REVISTA DELOS DESARROLLO LOCAL SOSTENIBLE

Water balance in Volta Redonda city - Rio de Janeiro state – Brazil

Balanço hídrico na cidade de Volta Redonda - estado do Rio de Janeiro – Brasil

DOI: 10.55905/rdelosv16.n48-009

Recebimento dos originais: 18/09/2023
Aceitação para publicação: 19/10/2023

Hugo Thaner dos Santos
Doctor of Applied Meteorology
Institution: Parque Natural Municipal Carlos Roberto Firmino de Castro
Address: Estrada Vereador Carlos Campbell Vieira, 1482, Barra Mansa - RJ
E-mail: hugo.smmadsbm@gmail.com

Sergio Nascimento Duarte
Doctor in Agricultural Engineering
Institution: Universidade de São Paulo
Address: Avenida Pádua Dias, 11, Piracicaba - SP
E-mail: snduarte@usp.br

ABSTRACT
Cities do not perform assertive water resources' management, mainly due to lack of hydrological studies in the literature. Volta Redonda City fits this context, since it experiences several extreme rainfall events. The aims of the current study are to present estimates for evapotranspiration, water shortage and percolation, to address critical water-availability months and to feature the climate in the investigated region, based on the water balance method by Thornthwaite and Mather. Meteorological data recorded between 2001 and 2021, provided by the National Water and Basic Sanitation Agency and by the State Environmental Institute, were used to analyze water availability in the investigated city. Volta Redonda presented actual evapotranspiration equal to 90.6 mm month^{-1}; water deficit equal to 13.0 mm month^{-1} and water surplus equal to 22.8 mm month^{-1}. Climate in the region is humid; it presents small water shortage throughout the year and critical water availability from March to October. These months require greater attention in water management processes due to high deficit values recorded for water balance. Results in the current study are pioneering, since they present the analysis of meteorological data previously used for air quality control, only. Volta Redonda needs assertive water management, since it recorded higher water deficits than surpluses in 13 of the 20 analyzed years.

Keywords: drought, rainfall events, Paraíba do Sul River, extreme events, southern Rio de Janeiro.

RESUMO
As cidades não realizam uma gestão assertiva dos recursos hídricos, principalmente devido à falta de estudos hidrológicos na literatura. A cidade de Volta Redonda se encaixa nesse contexto, já que vive diversos eventos pluviométricos extremos. Os objetivos do presente estudo são apresentar estimativas de evapotranspiração, escassez de água e percolação, abordar meses

críticos de disponibilidade de água e caracterizar o clima na região investigada, com base no método de balanço hídrico por Thornthwaite e Mather. Dados meteorológicos registrados entre 2001 e 2021, fornecidos pela Agência Nacional de Água e Saneamento Básico e pelo Instituto Estadual do Ambiente, foram utilizados para analisar a disponibilidade de água na cidade investigada. Volta Redonda apresentou evapotranspiração real igual a 90,6 mm mês-1; déficit hídrico igual a 13,0 mm mês-1 e excedente hídrico igual a 22,8 mm mês-1. O clima na região é úmido; apresenta pequena escassez de água ao longo do ano e disponibilidade crítica de água de março a outubro. Estes meses exigem uma maior atenção nos processos de gestão da água devido aos elevados valores de défice registrados no balanço hídrico. Os resultados do presente estudo são pioneiros, pois apresentam a análise de dados meteorológicos usados anteriormente apenas para controle da qualidade do ar. Volta Redonda precisa de uma gestão assertiva da água, já que registrou déficits hídricos superiores aos superávits em 13 dos 20 anos analisados.

Palavras-chave: seca, eventos pluviométricos, Rio Paraíba do Sul, eventos extremos, sul do Rio de Janeiro.

1 INTRODUCTION

Extreme rainfall events are observed and reported on a daily basis, in different cities, both in Brazil and abroad. Floods and droughts happen every year; these extreme events are, oftentimes, not properly measured and it impairs the implementation of assertive water resources' management (CAMPOS et al. 2021; PIMENTEL & TEIXEIRA, 2023

Water resources' management lies on planning rational water use by agriculture, industry, commerce and people. However, it is worth emphasizing that such a water-use planning must take into account extreme minimum rainfall events, i.e., drought periods (ABATAN et al. 2022; TODOTE et al. 2021).

Drought takes place in months accounting for low air humidity rates. Low water content in the soil features agricultural drought, low water levels in reservoirs feature hydrological drought, whereas low incidence of rainfall events features meteorological drought (RAPOSO et al. 2023).

