPAMA RIVER BASIN (PERNAMBUCO-BRAZIL)

José Ráurium Bacalhau[1], Alfredo Ribeiro Neto[*2] and Suzana Maria Gico Lima Montenegro[2]

[1]Water and Climate Agency of Pernambuco State, Brazil

[2]Department of Civil Engineering, Federal University of Pernambuco, Brazil

Received 24 May 2016; received in revised form 12 October 2016; accepted 18 October 2016

Abstract: The vulnerability of water resources systems is highly influenced by the climate variability of the region. The effects are amplified when the region has high population density and important economic activities such as the Recife Metropolitan Region (RMR), whose population is 3.8 million inhabitants, corresponding to 51% of the urban population in Pernambuco State. The Pirapama reservoir was designed to produce 5.6 m^3/s, which corresponds to 37% of the total water demand of the RMR. The objective of the paper is to define strategies for the Pirapama reservoir operation by using guide curves and taking into account the climate variability, particularly drought events, to minimize or even avoid the conditions of rationing and collapse of its storage. The rainfall-runoff model SMAP was used to simulate input streamflow in the period 1933−2014 and the water allocation model Acquanet was used to simulate the operation rules proposed. The guide curves were defined based on the Standard Runoff Index, which classify the input inflow in drought categories. For each drought category, a response goal was defined for withdrawal reduction. This strategy may be an efficient tool to deal with the climate variability present in Northeast Brazil, which can be amplified with the effects of the climate change. In this sense, the development of sustainable operation rules can be considered an adaptation measure for reducing the impacts of possible climate changes in the future.

Keywords: Water security; adaptation measure; drought; water resources system

* Correspondence to: Alfredo Ribeiro Neto. E-mail: alfredoribeiro@ufpe.br

INTRODUCTION

The maintenance of the water resources systems for meeting the demands is a challenger today due to human drivers such as population growth, urbanization of large urban centers, land use change, economic growth, among others. All these elements affect both the quantity and the quality of existing water.

According to UN-Water (2013), the definition of water security involves access to adequate quantities of acceptable quality water, preserving of ecosystems and protection against water-related disasters. This implies in risk management that the population and the environment are subject such as extremes of droughts and floods and management failures.

In this sense, public supply reservoirs are one of the most requested components of the water system. Considering that they are used for a temporal and spatial water regularization, reservoirs supply the needs of meeting the demands in periods of shortage and works, in some cases, for flood control.

The climate variability must be taken into account to establish operation rules in complex water resources systems. The consequences of low rainfall rates are streamflow below the average, compromising reservoirs storage and generating impacts related to water scarcity. One of the possible impacts of the future climate change may be the intensification of extreme events of drought and flood. The Northeast Brazil is a key vulnerable region, where studies indicate the impacts of the IPCC (Intergovernmental Panel on Climate Change) climate scenarios (Ribeiro Neto *et al.*, 2014; Montenegro and Ragab, 2012; Marengo *et al.*, 2009).

The strategies aiming to improve the reservoir operation rules may be considered an adaptation measure to mitigate the impacts of climate variability and climate change (Zhou and Guo, 2013; Ward *et al.*, 2013). This measure may be especially useful in vulnerable regions such as Northeast Brazil.

In Brazil, big cities have been affected by drought occurred in 2015 in the Southeast, and since 2012 in the Northeast semiarid, resulting in 2013 in the worst drought of the last 50 years, according to report Statement on Status of the Climate by the World Meteorological Organization (WMO, 2014). Between march and may 2013, in Pernambuco State (Northeast Brazil), the Pirapama reservoir had water rationing regime, showing the deficiencies of the operation rules applied in that reservoir.

Public managers and researchers have applied tools in an attempt to mitigate these impacts. One example is the weather and climate forecasting, where the rain forecasting is used as input to management models applied by end users for specific purposes (Braga *et al.*, 2013).

To deal with the uncertainties associated with climate, Cardoso *et al.* (2006) proposes to incorporate weather/climate information in water allocation process in Ceará state, aiming to determine optimal policies in the operation of the Jaguaribe-Metropolitan System reservoirs.

Another important analysis performed by Georgakakos *et al.* (2012), has been to compare the value of the adaptive management of reservoirs compared to traditional operation practices in the water system of the central valley of Northern California in the United States.

The objective of this study is to define strategies for the operation of an important reservoir in one of the most populated areas in Northeast Brazil by using guide curves and taking into account the climate variability, particularly drought events, to minimize or even avoid the conditions of rationing and collapse of its storage.

STUDY AREA

The Pirapama River Basin (PRB) is located in the mid-south of the Recife Metropolitan Region. Recife city is the capital of Pernambuco State. The main course of the Pirapama River is 80 km long and its drainage area has 603 km^2 (**Fig. 1**).

The precipitation in the PRB decreases in the direction East-West. Close to the coast, the total annual precipitation is about 2300 mm, whilst the extreme Northwest is 1300 mm. The duration of the dry season is also influenced by the climate heterogeneity. In the East, the dry season lasts three months and in the west the duration is six months.

The original land cover is Mata Atlantica forest, but in the present day, the forest was replaced by sugarcane and pasture. Few areas remain with the original land cover.

