https://doi.org/10.5194/hess-2020-283
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Reservoir evaporation in a Mediterranean climate: Comparing direct methods in Alqueva Reservoir, Portugal

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Abstract. Alqueva Reservoir is one of the largest artificial lakes in Europe and is a strategic water storage for public supply, irrigation, and energy generation. The reservoir is integrated within the Multipurpose Alqueva Project (MAP), which includes almost 70 reservoirs in a water-scarce region of Portugal. The MAP contributes to sustainability in southern Portugal and has an important impact for the entire country. Evaporation is the key component of water losses from the reservoirs included in the MAP. To date, evaporation from Alqueva Reservoir has been estimated by indirect methods or pan evaporation measurements. Eddy covariance measurements were performed at Alqueva Reservoir from July to September in 2014 as this time of the year provides the most representative evaporation volume losses in a Mediterranean climate. This period is also the most important for irrigated agriculture, and is therefore the most problematic part of the year in terms of managing the reservoir. The direct pan evaporation approach was first tested and compared to eddy covariance evaporation measurements. A relationship was then established based on a pan coefficient (K_{pan}) multivariable function by using the identified governing factors: air temperature, relative humidity, wind speed, and incoming solar radiation. The modelled K_{pan} was 0.59, 0.57, 0.57, and 0.64 in June, July, August, and September, respectively. Consequently, the daily mean reservoir evaporation (E_{Res}) was 3.9 mm d^{-1}, 4.2 mm d^{-1}, 4.5 mm d^{-1}, and 2.7 mm d^{-1} for this 4-month period and the total modelled E_{Res} was 455.8 mm. The correlation between the estimated evaporation and the measured EC evaporation had an R^2 value of 0.7. The developed K_{pan} function was validated for the same period in 2017, and yielded an R^2 value of 0.68.

This study provides an applicable method for calculating evaporation based on pan measurements in Alqueva Reservoir, which can support regional water management. Moreover, the methodology presented here could be applied to other reservoirs, and the developed equation for Alqueva Reservoir could act as a first evaluation for the management of other Mediterranean reservoirs.

1 Introduction

Reservoirs and water storage are essential in the Mediterranean region for securing urban and industrial water supply, irrigation, and energy generation due to the huge challenge presented by water scarcity in this part of the world (Hoekstra et al., 2012; Alcon et al., 2017; Tomas-Burguera et al., 2017; Rivas-Tabares et al., 2019). Reservoir evaporation is one of the most important components of the water balance, and thus it should be accurately evaluated (Liu et al., 2016). This is important in southern Europe as large investments have been made in irrigation areas here. For instance, in southern Portugal, the Multipurpose Alqueva Project (MAP) with almost 70 reservoirs is the most important example of such investment. The MAP contributes to sustainability in southern Portugal and has an important impact for the entire country. Alqueva Reservoir is the largest surface water reservoir in southern Europe, with a submerged area of 250 km^2 and total storage volume of 4150 hm^3 at full capacity. Each 10 mm of evaporation represents a water loss of 2.5 hm^3, which could be sufficient to irrigate almost 850 ha of land containing olive trees, and therefore corresponds to an estimated annual return of 1.1 million Euros.

The methodology of (Kohli and Frenken, 2015) that is used to estimate evaporation for artificial reservoirs is based on crop evapotranspiration by assuming a crop coefficient equal to 1.0, thus meaning that reservoir evaporation is equal to the reference evapotranspiration. Most reservoir managers in the MAP estimate evaporation based on the reference evapotranspiration. Some water system managers include another simplification using 1000 mm as the reservoir annual evaporation. In the case of Alqueva Reservoir, with an average reference evapotranspiration of 1270 mm per year, the evaporation can be 325 hm^3 or 10% of the total usage volume. This means that the local water budget balance has to be well studied to guarantee the sustainability of this important upstream reservoir. An increased accuracy in the evaporation estimation for Alqueva Reservoir is required due to the projected increase of the irrigation area for the MAP and the importance of regional socio-economic development. A previous study regarding evaporation from Alqueva Reservoir used indirect methods including the energy budget approach, aerodynamic methods, a combination approaches, and a lake model ('FLAKE') (Rodrigues, 2009). This work was based on measurements of Class A pan evaporation, located in a floating platform in Alqueva Reservoir, between 2002 and 2006, and the comparison with evaporation values obtained by the energy budget approach to establish monthly pan coefficients. However, there has not been a systematic analysis of the governing factors relating to pan evaporation and reservoir evaporation at Alqueva Reservoir. Accordingly, the current study reports on direct evaporation measurements that used eddy covariance (EC) equipment installed on the existing floating platform in Alqueva Reservoir, which is part of the framework of the ALEX project (www.alex2014.cge.uevora.pt). Offshore measurements were conducted from June to September 2014 as this is the most representative part of the year for the evaporation volume in a Mediterranean climate, and represents 60% of the total reference evapotranspiration. This period is also the most important in terms of irrigation, and is therefore the most problematic part of the year for the management of Alqueva Reservoir.