Volta Redonda, which is located in Southern Rio de Janeiro State, is one of the most populous cities in the whole state. It is part of Middle Paraíba do Sul hydrographic basin, besides composing the country's main road axis. In addition, it hosts the largest steel company in the country, as well as preserved fragments of the Atlantic Forest biome (SANTOS & DUARTE, 2023).

Water supplied to Volta Redonda City fully derives from Paraíba do Sul River; consequently, the entire city depends on the perennity of this river, as well as its normal surface and subsurface drainage processes, to ensure its full water supply. However, Volta Redonda often registers extreme minimum rainfall events, on a yearly basis, and it leads to decreased water supply frequency and lower water levels in Paraíba do Sul River.

The oldest rain gauge operating in Volta Redonda belongs to the National Water and Basic Sanitation Agency (also known as ANA); it has been monitoring rainfall events in the city since 1944. Air temperature in Volta Redonda has been monitored by meteorological stations belonging to the State Institute of the Environment (also known as INEA) since 2001. However, Volta Redonda rainfall and thermal data were not yet jointly analyzed to help better understanding water availability in the city, based on data collected *in situ* and on scientific research (PAULA & OLIVEIRA, 2021; PIMENTEL & TEIXEIRA, 2023).

Given the incidence of drought events, it is necessary monitoring rainfall events taking place in cities, along with air temperature, to enable estimating evapotranspiration, as well as water shortage and percolation in the soil. It must be done to help better understanding water availability in the investigated city all year long, as well as to propose assertive solutions for water management processes to be implemented in it (ABREU & HERNANDEZ, 2021; AUMASSANE & GASPARI, 2023).

If one takes rainfall as the only water source, the first water-use priority lies on evapotranspiration, whereas the second priority lies on water storage in the soil. Once plants' water demands and soil's storage capacity are met, if there is still water available, this water layer is percolated. Therefore, water availability in the soil can be estimated on a monthly basis, based on the Climatic Water Balance proposed by Thornthwaite and Mather (1955) (TODOTE et al. 2021; MOURA et al. 2023).

The aims of the current study were to present estimates for evapotranspiration, water shortage and percolation, to address critical water-availability months and to feature climate in the investigated region, based on the water balance method by Thornthwaite and Mather.

2 MATERIALS AND METHODS

2.1 METEOROLOGICAL DATA

Volta Redonda's rainfall and thermal data recorded from 2001 to 2021 were herein analyzed. The aforementioned data are available at HidroWeb portal, which belongs to the National Water and Basic Sanitation Agency (ANA), and at the Air Quality and Meteorology Database of the State Institute of the Environment (INEA), respectively.

2.2 WATER BALANCE

Annual thermal index was calculated based on mean monthly air temperatures. This index was used to estimate the potential monthly evapotranspiration rate in Volta Redonda, from 2000 to 2021, through Equations 1, 2, 3 and 4 (MARIN, 2021).

$$I = \sum_{i=1}^{12} i_t \tag{1}$$

$$i_t = \left(\frac{T_i}{5}\right)^{1,514} \tag{2}$$

$$ETp = q.16\left(10\frac{T_i}{I}\right)^{a} \tag{3}$$

$$a = \left[\left(6{,}75.10^{-7}\right).I^3\right] - \left[\left(7{,}71.10^{-5}\right).I^2\right] + \left[\left(1{,}792.10^{-2}\right).I\right] + 0{,}4924 \tag{4}$$

Wherein:

I = annual thermal index, dimensionless;
i_t = monthly thermal index, dimensionless;
T_i = monthly temperature, °C;
ETp = potential evapotranspiration, mm month^{-1};
a = meteorological constant, dimensionless; and
q = correction factor, dimensionless.

Correction factor (q) was estimated based on Earth:Sun ratio, by taking Volta Redonda's latitude as 22.5° S, through Equations 5, 6, 7 and 8 (PEREIRA et al. 2002).

REVISTA DELOS DESARROLLO LOCAL SOSTENIBLE

$$q = \frac{n_i}{30}\frac{N_i}{12} \tag{5}$$

$$N_i = \frac{2H}{15} \tag{6}$$

$$\arccos H = -tg(\theta)tg(\delta) \tag{7}$$

$$\delta = 23{,}45\,sen\left[\frac{360}{365}(284 + D_j)\right] \tag{8}$$

Wherein:

q = correction factor, dimensionless;
n_i = number of days in the month, dimensionless;
N_i = mean length of the day in the month, hours;
H = sunrise hour angle, degrees;
θ = latitude, degrees;
δ = solar declination, degrees; and
D_j = day of the year, dimensionless.

