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Comparison of water balance method and alternative evaporation methods applied to the Aswan High Dam Reservoir

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Abstract

Aswan High Dam Reservoir (AHDR) is a large human-made reservoir situated in southern Egypt and northern Sudan. The reservoir is located in a typical arid zone so that evaporation results in a significant water loss from the reservoir. To quantify these evaporation water losses, different methods can be applied. The water balance method was used to estimate water losses of the AHDR during 43 open-water seasons. Compared to earlier publications, this study used longer time series data and more evaporation approaches. Moreover, we evaluated the deviation between evaporation rates as derived from the water balance method and as calculated using 16 evaporation/evapotranspiration formulas. Five approaches are not well suited for use at the AHDR because they underestimated evaporation rates (e.g. Stephens-Stewart model), or overestimated evaporation rates (e.g. de Bruin model). Annual evaporation rates obtained by the Bowen ratio energy balance method at the three floating stations Raft, Allaqi and Abu Simbel were estimated at 7.9, 6.9 and 6.7 mm d^{-1}, respectively. The monthly water losses of the years 1978 to 1984, a period with reasonable evaporation rates, are used to estimate the evaporation losses. The results of the study show a systematic deviation between the monthly average values determined using the water balance method through the period 1978 to 1984 and the monthly mean values determined by the 16 evaporation calculation approaches at three floating stations. This deviation is particularly clear in the months of May, June and September (primarily lower estimates) as well as in July (primarily higher estimates). The deviation can be attributed to the simplicity of the water balance method as well as to its limited suitability for large reservoirs as the AHDR over short periods like a month. Among the 16 evaporation calculation approaches the mass transfer method provided the most reasonable results under the given site conditions.

Zusammenfassung

Der Assuan Staudamm (Aswan High Dam Reservoir, AHDR) liegt in Südägypten und Nord-Sudan in einer ariden Zone mit hohen Verdunstungs-Verlusten. Um diese Verluste zu berechnen, können verschiedene Methoden angewandt werden. Als Referenzmethode wurde eine 43-jährige Messreihe der Wasserbilanzdifferenz genutzt. Im Vergleich zu früheren Studien wurden für diese Studie mehr Methoden und ein längerer Datensatz verwendet. Insgesamt wurden die Ergebnisse von 16 Verdunstungsformeln verglichen und die Abweichung von den aus der Wasserbilanz ermittelten Werten berechnet. Fünf Methoden sind ungeeignet, weil sie die realen Werte unter- (z. B. das Stephens-Stewart Modell) oder überschätzen (z. B. de Bruin Modell). Mit der Bowen-Ratio

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Energiebilanz-Methode wurden für die schwimmenden Messstationen Raft, Allaqi and Abu Simbel mittlere Verdunstungsraten von jeweils 7.9, 6.9 und 6.7 mm d^{-1} berechnet. Zur Abschätzung der Verdunstungsverluste wurden die Daten der Jahre 1978 bis 1984 verwendet, da für diesen Zeitraum eine optimale und repräsentative Datenbasis vorlag. Die Datenanalyse der Monatswerte ergab systematische Abweichungen für die 16 Methoden und die drei Messsstationen. Besonders hoch waren die Differenzen in den Monaten Mai, Juni und September (Unterschätzung) und im Juli (Überschätzung). Die Ursachen dieser Abweichungen können vor allem auf die vereinfachte Abschätzung mit der Wasserbilanzmethode und ihre Anwendbarkeit auf große Stauseen und kurze Zeiträume zurückgeführt werden. Unter den gegebenen Randbedingungen ergab die aerodynamische Methode die beste Abschätzung der Verdunstungsraten.

Keywords Aswan High Dam Reservoir (AHDR), water balance method, evaporation, methods comparison

1. Introduction

Water storage in reservoirs is one of the mechanisms for dealing with the fluctuation of water supply and demand (*Wisser* et al. 2013). Constructing large surface reservoirs can be used to increase the water resources during the low flow limiting periods and drought seasons (*Shiklomanov* 1998). The main uses of surface water reservoirs include flood control, municipal water supply, power generation, irrigation, commercial and recreational fisheries and navigation. About 70% of the rivers around the world are obstructed by large reservoirs (*Nilsson* et al. 2005).

The loss of water from reservoirs is a great challenge in water-scarce and arid areas, in particular, the evaporation losses. In dry areas, the evaporation losses from reservoirs can be astounding (*Goldsmith* and *Hildyard* 1986). Reservoirs can be considered one of the greatest freshwater consumers because they lose too much water by evaporation in water-scarce regions, leading to a lack of water resources (*Shiklomanov* 1998). Evaporation is the dominant loss from the system but, contrary to losses by infiltration, the evaporative loss does not have any direct benefits to the environment of the reservoir (*Abbasi* and *Giesen* 2012).

Before erecting the Aswan High Dam (AHD), the water losses from the Aswan High Dam Reservoir (AHDR) were estimated at 10 km^3 yearly, of which 9 km^3 were evaporation losses. The average seepage losses were rationally evaluated as 1 km^3 yr^{-1} (*Wafa* and *Labib* 2000). For many years, the Ministry of Water Resources and Irrigation (MWRI) in Egypt adopted the evaporation value 7.54 mm d^{-1}, a depth of 2.7 meters per year, as the mean annual evaporation rate from the reservoir surface. The maximum and minimum values were determined in June and December as 10.80 mm d^{-1} and 3.95 mm d^{-1}, respectively (*Whittington* and *Guariso* 1983). *Afifi* and *Osman* (1993) calculated the annual evaporation losses during the period from 1964/1965 to 1990/1991 as 9.6 km^3. They used half the value of Piche evaporimeter observations, estimated by *Hurst* and *Black (1955)*, and corresponding monthly water surface areas of reservoir obtained from survey maps. *Sadek* et al. (1997) had to rely on a limited dataset collected from ground stations erected around the AHDR. They used five different methods, namely water balance, energy balance, Dalton, Penman and Complementary Relations Lake Evaporation (CRLE) model (Morton), to assess the evaporation losses from the AHDR. Research results indicate that the minimum average annual evaporation was 5.7 mm d^{-1} for CRLE, and the maximum was 7.1 mm d^{-1} for Dalton. The average annual evaporation for all approaches, after excluding the Dalton method as it provided high evaporation values, is 6.0±0.3 mm d^{-1}. *Omar* and *El-Bakry* (1981) used meteorological data collected during expeditions to the AHDR over the years 1970 to 1971. The authors calculated the evaporation rates by the bulk aerodynamic and energy budget methods. They determined the average annual evaporation as 7.4 mm d^{-1} with a maximum evaporation rate of 10.9 mm d^{-1} in June and a minimum evaporation rate of 3.8 mm d^{-1} in January. *Elsawwaf* et al. (2010a) compared the evaporation rates obtained by six evaporation approaches with the rates determined using the Bowen ratio energy budget (BREB) method. The used data were obtained from three hydro-meteorological stations deployed on the AHDR over the period from 1995 to 2004 to update the previous evaporation estimates. Research findings indicate that the evaporation rates are in the range of 2.5 to 11.2 mm d^{-1} with an average evaporation rate of 5.9 mm d^{-1}.

For the Doosti dam reservoir in Iran, *Majidi* et al. (2015) used limited data to test and rank 18 evaporation methods based on the BREB method to determine the most appropriate evaporation methods. The result of the study showed that the Jensen-Haise, Makkink, Penman and de Bruin methods were among the most consistent methods with BREB. They concluded that methods, which rely only on air temperature, or air temperature combined with day length, were practical options for estimating the evaporation rates in the study area because of their simplicity, low sensitivity and high accuracy.