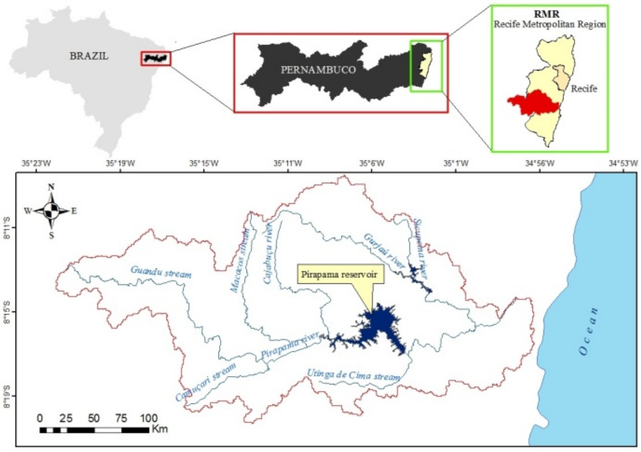

Fig. 1 Location of the Pirapama River Basin.

The PRB has two reservoirs that contribute for supplying water to Recife Metropolitan Region (RMR). The reservoirs Pirapama and Gurjau supply water for 1.5 million inhabitants, which corresponds to a demand of 6.5 m^3/s. This discharge is about 39% of the water supplied by the water supply systems of the RMR (Rodella, 2014). In the total, 14 municipalities make up the RMR. The population is 3.8 million inhabitants, corresponding to 51% of the urban population in Pernambuco State. The total water demand in the RMR is 15.1 m^3/s. The source of the water comes from surface reservoirs (66%), groundwater (13%) and withdrawal directly from the rivers. The Pirapama reservoir was designed to produce 5.6 m^3/s and its capacity is 61 million cubic meters. The drainage area of the reservoir is 338 km^2.

MATERIALS AND METHODS

Data

The average precipitation was calculated using the hydrometeorological network of the Brazilian National Water Agency (ANA) and Water and Climate Agency of Pernambuco (APAC). The period of data is from 1933 to 2014 and it considered 33 raingauges and 1 streamgauge (**Fig. 2**). The Pirapama streamgauge used in the calibration of the rainfall-runoff model has data for the period 1987−1996 and drainage area of 371 km^2.

The Digital Terrain Model SRTM was used for the watershed delineation in the dam cross section of the Pirapama reservoir and in the mouth of the river.

The potential evapotranspiration (ETP) was calculated using the Hargreaves method and the climatological data from Escada station (shown in **Fig. 2**).

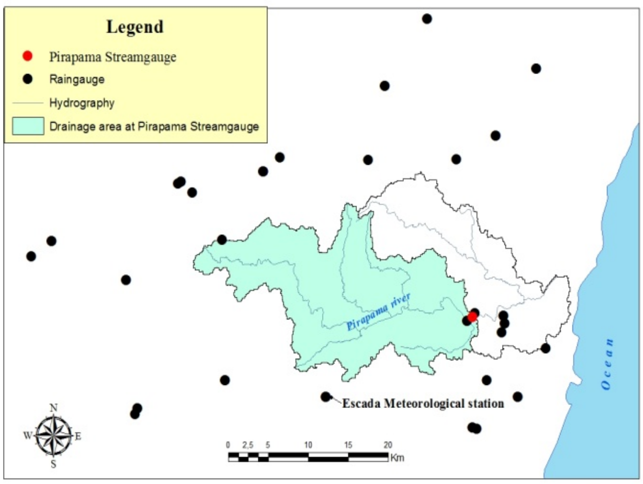

Fig. 2 Hydrological stations in the PRB.

Rainfall-runoff model

Considering the size of the watershed, the data availability and the objectives of the research, the lumped hydrological model SMAP was chosen. The SMAP (Soil Moisture Accounting Procedure) model (Lopes *et al.*, 1981) has been applied in other watersheds with similar characteristics, such as the basins of the rivers Gramame, Mumbaba and Mamuaba located in the state of Paraiba in Brazil (Porto *et al.*, 2008), the Piranhas-Açu river basin (ANA, 2012), and in Ceará state (Ceará, 2005) for the Water Resources Management Plan. The SMAP may run with daily or monthly time step. For runoff separation, the model uses SCS algorithm. The model simulates water budget based on three reservoirs representing the surface and unsaturated zones (soil) and saturated soil (aquifer). The input data are precipitation, potential evapotranspiration and streamflow for parameter calibration. The streamflow data available was divided in two periods for calibration and validation. The evaluation of the model performance considered the following criteria:

$$NS = 1 - \frac{\sum_{t=1}^{n}\left(Q_{mea} - Q_{sim}\right)^2}{\sum_{t=1}^{n}\left(Q_{mea} - \overline{Q_{mea}}\right)^2} \quad (1)$$

$$\Delta V(\%) = \frac{\sum\left(Q_{mea} - Q_{sim}\right)}{\sum\left(Q_{mea}\right)} \cdot 100 \quad (2)$$

$$R(\%) = [Q(mm)/P(mm)].100 \quad (3)$$

where NS is Nash-Sutcliffe coefficient; ΔV is volume error; Q_{mea} is the measured streamflow; Q_{sim} is the simulated streamflow; $\overline{Q_{mea}}$ is the measured average streamflow; R is the runoff coefficient; Q(mm) is the streamflow in millimeters; and P(mm) is the average precipitation in millimeters.