Water storage in the soil in Volta Redonda City was estimated by setting its available water capacity (CAD) at 100 mm, based on Equations 9, 10 and 11 (PEREIRA et al. 2002).

$$ARM_i = CAD.e^{\left(\frac{NegAc_i}{CAD}\right)} \tag{9}$$

$$NegAc_i = CAD.\ln\left(\frac{ARM_i}{CAD}\right) \tag{10}$$

$$ALT_i = ARM_i - ARM_{i-1} \tag{11}$$

Wherein:

ARM_i = monthly water storage in the soil, mm;
CAD = available water capacity, mm;

$NegAc_i$ = monthly accumulated negative value, mm;
ALT_i = monthly change in soil water, mm; and
ARM_{i-1} = soil water storage in the previous month, mm;

Actual evapotranspiration was estimated based on the following data: monthly rainfall rate, monthly soil-water change and monthly potential evapotranspiration (Equations 12 and 13). Monthly water shortage was calculated based on monthly values recorded for potential and actual evapotranspiration (Equation 14). Water surplus was calculated based on both rainfall rate and potential evapotranspiration (Equations 15 and 16) (PEREIRA et al. 2002).

$$ETr_i = ETp_i \quad \text{if } (P_i - ETp_i) \geq 0 \tag{12}$$

$$ETr_i = P_i + |ALT_i| \quad \text{if } (P_i - ETp_i) < 0 \tag{13}$$

$$DEF_i = ETp_i - ETr_i \tag{14}$$

$$EXC_i = P_i - ETp_i \quad \text{if } (P_i - ETp_i) \geq 0 \tag{15}$$

$$EXC_i = 0 \quad \text{if } (P_i - ETp_i) < 0 \tag{16}$$

Wherein:

ETr_i = actual evapotranspiration, mm month^{-1};
ETp_i = potential evapotranspiration, mm month^{-1};
P_i = rainfall, mm month^{-1};
ALT_i = change in soil water, mm month^{-1};
DEF_i = water shortage, mm month^{-1}; and
EXC_i = water surplus; mm month^{-1}.

Estimates of water input and output in water balance were confirmed through Equations 17, 18, 19 and 20 (ROLIM et al. 1998; MARIN, 2021).

$$\sum ALT = 0 \tag{17}$$

$$\sum P = \sum ETp + \sum (P - ETp) \quad (18)$$

$$\sum ETp = \sum ETr + \sum DEF \quad (19)$$

$$\sum P = \sum ETr + \sum EXC \quad (20)$$

Wherein:

ALT = annual change in soil water, mm;
P = annual rainfall, mm;
ETp = annual potential evapotranspiration, mm;
ETr = actual annual evapotranspiration, mm;
DEF = annual water shortage, mm; and
EXC = annual water surplus, mm.

2.3 CLIMATE CLASSIFICATION

Climate in Volta Redonda City was featured according to Thornthwaite’s methodology, based on using annual values recorded for potential evapotranspiration, as well as for water surplus and shortage (Equations 21, 22 and 23) (TODOTE et al. 2021).

$$I_h = \left(\frac{EXC}{ETP}\right)100 \quad (21)$$

$$I_a = \left(\frac{DEF}{ETP}\right)100 \quad (22)$$

$$I_u = I_h - 0{,}6 I_a \quad (23)$$

Wherein:

