







Effects of floating macrophytes on open-water evaporation in a Brazilian tropical reservoir

Italo Sampaio Rodrigues^{a,b,*} , Carlos Alexandre Gomes Costa^a ,
Adunias dos Santos Teixeira^a , Iran Eduardo Lima Neto^c , Fernando Bezerra Lopes^a ,
José Carlos de Araújo^a 

^a Department of Agricultural Engineering, Federal University of Ceará, Brazil

^b Department of Geography and Environment, University of Lethbridge, Canada

^c Department of Hydraulic and Environmental Engineering, Federal University of Ceará, Brazil

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ABSTRACT

This paper aims to estimate the open-water evaporation (from 1990 to 2021) in an urban reservoir in Brazil and assess the relationship between floating macrophyte coverage (MC) and open-water evaporation, as well as their spatial variability. The Surface Energy Balance System for Water (AquaSEBS) provided similar (root mean square error of 0.5 mm/day) results to reference measurements of class A pan (correction coefficient of 0.7). The discharge of sewage into this urban tropical reservoir resulted in a portion of this reservoir being covered by floating macrophytes. During the study period, positive trends of floating MC area were observed. The days with floating macrophytes depicted higher spatial variability over the open-water evaporation. Furthermore, MC was negatively correlated with the open-water evaporation flux ($R^2 = 0.65$) and led on average to a 17 % reduction (varying from 9 % to 35 %) in the estimated evaporation rate in the free water surface. Overall, the results of this study demonstrate the usefulness of remote sensing products to estimate reservoir open-water evaporation and outline the need to better understand the relationship between MC and reservoir open-water evaporation in tropical and semi-arid areas.

1. Introduction

The semi-arid Brazilian Northeast Region (BNR) suffers from water scarcity as a result of low and irregular rainfall associated with high potential evaporation rates (Azevedo et al., 2018; Raulino et al., 2021; Costa et al., 2021), often exceeding 2,000 mm per year (Mamede et al., 2012). To ensure secure water supply across the state of Ceará (part of the BNR), thousands of small dams and some large reservoirs (over 30,000 reservoirs, see Mamede et al., 2018) were built to capture and store water during the short periods of excess rainfall and create a reserve for the dry season (Campos et al., 2016; Rabelo et al., 2021). The high-density network of reservoirs across the state affects significantly water availability for local communities (Malveira et al., 2011), power demand (Nascimento et al., 2019), sediment dynamics (Lima Neto et al., 2011), and flood and drought mitigation (Peter et al., 2014).

High evaporation in the area increases the possibility of water scarcity and, therefore, significantly affects the primary function of

these reservoirs. The reservoir morphology is one of the main drivers of evaporation, as reservoirs are typically slightly convex and shallow, which results in a high exposure surface even for low storage volumes (Campos et al., 2016). Assessing the evaporation losses is the basis for an accurate evaluation of the real and potential volume of available water in the BNR (Rodrigues et al., 2021a).

A variety of equations and methods are available to estimate the reservoir evaporation rate; they are generally based on solar radiation and temperature, mass-transfer, pan coefficient, turbulent vortex covariance, energy budget, or a combination of the aforementioned methods (McMahon et al., 2016). Besides, a number of predictive methods have been developed recently, such as artificial neural networks (Keshtegar et al., 2019), machine learning (Yaseen et al., 2020), hydrologic models coupled with climate modeling systems (Friedrich et al., 2018) or eddy covariance systems (Xiao et al., 2018), floating evaporation pan in a free-water surface (Masoner et al., 2008), remote sensing (RS) (McCabe et al., 2019), and combining RS with modeling

* Corresponding author. Department of Agricultural Engineering, Federal University of Ceará, Brazil.
E-mail address: italo.rodrigues@uleth.ca (I.S. Rodrigues).

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approaches (Zhao and Gao, 2019; Zhao et al., 2020).

Regarding evaporation, recent studies suggested that eutrophication would attenuate evaporation rates in lakes (Mesquita et al., 2020; Mesquita and Lima Neto, 2022). Many reservoirs in the BNR are prone to eutrophication. This process is the result of sediment and nutrient transfer from the catchment to the reservoirs resulting in elevated nutrient concentrations, including phosphorus (Lira et al., 2020; Rocha and Lima Neto, 2021a, 2021b, 2022; Wiegand et al., 2021; Lima Neto et al., 2022). Reservoir eutrophication is directly related to nutrient content, which also influences the growth of macrophytes. Sediment deposition reduces storage capacity and modifies the reservoir morphology, making it shallower and more susceptible to evaporation losses (De Araújo et al., 2006). Nutrient input in reservoirs may, however, decrease the evaporation rate as a consequence of reduced light penetration due to high turbidity (Mesquita et al., 2020; Havens and Ji, 2018). In addition, heavy rainfall generates high river flows, which resuspend sediments and associated nutrients from the hypolimnion zones, leading to macrophyte growth (Fraga et al., 2020). Floating macrophytes can be observed in thousands of reservoirs scattered across the BNR, most likely due to the highly eutrophic waters (De Toledo et al., 2014; Coelho et al., 2017; Zhang et al., 2018; Araújo et al., 2019).

While existing studies (e.g., Anda et al., 2018; Sánchez-Carrillo et al., 2004; Wondim and Melese, 2023) have quantified how floating macrophytes reduce evaporation within their immediate coverage area, their effects on the open water areas of the lake have yet to be explored. Therefore, since the presence of floating macrophytes is common in reservoirs in the state of Ceará, Brazil, and other tropical and semi-arid areas, understanding the effect of macrophyte growth on the open water evaporation rates is crucial for a better comprehension of reservoir dynamics. Thus, this research seeks to estimate open-water evaporation in

lakes using a remote-sensing-based model, to investigate the influence of floating macrophyte coverage (MC) on reservoir open-water evaporation. Besides, we aim at evaluating how macrophytes influence the spatial variability of open-water evaporation.