The EC method is usually applied in research because it is a non-invasive technique and provides the most accurate and reliable method for estimating evaporation (Stull, 2001; Allen and Tasumi, 2005; Tanny et al., 2008; Rimmer et al., 2009). The method is theoretically based on the correlation between the vertical wind speed and air moisture content fluctuation, which is a reliable and accurate way to measure open-water evaporation in the location where it is installed (Blanken et al., 2000; Tanny et al., 2008; Nordbo et al., 2011; Richardson et al., 2012; Vesala et al., 2012; Liu et al., 2015; Ning et al., 2015; Ma et al., 2016). The turbulent fluxes over the water surface, which can be obtained with direct and continuous measurements, evaluate the exchange of water and energy between the surface and the atmosphere (Arya, 2001; Potes et al., 2017). However, it requires sophisticated instrumentation that is capable of accurately recording the minimum variations in wind speed, air temperature, and humidity with a high sampling frequency. Furthermore, the equipment is quite expensive and

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Preprint. Discussion started: 15 July 2020
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requires continuous maintenance, which means that is not possible to perform regular measurements. Several studies using EC measurements to evaluate reservoir evaporation have been conducted in various places worldwide (Blanken et al., 2000; Nordbo et al., 2011; Zhang and Liu, 2014; Metzger et al., 2018; Jansen and Teuling, 2020). Another technique to estimate the actual reservoir evaporation based on direct measurement is that of pan evaporation (Riley, 1966). The World Meteorological Organization suggests pan evaporation as the standard method for measuring open-water evaporation (Gangopadhyaya, 1966). However, the relationship between evaporation and meteorological parameters at the pan and in open waterbodies differs. Pan measurements generally overestimate evaporation from large waterbodies because, in contrast to a lake, a pan receives large quantities of energy through its base and sides, and thus becomes much hotter than a lake. Moreover, the surface area of the water in the pan is much smaller than that of a lake, thus allowing a greater air renewal over the free surface (Jacobs et al., 1998; Lim et al., 2013; Yu et al., 2017). The measured pan evaporation rates are normally 30% higher than lake evaporation at the annual scale. The monthly pan coefficients can differ from the commonly used coefficient of 0.7 by more than 100% (Kohler et al., 1955; Linsley et al., 1982; Ferguson et al., 1985). The relationship between pan evaporation and lake evaporation must be a function of meteorological parameters. The pan evaporation method remains the cheapest and simplest method; hence, this evaporimeter remains the most commonly used instrument to quantify reservoir evaporation.

The Portuguese public company (Empresa de Desenvolvimento e Infraestruturas do Alqueva - EDIA) that is responsible for the construction and operation of the MAP has a meteorological station with a Class A evaporation pan. The parametrisation of a pan coefficient to convert the measured pan evaporation to reservoir evaporation would provide the MAP with an expeditious reservoir management tool.

Accordingly, the aims of this study are: (i) to evaluate the actual evaporation rates from Alqueva Reservoir at the EC and Class A pan evaporation locations, and to then analyse their variability with meteorological parameters (i.e. air temperature, relative humidity, wind speed, and radiation); (ii) to estimate the pan coefficient (K_{pan}) for the reservoir as an indirect multi-variable function, and to assess the capacity of pan evaporation to retrieve the evaporation component when EC measurements are unavailable. The study was undertaken using data for the period from June to September 2014, and was validated using data from the same period in 2017.

Section 1 of this paper introduces the aims of the study, and Section 2 presents the measurement site, instrumentation, and data. The methodology used in this study is detailed in Section 3, and the results are presented and discussed in Section 4. Finally, Section 5 summarises the major conclusions.

2 Measurement site, instrumentation, and data

2.1 Alqueva Reservoir

Alqueva Reservoir is located within Guadiana River in Alentejo, southern Portugal (Fig. 1). The reservoir is the largest artificial lake in southern Europe (EDIA, 2020), with an average depth of 16.6 m and maximum depth of 92.0 m at full capacity. The reservoir has a total capacity of 4150 hm^3 and a water surface area of 250 km^2. Alqueva Reservoir is the upstream reservoir of the MAP, which supplies approximately 200 000 inhabitants, irrigates 120 000 ha (165 000 ha in the near future), and has

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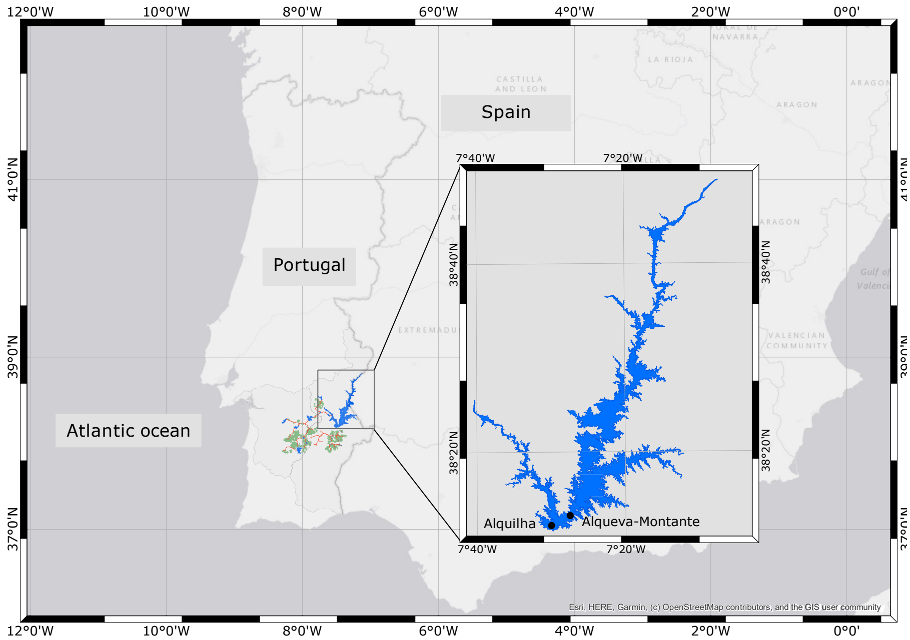