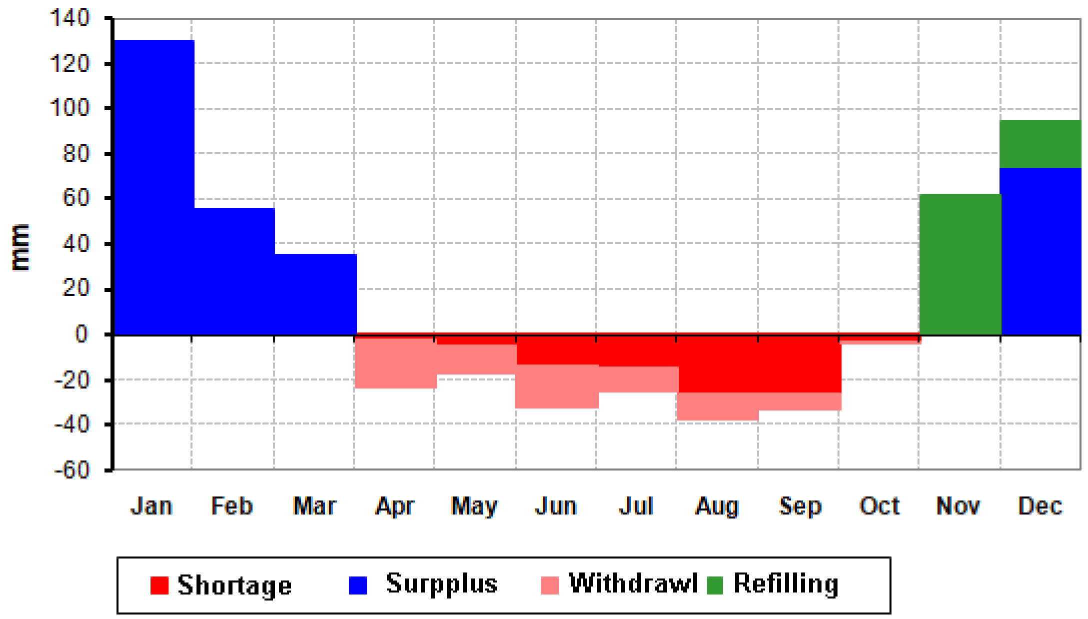
I_h = water index, dimensionless;
EXC = annual water surplus, mm;
ETp = annual potential evapotranspiration, mm;
I_a = aridity index, dimensionless;
DEF = annual water shortage, mm; and
I_u = humidity index, dimensionless.

3 RESULTS AND DISCUSSION

According to the water balance, Volta Redonda presents high water availability from the second half of October to late January, when high flood frequency is often recorded in it. Closer attention must be paid to drainage systems' maintenance at this time of the year (Figures 1, 2 and 3) (SANTOS & DUARTE, 2021; PIMENTEL & TEIXEIRA, 2023).

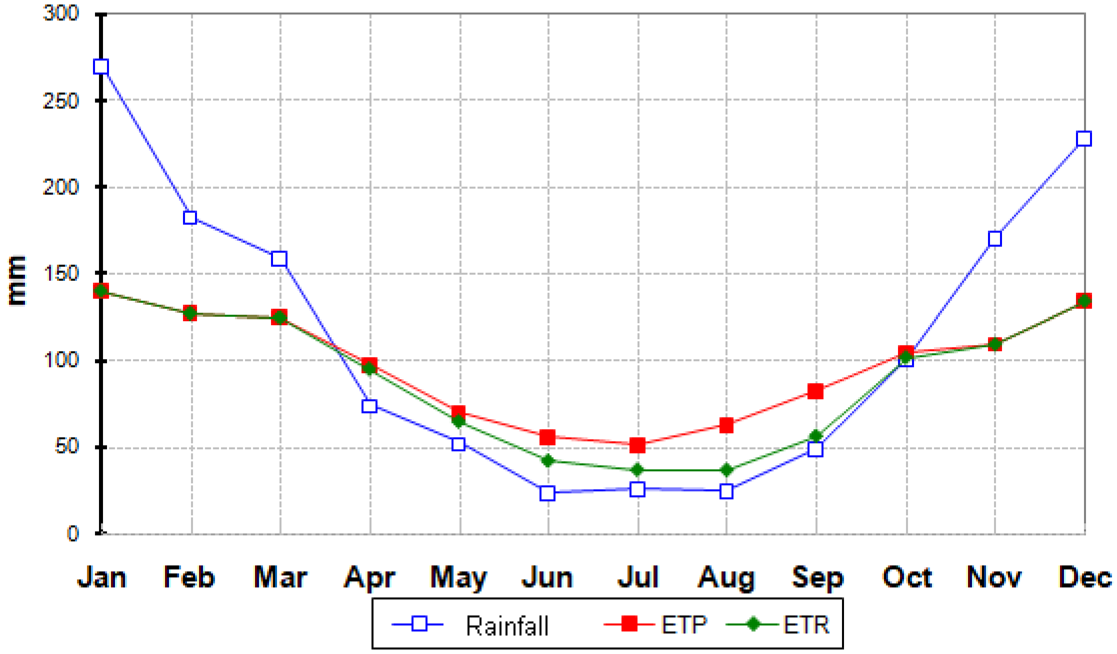
February was Volta Redonda's water balance threshold, since this is the time when the city presented significant decrease in rainfall rates in comparison to January. This factor emphasizes the water shortage that starts in March (Figures 2 and 3). This result was also observed by Silva Júnior et al. (2018), who analyzed rainfall data from Northwestern São Paulo State to help better understanding the critical agricultural months in Ilha Solteira region – SP.