The study begins with a description of the study area (2.1) and the modelling framework (2.2), followed by remote sensing data processing (2.3), macrophyte extent estimation (2.4), evaporation modelling (2.5), in-situ validation (2.6), and statistical analysis (2.7). It will conclude with an examination of macrophyte-evaporation interactions (2.8). The results in Section 3 show how precise the model is (3.1), estimates of evaporation using remote sensing (3.2), changes in macrophyte cover (3.3), and the relationship between macrophyte cover and evaporation from open water (3.4). Section 4 discusses the spatial evaporation dynamics (4.1), macrophyte impacts (4.2), and uncertainty sources (4.3). Section 5 synthesizes the consequences for water resource management.

2. Methodology

2.1. Study area

The study was conducted in the Santo Anastácio Reservoir (Fig. 1), which is located on the campus of the Federal University of Ceará (UFC) (Fortaleza, Brazil). Santo Anastácio has a total capacity of about 0.4 hm³, area of 0.16 km² which tends to maintain its level practically constant through the year, as it is supplied by a polluted urban drainage channel (Araújo et al., 2019; Fraga et al., 2020; Mesquita et al., 2020), and the catchment area is considerably impermeable (Mesquita et al., 2020). Therefore, this reservoir does not supply any community. This reservoir is located in a coastal area, classified as tropical wet and dry (Aw/As) according to Köppen's climate classification. The mean



Fig. 1. Location of the study reservoir (Santo Anastácio) in the state of Ceará, Brazil, and details of the urban drainage channel that supplies this reservoir.

interannual temperature is 26 °C, wind speed is 4.0 m/s, solar radiation is 2800 h/year, relative humidity is 78 % and rainfall is 1600 mm/year (INMET, 2019).

2.2. Modelling framework

The impact of floating macrophytes on reservoir open-water evaporation analysis workflow adopted five steps, as shown in Fig. 2: i) Acquisition of remote sensing data; ii) Identification of floating MC and open water extent in the Santo Anastácio reservoir; iii) Estimation of reservoir open-water evaporation; iv) Evaporation model validation; and v) Assessment of the impact of floating macrophytes on the spatial variability of open-water evaporation.

2.3. Remote sensing data and processing

The investigation period spanned from 1990 to 2021 and used a total of ten satellite scenes: fifteen from Landsat 5 and eleven from Landsat 8, as shown in Fig. 2. In total, 26 scenes were used (Collection 2, Level 2 surface reflectance), which represents about 4 % of the total catalogue; the reason is the high cloud cover of the Atlantic Ocean. These scenes were acquired through the United States Geological Survey portal (Missions, 2016). As the majority of evapotranspiration is in the dry season (>80 %, as noted in De Araújo and González-Piedra, 2009; Mamede et al., 2012), the chosen months were all between June and December.

2.4. Estimation of the surface extent of floating macrophytes

The unsupervised k-means classification algorithm was used to assess and extract the open water and floating macrophyte surface extent of the ten satellite scenes. K-means is a well-known partitioning clustering method, widely adopted due to its simplicity and efficiency in application (Han et al., 2011). This approach was also adopted by other authors in the study region (Silva and Souza, 2018; Brasileiro et al., 2016) and has proved highly accurate with *in-situ* measurements of vegetation and open water extent. The spectral absorptions ranging between 440 and 560 nm and of 670 nm, characteristic of floating macrophytes (Matthews, 2011), were used in this study. Furthermore, the reservoir under study (Santo Anastácio) is artificially perennialized from urban sewage while receiving significant phosphorus influx, leading to eutrophic and hypereutrophic conditions, as documented by Araújo et al. (2019), Fraga et al. (2020) and Mesquita et al. (2020). Thus, there is always water flowing into the spillway; therefore, everything that is not open water on the reservoir surface consists of floating macrophytes. The unsupervised classification was performed using the software QGIS version 2.18.

2.5. Remote sensing-based evaporation model

The open water evaporation rate was estimated with the remote sensing algorithm Surface Energy Balance System for Water (AquaSEBS,

see Abdelrady et al., 2016). The algorithm is a modification from Su (2002) and was created to estimate the heat fluxes by fusing satellite data and hydro-meteorological field data. AquaSEBS was chosen because it has been validated on the study region (Rodrigues et al., 2021a, 2021b) and worldwide (Losgedaragh and Rahimzadegan, 2018). AquaSEBS requires three types of datasets: (i) remote sensing data: emissivity, surface albedo and surface temperature of the water (°C); (ii) meteorological data: air temperature (°C), wind speed (m/s), air humidity (%); and vapor pressure deficit (hPa); and (iii) radiative forcing parameters: downward shortwave (W/m^2) and long-wave radiations (W/m^2). The understanding of the spatial evaporation dynamics on the surface of reservoir open water is made possible using remote sensing-based model (i.e., AquaSEBS). For the temporal estimation of open-water evaporation Landsat 5 (Thematic Mapper – TM) and 8 (Optical Land Imager – OLI) were used.

AquaSEBS calculates the instantaneous latent heat flux of open-water evaporation using energy balance (Equation (1)), and as a result, evaporation is computed for each pixel of the scene. The energy balance of the water surface can be expressed as it follows: The daily open-water evaporation E_d (mm/day) was obtained using Equation (1):

$$E_d = \frac{R_n - G_0 - H}{\lambda v \rho} \quad (1)$$

R_n is net radiation at the water surface (W/m^2), G_0 is the water heat flux (W/m^2), H is sensible heat to the air (W/m^2), λv is the latent heat of vaporization (assumed 2.5 MJ/kg), ρ is the density of water (assumed 1000 kg/m³). The detailed equations used to calculate open-water evaporation using AquaSEBS can be found in the Supplementary Material A and Table S1. The Raster Calculator tool (implemented in QGIS version 2.18) was applied to perform the AquaSEBS. The AquaSEBS algorithm was applied exclusively to estimate evaporation from the open water pixels of the reservoir. The AquaSEBS outputs raster data that shows the spatial variation of open-water evaporation. The data was visually interpreted to analyze the spatial variation of open-water evaporation during periods with and without presence of floating MC. Thus, assessing the higher or lower spatial variability of floating macrophytes on the open-water evaporation.

2.6. In-situ measurements and reference data

To assess the efficiency of the AquaSEBS model, a class A pan evaporimeter with classic installation (CAPC) was used, as its data spanned from 1970's up to date. The CAPC was placed on the ground at UFC, around 1.0 km from the Santo Anastácio Reservoir. The correction coefficient (K_p) was assumed to be 0.7 (Linacre, 1994; Mamede et al., 2012).