Figure 1. Multipurpose Alqueva Project (MAP) location. The expanded map is of Alqueva Reservoir, showing two meteorological stations: Alquilha and Alqueva-Montante.

an installed hydroelectric power of 530 MW. The Alqueva River basin cover 55 289 km^2 and is shared with Spain (85% of the area). The mean annual precipitation in the Alqueva River basin is less than 550 mm (for the Portuguese portion) and the mean annual runoff at the border gauging station (Monte da Vinha station) is 23 mm. At the reservoir, the annual reference evapotranspiration is 1270 mm, as determined by the Food and Agriculture Organization (FAO) Penman–Monteith equation. More than 80% of rainfall occurs between October and April, and during the summer the maximum air temperature ranges on average from 31 ºC to 35 ºC (July and August), often reaching values of > 40 ºC. The region is classified as a Csa region according to the Koppen climate classification, which corresponds to a Mediterranean climate (i.e. a temperate climate with dry, hot summers). The summer local time (LT) in Portugal is coordinated universal time (UTC) + 1.

2.2 Instrumentation, data sources, and quality

Class A pan evaporation

Alquilha meteorological station (38° 13’ 22.80” N, 07° 30’ 03.60” W; elevation of 162 m) is located on the first island upstream of the dam (Fig. 1). The station is part of the environmental monitoring network of Alqueva Reservoir and is monitored by EDIA, which manages the MAP. The hourly weather variables measured at the station include rainfall (rain-gauge: YOUNG/52202), air temperature and relative humidity (combined sensor: HYDROCLIP), wind speed (3 m above ground) and direction (anemometer and direction sensor: CLIMA), incoming solar radiation (irradiance sensor: IMTSolar/Si-01TCext), and

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water level readings of a Class A pan (level sensor: Druck/1830). In consideration of the fact that the station is located on a small island within the reservoir, a very large water fetch upwind of the pan was taken into account in this study. The hourly Class A pan evaporation was equal to the hourly level depletion, and accounted for the rainfall effect and discarded the 3 h period after each refill of the pan. The daily pan evaporation was calculated by considering the starting time water-level, the ending time water-level, and the upward (water out of the pan) and downward (water into the pan) water level change during a day. For the study period (June to September 2014), 18% and 15% of the data was discarded at hourly and daily scales, respectively, during the quality control process.

Eddy covariance system

Alqueva-Montante (38° 13' 24.75" N, 07° 27' 34.18" W) meteorological and hydrologic station (Fig. 1) is part of the Portugal Network for Water Resource Monitoring (https://snirh.apambiente.pt). Measuring equipment is installed on a floating platform to measure air temperature, relative humidity, wind speed/direction, downward radiation, pressure, and precipitation. These parameters (except for precipitation as this is accumulated during a given period) are measured at a frequency of 1 value per minute, while averages are calculated for 30 min. The weather station also measures the reservoir water temperature and water quality parameters, which are not used in the present study. The maximum water depth is 65 m at the station site and the shore distance is farther than 300 m; however, these values vary a little due to the type of platform anchorage (i.e. by ropes tied to three sunken blocks), thus allowing longitudinal displacements and rotation on itself.

Within the framework of the ALEX project (www.alex2014.cge.uevora.pt), this instrumented floating platform was equipped with one EC system—an integrated open path CO2/H2O gas analyser and 3D sonic anemometer (IRGASON; Campbell Scientific)—at a height of 2 m above the reservoir surface. The variables measured by the IRGASON were u, v and w components of wind speed, sonic temperature (computed from the measured sound speed), H2O and CO2 concentration, and sonic anemometer and gas analyser quality flags. Data were sampled at 20 Hz and the filter time delay was 200 ms (Potes et al., 2017). Turbulent time-series were linearly detrended and a double-axis rotation was applied to the wind speed components. Turbulent fluxes of momentum, heat, and mass (H2O) were calculated as 30 min covariances between the fluctuations of the vertical wind component (w) and temperature and the H2O concentration, respectively. The air density fluctuations were corrected for thermal expansion and water vapour dilution, and the sonic temperature was corrected for humidity. These corrections were then applied to the flux calculations (Potes et al., 2017). Furthermore, data quality criteria and filters were applied for the study period. Approximately 3% of the original data was discarded based on i) a signal strength (from the gas analyser) of < 0.7, ii) footprints (fetch) with values of X90 of > 300 m, and iii) all data leading to negative values for the H2O covariances as this resulted in negative latent heat (evaporation) fluxes. It was not considered any contamination of the measurements by the platform, according to the wind direction; the predominant wind direction was between 210º and 360º (68% with 30 min resolution), and 97% of the mean speed wind measurements (with 30 min resolution) were < 6 ms^{-1} (Fig. 2). To understand the impact of applying a filter of wind direction to the EC evaporation dataset, a comparison was made between the daily cycle without any wind direction filter and with a wind direction filter of i) 180º and ii) 100º (Fig. 3a). The correlations between the daily cycle with a 180º filter and without a filter (R^2 = 0.985) and between the daily cycle with a 100º filter and without a filter (R^2 = 0.993) are presented in Fig. 3b and 3c.

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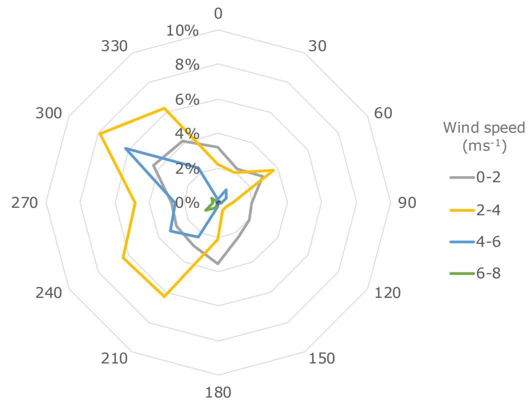

Figure 2. Wind rose for Alqueva-Montante meteorological station from June to September 2014.