Reservoir simulation

The Pirapama reservoir was simulated using Acquanet network flow model (Porto *et al.*, 2003). Acquanet is based on the ModSim model developed at Colorado State University by Labadie (1998). The components of the water resources system are represented by nodes (reservoirs, confluences, demands, withdrawals and so forth) and links (stream reaches, pipelines, and canals). The network model needs information on water demand, operation rules and demand priorities. The input discharge in the Pirapama reservoir is calculated with the SMAP model after its calibration. The Acquanet has been applied in many water resources systems in Northeast Brazil aiming to evaluate climate change scenarios (Ribeiro Neto *et al*., 2014) and water allocation (Miranda and Mauad, 2015; Carvalho *et al.*, 2008). The water from Pirapama reservoir is used to supply human demand. The historic withdrawal of the period 2011−2014 was used to simulate the reservoir storage and evaluate Acquanet network model.

Drought index

The drought indexes have been used with the objective of characterizing and modeling properly the drought phenomenon. The indexes are represented by a numeric value instead of the raw data of precipitation, streamflow and other water availability indicators. It is possible to synthesize the hydrological processes in a unique value that represents the humid condition in a certain place.

The drought events have become an important indicator for investment in water management. Its monitoring is essential to mitigate the negative impacts of climate variability and propose actions suitable to each stage of severity. Aiming to quantify the drought events, Serra (2014) evaluated the application of drought characterization index in precipitation series - SPI (Standardized Precipitation Index) to streamflow series in order to analyze downstream changes in the flow regime of a dam before and after construction.

The evaluation of drought periods during the 82 years of data available for PRB may be performed defining an indicator of the drought and its severity. The Standard Runoff Index (SRI) was chosen to normalize the input discharge in the Pirapama reservoir. The application of the SRI is similar to the SPI (Shukla and Wood 2008; Mo, 2008).

The monthly streamflow series was fit to the gamma probability distribution function. The probability of each value is associated to the standardized normal variable as described by McKee *et al.* (1993). **Table 1** shows the classes of SPI and the respective drought category. The classes of SRI presented in **Table 1** were defined based on the SPI values. The values were adapted to have severe class wider than original SPI values. The SRI values greater than -0.19 were classified as normal.

Figure 3 shows a scheme which helps the understanding of the definition of the storage state in the reservoir using only two years (2012−2013). The values of the **Table 1** were used to classify each monthly streamflow in Mild, Moderate, Severe and Extreme categories (**Fig. 3c**). The next step was to calculate the percentage of the input streamflow with relation to the median (**Figs 3d-e**). Instead of using mean streamflow, the median monthly value was used to decrease the influence of the extreme values that tend to exacerbate the mean values. The percentage average for the entire simulation period (1933−-2014) can be seen in **Table 2**.

Guide curves

Guide curves are reservoir operation rules used to indicate target volumes according to specific objectives. For the Pirapama reservoir, the main role of the guide curves is to avoid and minimize the risk that the reservoir reaches the state of rationing or collapse.

This study considered the hypothesis that the input streamflow is representative of the severity level in the reservoir storage. Using this idea, the values of the **Table 2** can be extrapolated to be applied in the reservoir storage as shown in **Table 3**. The percentage of the storage with relation to median value was used to define triggers for water withdrawal reduction. The values of "response goal" (third column) were obtained from the document Drought Management Plan in Cities: Jucazinho System (Souza Filho *et al*., 2014). It is a plan developed for facing drought events in Jucazinho reservoir in the Capibaribe River Basin, one of the most important basins in Pernambuco State. A work group composed by stakeholders defined the values of the third column in **Table 3**.

Table 1. Classes of SPI by McKee *et al.* (1993) and SRI in the present study.

SPI values	SRI values	Drought category
–	≥ -0.19	Normal
0 to -0.99	-0.19 to -0.49	Mild
-1.00 to -1.49	-0.50 to -0.99	Moderate
-1.50 to -1.99	-1.00 to -1.99	Severe
≤ -2.00	≤ -2.00	Extreme

Table 2. Percentage average of streamflow with relation to the median value considering the period 1933−2014.