The Penman-Monteith equation was also used as a second method to estimate the reference evaporation. The hydrometeorological data (vapor pressure, relative humidity and wind speed) were obtained from the UFC Campus, nearly 1.0 km from the Santo Anastácio Reservoir. The E_d was obtained using Equation (2):

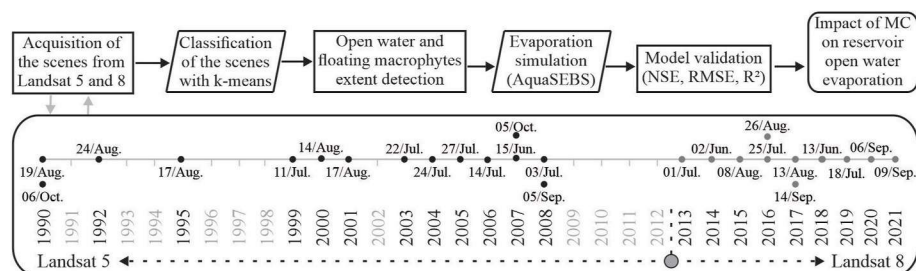


Fig. 2. Flow chart of the methodology used to assess the impact of floating MC on reservoir open water evaporation. Dates - Landsat 5 and 8 scenes availability; Years in black – Years with available scenes; Years in grey – Years without available scenes.

$$E_d = \frac{\Delta(R_n - G_0) + \rho_a c_p \left(\frac{e_s - e_a}{r_a} \right)}{\lambda \left(\Delta + \gamma \left(1 + \frac{r_s}{r_a} \right) \right)} \quad (2)$$

where R_n is the net radiation incident upon the water surface (W/m^2), γ is the psychrometric constant ($kPa/^\circ C$) (reference value: $0.054 kPa/^\circ C$); Δ is the rate of change of the saturation vapor pressure with temperature ($kPa/^\circ C$), G_0 the internal water body heat flux (W/m^2), ρ_a is the air density for a given air pressure (kg/m^3); c_p represents the specific heat of the air ($MJ/kg^\circ C$), e_s the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa); r_a represents air resistance (s/m), r_s is surface resistance (s/m ; considered as 0 for open water), and λ represents the volumetric latent heat coefficient ($2453 MJ/m^3$). For more details on how all the aforementioned parameters were calculated, see Monteith (1965) and Zotarelli et al. (2010).

2.7. Statistical analysis

The Nash Sutcliffe (NSE) (Nash and Sutcliffe, 1970), root mean square error (RMSE), percentage bias (PBIAS) and coefficient of determination (R^2) were used as objective functions to compare the reference open-water evaporation obtained from the class A pan and Penman-Monteith equation, and those estimated from the AquaSEBS model. These statistics were calculated based on the average of all evaporation pixels resulting from the AquaSEBS (as per Rodrigues et al., 2021a, 2021b).

Statistical trend analysis was performed to evaluate the MC area trends spanning 31 years using the Mann-Kendall method, alongside Sen's slope test (Mann, 1945; Kendall, 1957), utilising pyMannKendall (Hussain and Mahmud, 2019). The nonparametric Mann-Kendall test serves as a valuable tool for trend analysis due to its robustness against outliers, lack of distributional assumptions, and minimal sensitivity to abrupt shifts in time series (Rodrigues et al., 2024a;b; Soares et al., 2024). To assess trends in the MC area three hypotheses were considered: (i) trend is present over the specified period, (ii) a positive trend is observed, and (iii) a negative trend is noted. A significance level or p-value of 0.05 was assumed.

2.8. Impact of floating macrophyte cover on open-water evaporation

To assess the impact of floating macrophytes on open-water evaporation, the evaporation estimates of the AquaSEBS algorithm were used in Equation (3) to calculate the relative (%) reduction of evaporation (MC_{re}) between 1995 and 2015:

$$MC_{re} = \frac{(EM^c - EM)}{EM^c} \quad (3)$$

Where EM^c is the average open-water evaporation rate without MC

(mm/day) and EM is the open-water evaporation rate (according to AquaSEBS results) with a floating MC (mm/day). In order to classify the days with and without macrophytes the classification from Deppe and Lathrop (1992) was used, which considers four classes of floating MC: No floating macrophytes/sparse (i.e. <25 % cover), moderate (from 25 to 50 %), dense (from 50 to 75 %), and very dense (from 75 to 100 %).

3. Results

3.1. Model accuracy

Fig. 3 displays the average evaporation pixels of AquaSEBS for the open water of the Santo Anastácio reservoir along with reference data class A pan evaporimeter with classic installation (CAPC) and Penman-Monteith equation. Performance was high, with an NSE ranging from 0.51 to 0.53, RMSE from 0.55 to 0.45 mm/day, R^2 from 0.92 to 0.94, and PBIAS from -2.84 % to 6.67 %. These small errors and bias make it possible to use AquaSEBS for estimating the Santo Anastácio reservoir open-water evaporation. The evaporation volume losses of the Santo Anastácio reservoir amounted to values between 350 and 1,040 m^3/day . The daily evaporation estimates (AquaSEBS), and reference (CAPC and Penman-Monteith) datasets are shown in Supplementary material B, Table S2.

3.2. Remote sensing to estimate reservoir open-water evaporation

Applying the AquaSEBS to the scenes made it possible to evaluate the spatial variability of evaporation at the respective open water surface (Fig. 4). The higher evaporation rates were noticed on the days with the greater free water surface, i.e., without macrophyte cover (MC). In contrast, the days with higher MC depicted lower evaporation rates as well as higher spatial variability over the free surface of the water (Fig. 4).

3.3. Estimates and trends of floating-macrophyte cover

The open water surface area of the Santo Anastácio reservoir was outlined, and it varied considerably. This was directly related to variations in floating MC (Fig. 5a), as also noted in Fraga et al. (2020) and Mesquita et al. (2020). From 1990 to 2021, significant (p-value 0.05) positive trends of MC area ($+0.0007 km^2/year$ or increase of $0.02 km^2$ in 31 years) were observed (Fig. 5b). Compared to the Santo Anastácio reservoir area (i.e., $0.2 km^2$), the positive trend of MC area indicates an increase of ~10 % over the last three decades.