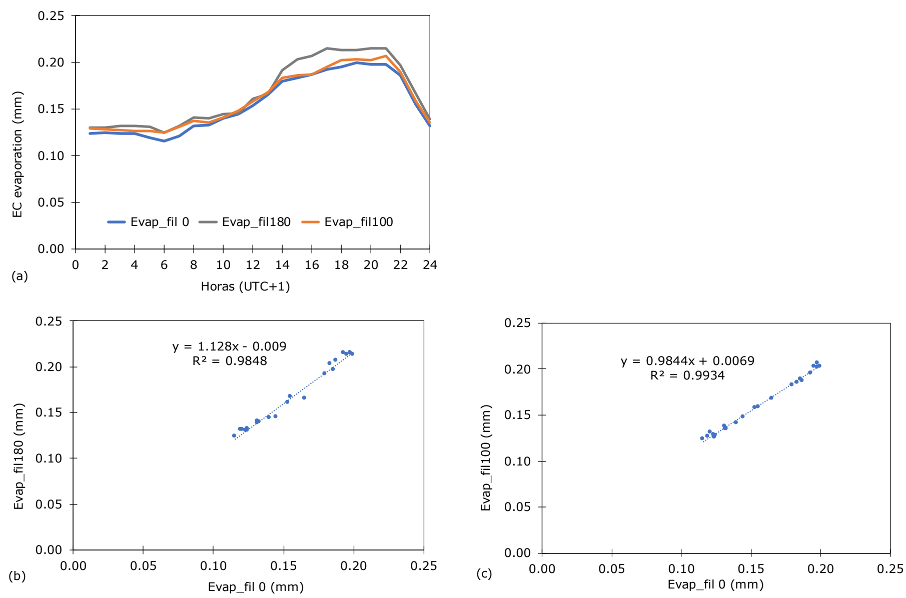

Figure 3. (a) Daily cycle of the eddy covariance (EC) evaporation (E_{EC}) with and without wind direction filters; (b) correlation between the EC evaporation with a 180º wind direction filter ('Evap_fil180') and without the filter ('Evap_fil 0'); (c) correlation between the EC evaporation with a 100º wind direction filter ('Evap_fil100') and without the filter ('Evap_fil 0'), for Alqueva-Montante station from June to September 2014.

3 Methodology

This section describes the methodology used to estimate evaporation from Alqueva Reservoir based on the measurements taken at Alquilha station. It is proposed that the actual evaporation from the reservoir could be estimated using the relationship between the Class A pan evaporation measurements (at Alquilha station) and a pan coefficient multivariable function.

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Although the conditions surrounding a site can influence the pan coefficient, this aspect is not considered here as the fetch in the wind direction was not relevant, as mentioned Section 2.2. The pan evaporation and EC measurements were used to develop a multivariable pan function. First, relationships were determined between the EC measurements and meteorological parameters (air temperature, relative humidity, wind speed, and solar radiation) measured at Alqueva-Montante station. A sensitive analysis at the hourly scale was also performed for the factors governing evaporation from Alqueva Reservoir. The daily cycle of evaporation and normalised meteorological parameters were analysed to assess their behaviour during the day. Second, the relationships were determined between pan evaporation measurements and the same meteorological parameters, but as measured at Alquilha station (at hourly and daily scales). Third, the daily multivariable pan coefficient series was calculated. Forth, a function was fitted to this series based on the physical relationship between the meteorological parameters measured at Alquilha station (at the daily scale). Several functions were attempted, and the one leading to a better determination coefficient (R^2) was chosen. In order to find the optimal parameter estimates, the Generalized Reduced Gradient (GRG) method (Lasdon et al., 1974) (Lasdon et al., 1974) was used with the aid of the Excel solver tool. The best parameter estimates were those that minimised the residual sum of squares.

4 Results and discussion

4.1 Eddy covariance evaporation

The total EC evaporation measured from June to September 2014 was 450.1 mm. The mean daily EC evaporation in June, July, August, and September was 3.7 mm d^{-1}, 4.0 mm d^{-1}, 4.5 mm d^{-1}, and 2.5 mm d^{-1}, respectively. The correlations between the hourly EC evaporation and wind speed, air temperature, relative humidity, and incoming solar radiation are presented in Fig. 4. At the hourly scale, positive trends were observed between the EC evaporation and i) wind speed (R^2 = 0.50) and ii) air temperature (R^2 = 0.20), whereas a negative trend was found between open evaporation and relative humidity (R^2 = 0.30). There was no trend between open evaporation and incoming solar radiation.

The daily cycles of evaporation and the meteorological parameters allow the variation during an average day to be analysed. Normalisation of the mean values of the meteorological parameters was performed to unify the scale of the parameters. The daily cycle of evaporation and the four normalised meteorological parameters measured at Alqueva-Montante station are presented in Fig. 5. As expected, the air temperature and relative humidity exhibited opposite trends. There was a slight variation in the wind speed during the morning and an considerable increase after 10:00 LT, which induced a variation in evaporation. After 6:00 LT, evaporation increased continuously until 21:00 LT, along with increasing radiation and wind speed but decreasing relative humidity. Incoming solar radiation contributed to evaporation with a delay corresponding to the variation in the energy stored in the water column. Increased solar radiation led to an increase in the stored energy in the water column when the air temperature was higher than the water temperature. The air temperature subsequently reduced in comparison to the water temperature, and the energy was released to the air, thereby increasing evaporation. An evaporation inflection point occurred at 14:00 LT when the incoming solar radiation began to reduce. Accordingly, evaporation began to reduce at 21:00 LT when there was no solar radiation.