While these studies provide different values for the estimation of evaporation, a systematic comparison and evaluation of methods, in particular the water balance method, are still missing. Therefore, the objectives of this study are: (1) to determine the water losses from the AHDR using the water balance method; (2) to determine the evaporation rate from the AHDR using 16 alternative evaporation/evapotranspiration methods; and (3) to measure the deviation between evaporation rates determined by the evaporation/evapotranspiration methods and the evaporation rate estimated by the water balance method.

2. Materials and methods

AHDR is a large surface water reservoir that is located in southern Egypt and northern Sudan and extends between latitudes 20°27′ to 23°58′ N and longitudes 30°35′ to 33°15′ E (*Entz* 1976). AHDR was formed by constructing the AHD across the Nile River at Aswan in 1960. The AHDR is situated in a hyper-arid area where precipitation is extremely scarce. The mean wind speed over the year is in the range of 4.2 to 5.3 m s^{-1} (15 to 19 km h^{-1}) and its direction is NW-NE (*Elshemy* 2010). The mean slope of the mountainous eastern shoreline of the AHDR is steeper than the flat and wide western one (*El Shahat* 2000). The storage capacity of the AHDR at maximum water level (182 m a.s.l.) was estimated as 162.3 km^3 with an area of 6,540 km^2. The length of the AHDR at maximum level is about 500 km, partitioned into Nasser Lake in Egypt (350 km) and Nubia Lake (150 km) in Sudan with an average width of 12 km (*Elshemy* 2010).

The hydrological data of the AHDR, as water volume arriving the south mouth of AHDR, water elevation of the AHDR and water volume arriving the AHD for the period 1968 to 2011, was used to estimate the water losses with the water balance method. The meteorological data were obtained from three floating stations distributed along the reservoir as shown in *Figure 1*. These stations are: Raft (2 km upstream of the AHD), Allaqi (75 km upstream of the AHD) and Abu Simbel (280 km upstream of the AHD). The three stations provided measurements of air temperature, relative humidity, lake temperature, wind speed (depicted in *Figs. 2, 3* and *4*), wind direction, net radiation, barometric (atmospheric) pressure and water temperature profile measurements over the full depth of the reservoir. The available time series data of Raft station cover the period from January 1995 to December 2011, at Allaqi station data from February 1995 to October 2011 are available, and at Abu Simbel station measurements were carried out from January 1999 to December 2011. The total period of missing data at Abu Simbel station is 14 months distributed over the years 1999, 2005 and 2009. The amount of missing data at the Raft station is less than eleven months distributed over 16 years. The fraction of missing data at Allaqi is the largest among the three stations. The total period is about 30 months distributed over the years from 1995 to 2000 and from 2008 to 2010.

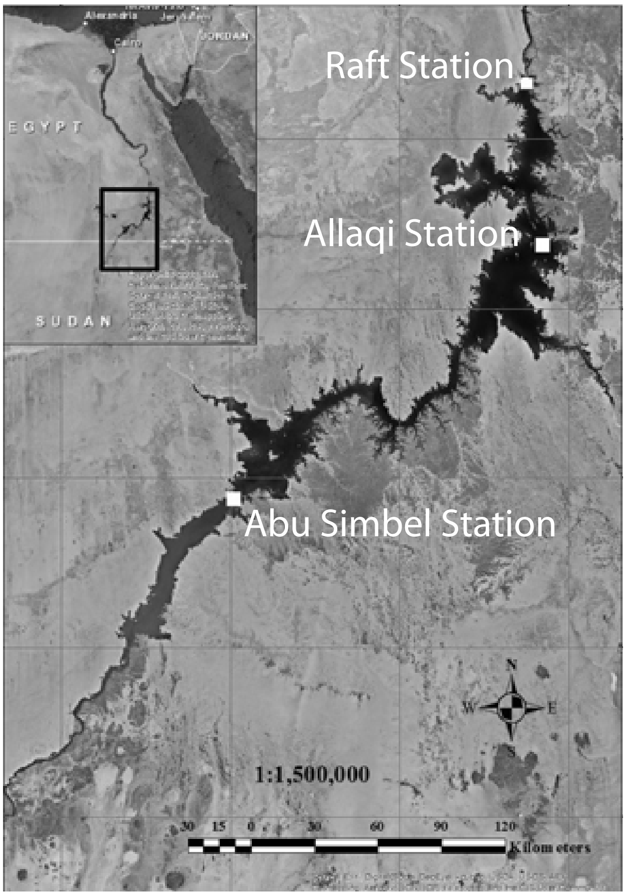

Fig. 1 Location map of the Aswan High Dam Reservoir (AHDR) and the floating stations, Egypt. Source: Own elaboration

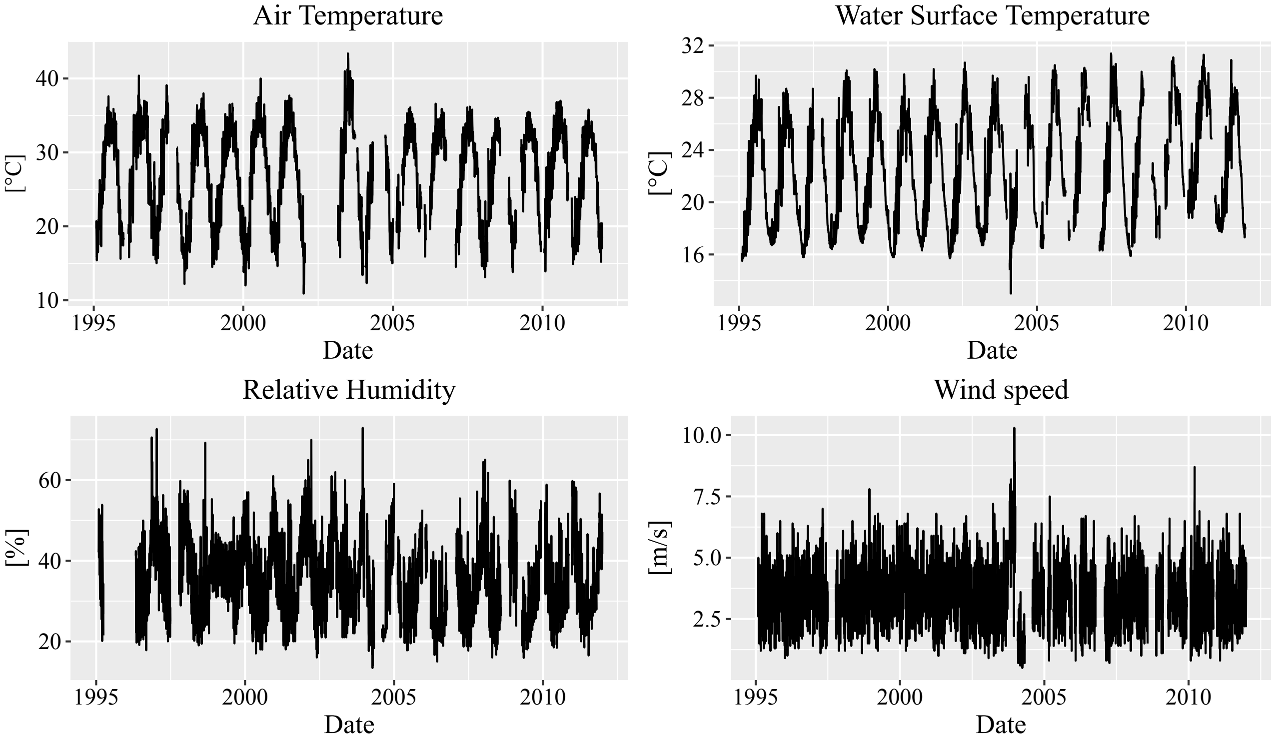

Fig. 2 Time series of daily climate data from Raft station, Aswan High Dam Reservoir (AHDR), Egypt. Source: Own elaboration