Fig. 5 illustrates how the amount of floating macrophytes in the Santo Anastácio reservoir varies throughout the years. The largest extent of MC occurred on September 14, 2017 (50 % cover). Overall, twelve scenes showed a floating MC (Aug. 24, 1992; Aug. 17, 1995; Jul. 11, 1999; Aug. 17, 2001; Jul. 01, 2013; Jun. 06, 2014; Aug. 08, 2015; Jul.

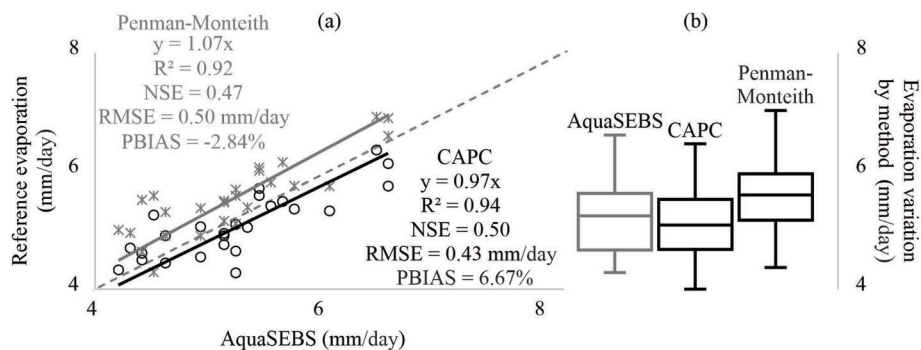


Fig. 3. Performance of modeled open-water evaporation (x-axis) using AquaSEBS compared with reference evaporation (y-axis) (CAPC, and the Penman-Monteith equation) (a). Variation of evaporation rates according to the scattered values (b).

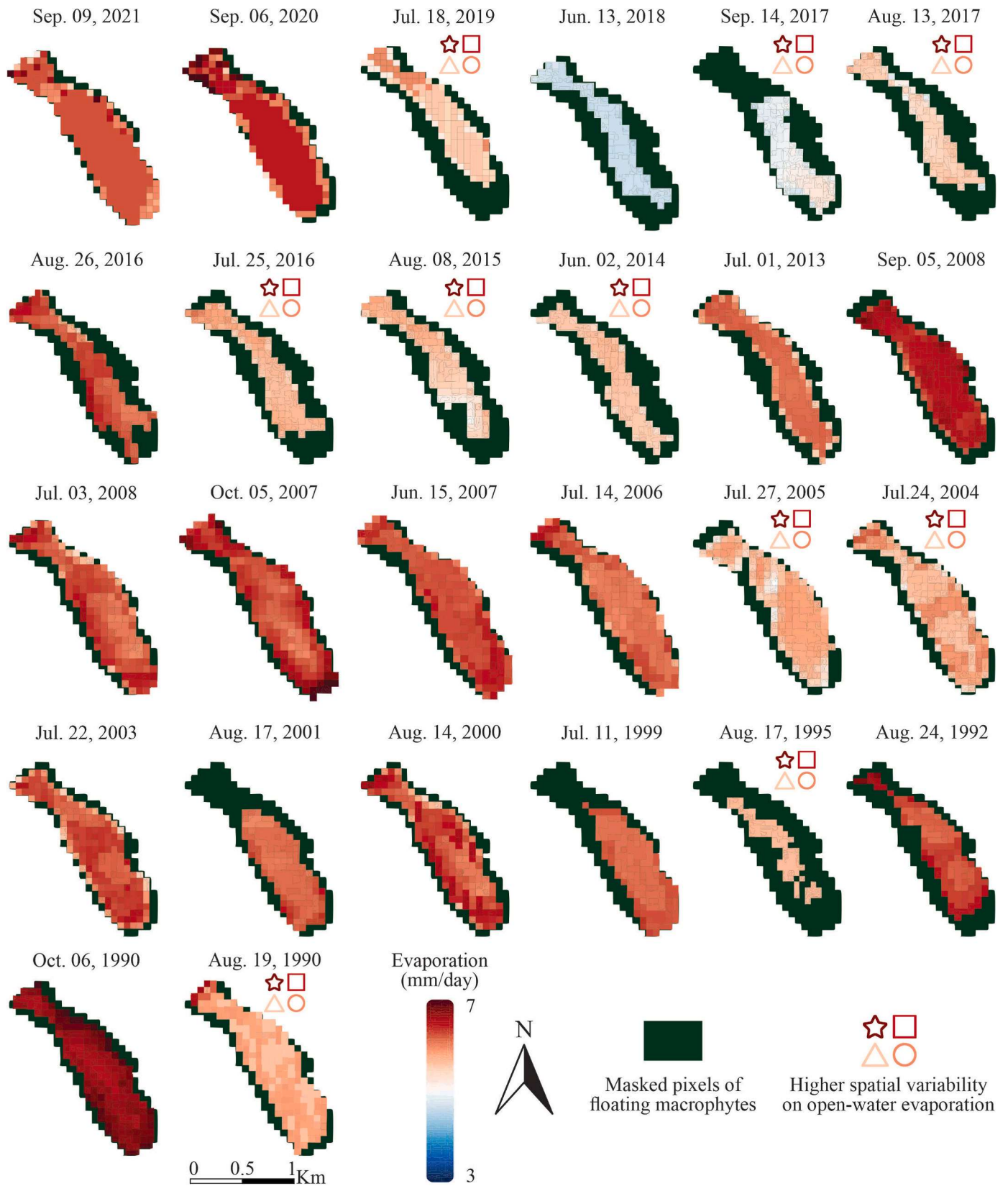


Fig. 4. Spatial variation of open-water evaporation of the Santo Anastácio reservoir.

25, 2016; Aug. 26, 2016; Aug. 13, 2017; Sep. 14, 2017; and Jun. 13, 2018), while the other eleven scenes did not (Aug. 14, 2000; Jun. 22, 2003; Jul. 07, 2004; Jul. 27, 2005; Jul. 14, 2006; Jun. 15, 2007; Oct. 05, 2007; Jul. 03, 2008; Sep. 05, 2008). Fig. 6 illustrates the different

extents of floating MC on the Santo Anastácio reservoir.