Drought category	Value (%)
Mild	83.41
Moderate	62.38
Severe	38.78
Extreme	20.00

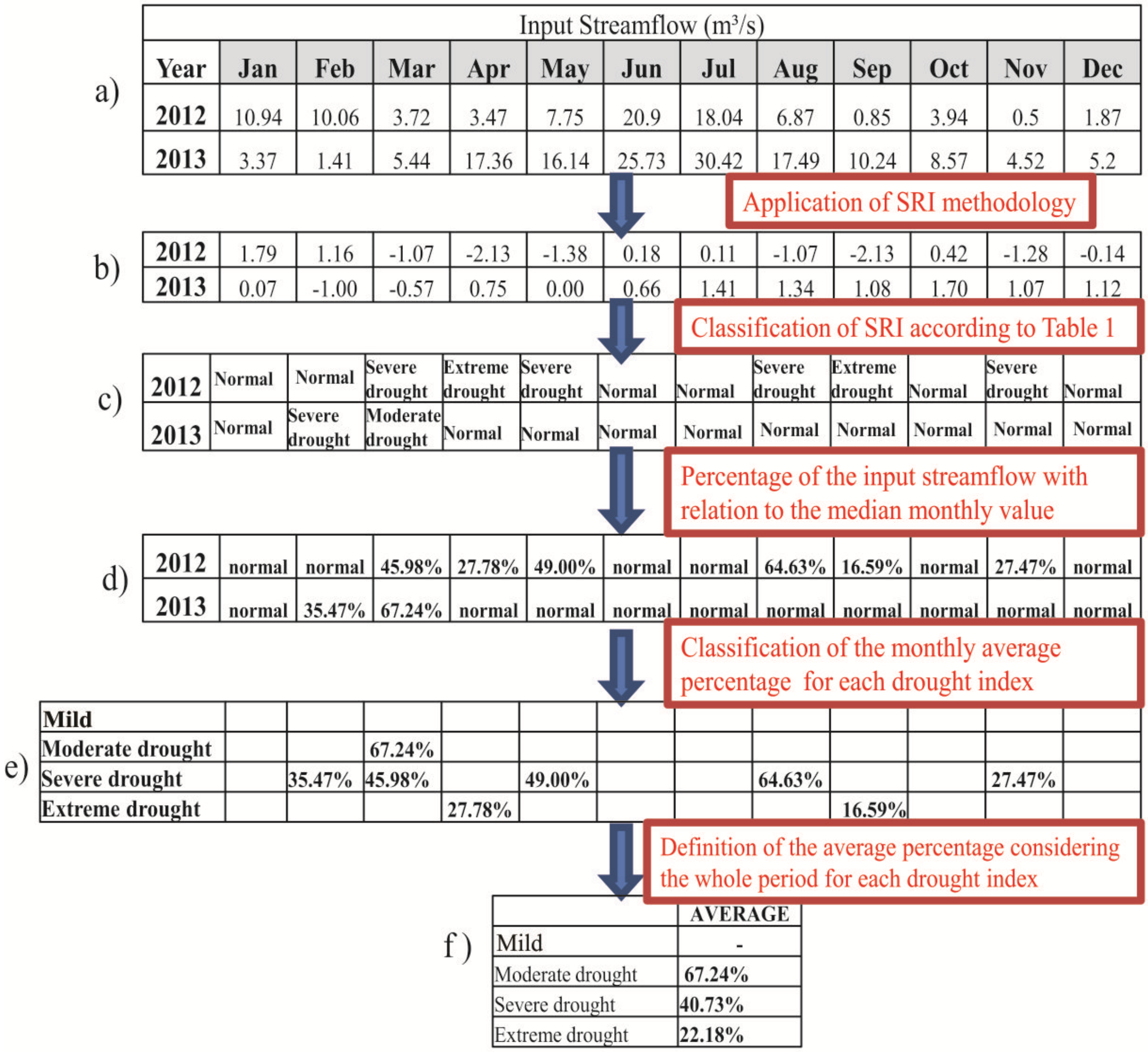

Fig. 3 Steps for classification of the input streamflow according to drought categories (example for 2012−-2013).

The guide curves of the Pirapama reservoir were obtained after the simulation with the Acquanet network model, when the reservoir storage monthly series of the period 1933−2014 was available to calculate the median volume (black line in **Fig. 4**). The other curves in **Fig. 4** were obtained applying the percentages showed in the second column of the **Table 3**.

The evaluation of the effectiveness of the reservoir operation rules considers the values showed in **Table 4**. It is calculated by the period of time that the reservoir storage remains in its normal condition, rationing and collapse.

Table 3. Drought triggers for withdrawal reduction.

State	Percentage of the storage with relation to median value	Response goal
Mild	85%	10% withdrawal reduction
Moderate drought	65%	20% withdrawal reduction
Severe drought	40%	30% withdrawal reduction
Extreme drought	20%	60% withdrawal reduction

Source: Souza Filho *et al.* (2014)

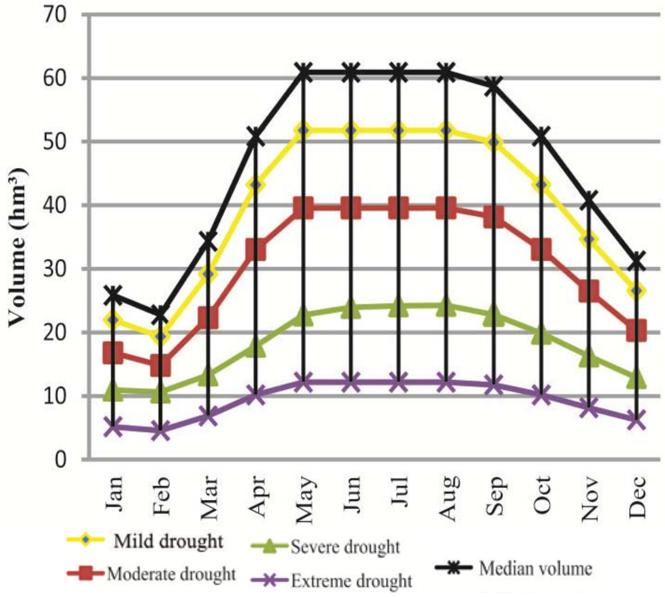

Fig. 4 Guide curves for Pirapama reservoir.

The lower limit for the normal condition in **Table 4** took into account the water rationing occurred in 2012. The state agency on duty water resources management APAC established the water rationing when the storage in the Pirapama reservoir achieved 20%. The lower limit for the rationing state (5%) was defined based on the minimum volume designed (2.3%).