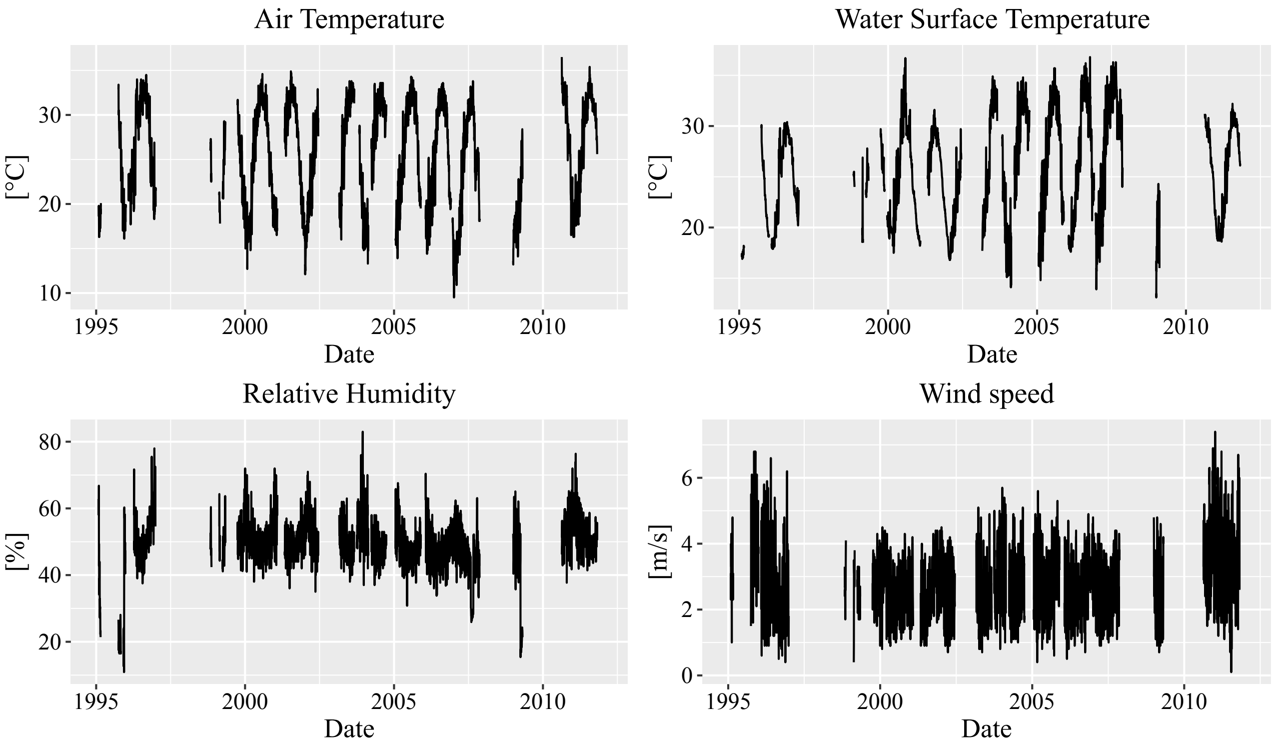

Fig. 3 Time series of daily climate data from Allaqi station, Aswan High Dam Reservoir (AHDR), Egypt. Source: Own elaboration

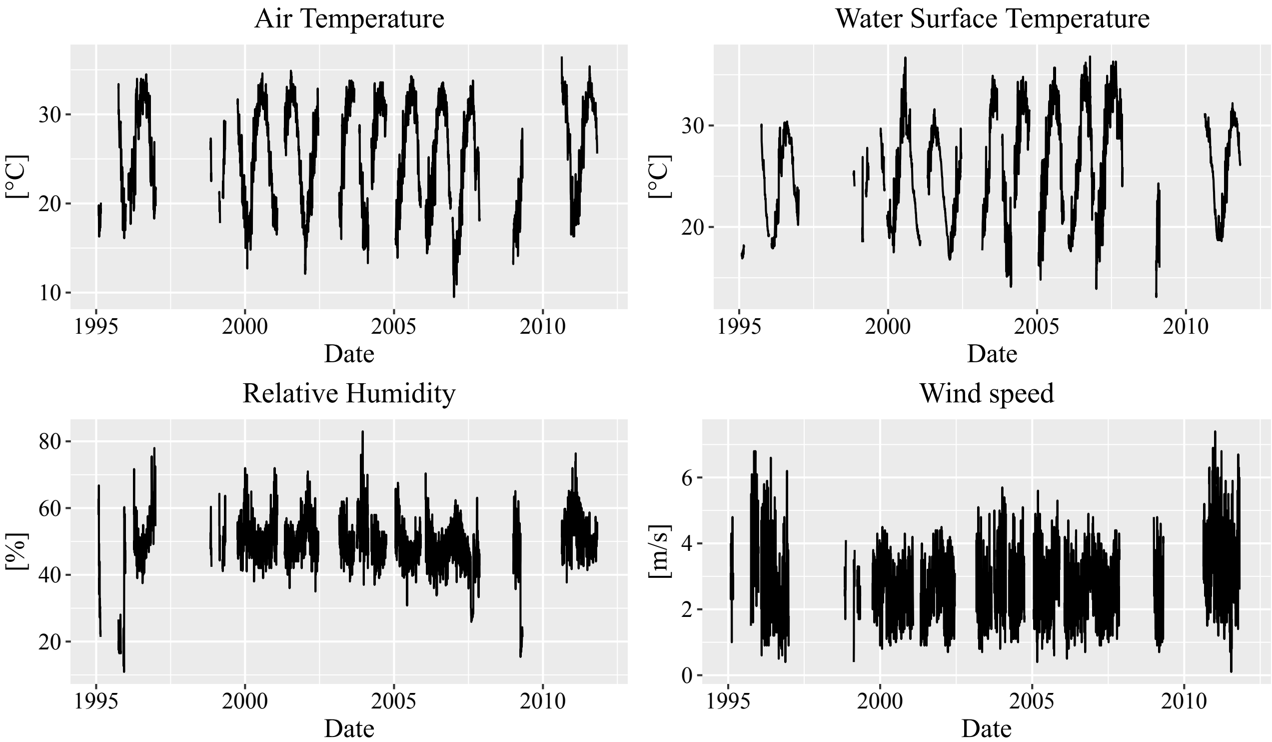

Fig. 4 Time series of daily climate data from Abu Simbel station, Aswan High Dam Reservoir (AHDR), Egypt. Source: Own elaboration

2.1 Water balance method

The water balance method is a simple method to determine the water losses over a specified period. The water balance equation seems deceptively simple: Water inflow equals water outflow plus or minus the change in storage (*Winter* 1981). The water balance equation can be expressed regarding the volume of water losses per unit time as:

$$Q_1 - L - Q_A + P \pm \Delta S = 0 \quad (1)$$

where:

$$Q_1 = Q_d - Q_{S,L} \quad (2)$$

$$Q_A = Q_{D,S} + Q_T \quad (3)$$

$$\Delta S = S_2 - S_1 \quad (4)$$

Q_1 is the inflowing discharge calculated at the entrance of the reservoir, L is the total actual loss from the reservoir, Q_A is the water volume arriving at the AHD, P is the precipitation on the water surface of the AHDR, and ΔS is the change in storage content during the time interval (month in this study). S_2 and S_1 are the water volumes of the reservoir at the end and at the beginning of the time interval, and Q_d is the discharge measured at Dongola gauging station, which is located 780 km upstream AHD (*Fig. 5*). $Q_{S,L}$ is estimated as 1% of the discharge measured at Dongola and representing Sudan abstract in the reach between Dongola and entrance of the reservoir in addition to the transmission water losses in this reach. This percentage does not remain constant: the Ministry of Water Resources and Irrigation (MWRI) in Egypt estimated the transmission water losses in the reach between Dongola and the entrance of the reservoir as 0.3% (*Omar* and *El-Bakry* 1981). Downriver the value is approximately 1% due to irrigation demands in this reach. Also, *Sadek* et al. (1997) estimated a 1% loss of the Dongola station discharge. $Q_{D,S}$ is the outflow discharge downstream AHD and Q_T is the outflow discharge through Tushka spillway at 270 km upstream the AHD (if any). The main annual rainfall on the AHDR area is less than 10 mm yr $^{-1}$ (*Shahin* 1985). Therefore, the above equation can be re-written as:

$$Q_1 - L - Q_A \pm \Delta S = 0 \quad (5)$$

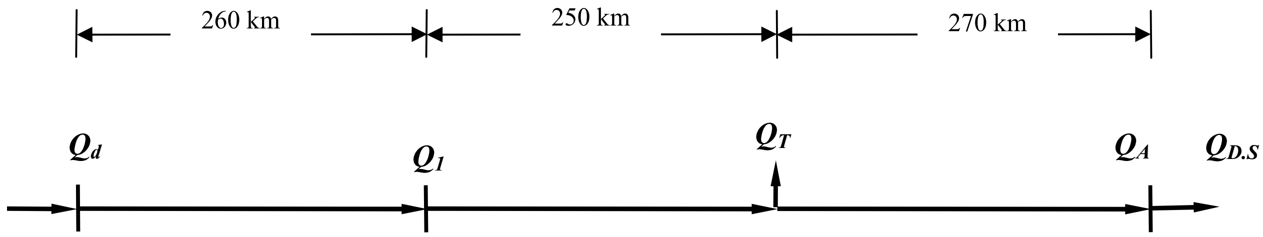

Fig. 5 Water flows into and out of the Aswan High Dam Reservoir (AHDR). Source: Own elaboration

The hydrological data for 43 years, from the water year (August to July) 1968/1969 to the water year 2010/2011, are used to estimate the water losses from AHDR by the water balance method. The monthly values of the water volume measured at Dongola gauge station, the water volume arriving upstream AHD, and the change of water volume of AHDR are used to estimate the monthly water losses.

2.2 Evaporation methods

Several evaporation models were selected to determine the evaporation rates in the AHDR using meteorological data collected at three floating stations. Some of these evaporation models are mainly used for terrestrial sites but they can also be used for lakes and reservoirs (*Rosenberry* et al. 2007; *Elsawwaf* et al. 2009, 2010; *Majidi* et al. 2015). The evaporation methods are grouped, as depicted in *Table 1*, into six groups: (i) the energy balance, (ii) the combination, (iii) the solar radiation-temperature, (iv) the Dalton, (v) the temperature and (vi) the temperature/day length approaches.

Table 1 Methods for estimation of evaporation rate (E). Source: Own elaboration*

Method	Reference	Equation
		Energy budget
BREB	*Harbeck* et al. (1958)	$E = \frac{Q_n + Q_v - Q_x}{\rho_w\left(L(1+BR) + c_w(T_0 - T_b)\right)} \times 86.4 \times 10^6$
		Combination group
Priestley-Taylor	*Priestly* and *Taylor* (1972)	$E = \alpha\left(\frac{\Delta}{\Delta+\gamma}\right)\left[\frac{Q_n - Q_x}{L\,\rho_w}\right] \times 86.4 \times 10^6$
De Bruin-Keijman	*De Bruin* and *Keijman* (1979)	$E = \left(\frac{\Delta}{0.85\Delta + 0.63\gamma}\right)\left[\frac{Q_n - Q_x}{L\,\rho_w}\right] \times 86.4 \times 10^6$
Penman	*Brutsaert* (1982)	$E = \left(\frac{\Delta}{\Delta+\gamma}\right)\left[\frac{Q_n - Q_x}{L\rho_w}\right] \times 86.4 \times 10^6 + \left(\frac{\gamma}{\Delta+\gamma}\right) \times [0.26(0.5 + 0.54U_2)(e_s - e_a) \times 10^{-2}]$
Brutsaert-Stricker	*Brutsaert* and *Stricker* (1979)	$E = (2\alpha - 1)\left(\frac{\Delta}{\Delta+\gamma}\right)\left[\frac{Q_n - Q_x}{L\rho_w}\right] \times 86.4 \times 10^6 - \left(\frac{\gamma}{\Delta+\gamma}\right) \times [0.26\,(0.5 + 0.54U_2)(e_s - e_a) \times 10^{-2}]$
De Bruin	*De Bruin* (1982)	$E = 1.192\left(\frac{\alpha}{1-\alpha}\right)\left(\frac{\gamma}{\Delta+\gamma}\right)\left[\frac{(2.9 + 2.1U_2)(e_s - e_a) \times 10^{-2}}{L\,\rho_w}\right] \times 86.4 \times 10^6$

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		Solar radiation, temperature group
Jensen-Haise	*Ward* and *Trimble* (2003)	$E = \frac{C_T\,(T_a - T_x) \times Q_s}{11.6 \times L} \times 10^6$
Makkink	*Delclaux* et al. (2007)	$E = a_1(\frac{\Delta}{\Delta+\gamma})\left[\frac{Q_s}{L\rho_w}\right] \times 86.4 \times 10^6 + b_1$
Stephens-Stewart	*Elsawwaf* et al. (2010)	$E = \left(a_2\left(\frac{9 \times T_a}{5} + 32\right) + b_2 \times (Q_s \times 3.495 \times 10^{-2})\right)$
Hargreaves	*Delclaux* et al. (2007)	$E = a_3(T_a + b_3)\left[\frac{Q_s}{L\rho_w}\right] \times 86.4 \times 10^6$
		Dalton group
Mass transfer	*Harbeck* et al. (1958)	$E = NU_2(e_0 - e_a) \times 86.4 \times 10^6$
Ryan-Harleman	*Rasmussen* et al. (1995)	$E = \frac{(2.7(T_0 - T_a)^{0.333} + 3.1U_2)(e_0 - e_a) \times 10^{-2}}{L\,\rho_w} \times 86.4 \times 10^6$
		Temperature group
Papadakis	*Rosenberry* et al. (2007)	$E = 0.5625\left(e_s\max \times 10^{-2} - (e_s\min \times 10^{-2} - 2)\right)\left(\frac{10}{d}\right)$
Thornthwaite	*Watson* (1993)	$E = \left(1.6\left(\frac{10T_a}{I}\right)^{6.75\times10^{-7}I^3 - 7.71\times10^{-5}I^2 + 1.79\times10^{-2}I + 0.49}\right)\left(\frac{10}{d}\right)$
		Temperature, day length group
Blaney-Criddle	*Rosenberry* et al. (2007)	$E = (0.0173T_a - 0.314) \times T_a \times \left(\frac{D}{D_{TA}}\right) \times 25.4$
Hamon	*Rao* et al. (2011)	$E = 0.1651 \times L_{day} \times \rho_{sat}$