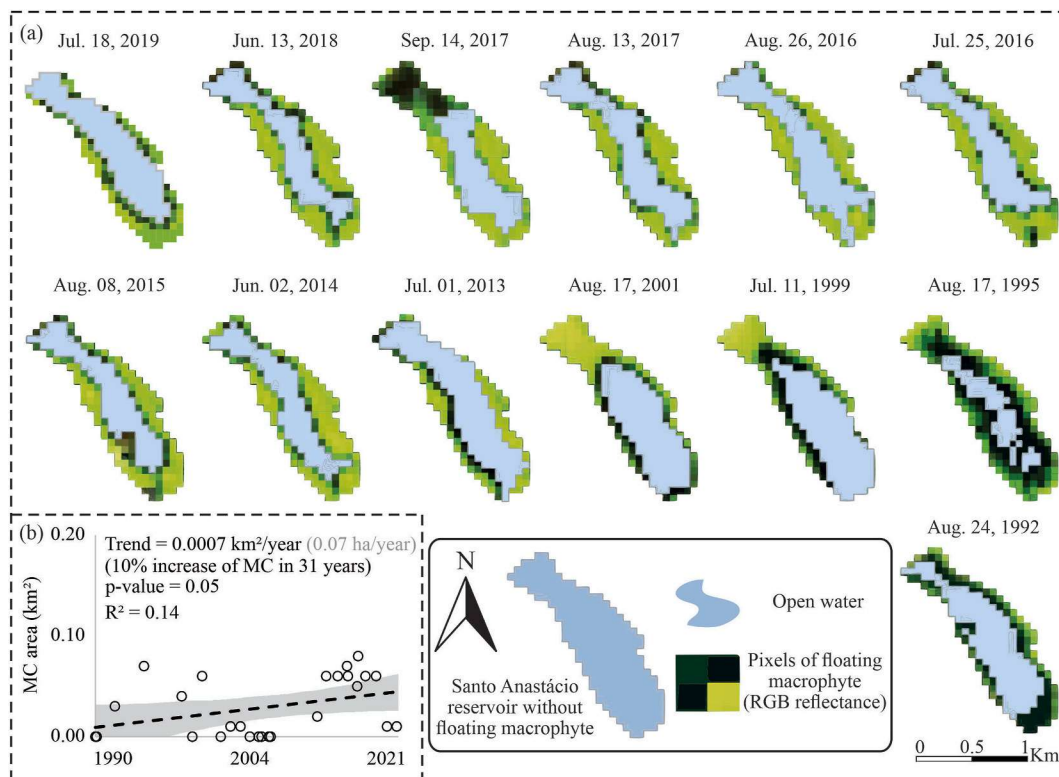


Fig. 5. Remote sensing-based images of the Santo Anastácio reservoir open water and floating MC (a), and trends of MC area per year (b). Shaded grey areas represent 95 % confidence intervals.

3.4. Relationship between macrophyte cover and reservoir open-water evaporation

Fig. 7a reveals that there is a strong negative correlation ($R^2 = 0.65$) between the extent of floating macrophytes and the open-water evaporation, which suggests that evaporation from the reservoir open water decreases as the MC grows. In addition, Fig. 7b depicts that the reduction of open-water evaporation due to floating MC may vary between 1 % (Jun. 22, 2003) to 35 % (Aug. 13, 2018) according with the floating MC. Additionally, Fig. 7b also displays a high positive relationship ($R^2 = 0.73$) between the macrophyte-cover and reduction of evaporation, which agrees with Fig. 7a, also demonstrating that as the MC increases, open-water evaporation decreases. On days when the MC area reached at least 38 %, the reduction in evaporation rate due to the MC ranged from 9 % to 35 %, resulting in an average reduction of 17 % (Fig. 7c and d). Furthermore, a positive trend of MC has been seen on the reservoir surface since 1990, however a significant rise occurred post-2013 (Fig. 7c). The daily open water area, MC area, and percent reduction of open-water evaporation in Santo Anastácio reservoir are shown in Supplementary material C, Table S3.

4. Discussion

4.1. Reservoir open-water evaporation spatial dynamics

Remote sensing (RS) provides a spatial view of evaporation from the reservoir open water surface. Generally, evaporation rates are higher at the edges of the water body and in the dam area than in the central part (Rodrigues et al., 2021a; Rocha et al., 2023), which agrees with what has been seen in this study in the days without MC. When comparing evaporation rates from the days with and without MC, the days without floating macrophytes showed higher evaporation rates and less spatial variability.

This difference in evaporation between these two conditions may be

explained by the presence or absence of floating macrophytes surrounding the open water. The MC areas can lessen the aerodynamic effects around the reservoir open water and, through the macrophyte evapotranspiration, increasing the local air humidity and reducing air temperature, which reduces the thermal energy retained in the reservoir. The influence of these three effects extends beyond the area covered by floating macrophytes, impacting the adjacent open water as well area as well. Consequently, this leads to a decrease in evaporation from open-water reservoirs.

The macrophytes may have a significant impact on the spatial evaporation dynamics, increasing local air humidity through transpiration and reducing wind speed (due to their higher rugosity than open water), which in turn results in a lower open-water evaporation rate, essentially close to the MC clusters, which could explain why days with MC have higher spatial variability. Similar behavior was observed in eight Brazilian semiarid reservoirs by Rodrigues et al. (2021a, 2024c), who used the AquaSEBS equation and noticed a reduction of evaporation (18 %–31 %) near riparian vegetation.

4.2. Effect of floating macrophytes on reservoir open-water evaporation

As a result of the extensive discharge of untreated sewage and solid waste along the urban drainage channel, the Santo Anastácio reservoir has a high coverage of floating macrophytes (Fraga et al., 2020). Araújo et al. (2019) confirm that the hypereutrophic ecosystem of Santo Anastácio reservoir has a higher-than-normal (between 0.5 and 7.0 mg/L, exceeding the permissible thresholds for lakes of 0.03 mg/L, according to the Brazilian National Environmental Council Resolution 357/05 (CONAMA, 2005) concentration of nutrients (particularly phosphorus and nitrogen) due to sewage discharges. The area of floating macrophytes is increased by the favorable effects of an excessive nutrient content in reservoirs with algal development (Coelho et al., 2017; Zhang et al., 2018).