RESULTS AND DISCUSSION

Rainfall-runoff simulation

The average spatial precipitation was calculated with the inverse distance weighted method. **Table 5** shows the period of calibration and validation and the performance of the rainfall-runoff simulation. The values of the model parameters were determined by try and error. **Figures 5** and **6** present the results of the calibration and validation comparing monthly measured and simulated streamflow.

Table 4. Volume zones for evaluation of the performance of the reservoir operation rules.

State	Volume (hm^3)	Volume (%)
Normal	> 12.8	> 20
Rationing	3.04 − 12.18	5 – 20
Collapse	< 3.04	< 5

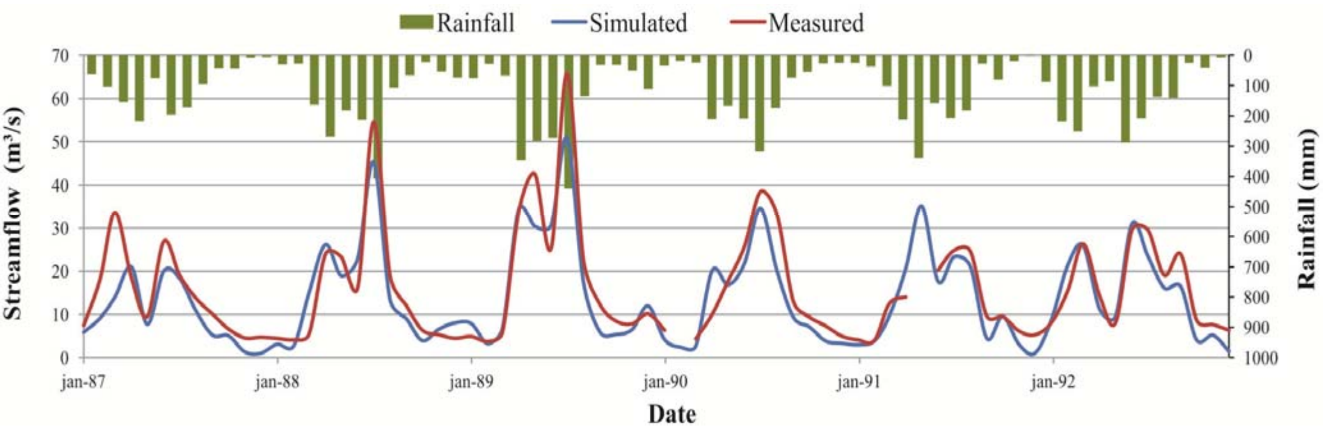

Fig. 5 Simulated and measured streamflow in the calibration period at Pirapama streamgauge.

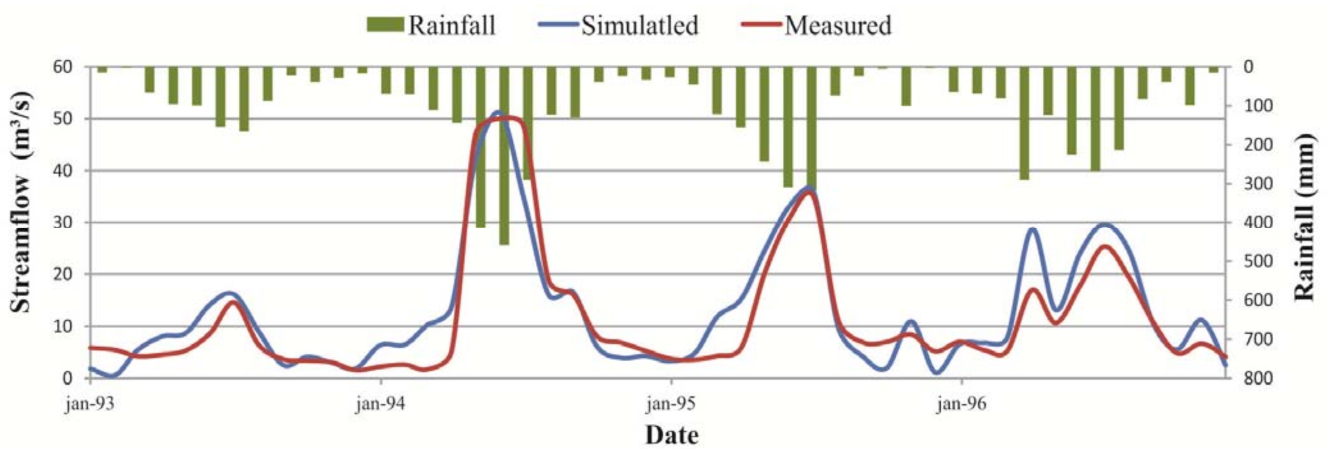

Fig. 6 Simulated and measured streamflow in the validation period at Pirapama streamgauge.

Table 5. Performance of the model at Pirapama streamgauge.

Simulation	Period	NS	ΔV(%)	R-meas. (%)	R-sim. (%)
Calibration	1987–1992	0.71	10.69	88.69	77.01
Validation	1992–1996	0.86	-10.46	69.19	76.43

The model performance can be considered suitable for the objectives of the work. The hydrological simulation with SMAP model had a result considered "good", where NS coefficient is higher than 0.65 and volume error is lower than 15% (Moriasi *et al.*, 2007). The hydrological model calibration plays an important role because the water availability will be determined by simulation.

After the model calibration and validation, SMAP was used to generate input streamflow in the Pirapama reservoir. The simulation corresponds to the period between January 1933 and December 2014, comprising 82 years.