*where Q_n net radiation (W m^{-2}); Q_v net advective energy (Wm^{-2}); Q_x change in thermal energy storage (W m^{-2}); BR, Bowen ratio, dimensionless; T_o lake surface temperature (°C; °F for the Blaney–Criddle equation); ρ_w density of evaporating water (998 kg m^{-3}); L Latent heat of vaporization (J kg^{-1}); c_w specific heat capacity of water (4186 J kg^{-1} K^{-1}); T_b reference base temperature (assume 0 °C); α = 1.26, Priestley-Taylor constant, dimensionless; Δ slope vapor pressure curve (Pa K^{-1}); γ psychometric constant (Pa K^{-1}); e_s saturated vapor pressure at temperature of the air (Pa); e_a vapor pressure at 2 m above the water surface (Pa); e_o saturation vapor pressure at the water–surface temperature (Pa); e_s max and e_s min = saturated vapor pressures at daily maximum and minimum air temperatures (Pa); N coefficient of efficiency of vertical transport of water vapor by eddies driven by the wind ($N = \frac{0.622\rho_a}{P_a\rho_w}\frac{0.16}{\left[\ln\left(\frac{Z_m - Z_d}{Z_o}\right)\right]^2}$) (Pa^{-1}), ρ_a density of air [1.220 kg m^{-3}], Z_m height at which wind speed and air vapor pressure are measured; Z_d zero–plane displacement [m], Z_d=0 m over typical water surfaces; Z_o roughness height of the surface [m]; Z_o=2.30×10^{-4} m over typical water surfaces; T_a air temperature at 2 m above the AHDR surface (°C); U_2 wind speed at 2 m above AHDR surface (m s^{-1}); d number of days in the month; I annual heat index ($I = \Sigma\, i$, $i = (T_a/5)^{1.514}$); D hours of daylight; D_{TA} total annual hours of daylight for specific latitude; Q_s solar radiation (W m^{-2}); T_x intercept of the temperature axis ($T_x = -2.5 - 1.4 \times 10^{-3}(e_s\max - e_s\min) - H/550$) (°C); C_T temperature coefficient ($C_T = \frac{1}{C_1 + 7.3C_H}$); $C_1 = 38 - \frac{2H}{305}$; $C_H = \frac{5.0\text{ kPa}}{e_s\max - e_s\min}$, H the water level of AHDR (m); L_{day} daytime length; ρ_{sat} saturated vapour density (g m^{-3})$\left(\rho_{sat} = \frac{216.7 \times e_s \times 10^2}{T + 273.3}\right)$; a_1=0.77, a_2=0.008, a_3=0.0145, b_1=0.2, b_2=−0.19, b_3=17.8; the multipliers 10, 10^{-2}, 25.4, and 86.4 × 10^6 are conversion factors to mm d^{-1}.

Q_n values were identified according to the FAO-56 procedure (*Allen* et al. 1998). Q_x was computed from the daily temperature profile of the water body at depths 0, 2, 5, 10, 15 and 20 m. The formula for the change in heat storage in the water body (Q_x) can be expressed as:

$$Q_x = \rho_w c_w \quad 0.5 \sum_{i=1}^{5} [\Delta t_i + \Delta t_{i+1}] \, \Delta z \Big) \tag{6}$$

where Δt_i , Δ t_{i+1} are water temperature differences between two timepoints of one day, frequently measured at two depths. Δz_i is the layer thickness (depth zone). The output values of Equation (6) were multiplied by 11.574×10^{-6} to convert the unit of Q_x to W m^{-2}. The monthly Q_x values of the three hydrometeorological stations are shown in *Figure 6*. The net decrease or increase in Q_x equals –0.43, –24.6 and 1.2 W m^{-2} through the whole period at Raft, Allaqi and Abu Simbel stations respectively. These values should be close to zero, which only applies to Raft and Abu Simbel. The stored heat in reservoirs is mainly governed by the surface energy exchanges rather than the energy exchanges at the water-soil interface and the energies associated with the inflows and outflows (*Henderson-Sellers* 1986). Therefore, the Q_v term (net advective energy by groundwater, precipitation, and stream flow) can often be neglected if the reservoir water volume is large compared to the water volumes flowing in and out of the reservoir or if the temperature values are convergent (*Finch* and *Calver* 2008). *BR* (Bowen ratio) is the ratio of sensible heat to latent heat and is calculated as:

$$BR = \frac{c_{pa} P_a}{0.622 L} \frac{T_0 - T_a}{e_o - e_a} \tag{7}$$

where c_{pa} is the specific heat capacity of moist air at constant pressure (1.01 kJ kg^{-1} K^{-1}).

3. Results and discussion

3.1 Water balance method

The total annual water losses during the period from 1968/1969 to 2010/2011 amounted to 413 km^3, giving an average annual value of 9.6 km^3 yr^{-1}. This means that the annual average water loss is close to the target value (10 km^3 yr^{-1}). However, there has been some unusual variance in water loss in this period, as depicted in *Figure 7*. The monthly evaporation rates of the periods from 1968 to 2011, 1995 to 2011 and 1978 to 1984 are used to approximate the evaporation losses as depicted in *Figure 8*. The evaporation rates of the periods from 1968 to 2011 and from 1978 to 1984 are relatively similar. However, the period from 1978 to 1984 has two advantages: Firstly, there has not been unusual variance in water loss in this period and, secondly, the water elevation started to decrease during this period. This means there is no loss by absorption (loss because of saturation of dry rock). Also, the seepage water loss is expected to be lower. In general, the seepage loss is very low and can be neglected (estimated as 0.24 km^3 yr^{-1} (*Aziz* et al. 2014). The uncertainty of the discharge measurements at Dongola station, which is required to determine the error boundaries of the water balance method, is unknown. The average annual evaporation rate was estimated, during the period 1978–1984, as 5.5 mm d^{-1} with a maximum in July (10.1 mm d^{-1}) and a minimum in February (3.3 mm d^{-1}). The evaporation in July and August is about two times the other values (*Fig. 8*).

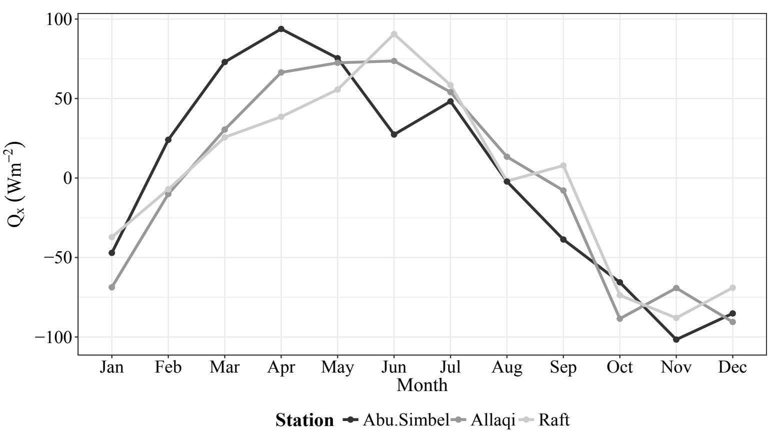

Fig. 6 Change in heat content at all hydrometeorological stations determined by Equation (6). Source: Own elaboration