Additionally, intensive precipitation with subsequent high in flow



Fig. 6. Santo Anastácio reservoir on September 25, 2018, with small area of floating macrophytes cover (a), and on Sep. 16, 2019 (b), Dec. 19, 2019 (c) partially covered by floating macrophyte, and on Sep. 02, 2020 (d) with extensive floating MC.

discharge add even more nutrients to the Santo Anastácio reservoir, since urban runoff in the catchment leads to a variety of solid waste (organic substances) and sewage being discharged into the reservoir, herewith controlling the nutrient dynamics in this water body (Araújo et al., 2019). Since the 1990s the nutrient input has increased over the years due to a population rise in the study area, which means even more sewage has flown into the Santo Anastácio reservoir (Fraga et al., 2020). This increase of sewage discharge within the reservoir justifies the significant positive trend of floating macrophytes (total increase of ~10 % over the past of three decades), essentially after 2013, despite the removal of macrophytes occurring at least twice a year.

During the dry season (July–December) these nutrients naturally precipitate in the hypolimnion. During the rainy season (January–June), however, the excessive and intense rainfall results in high river discharge, leading to the resuspension of these nutrients from the hypolimnion with high mixing speed and turbulence intensities (Pereira et al., 2022), as Santo Anastácio is a shallow reservoir (Fraga et al., 2020) and enables the nutrients consumption and growth of macrophytes during the dry season (Araújo et al., 2019). Nutrient resuspension may promote macrophyte proliferation, as was also verified by Mesquita et al. (2020) in the same reservoir. One of the key functions of macrophytes is the uptake of dissolved nitrogen and phosphorus, and subsequent assimilation of these nutrients into macrophyte biomass (Gao et al., 2009; Vymazal, 2013).

The increase of floating MC on the reservoir surface negatively correlates with the open-water evaporation rate. Similarly, Sánchez-Carrillo et al. (2004) found, in Central Spain, that increased MC leads to a decrease of total evapotranspiration (evaporation from open water areas and transpiration from floating MC), gauged as a negative correlation with R^2 0.15. These findings corroborated with our results: R^2 0.65, and reduced evaporation on macrophyte-cover days of an average of 17 %.

A relevant aspect caused by water pollution is the reduction of light penetration in the liquid mass due to high turbidity that normally characterizes hypereutrophic surface water bodies (Havens and Ji, 2018) and decreases the albedo (Jin et al., 2004), just like floating macrophytes that can also prevent the passage of light. Mesquita et al. (2020) also noted with regard to the Santo Anastácio reservoir that an increase in phosphorus concentration may attenuate evaporation rates (~15 %, depending on the amount of nutrients). The presence of floating macrophytes can, furthermore, increase water losses through evapotranspiration (Jiménez-Rodríguez et al., 2019), and raise air humidity on the reservoir surface, which makes open-water evaporation even more difficult given the negative correlation. Other limnological parameters should also be evaluated as they can influence the energy balance and, consequently, the evaporation process: submerged macrophytes (Rinke et al., 2010), water color (Persson and Jones, 2008), the depth of the water column and sediment characteristics (Herb and

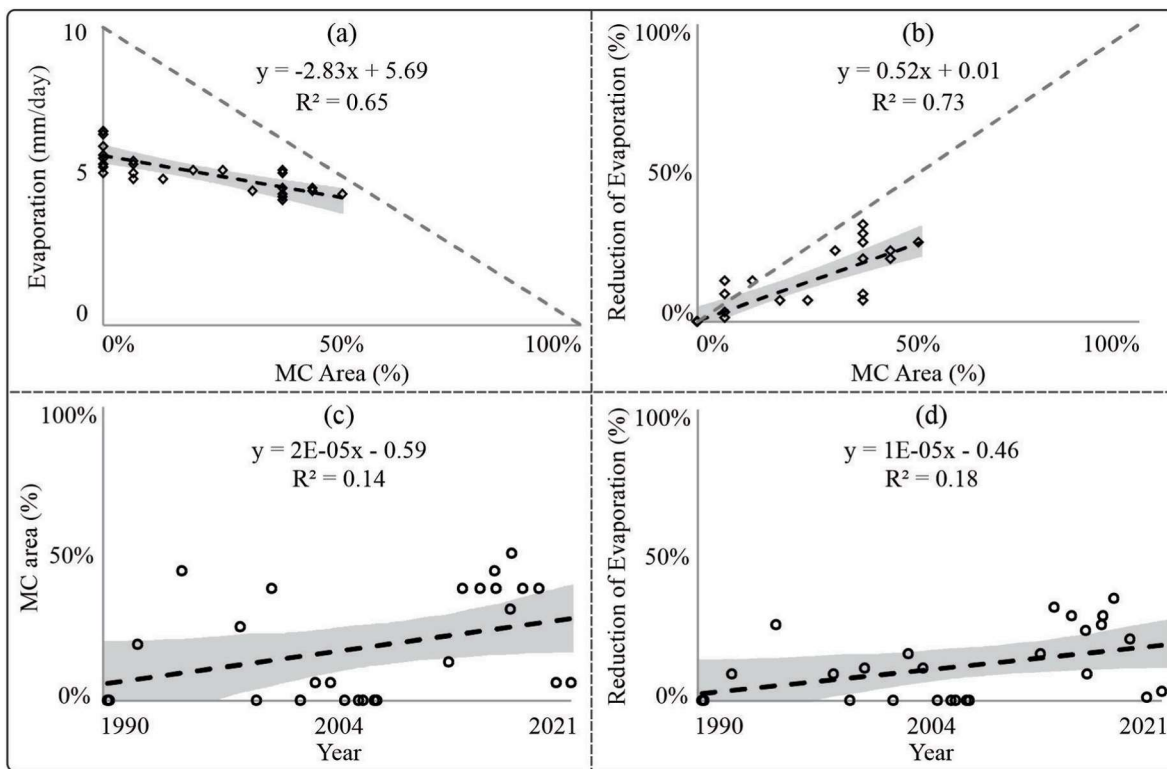


Fig. 7. Correlation between macrophyte-cover (MC) and open-water evaporation modeled with AquaSEBS algorithm (a); Correlation between percentage reduction of evaporation due to floating MC and MC area (b); Temporal variations of MC area (c) and reduction of evaporation due to floating MC (d) from 1990 to 2021. Shaded grey areas represent 95 % confidence intervals.