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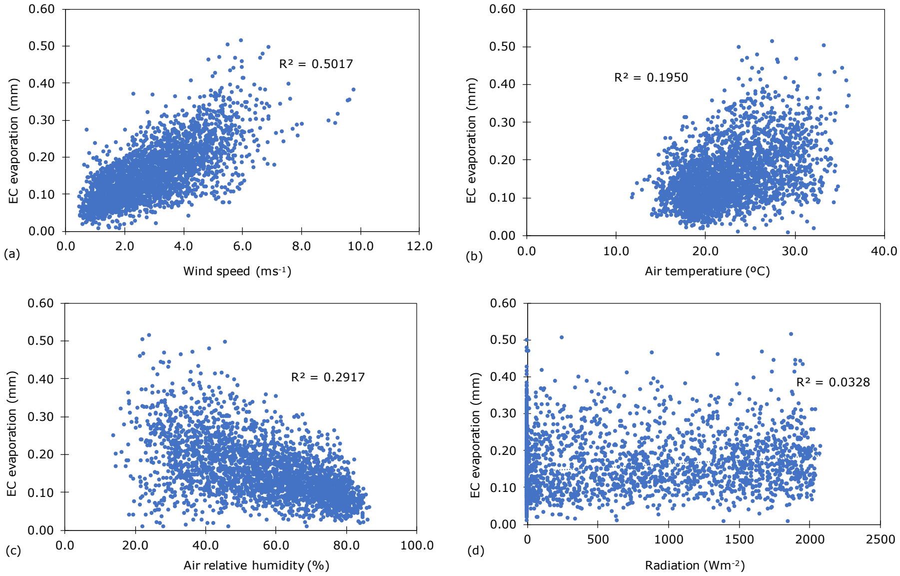

Figure 4. Hourly correlation between the eddy covariance (EC) evaporation (E_{EC}) and (a) wind speed (U), (b) air temperature (Ta), (c) relative humidity (RH) of air, and (d) solar radiation (Rad) at Alqueva-Montante station.

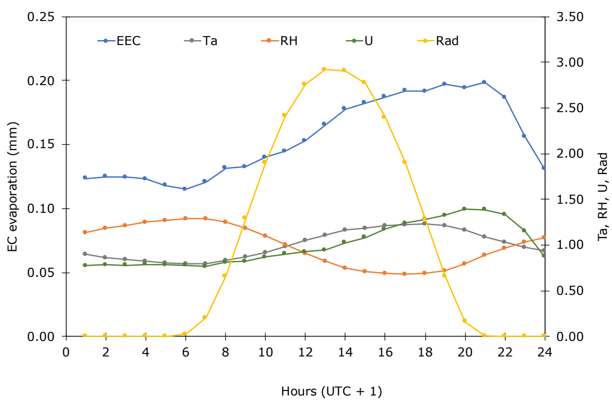

Figure 5. Mean daily cycle of the eddy covariance (EC) evaporation (E_{EC}) (left y-axis) and normalised air temperature (Ta), relative humidity (RH) of air, wind speed (U), and solar radiation (Rad) (right y-axis) from June to September 2014 at Alqueva-Montante station.

4.2 Class A pan evaporation

The total pan evaporation measured from June to September 2014 was 797.9 mm. The mean daily pan evaporation in June, July, August, and September was 6.9 mm d^{-1}, 7.7 mm d^{-1}, 7.3 mm d^{-1}, and 4.3 mm d^{-1}, respectively.

As for the EC evaporation, a positive trend was observed between the hourly pan evaporation and air temperature (R^2 = 0.55), whereas a negative trend was found between the hourly pan evaporation and relative humidity (R^2 = 0.53). On contrary,

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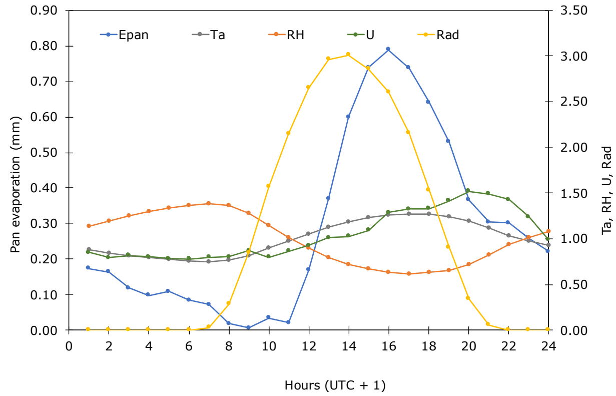

Figure 6. Mean daily cycle of pan evaporation (E_{pan}) (left y-axis) and normalised air temperature (Ta), relative humidity (RH) of air, wind speed (U), and solar radiation (Rad) (right y-axis) from June to September 2014 at Alquilha station.

a positive trend was determined between the hourly pan evaporation and incoming solar radiation (R^2 = 0.35), and a weak positive trend was evident between the hourly pan evaporation and wind speed (R^2 = 0.05). The daily cycle of evaporation and the four normalised meteorological parameters (wind speed, air temperature, relative humidity, and solar radiation) measured at Alquilha station are presented in Fig. 6. The most important differences that were observed are the dominance of the wind speed over solar radiation in the morning period (until 11:00 LT), even with the reduction of the relative humidity. When the wind speed increased, the trend of pan evaporation followed the trend of solar radiation but with a delay, whereby the maximum value was at 16:00 LT when the relative humidity was at the minimum. Pan evaporation reduced as the air relative humidity increased.