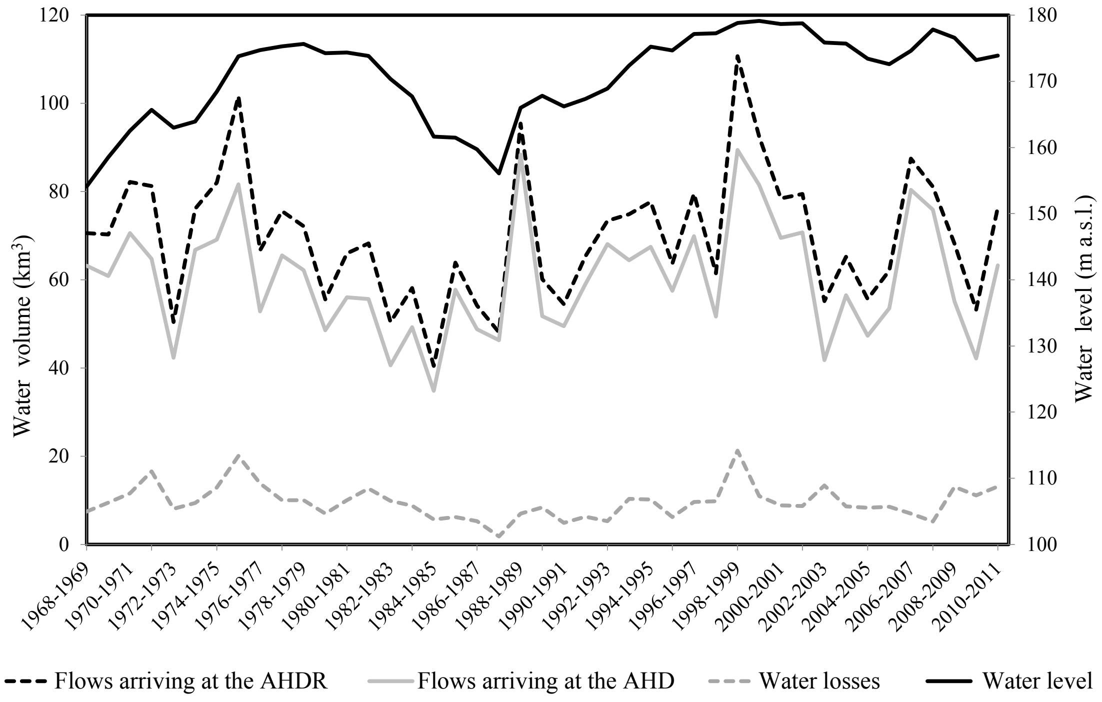

Fig. 7 *Annual water losses as derived by the water balance method, depicted with the flows arriving at the Aswan High Dam Reservoir (AHDR), flows arriving at the Aswan High Dam(AHD), and average water level. Source: Own elaboration*

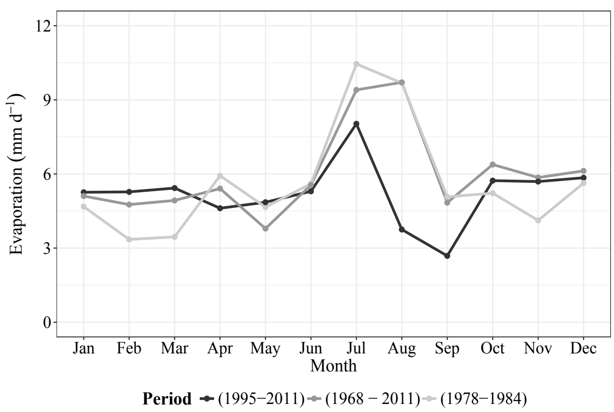

Fig. 8 *Annual water losses as derived by the water balance method, depicted with the flows arriving at the Aswan High Dam Reservoir (AHDR), flows arriving at the Aswan High Dam(AHD), and average water level. Source: Own elaboration*

3.2 Alternative evaporation methods

3.2.1 The Bowen ratio energy balance (BREB) method

In this method, the evaporation from a water body is determined as the energy term required to close the energy budget when all the other terms of the budget of the water body are known. If the sensible heat flux term (the amount of energy directly warming the air) is not measured directly, then it can be replaced by the Bowen ratio (BR, defined as the ratio between the sensible and latent heat fluxes) in the energy balance equation (*Finch* and *Calver* 2008). As presented in *Table* 2, the BR at Raft station are more negative than the values at Allaqi and Abu Simbel stations, which is explained by the higher negative values of the (T_0–T_a). The value of evaporation rate loses its numerical meaning when the Bowen ratio approaches –1.0 (*Ohmura* 1982), as it occasinally occurred at Raft station. As depicted in *Figure 9*, the BREB determined the highest evaporation rates at Raft station because of the high negative values of BR. The evaporation rates, as well as the BR values at Allaqi and Abu Simbel station are very similar. In general, the BREB is a very sensitive method and requires high-quality data to obtain a good result over open water surfaces. The average annual evaporation rates determined by the BREB at the three floating stations are represented in *Table 3.*

Table 2 Mean monthly Bowen ratios (computed from daily values) at the three floating stations. Source: Own elaboration

Month	Floating stations		
	Abu-Simbel	Allaqi	Raft
January	0.059	0.050	–0.007
February	–0.035	0.076	–0.107
March	–0.079	0.002	–0.196
April	–0.075	–0.020	–0.318
May	–0.086	–0.045	–0.342
June	–0.077	–0.013	–0.283
July	–0.072	–0.002	–0.195
August	–0.079	–0.008	–0.146
September	–0.058	–0.006	–0.150
October	–0.017	0.001	–0.117
November	0.066	0.006	–0.062
December	0.112	0.023	–0.004

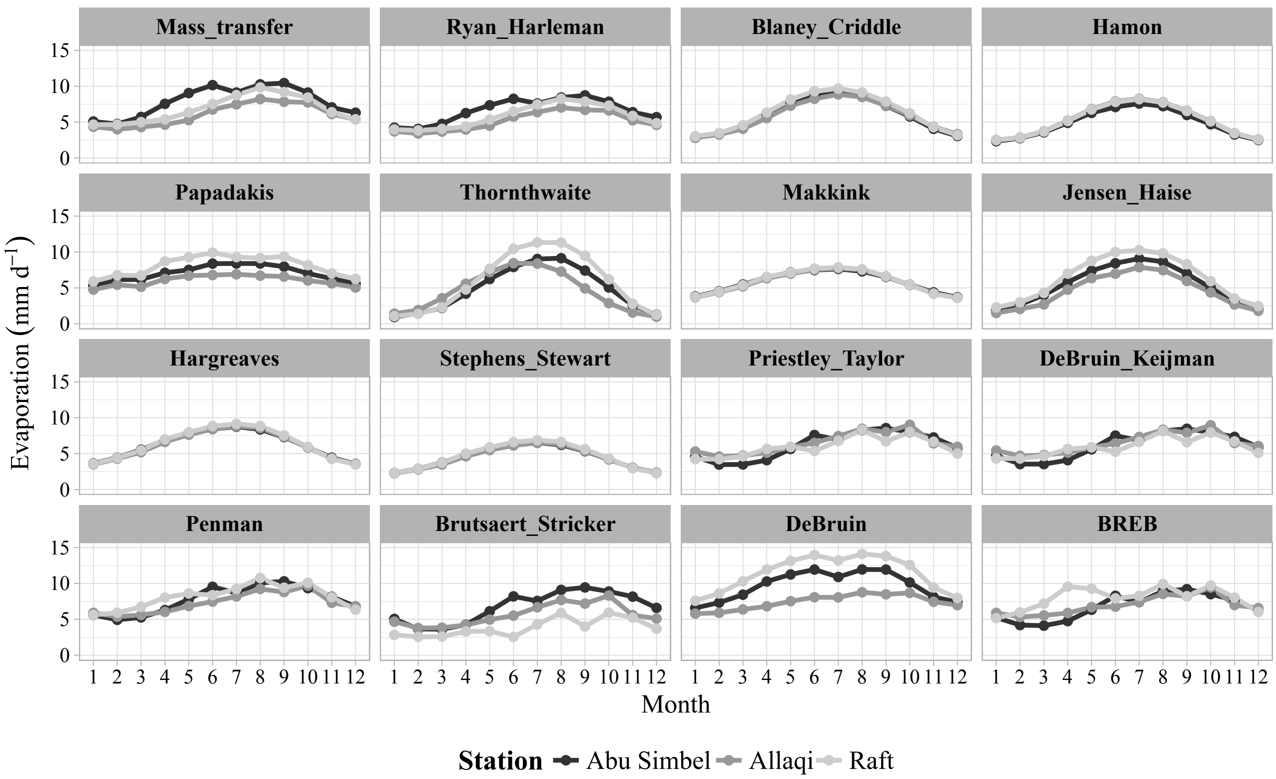

Fig. 9 Daily evaporation rates at the floating stations (mm d^{-1}) averaged per month as estimated by 16 evaporation methods listed in Table 1. Source: Own elaboration

Table 3 Daily evaporation values at the floating stations (mm d^{-1}) averaged per year as estimated by 16 evaporation methods listed in Table 1. Source: Own elaboration