Stefan, 2004). In fact, [Anda et al. \(2018\)](#) measured three evaporation scenarios based on a Class A pan evaporation rate, with sediment cover and submerged aquatic macrophytes in a shallow lake at Keszthely (Hungary), between 2014 and 2016. Overall, the open-water evaporation rate was lower in the macrophyte scenario (there was humidity resulting in a cooler micro-weather condition), followed by the sediment methodology (which reflects part of solar radiation), and lastly by reference evaporation in the normal Class A pan evaporimeter.

However, a floating MC can also help to reduce the aerodynamic effect on a reservoir open water surface, act as a barrier of protection against wind speed and increasing surface rugosity. The previous is in accordance with Linacre’s theory ([Monteith, 1976](#)), which suggests a reduction in water loss by open-water evaporation when macrophyte areas increase, due to the micrometeorology impact of the macrophyte-belt (i.e., high air humidity, limited air exchange because of a decrease in wind speed, lower air temperatures and weaker solar irradiance) in aquatic ecosystems. Furthermore, the water temperature under the floating macrophytes is decreased ([Shivers et al., 2018](#)), since the vegetation blocks the sun light (i.e., solar radiation), resulting the shadow effect over the covered area. Therefore, the internal temperature of the reservoir reduces with the increase of the floating macrophyte-covered area, which partially explains the open-water evaporation abatement.

The internal lower water temperature of the reservoir may explain why evapotranspiration losses are higher in floating macrophytes compared to open water areas. This agrees with [Wondim and Melese \(2023\)](#), who assessed the evapotranspiration rate of floating macrophytes in Lake Tana (Ethiopia), revealing an average rate of 9.1 mm/day, which is significantly higher than the average open-water evaporation rate of 5.9 mm/day. Similar patterns were observed in a semiarid region of Egypt ([Rashed, 2014](#)) and tropical region of Costa Rica ([Jiménez-Rodríguez et al., 2019](#)), indicating that floating macrophytes exhibit higher evapotranspiration rates compared to open

evaporation. Furthermore, [Jiménez-Rodríguez et al. \(2019\)](#) indicated that the presence of emergent macrophytes such as *Thalia geniculata* and *Typha domingensis* Pers will enhance the evaporation flux during the dry season more significantly than floating macrophytes or open water surfaces.

Floating macrophyte areas are abundantly present in many surface reservoirs as an indicator of poor water quality. In the Northeast of Brazil, this issue is well explored by [Zhang et al. \(2018\)](#) and [Coelho et al. \(2017\)](#); these authors exposed the relevant effect of macrophyte-covered areas on reservoirs. Their analysis monitored the effective water surface areas in nine reservoirs considering their various conditions in terms of water levels, macrophyte growth stages and terrestrial vegetation coverage.

[Ersoy et al. \(2020\)](#) proved that variations in water temperature, nutrient availability, and water level caused by climate change directly influenced macrophyte growth. Considering that the majority of endemic species are found in tropical lakes, a high number of macrophyte species may become extinct due to climate change and other anthropogenic stresses ([Lind et al., 2022](#)).

The present study displays how floating macrophytes in the Santo Anastácio reservoir tend to decrease the open-water evaporation rate (17 %). All in all, floating macrophytes impact reservoir water quality and open-water evaporation. For instance, MC increases surface rugosity, which decreases wind speed; they also reduce solar penetration within the reservoir, resulting in a shading effect that contributes to cooler water temperatures; additionally, elevated evapotranspiration rates were observed in MC, potentially raising the relative humidity on the reservoir surface and reducing open-water evaporation. [Fig. 8](#) provides a concise conceptual overview of the effects of MC on reservoir.

4.3. Sources of uncertainty

Although the AquaSEBS demonstrated good accuracy with respect to

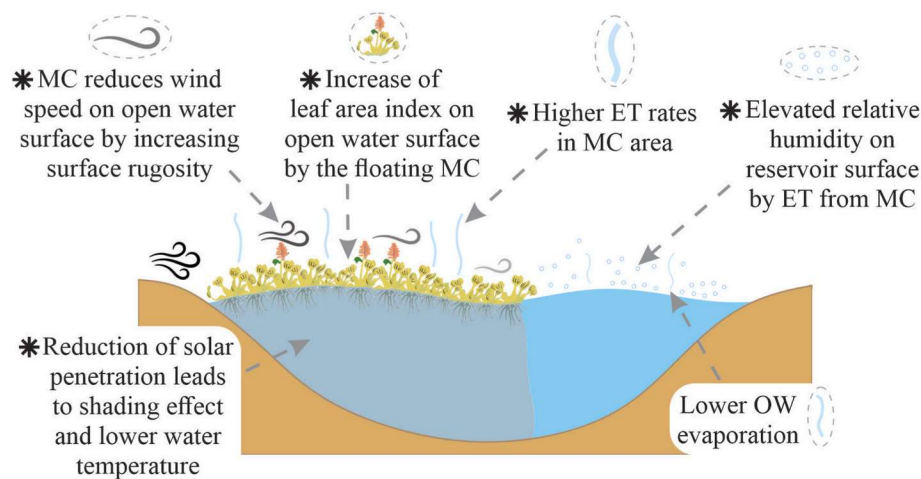


Fig. 8. Effects of macrophyte-cover (MC) on hydroclimatic parameters and evaporation in open water (OW) areas

* - MC effects supported by literature: Reduction of solar penetration leads to shading effect and lower water temperature from Havens and Ji (2018), Rinke et al. (2010), Shivers et al. (2018); MC reduces wind speed on open water surface by increasing surface rugosity from Monteith (1976); Increase of leaf area index on open water surface by the floating MC from Nicholson and Best (1974); Higher ET (evapotranspiration) rates in MC area from Jiménez-Rodríguez et al. (2019), Rashed, (2014), and Wondim and Melese (2023); Elevated relative humidity on reservoir surface by ET from MC Jiménez-Rodríguez et al. (2019), Monteith (1976), and Wondim and Melese (2023).

the reference data, several sources of uncertainty may be present in this evaluation: i) Reference dataset (CAPC and Penman-Monteith equation), ii) remote sensing data – surface and air temperature and shortwave radiation, iii) satellite limitations - scene availability.