The evaluation of the Acquanet network flow model in the period 2011–2014 was also important to verify the suitability of the model in representing the system.

Simulation of the current operation rule

The Pirapama reservoir started its operation in 2011. The Acquanet network model simulation covers the period 2011–2014, which was compared with the volume monitored by APAC. **Figure 7** shows the measured and simulated storage in Pirapama reservoir.

It is possible to verify that measured and simulated storage have a good correlation of 84%, allowing affirming that Acquanet represented satisfactorily the system. After this evaluation, Acquanet was run for the period 1933–2014 considering the average water withdrawal of 4,830.00 L/s continuously. **Figure 8** shows the result of the Acquanet simulation, where rationing and collapse levels are highlighted. The reservoir storage in 66 months is outside of the normal condition, which corresponds to five and a half years in the period of 82 years. It is important to emphasize the median monthly volume in **Fig. 4** refers to the simulated series of **Fig. 8**.

Simulation of an alternative operation rule

It is proposed an operation rule whereas the water withdrawal is reduced according to the reservoir storage. The simulation result from **Fig. 8** was used to identify the drought category in each month. When the monthly storage reached the target volumes of the guide curves (**Fig. 4**), the water supply (4830 L/s) is reduced according to the response goals of the **Table 3**. The Acquanet was run again with the new water supply (result in **Fig. 9**).

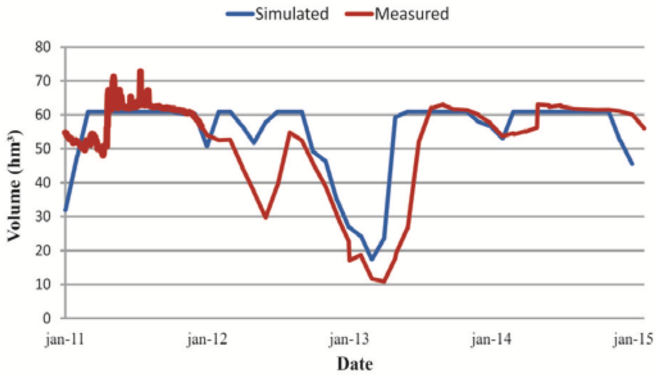

Fig. 7 Measured and simulated storage in the Pirapama reservoir.

Table 6. Amount of months per reservoir condition.

Condition	Current	Alternative
Normal	918	980
Rationing	39	4
Collapse	27	0

The results of the simulation with the current and alternative operation rules are shown in **Table 6**. During the 82 years of simulation with the alternative operation rules, only 4 months stayed in the rationing condition and none in collapse, showing remarkable improvement in the effectiveness on reservoir operation.

In terms of water retained in the reservoir during the period of simulation, the average storage is 47.79 hm^3 with current operation rules and 45.74 hm^3 with alternative operation rules. In terms of percentage, the increasing of the retained volume is only 4.48%. However, it is clear the benefits in avoiding non favorable conditions for water supply and improving water security for a huge population in terms of domestic supply and its impacts on basic services and industrial sector.

The need for improvement of reservoir operation rules has been recognized in other regions under threat of climate variability and change. After the simulation of scenarios of climate change and water demand increasing in the Rozva reservoir, in Zimbabwe, Ncube *et al.* (2011) have concluded that the decision makers should anticipate the consequences of the impacts. Ward *et al.* (2013) have proposed the application of the dynamic management in the Angat Dam in Philippines. This adaptation strategy adjusts the water allocation each year during the dry season based on seasonal forecasts and updated climate normals.

The premise that the storage in the reservoir is an indicator for occurrence of severe drought events has also been assumed by Chang and Wang (2013). Using neural network, the authors established the relationship between input and output patterns for definition of restriction in irrigation water supply.

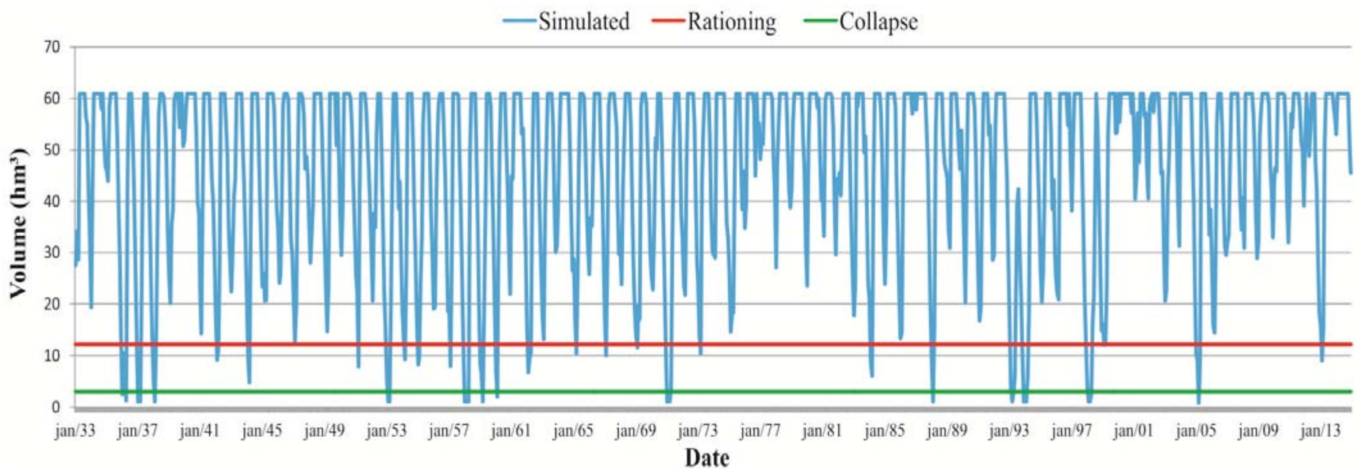

Fig. 8 Simulated storage considering the current operation rules.