Method group	Method	Floating stations		
		Abu-Simbel	Allaqi	Raft
Energy budget	Bowen ratio energy balance (BREB)	6.7	6.9	7.9
Combination group	Priestley-Taylor	6.1	6.4	6.0
	DeBruin-Keijman	6.1	6.4	5.9
	Penman	7.7	7.3	8.1
	Brutsaert-Stricker	6.7	5.6	4.2
	DeBruin	9.7	7.4	11.4
Solar radiation, temperature group	Jensen-Haise	5.4	4.5	6.3
	Makkink	5.8	5.8	5.9
	Stephens-Stewart	4.4	4.4	4.6
	Hargreaves	6.3	6.2	6.4
Dalton group	Mass-transfer	7.2	6.0	6.8
	Ryan-Harleman	6.6	5.1	5.8
Temperature group	Papadakis	7.0	6.0	8.0
	Thornthwaite	4.8	4.5	5.8
Temperature, day length group	Blaney-Criddle	5.9	5.8	6.3
	Hamon	4.9	5.2	5.2

3.2.2 Combination group

Combination methods include available energy and aerodynamic terms. The Penman method combines the mass transfer and energy budget methods and excludes the requirement for surface temperature to obtain an equation for the evaporation rate from open water (*Majidi* et al. 2015). The Priestley-Taylor method neglects the aerodynamic term in Penman's equation and uses a constant α (as correction factor) with the energy component. *Priestley* and *Taylor* (1972) estimated the average value of α at 1.26. *De Bruin* and *Keijman* (1979) derived their equation based on the Priestley-Taylor equation. They replaced the term $\alpha(\Delta/(\Delta+\gamma))$ by the term $(\Delta/(0.85\Delta+0.63\gamma))$ because they found diurnal variation in the value of α and suggested that the conditions producing such variation would be expected from many lakes. Also, they found a very good agreement between the evaporation determined from the energy budget and that determined using their Formula (*Finch* and *Calver* 2008). *Brutsaert* and *Stricker* (1979) formulated the Advection-Aridity (AA) model using a simple, empirically based, linear approximation for the wind function proposed by *Penman* (1948) and substituting this approximation into the Penman equation. They also used the Priestley-Taylor equation for partial equilibrium evaporation (*Hobbins* et al. 2001). *De Bruin* (1982) found that it is often not possible or too expensive to get satisfactory measurements of Q_n and Q_x for a large water body. Thus, he combined the Penman and Priestley-Taylor equations and excluded the energy components (*Finch* and *Calver* 2008). As depicted in *Figure 9*, the evaporation rate at the three floating stations determined by the Priestley-Taylor and de Bruin-Keijman approaches are very similar. The Penman method determined relatively high evaporation rates compared to Priestley-Taylor and de Bruin-Keijman approaches, while de Bruin-Keijman overestimated the evaporation rate. Evaporation rates determined by Brutsaert-Stricker at Raft station are very low and not realistic for the site's climate conditions.

3.2.3 Solar radiation, temperature group

The evaporation rate determined by the four temperature–radiation methods increases when the value of Q_s and increases. This explains the high evaporation rate in July and August. The coefficients used in these methods emphasize the influence of Q_s and T_a to some extents (*Rosenberry* et al. 2007). The evaporation rate estimated by Hargreaves and Makkink approaches are convergent. The Stephens-Stewart and Jensen-Haise approaches are not well suited for use at the AHDR because they underestimated evaporation rate as shown in *Figure 9*. In general, these approaches showed a low sensitivity for the input data.

3.2.4 Dalton group

Both methods, mass transfer and Ryan-Harleman, based on Dalton theory and rely on the terms of U_2 and $(e_0–e_a)$ in addition to $(T_0–T_a)$ in case of Ryan-Harleman. The value of the mass transfer coefficient is specific for the characteristics of the site used to record the meteorological data (*Finch* and *Calver* 2008). The Ryan-Harleman equation was developed to determine the evaporation from heated water bodies. In that case, both forced convection driven by wind and free convection driven by buoyancy control the evaporation rates, while for natural water bodies forced convection is the dominant factor (*Dadaser-Celik* and *Stefan* 2008). The low values of the wind speed and the vapor pressure gradient explain the smaller rate of evaporation determined by both methods at Allaqi station. In general, the mass transfer method is well suited for use because of its simplicity and reasonable accuracy.

3.2.5 Temperature group

The Papadakis method depends on the differences in the saturated vapor pressure above the water body at maximum and minimum air temperatures. Thornthwaite's method is based on the air temperature with an adjustment made for the number of daylight hours. This means, it is logical that the evaporation rates increase when air temperature increases. *Figure 9* shows that the seasonal amplitude between the minimum and maximum monthly evaporation rates determined by both approaches are different. This seasonal amplitude was estimated as 10 mm d^{-1} in case of the Thornthwaite approach, while it was 2 mm d^{-1} in case of the Papadakis method. Thornthwaite determined evaporation rates less than 2 mm d^{-1} in January and December at the three stations. These low rates are not well suited to the climate conditions of the AHDR. The higher values of air temperature at the Raft station explain the higher evaporation rate estimated at this station.

3.2.6 Temperature, day length group

Blaney-Criddle correlated the measured evaporation rates per month with the monthly mean air temperature times the proportion of daylight hours to the total annual hours of the daylight to develop a monthly empirical evaporation coefficient (*Majidi* et al. 2015). The Hamon approach formulated a simple equation to determine the potential evapotranspiration given mean air temperature and day length (*Majidi* et al. 2015). It is often used to estimate lake evaporation because of its simplicity. As shown in *Figure 9*, the evaporation rate determined at the three stations by the Blaney-Criddle approach, as well as the Hamon approach, are convergent because the daylight values at the three stations are comparable. The Hamon approach underestimated evaporation rates at the three stations.

To measure the relation among the different methods, two measures were used: (1) the percentage root mean square error (*%RMSE*) and (2) the percentage mean absolute error (*%MAE*):

$$\%RMSE = \sqrt{\frac{\sum (V_{modelled} - V_{obs})^2}{n}} \times \frac{100 \times n}{\sum V_{obs}} \quad (8)$$

$$\%MAE = \frac{\sum |V_{modelled} - V_{obs}|}{\sum V_{obs}} \times 100 \quad (9)$$

$V_{modelled}$ and V_{obs} are the evaporation rates determined by the approaches listed in *Table 1* and evaporation rates determined by water balance method respectively; n is the total number of observations.

As depicted in *Figure 10*, the obtained values from *%RMSE* and *%MAE* are greater than 50%, which means a weak relation between the modeled and observed values. Also, *Figure 11* shows a systematic deviation between the monthly averages determined by water balance and the 16 approaches at the three floating stations. This deviation is clear in the months of May, June, July and September.