The evaporation rate in the CAPC differs by season. During dry season, when heat is stored in the reservoir, evaporation is higher in the CAPC compared with the lake, whereas during the wet/rainy season when the stored heat is released, the reservoir can evaporate more than the Class A pan evaporimeter on the ground (Farnsworth et al., 1982). To solve this issue, a Class A evaporimeter could be installed in the water tank (Pinto, 2009), this type of measurement performs accurate evaporation from lakes, as reported by Masoner et al. (2008) and Rodrigues et al. (2022). The instrument is installed in the water which causes a reduction of the solar transfer of heat through the edge of the tank resulting in behavior similar to a natural reservoir.

Another uncertainty associated with the CAPC is related to water quality, which is likely to be better in a pan compared with a reservoir. Inferior water quality tends to reduce the evaporation rate in a natural water body (Mesquita et al., 2020; Mesquita and Lima Neto, 2022). The Penman-Monteith equation was also used for reference data purposes. However, even though this equation accurately represents evaporation, its main problem is the reliance on a large amount of in-situ climatological data, which is rarely available in the Brazilian semiarid region.

When the satellite scene is captured, air and surface temperature and shortwave radiation estimations take place, but these variables are not constant during the day. Variations in these parameters can cause changes in evaporation estimations when employing the AquaSEBS model, since they are one of the most sensitive parameters (Abdelrady et al., 2016). Thus, it is essential to estimate these parameters with precise methods such as those used in this study to analyze the satellite images of Landsat 5 and Landsat 8. Kalma et al. (2008) explains that instantaneous estimates by satellite-based sensors must be extrapolated with the help of improved temporal scaling approaches; the same applies to accurate gap-filling procedures in the case of temporal scaling being affected by intermittent satellite coverage. Multi-resolution data from different remote sensing-based sensors (i.e., data fusion) gathered with other methodologies may assist with this development. Mueller et al. (2011) compared global multiannual datasets from satellite-derived observations, in-situ measurements, reanalysis products and atmospheric water balance datasets, and found high accuracy between those data acquisition approaches.

Scene availability is another limiting factor, which is caused by the cloud cover effect. Intermittent cloud cover interferes with the temporal availability of scenes and prevents the use of this methodology with a wider range, especially during the rainy season (period of January to June in the study area). For example, in the present study, from 1990 to 2018, only fifteen scenes from Landsat 5 and eight of Landsat 8 were used. To overcome this problem a satellite or other type of remote sensing technology with higher temporal resolution and with a thermal band could be used, increasing the daily chances of capturing the desired region, although there may be significant differences in characteristics. Mokhtari et al. (2021), for instance, used not only Landsat 8 scenes, but also those of Remotely Piloted Aircraft Systems (RPAS) to estimate evapotranspiration in Northern California (U.S.A.).

Uncertainties exist in both approaches: computer simulations (e.g., using the calibrated Stephens–Stewart equation) and measurements (Class A pan). It would be valuable to have more measured data from other years, which would help to enhance calibration performance. However, the installation of a Class A Pan in water is more expensive and requires a higher level of attention from the operator than a classic installation. Finally, there are natural constraints (e.g., cloud cover) that may hinder sensors of high spatial and high temporal resolution in the Brazilian Northeast Region; what is needed for evaporation monitoring is a clever combination of well-placed in-situ measurements (Feitosa et al., 2021), occasionally complemented by remote sensing observations (Zhao and Gao, 2019; Rodrigues et al., 2021a, b; Rodrigues et al., 2024a; b, c).

5. Conclusions

The AquaSEBS model accurately predicted the open-water evaporation in a tropical reservoir of the Brazilian Northeast region. From 1990 to 2021, significant positive trends of floating macrophyte area were observed. The presence of floating macrophytes generate greater spatial variability of evaporation over the free surface of the water. The results also indicated a negative correlation (0.65) between the spatial extent of floating macrophytes and open-water evaporation rates, with an average floating MC of 30 %, and estimated a reduction of 17 % on the average evaporation rate. Floating macrophytes may reduce open-water evaporation by the combined effect of shading, which attenuates radiation; and wind hindering, which mitigates the aerodynamic effect. However, according to the literature, the combination of

evaporation from reservoir open water and transpiration from MC areas would result in greater evapotranspiration volumes compared to the reservoir without any MC. Future research should evaluate the nexus between the rainfall and macrophyte blooms, aiming to determine how floating macrophytes tend to grow in relation to the amount and intensity of precipitation. Overall, the use of remote sensing made it possible to assess evaporation-macrophyte interdependence, and this finding reinforces the potential for applying the RS tool to water resource management. In the end, a cautionary note about MC is needed, as their presence in urban reservoirs is, in this instance, linked to sewage pollution. This might lead to eutrophication, the spread of potential waterborne diseases, heavy metal contamination, odors, loss of habitats, and fish mortality, among other undesirable consequences. The drawbacks to public health and quality of life overshadow any advantages that may come from reducing open water evaporation. Consequently, there exist additional eco-friendly alternatives for minimizing evaporation, for instance, floating photovoltaics.

CRedit authorship contribution statement

Italo Sampaio Rodrigues: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Carlos Alexandre Gomes Costa:** Writing – review & editing, Supervision, Project administration, Formal analysis, Conceptualization. **Adunias dos Santos Teixeira:** Writing – review & editing, Supervision, Project administration, Formal analysis, Conceptualization. **Iran Eduardo Lima Neto:** Writing – review & editing, Supervision, Project administration, Formal analysis, Conceptualization. **Fernando Bezerra Lopes:** Writing – review & editing, Project administration, Formal analysis, Conceptualization. **José Carlos de Araújo:** Writing – review & editing, Project administration, Formal analysis, Conceptualization.

Ethics approval and consent to participate

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Consent for publication

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jsames.2025.105683>.

Data availability

Data will be made available on request.

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