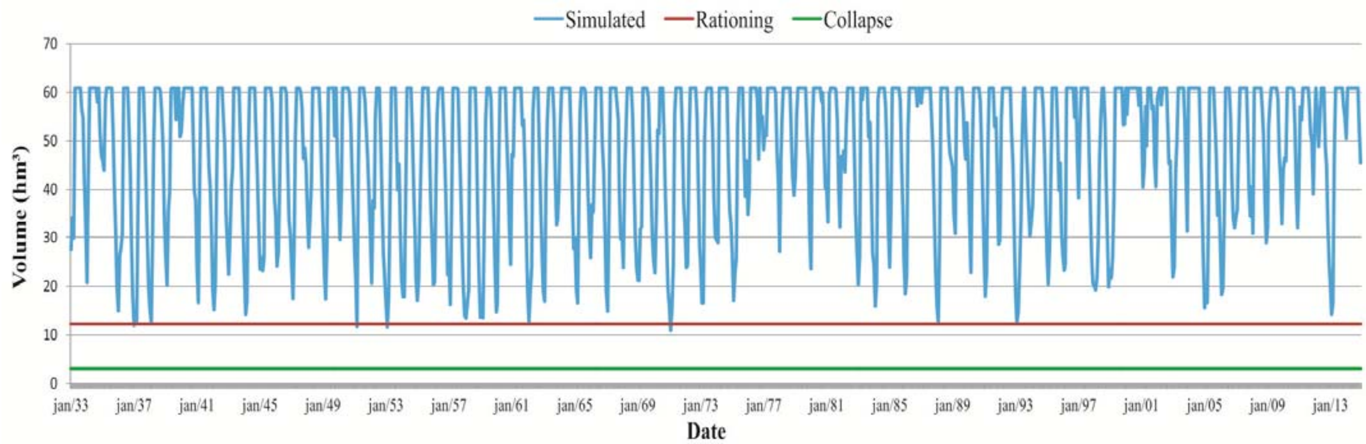

Fig. 9 Simulated storage considering the alternative operation rules for Pirapama reservoir.

CONCLUSION

The use of the current operation rules in the Pirapama reservoir may be unsustainable, considering the volume of water withdrawal from it. During the period between December 2012 and March 2013, the storage fell to the minimum values, obligating the state government to implement the rationing.

The assumption that the input streamflow is representative of the reservoir storage can be considered satisfactory for the purposes of the methodology. It is also possible to conclude that the percentage of withdrawal reduction (**Table 3**) obtained from other reservoir of the Pernambuco State did not jeopardize the effectiveness of the operation rules. Despite the satisfactory results, it is important to accomplish sensitivity analysis of the response goal values in **Table 3**. The new values assigned to the drought triggers would allow to verify the response in the reservoir conditions.

The operation rules proposed in this paper showed that it is possible to avoid the states of rationing and collapse in the reservoir applying drought triggers to reduce the water withdrawal. This strategy may be an efficient tool to deal with the climate variability present in Northeast Brazil, which can be amplified with the effects of the climate change. In this sense, the development of sustainable operation rules can be considered as an adaptation measure for reducing the impacts of possible climate changes in the future. The same operation rules can also be applied to the IPCC scenarios for evaluation of its effectiveness in reducing the vulnerability to climate change.

Acknowledgment This paper is a contribution of the Brazilian Network on Global Climate Change Research funded by CNPq Grant Number 550022/2014-7 and FINEP Grant Number 01.13.0353.00. The Research Grant 308464/2015-0 is also acknowledged.

REFERENCES

ANA – Agência Nacional de Águas (2012) *Plano de recursos hídricos da bacia do rio Piranhas-Açu RP-01-Relatório de programação*. http://piranhasacu.ana.gov.br/produtos/RP01.pdf. Accessed in 11 July 2014.

Braga, A.C.F.M., Silva, R.M., Santos, C.A.G., Galvão, C.O., Nobre, P. (2013) Downscaling of a global climate model for estimation of runoff, sediment yield and dam storage: A case study of Pirapama basin, Brazil. *J. Hydrol*. **498**(1), 46–58. Doi: 10.1016/j.jhydrol.2013.06.007

Cardoso, G.B.B., Martins, E.S.P.R., Souza Filho, F.A. (2006) Uso de otimização/simulação e previsão de afluências na operação tática dos reservatórios do sistema Jaguaribe-Metropolitano – CE. *Rev. Bras. Recur. Hídr.* **11**(4), 175–186.

Carvalho, M.A., Méllo Jr., A.V., Schardong, A., Porto, R.L.L. (2009) Decision support system for water allocation in irrigation projects. *Rev. Bras. Eng. Agríc. Amb.* **13**(1), 10–17. Doi: 10.1590/S1415-43662009000100002

Ceará (2005) Plano Estadual de Recursos Hídricos (PLANERH). Secretaria dos Recursos Hídricos-SRH. Fortaleza.