Figure 1 – Water availability, Volta Redonda-RJ, Brazil, 2001-2021



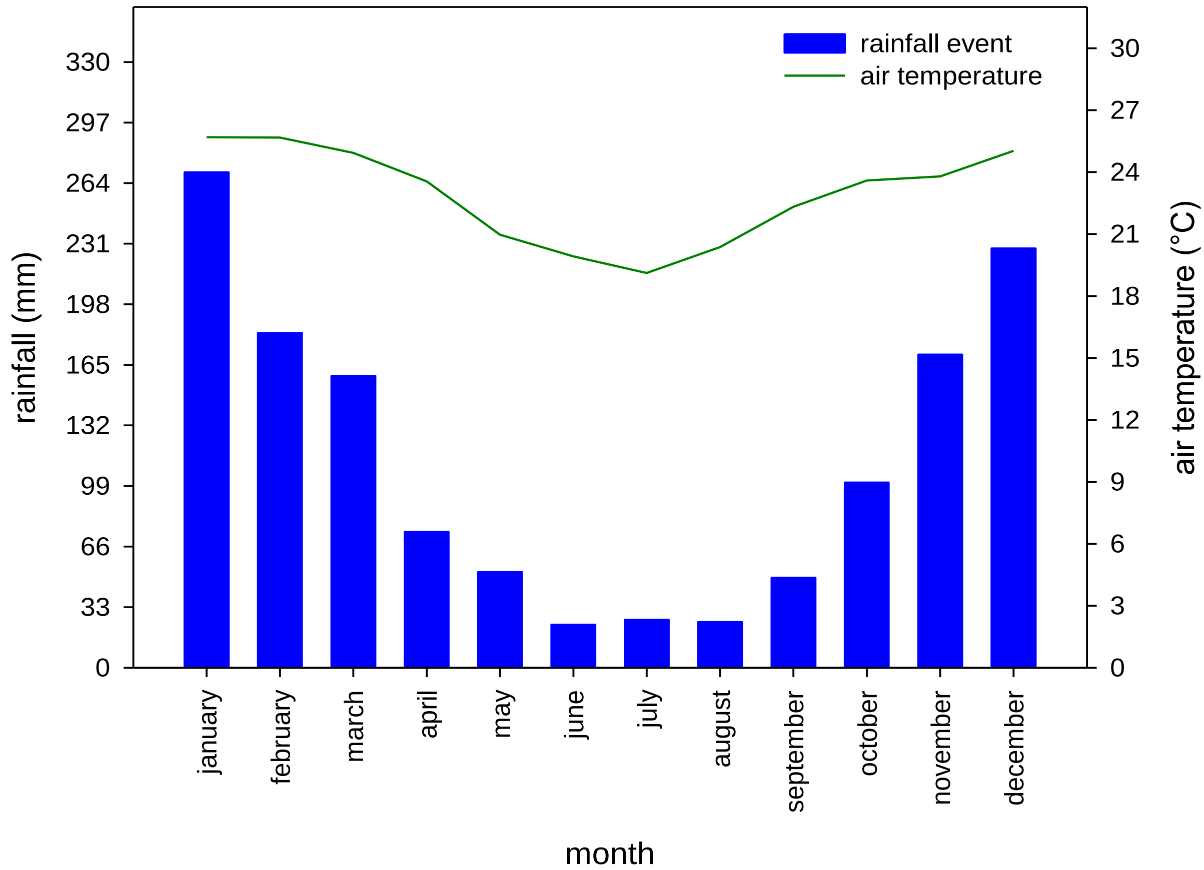
Source: Authors

Figure 2 – Water Balance by Thornthwaite and Mather (1955), Volta Redonda-RJ, Brazil, 2001-2021



Source: Authors

Figure 3 – Rainfall and air temperature data, Volta Redonda-RJ, Brazil, 2001-2021



Source: Authors

Based on the herein presented water balance results, it is possible stating that Volta Redonda has a drought period. Thus, the present water balance can be used to establish water management strategies aimed at water safety (BARROS et al. 2021; PIMENTEL & TEIXEIRA, 2023).

Results have shown that 2007, 2011, 2014 and 2021 were the driest years in Volta Redonda, a fact that can be explained by the El Ninõ in 2007, 2011 and 2021, as well as by the 2014 meteorological drought that affected the entire Brazilian Southeastern region (COSTA et al, 2018; CUNHA et al. 2019).