4.3 Correlation between EC evaporation and pan evaporation

Figure 7a shows a poor linear correlation between the EC evaporation and pan evaporation during the study period (R^2 = 0.37). This was also the case when observing the plots for each month (Fig. 7b–e; R^2 = 0.05–0.47). These results reveal the importance of finding a multivariable nonlinear function to correlate EC evaporation and pan evaporation. The daily cycles of the normalised pan evaporation and normalised EC evaporation are compared in Fig. 8. This shows that the two exhibited different behaviour, whereby pan evaporation varied widely over the day, with zero evaporation at 9:00 LT and the maximum at 16:00 LT. The maximum mean daily pan evaporation was 2.75-fold that of the mean daily value. In contrast, the daily cycle of the EC evaporation fluctuated comparatively little over the day. During the night and early morning, the EC evaporation was 80% of the daily mean value, with the minimum at 6:00 LT. During the late afternoon, the EC evaporation increased due to the increased wind speed (Fig. 5). The maximum daily mean evaporation occurred at 21:00 LT, when it was 125% of the daily mean value.

These results agree with a previous study by (Salgado and Le Moigne, 2010) for the same reservoir, whereby the authors also found an absolute minimum and maximum at 6:00 LT and 21:00 LT, respectively. Despite the fact that both types of

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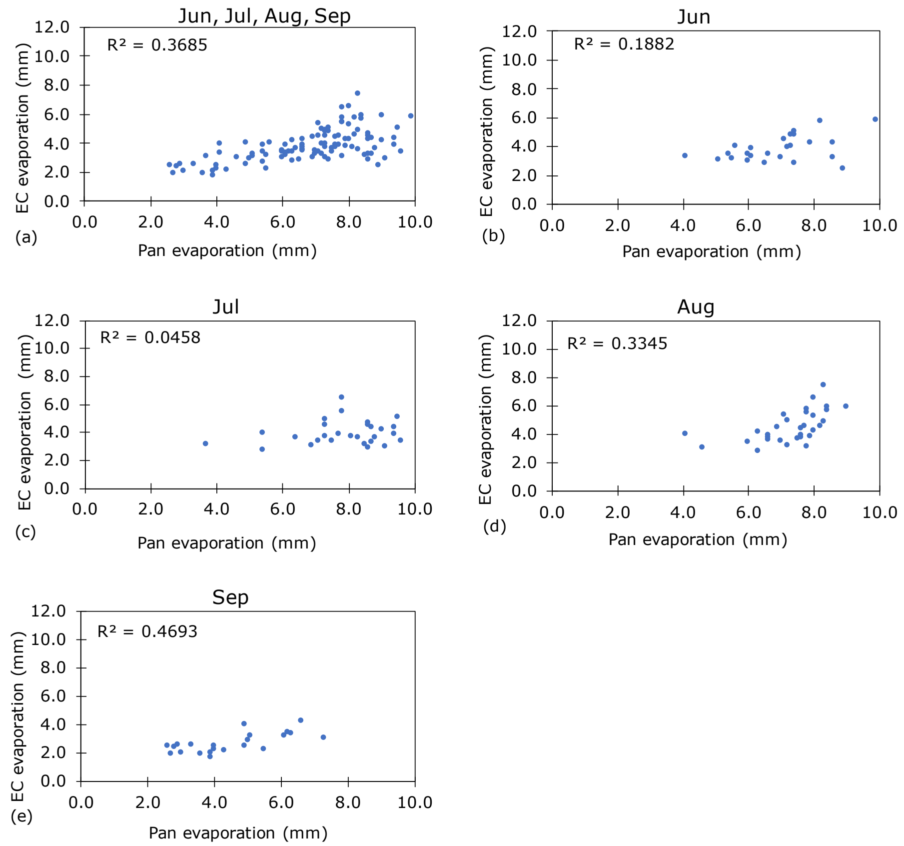

Figure 7. Correlation between the daily eddy covariance (EC) evaporation (E_{EC}) and the daily pan evaporation(E_{pan}): (a) June to September 2014; (b) June 2014; (c) July 2014; (d) August 2014; (e) September 2014.

205 evaporation measurement had similar times for their mean daily value (between 12:00 LT and 13:00 LT), the considerable dissimilarities over the day resulted from the large difference between the size of the pan and the size of the reservoir as these led to different heat storage capacities. Due to the reduced water height in the pan, the amount of energy it would have received through radiation and conduction through the walls of the pan is incomparably higher than that received by the reservoir water. Moreover, the reduced area of the pan would have tended to enhance the loss of water through evaporation because it facilitates the removal of air-saturated layers at the water–air interface.

4.4 Sensitivity analysis of pan evaporation and EC evaporation versus meteorological variables

A sensitivity analysis of the daily pan evaporation and daily EC evaporation with air temperature, relative humidity, wind speed, and solar radiation, was carried out. The results are presented in Fig. 9, and strengthen the ability to establish a relationship between the open EC evaporation and pan evaporation at the daily scale, as discussed in Section 4.5.