Chang, F.J. & Wang, K.W. (2013) A systematical water allocation scheme for drought mitigation. *J. Hydrol*. **507**(2), 124–133. Doi: 10.1016/j.jhydrol.2013.10.027

Georgakakos, A.P., Yao, H., Kistenmacher, M., Georgakakos, K.P., Graham, N.E., Cheng, F.-Y., Spencer, C., Shamir, E. (2012) Value of adaptive water resources management in Northern California under climatic variability and change: Reservoir management. *J. Hydrol*., **412–413**, 34–46. Doi: 10.1016/j.jhydrol.2011.04.038

Labadie, J. (1995) *MODSIM: River Basin Network Flow Model for conjunctive stream-aquifer management.* Program User Manual and Documentation, Colorado State University, Fort Collins.

Lopes, J.E.G., Braga, B.P.F., Conejo, J.G.L. (1981) Simulação hidrológica: Aplicações de um modelo simplificado. *Proc. III Simpósio Brasileiro de Recursos Hídricos*, 2, 42–62, Fortaleza.

Marengo, J. A., Jones, R., Alves, L. M., Valverde, M. C. (2009) Future change of climate in South America in the late twenty-first century: intercomparison of scenarios from three regional climate models. *Clim. Dynam*., **35**, 1073–1097. Doi: 10.1007/s00382-009-0721-6

McKee, T.B., Doesken, N.J., Kleist, J. (1993) The relationship of drought frequency and duration to the time scales. *Proc. Conference on Applied Climatology,* **8**. Anaheim, CA. Boston: American Meteorological Soceity, 179–184.

Miranda, R.B. & Mauad, F.F. (2015) Influence of sedimentation on hydroelectric power generation: case study of a Brazilian reservoir. *J. Energy Enging*. **141**(3). Doi: 10.1061/(ASCE)EY.1943-7897.0000183

Mo, K.C. (2008) Model-Based Indices over the United States. *J. Hydrometeor*. **9**, 1212–1230. Doi: 10.1175/2008JHM1002.1

Montenegro, S.M.G.L. & Ragab, R. (2012) Impact of possible climate and land use changes in the semiarid regions: a case study from North Eastern Brazil. *J. Hydrol*. **434**, 55–68. Doi: 10.1016/j.jhydrol.2012.02.036

Moriasi, D.N, Arnold, J.G, Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L. (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE*, **50**(3), 885–900.

Ncube S.P., Makurira, H., Kaseke, E., Mhizha, A. (2011) Reservoir operation under variable climate: Case of Rozva Dam, Zimbabwe. *Phys. Chem. Earth*, **36**(14-15), 1112–1119. Doi: 10.1016/j.pce.2011.07.059

Porto, R.L.L., Roberto, A.N., Schardong, A., Mello Júnior, A.V. (2003) Si*stema de suporte a decisão para análise de sistemas de recursos hídricos*. Métodos numéricos em recursos hídricos, edited by: Silva, R.C.V., ABRH, Porto Alegre.

Porto, R.Q., Melo, D.C., Almeida, C.N., Silans, A.M.B.P. (2008) Avaliação da escolha de diferentes Funções-Objetivo na calibração automática do modelo hidrológico SMAP. *Rev. Tecnol.* **29**(1), 27–36.

Ribeiro Neto, A., Scott, C.A., Lima, E.A., Montenegro, S.M.G.L., Cirilo, J.A. (2014) Infrastructure sufficiency in meeting water demand under climate-induced socio-hydrological transition in the urbanizing Capibaribe River basin – Brazil. *Hydrol. Earth Syst. Sci.*, **18**, 3449–3459. Doi: 10.5194/hessd-11-2795-2014

Rodella, L.M.A. (2014) Modelo de programação linear para apoio a decisão na distribuição de água de sistemas integrados de abastecimento. *PhD. Thesis*. Federal University of Pernambuco. http://repositorio.ufpe.br/ handle/123456789/12585. Accessed in 22 April 2016.

Serra, D.S. (2014) *Modelação de secas. Aplicação a casos de estudo*. Instituto Superior Técnico de Lisboa. https://fenix.tecnico.ulisboa.pt/downloadFile/395146394241/tese.pdf. Accessed in 06 August 2015.

Shukla, S. & Wood, A.W. (2008) Use of a standardized runoff index for characterizing hydrologic drought. *Geoph. Res. Letters*, **35** (2), Doi: 10.1029/2007GL032487.

UN-Water (2013) *Water Security & the Global Water Agenda - A UN-Water Analytical Brief*. United Nations University, Ontário-Canadá.

Ward, M.N., Brown, C.M., Baroang, K.M., Kaheil, Y.H. (2013) Reservoir performance and dynamic management under plausible assumptions of future climate over seasons to decades. *Climatic Change*, **118**(2), 307–320. Doi: 10.1007/s10584-012-0616-0

WMO – World Meteorological Organization (2014) *Statement on the status of the global climate in 2013*. WMO-No. 1130.

Zhou, Y. & Guo, S. (2013) Incorporating ecological requirement into multipurpose reservoir operating rule curves for adaptation to climate change. *J. Hydrol*. **498**, 153–164. Doi: 10.1016/j.jhydrol.2013.06.028