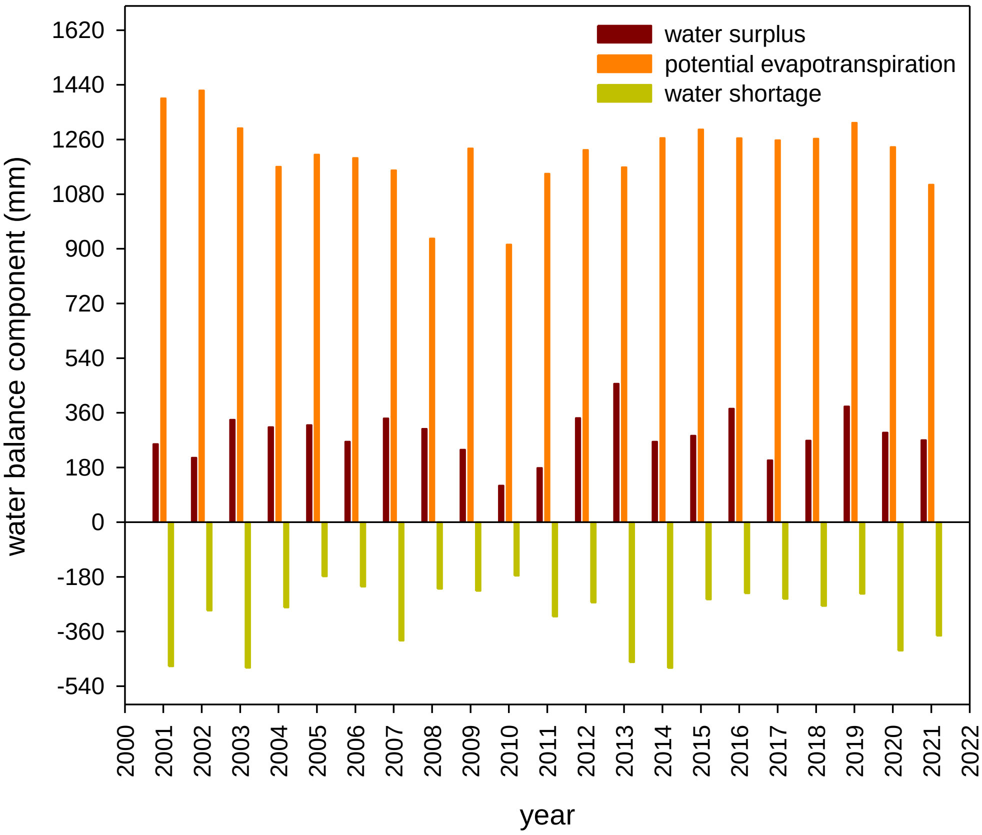
According to Formiga et al. (2015), the 2014 water crisis observed in Paraíba do Sul River basin has warned water resources' management bureaus about the need of continuously monitoring water resources, mainly the rainfall events, since Southern Rio de Janeiro State, the Metropolitan Region of Rio de Janeiro and Northern Rio de Janeiro State depend on this watershed, which is shared with two other states, namely: São Paulo and Minas Gerais.

Because rainfall is considered the only water input in the biosystem analyzed in the present water balance, monitoring rainfall incidence through rain gauges helps better understanding water availability for evapotranspiration purposes or the prevalence of latent heat flow in the environment to decrease water and to favor further rainfall formation (ROCHA et al, 2022).

Water storage in the soil is the second water balance priority. Volta Redonda should adopt rational and conservationist soil-use strategies to enable increasing water storage in it and to ensure the conservation of green areas near both Paraíba do Sul River and their respective tributaries, because vegetation contributes to rainfall formation, besides improving water storage capacity (ALVES et al, 2020).

The incidence of drought events in Volta Redonda can be confirmed through aridity (I_a = 14.9) and humidity (I_u = 21.2) indices established in the climate classification by Thornthwaite. Thirteen (13) of the 20 years analyzed in the current study recorded higher water shortage (in module) than water surplus values (Figure 4).

Figure 4 – Climate Classification by Thornthwaite, Volta Redonda-RJ, Brazil, 2001-2021



Source: Authors

Based on the analyzed aridity and humidity rates, climate in Volta Redonda is classified as humid, with small water shortage over the year. Vassouras and Piraí, which are municipalities close to Volta Redonda, had their rainfall and thermal data analyzed by Sentelhas et al (2016) and received the same climate classification as Volta Redonda (Table 4).