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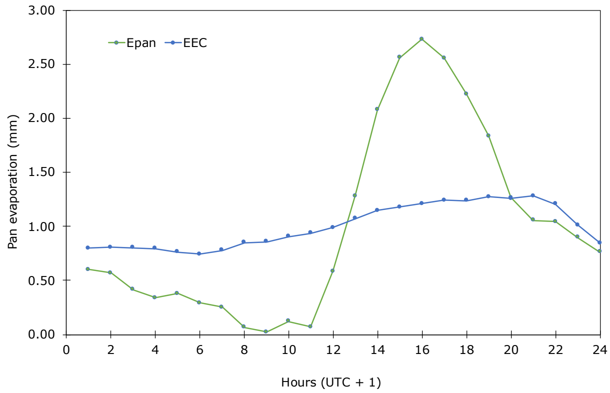

Figure 8. Mean daily cycle of the normalised pan evaporation (E_{pan}) and the eddy covariance (EC) evaporation (E_{EC}).

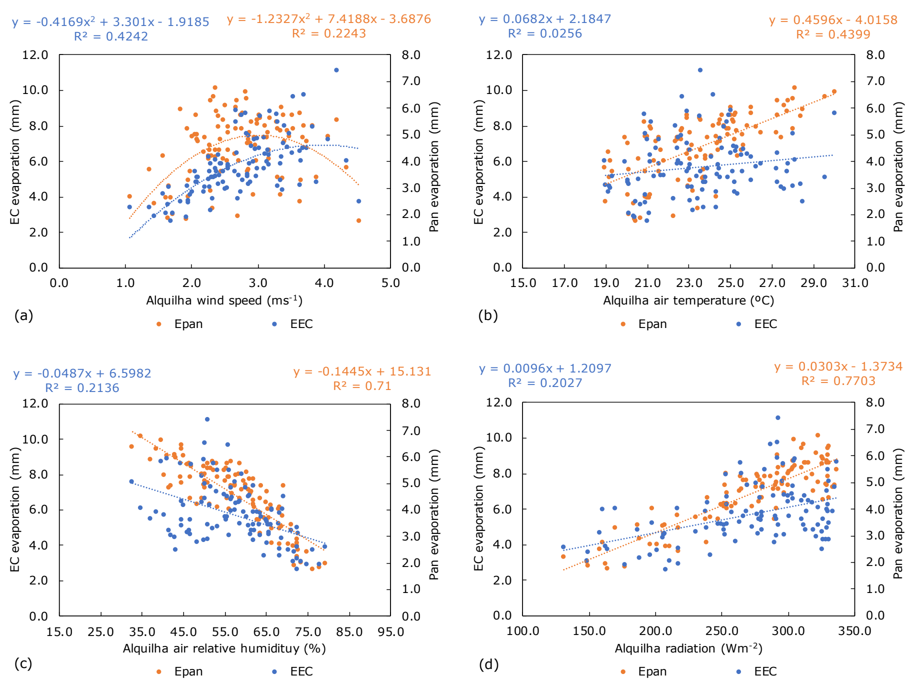

Figure 9. Sensitivity analysis of the daily eddy covariance (EC) evaporation (E_{EC}) and the daily pan evaporation (E_{pan}) from June to September 2014, with (a) wind speed; (b) air temperature; (c) relative humidity of air; (d) solar radiation.

215 ## 4.5 Pan evaporation coefficient model

The pan evaporation coefficient (K_{pan}) was calculated as a function of the four meteorological parameters measured at Alquilha station because this station will be used in the future to obtain data to support water managing and decision-making. Consequently, the reservoir evaporation (E_{Res}) will be estimated by the Alquilha Class A pan evaporation $E(_{pan})$ measure-

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ment (at Alquilha) multiplied by the modelled K_{pan}. The pan evaporation coefficient model was expressed by a multivariable function as Eq. (1):

$$K_{pan} = aU + bTa + cLN(RH) + dLN(Rad) + eTaLN(Rad) + f \quad (1)$$

where a, b, c, d, e, and f are specific constants; U is the average daily wind speed at a height of 2 m at the Alquilha station (m s^{-1}); Ta is the average daily temperature at Alquilha station (ºC); RH is the average daily relative humidity at Alquilha station (%); Rad is the total daily radiation at Alquilha station (W m^{-2}). By taking an objective function to minimise the residual sum of squares, the parametrisation of the specific constants was performed by optimisation using the GRG method; thus, Eq. (1) becomes Eq. (2):

$$K_{pan} = 0.0925U + 0.1531Ta - 0.2558LN(RH) + 0.2593LN(Rad) - 0.0308TaLN(Rad) + 0.3489 \quad (2)$$

The daily mean modelled K_{pan} for June, July, August, and September was 0.59, 0.57, 0.57, and 0.64, respectively. These values are slightly larger than those obtained directly by the ratio of the EC evaporation to pan evaporation (0.54). Previous work by (Rodrigues, 2009) presented monthly K_{pan} values of between 0.70 and 0.90 for the same summer period and reservoir. However, these values were estimated using the data from a floating pan on the platform at Alqueva-Montante station, and the reservoir evaporation was obtained by the energy budget approach.

Figure 10 presents the E_{Res} determined from the pan evaporation coefficient model and the measured EC evaporation. The R^2 value of 0.74 indicates that this model was able to estimate the E_{Res} quite well. The total modelled E_{Res} for the period from June to September was 455.8 mm, which corresponds to 101.3% of the EC evaporation and 76% of the site reference evapotranspiration calculated by the Penman–Monteith equation (Allen et al., 1998). The modelled daily mean E_{Res} in June, July, August, and September was 3.9 mm d^{-1}, 4.2 mm d^{-1}, 4.5 mm d^{-1}, and 2.7 mm d^{-1}, respectively.

The model's ability was tested for the period from June to September 2017 (Fig. 11; R^2 = 0.68); thus, the model could estimate the E_{Res} despite the high measured evaporation and the reduced number of available daily pan evaporation measurements.