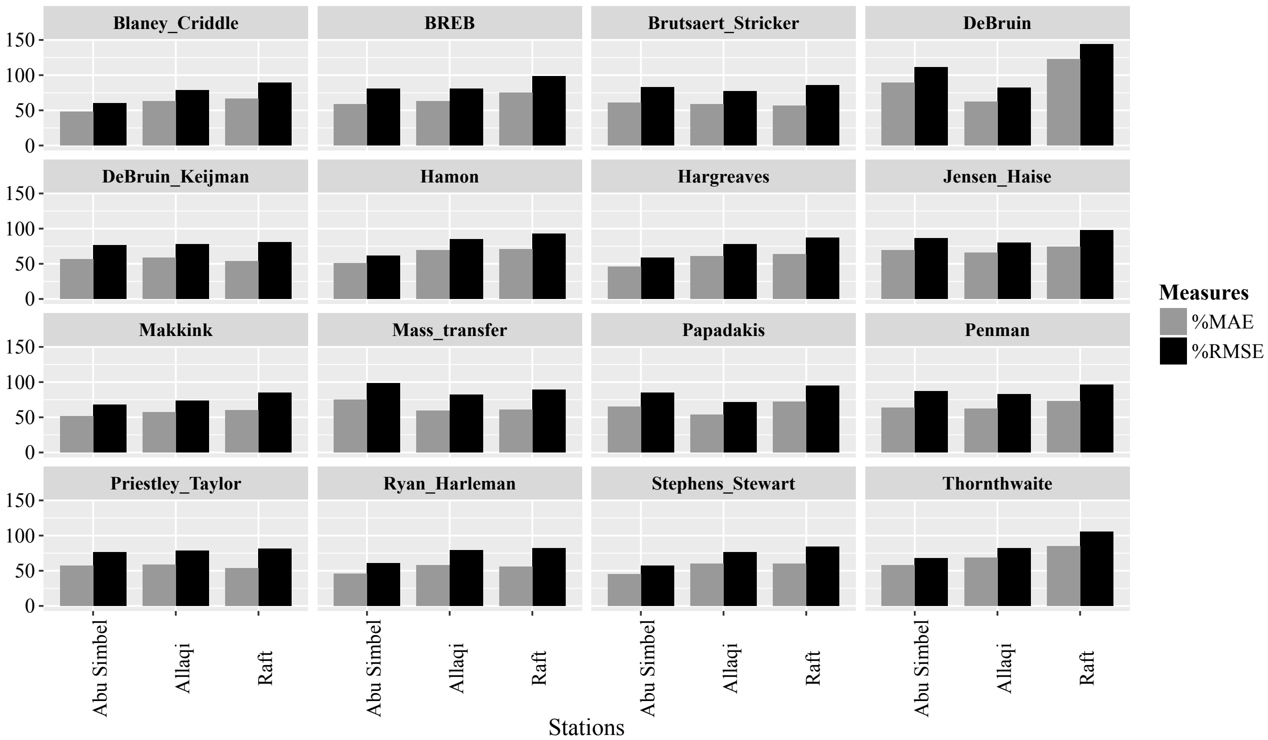

Fig. 10 Evaporation rate comparison for 16 different methods (cf. Table 1). Shown are the root-mean-square error (%RMSE) and mean absolute error (%MAE) as a percentage of the respective model estimate. Source: Own elaboration

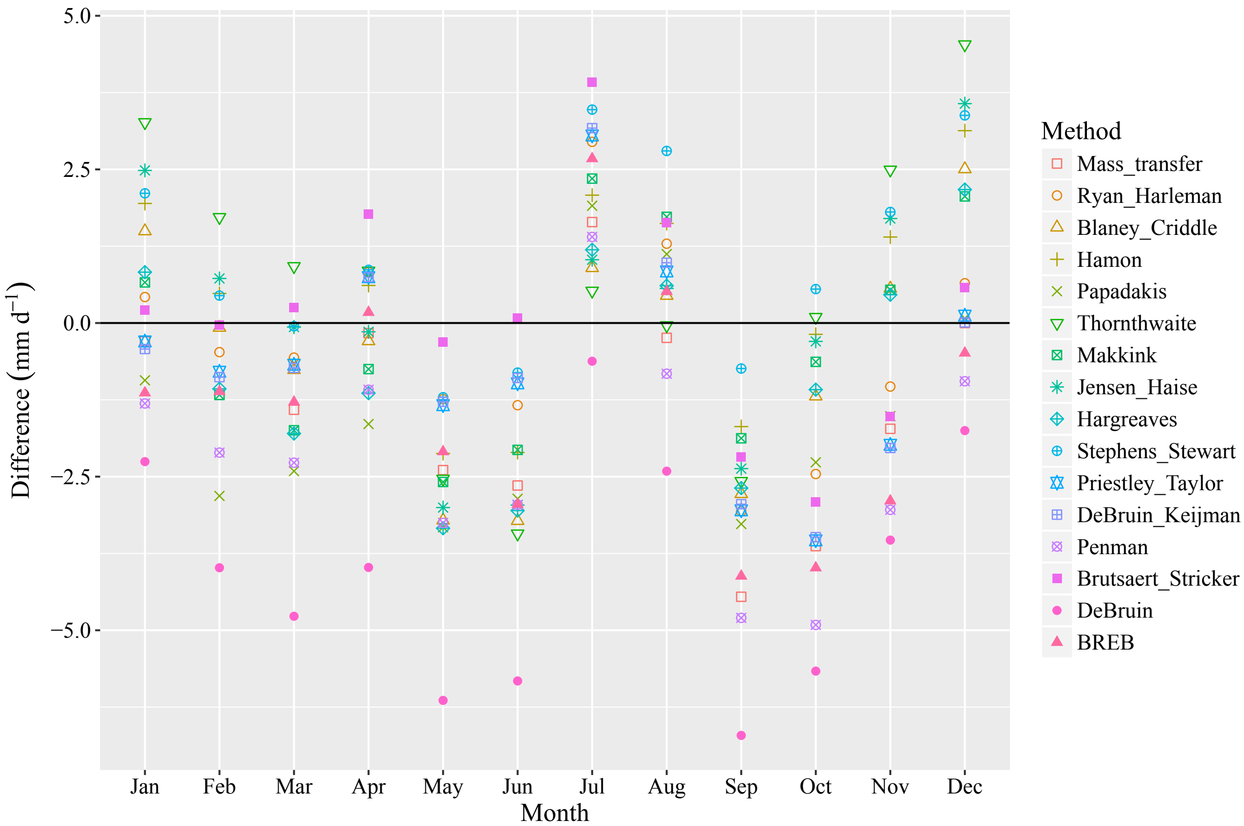

Fig. 11 Monthly mean differences (mm d^{-1}) between evaporation calculated with 16 estimation methods and the water balance method as the reference for the period 1978 until 1984. Source: Own elaboration

4. Conclusions

The total annual water losses of the AHDR, determined by the water balance method during the period from 1968/1969 to 2010/2011, amounted to 413 km^3, giving an average annual loss of 9.6 km^3 yr^{-1}. This means that the average annual water loss is around the designed value (10 km^3 yr^{-1}). The average annual evaporation rate, determined by the water balance method during the period from 1978 to 1984, is 5.5 mm d^{-1} with maximum evaporation in July (10.1 mm d^{-1}) and minimum evaporation in February (3.3 mm d^{-1}). Given the range of estimates derived from the different evaporation calculation methods, the average annual evaporation rate, estimated by the water balance method, provides a realistic value of 5.5 mm d^{-1}. Some average monthly evaporation rates estimated by the water balance method, compared with alternative methods, are not appropriate. These inappropriate values are due to uncertainties and inaccuracies of the estimated inflow based on the upstream Dongola station. The BREB, which is considered the most accurate method, estimated the evaporation rate at the three floating stations Raft, Allaqi and Abu Simbel at 7.9, 6.9 and 6.7 mm d^{-1} respectively. The highest evaporation rates at Raft station are due to the very negative values of the BR. The Penman approach estimated relatively higher evaporation rates as compared to the BREB. Stephens-Stewart, Thornthwaite, Jensen-Haise, and Hamon approaches are not quite suitable for the use at the AHDR because they severely underestimated evaporation rates obtained from the water balance reference method. De Bruin's approach overestimated evaporation rates at the Raft and Abu Simbel stations. All other approaches estimated realistic evaporation rates. The mass transfer method is considered the most appropriate method because of its simplicity, reasonable accuracy and low sensitivity to input data. The solar radiation and temperature approaches also show a low sensitivity for input data. The results of the study show systematic deviations between the monthly average values determined by the water balance method over the period from 1978 to 1984 and the monthly mean values determined by 16 approaches at the three floating stations. This deviation is clearest in the months of May, June, July and September.

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