Table 1 – Climate classification by TH, Volta Redonda – RJ, Brazil, 2001-2021

	Volta Redonda	Piraí*	Vassouras*
water index (I_h)	30.3	35.1	35.4
aridity index (I_a)	14.9	1.5	4.3
humidity index (I_u)	21.2	34.2	32.8

Source: *Sentelhas et al. (2016)

Although Volta Redonda, Vassouras and Piraí share the same watershed, they differ from each other in area and land use. Volta Redonda accounts for the smallest area and the largest soil waterproofing due to the extent of its urban perimeter. On the other hand, Vassouras and Piraí present urban perimeter smaller than that of Volta Redonda, but they account for large and preserved Atlantic Forest areas and their soil is mainly used for livestock, fruit growing and olericulture purposes. Based on this information, it is possible understanding differences recorded for aridity, evapotranspiration and water shortage index values in these municipalities (Tables 1 and 2).

Table 2 – Water availability in Middle Paraíba do Sul.

		Volta Redonda	Piraí*	Vassouras*
Air temperature (°C)		22.9	20.9	20.8
Water availability (mm)	Rainfall events	113.4	110.3	107.0
	Potential evapotranspiration	104.1	82.5	81.6
	Actual evapotranspiration	90.6	81.3	78.1
	Water shortage	13.0	1.2	3.5
	Water surplus	22.8	29.0	28.9

Source: *Sentelhas et al. (2016)

Volta Redonda recorded higher evapotranspiration values because its air is drier than that of Piraí and Vassouras, due to its small green area (forests, afforestation and agricultural fields); this effect is known as heat island. The drier air in Volta Redonda enhances plants' perspiration and the evaporation of water available in water bodies (PEREIRA et al. 1997).

Unlike Piraí and Vassouras, which have extensive green areas, much of Paraíba do Sul riverbed and their respective tributaries in Volta Redonda do not present riparian forests. Consequently, wind actions enhance water evaporation in Volta Redonda's water bodies, and it leads to higher evapotranspiration and water shortage values (FERNANDES et al. 2015).

Results in the current study are pioneering, since they refer to the analysis applied to data provided by meteorological stations that have only focused on monitoring air quality, so far. The present research emphasizes that Volta Redonda should implement assertive water resources' management strategies, given the high incidence of drought events observed in it, in the last 20 years, and its annual water shortage.

4 CONCLUSION

Volta Redonda experienced actual evapotranspiration equal to 90.6 mm month^{-1}, water shortage equal to 13.0 mm month^{-1} and water surplus equal to 22.8 mm month^{-1}, from 2001 to 2021.

According to the climate classification by Thornthwaite, climate in Volta Redonda is humid and presents small water shortage throughout the year.

Water availability in Volta Redonda reaches critical levels from March to October, when closer attention should be given to water management in this municipality, due to high water shortage values observed in its water balance.

REFERENCES

Abatan, A. A. Tett, S. F. B. Dong, B. Cunningham, C. Rudorf, C. M. Klingaman, N. P. Abreu, R. C. (2022). Drivers and physical processes of drought events over the State of São Paulo, Brazil. *Climate Dynamics*, 58, 3105–3119.

Abreu, P. A. S. Hernandez, F. B. T. (2021). Balanço hídrico climatológico normal e sequencial do município de Pereira Barreto -SP como auxilio para o planejamento da agricultura irrigada. *Irriga*, 1, 530-545.

Alves, J. D. N. Ribeiro, A. Rody, Y. P. Loos, R. A. Hall, K. B. (2021). Carbon uptake and water vapor exchange in a pasture site in the Brazilian Cerrado. *Journal of Hidrology*, 594, 1-10.

Aumassanne, C. M. Gaspari, F. J. (2023). Conceptos para manejo integrado de cuencas. caso de estudio: Río Colorado, Argentina. *Boletín Geográfico*, 45, 1-21.

Barros, F. C. Martins, S. C. F. Lyra, G. B. Silva, L. D. B. Francisco, J. P. Abreu, M. C. Lyra, G. B. (2021). Thornthwaite and Mather soil water balance model adapted for estimation of real evapotranspiration of the pasture. *Engenharia na Agricultura*, 29, 146-156.

Campos, J. A. Silva, D. D. Moreira, M. C. Menezes Filho, F. C. M. Environmental fragility and land use capacity as instruments of environmental planning, Caratinga River basin, Brazil. *Environmental Earth Sciences*, 80, 264-266.