5 Conclusions

The first aim of this study was to develop a method to evaluate the evaporation from Alqueva Reservoir based on Class A pan measurements, thus providing an evaluation tool for water management within the MAP and for other reservoirs with a Mediterranean climate.

Water fluxes were continuously measured from June to September 2014 by the EC method at Alqueva-Montante station to obtain accurate reservoir evaporation measurements. Data quality criteria and filters were applied, and 3% of the EC row data was rejected. The total EC reservoir evaporation from June to September 2014 was 450.1 mm, and the mean daily evaporation in June, July, August, and September was 3.7 mm d^{-1}, 4.0 mm d^{-1}, 4.5 mm d^{-1}, and 2.5 mm d^{-1}, respectively. At the hourly

https://doi.org/10.5194/hess-2020-283
Preprint. Discussion started: 15 July 2020
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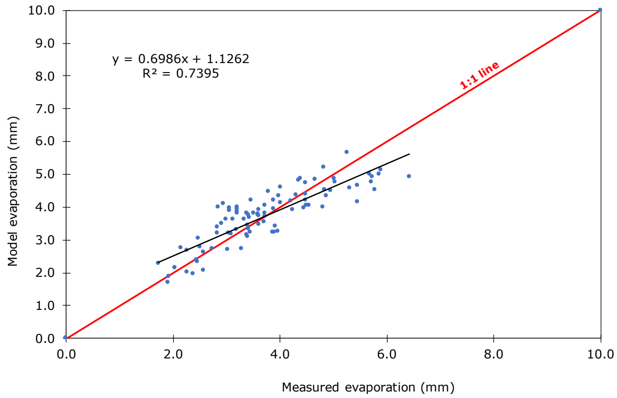

Figure 10. Modelled daily evaporation (E_{Res}) versus measured daily evaporation (E_{EC}) from June to September 2014.

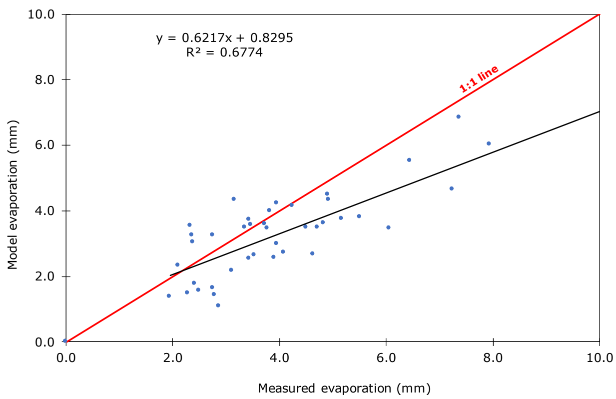

Figure 11. Modelled daily evaporation (E_{Res}) versus measured daily evaporation (E_{EC}) from June to September 2017.

scale, positive trends were observed between the EC evaporation and i) wind speed (R^2 = 0.50) and ii) air temperature (R^2 = 0.20), whereas a negative trend was found between open evaporation and relative humidity (R^2 = 0.30). There was no trend between open evaporation and incoming solar radiation.

The Class A pan installed at Alquilha station provided hourly and daily pan evaporation values. As result of the quality control process, 18% and 15% of the data were omitted at hourly and daily scale, respectively. The total pan evaporation from June to September 2014 was 797.9 mm, and the mean daily evaporation in June, July, August, and September was 6.9 mm d^{-1}, 7.7 mm d^{-1}, 7.3 mm d^{-1}, and 4.3 mm d^{-1}, respectively. Positive trends was observed between the hourly pan evaporation and i) air temperature (R^2 = 0.55), and ii) incoming solar radiation (R^2 = 0.35), whereas a negative trend was found between the hourly pan evaporation and relative humidity (R^2 = 0.53). There was no significative trend between the hourly pan evaporation and wind speed.

https://doi.org/10.5194/hess-2020-283
Preprint. Discussion started: 15 July 2020
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The K_{pan} was parametrised as a function of the wind speed, air temperature, relative humidity, and solar radiation measured at Alquilha station. The K_{pan} was 0.59, 0.57, 0.57, and 0.64 in June, July, August, and September, respectively. Consequently, the modelled daily mean E_{Res} was 3.9 mm d^{-1}, 4.2 mm d^{-1}, 4.5 mm d^{-1}, and 2.7 mm d^{-1} in June, July, August, and September, respectively. The total modelled E_{Res} was 455.8 mm, which corresponds to 101.3% of the measured EC evaporation from the reservoir. The correlation between the estimated evaporation and the measured EC evaporation had an R^2 value of 0.74.

The model was validated for the same summer period in 2017, and yielded an R^2 value of 0.68.

The model proposed in this study can assist and improve water management in the MAP. Moreover, the methodology could also be applied to other reservoirs, and the equation developed for Alqueva Reservoir could act as a first evaluation for the management of other Mediterranean reservoirs.

Author contributions. The three authors conceptualised the study. CMR designed and carried out the experiments. RCG performed the model simulations. MM wrote the first draft manuscript. All the three authors contribute to the analysis, interpretation and writing.

Competing interests. The authors declare that they have no conflict of interest

Acknowledgements. This work is funded by National Funds through the Foundation for Science and Technology (FCT) under Project UIDB/05183/2020, Project ALEX 2014 (EXPL/GEO-MET/1422/2013), Project ALOP (ALT20-03-0145-FEDER-000004), and AGIR (PDR2020-1.0.1-FEADER-031864).

https://doi.org/10.5194/hess-2020-283
Preprint. Discussion started: 15 July 2020
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