Costa, L. F. Farias, J. E. F. Chargel, L. T. (2018). A precipitação traduzida em índices: o Estado do Rio de Janeiro enfrentando a pior estiagem dos últimos 85 anos. *INEANA*, 5, 56-76.

Cunha, A. P. Zeri, M. Leal, K. D. Costa, L. Cuartas, L. A. Marengo, J. A. Tomasella, J. Vieira, R. M. Barbosa, A. A. Cunningham, C. Garcia, J. V. C. Broedel, E. Alvalá, R. Ribeiro-Neto, G. (2019). Extreme drought events over Brazil from 2011 to 2019. *Atmosphere*, 10, 642-655.

Fernandes, L. S. Silva, S. Silva, L. C. Acselrad, M. V. Pimentel, I. M. C. Farias, J. E. F. Johnsson, R. M. F. (2015). Águas do Rio: um panorama geral da disponibilidade hídrica no Estado fluminense. *INEANA*, 3, 6-25.

Formiga, R. M. Costa, L. F. Farias, J. E. F. Acserald, M. V. (2015). Segurança hídrica do Estado do Rio de Janeiro ante a transposição paulista de águas da Bacia Paraíba do Sul: relato de um acordo federativo. *INEANA*, 3, 48 – 69.

Marin, F. R. (2021). *Microclimatologia agrícola: introdução biofísica da relação planta-atmosfera*. Piracicaba: FEALQ.

Moura, D. M. B. Nascimento, D. T. F. Oliveira, I. J. (2023). Caracterização climática de Iporá, Goiás: Insumos para a avaliação da disponibilidade hídrica para abastecimento público. *Elisée*, 12, 10 - 13.

Paula, L. S. Oliveira, G. G. (2021). Incertezas associadas ao uso do sensoriamento remoto na estimativa do balanço hídrico. *Anuário do Instituto de Geociências*, 44, 6-12.

Pereira, A. R. Angelocci, L. R. Sentelhas, P. C. (2002). *Agrometeorologia: fundamentos e aplicações práticas*. Guaibá: Agropecuária.

Pereira, A. R. Villa Nova, N. A. Sediyama, G. C. (1997). *Evapo(transpi)ração*. Piracicaba: FEALQ.

Pimentel, P. G. Teixeira, W. G. (2023). Análise dos eventos hidrológicos críticos no bairro do Jardim Botânico, Rio de Janeiro. *DELOS: Desarrollo Local Sostenible*, 16, 1931-1945.

Raposo, V. M. B. Costa, V. A. F. Rodrigues, A. F. (2023). A review of recent developments on drought characterization, propagation, and influential factors. *Science of the Total Environment***,** 898, 550 – 553.

Rocha, A. E. Q. Santos, E. A. Patrignani, A. (2022). Partitioning evapotranspiration in a tallgrass prairie using micrometeorological and water use efficiency approaches under contrasting rainfall regimes. *Journal of Hidrology*, 608, 2-11.

Rolim, G. S. Sentelhas, P. C. Barbieri, V. (1998). Planilhas em ambiente EXCEL para os cálculos de balanços hídricos: normal, sequência e de cultura e de produtividade real e potencial. *Revista Brasileira de Agrometeorologia*, 6, 133-137.

Santos, H. T. Duarte, S. N. (2021). Heavy rainfall events in Volta Redonda. *IRRIGA*, 26, 801-813.

Santos, H. T. Duarte, S. N. (2023). Rainfall data adjustment to Volta Redonda macro-region. *Brazilian Journal of Biosystems Engineering*, 16, 1-8.

Sentelhas, P. C. Pereira, A. R. Marin, F. R. Angelocci, L. R. Alfonsi, R. R. Caramori, R. H. Swart, S. (2023, 08 de setembro) *Balanços hídricos climatológicos de 500 localidades brasileiras*. Recuperado de http://www.leb.esalq.usp.br/Nurma .

Silva Junior, J. F. Hernandez, F .B. T. Silva, I. P. F. Reis, L. S. Teixeira, A. H. C. (2018). Stablishment of critical months to irrigated agriculture from a water balance study. *Brazilian Journal of Biosystems Engineering*, 12, 122-131.

Thornthwaite, C. W. Mather, J. R. (1955). The water balance. *Publications in Climatology*. New Jersey: Drexel Institute of Technology.

Todote, V. A. L. Lyra, G. B. Abreu, M. C. (2021). Climatological water balance and climate classification of Thornthwaite and Mather for Benin, West Africa, in 1970-2015 period. *Engenharia na Agricultura*, 29, 291-302.