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Impact of Reservoir Evaporation Losses on Water Demand: A Case Study of Bontanga Reservoir, Northern Region of Ghana

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Abstract:
Reservoir evaporation losses are not negligible, they directly affect the reservoir water supply. This study was undertaken to estimate evaporation losses from the Bontanga reservoir and assess the impact of reservoir evaporation losses on water demand. The Energy balance, Aerodynamic, standard FAO Penman-Monteith, and Blaney-Criddle methods were employed to estimate reservoir evaporation rates during the irrigation season which runs from October to May. The water balance approach was applied to assess the impact of reservoir evaporation losses on water demand. In addition to the standard FAO Penman Monteith method, the study demonstrated that Aerodynamic method (R^2:0.97) and Energy balance methods (R^2:0.95) can accurately estimate the evaporation rate from Bontanga reservoir. The peak and average reservoir evaporation rates were 6.5 mm/day and 5.88 mm/day, respectively. The study also revealed that the seasonal evaporation loss represented 19.61 % of the reservoir capacity. The volume of seasonal reservoir evaporation loss (3,834,576.20 m^3) represented 0.46 times the seasonal irrigation water demand and 6.3 times the domestic water demand. ANOVA results ($p < 0.001$) showed that the seasonal water demand from multiple users differed significantly at 5 % level. To sustainably meet the reservoir water demand, it is recommended that programmes such as intensification of afforestation in the catchment area should be promoted as effective reservoir water management strategies. Adoption of these practices could lead to further studies on the effect of catchment vegetation restoration on reservoir evaporation and sedimentation.

Keywords: Aerodynamic, Blaney-Criddle, Energy balance, Penman Monteith, Reservoir Evaporation, Water Demand

1. Introduction

Approximately 1.2 billion people live in areas where water scarcity is severely affecting agricultural production [1]. The growing population and rising levels of economic development have increased the demand for water and food worldwide [2]. Furthermore, climate change and variability continue to cause adverse and irreversible losses in the ecosystem. The largest impacts have been recognized in arid regions of Africa, where there is an acute problem with reduced water security [3]. With increasing water demands from various users such as agriculture, municipal needs, industry, and recreational use, water resources need to be appropriately managed and optimized to satisfy population needs [4]

In Ghana, rainfed agriculture is affected by variable rainfall patterns, and severe droughts. According to [5], future water resource availability projections are uncertain. Climate change also threatens Ghana's water availability. The increasing frequency and severity of weather events, such as high temperatures and droughts, affect water availability, distribution, and utilization. This phenomenon particularly impacts vulnerable populations in Northern Ghana.

According to [6], reservoirs form a large portion of the water resources in the Northern Region of Ghana and Bontanga reservoir is one of such facilities. In addition to agricultural production, reservoirs also play an essential role in improving the social economy and the ecological environment. However, the recent decrease of reservoir capacity has raised concerns for water users and managers.

[7] carried out a study on estimating inflow and outflow components of a small reservoir in Gujarat, India. This was done by developing a water balance model. The results showed that a major portion (51 % of storage water) was lost through evaporation and only 21% of storage water was

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utilized for irrigation. It was recommended that suitable measures need to be adopted to check evaporation losses from reservoirs in arid and semi-arid regions for improved agricultural productivity.

Since water in the reservoirs is open to the atmosphere, evaporation losses are considerable and directly affect the water supply. Management of reservoirs and improved efficiency thus require accurate knowledge of evaporation. Open-water surface evaporation is a continuous hydrological process affected by various parameters such as solar radiation, air and water temperature, wind speed, vapor pressure deficit, atmospheric pressure, surface area, water depth and water quality [8]. Such evaporation losses from reservoirs are of interest to scientists and planners because they affect water supply [9]. According to [10], methods of estimating open water surface evaporation are categorized into the following significant approaches: pan evaporation, water balance, energy balance, mass transfer, combination of mass transfer and energy balance, and empirical methods.

Evaporation losses aggravate the problem of water shortage. According to [11], lack of information on reservoir evaporation losses has an impact on reservoir management and water safety. In order to effectively investigate the impact of reservoir evaporation losses on water demand, it was necessary to first accurately quantify reservoir evaporation. Assessing reservoir evaporation losses is vital for optimal water resource allocation among multiple users.

With regards to reservoir management, the fundamental challenge is to satisfy the water demands of different users without compromising the system [12], With the increase of settlements, livestock, and farming operations within the vicinity of Bontanga reservoir, competition for water amongst multiple users is inevitable.

With the lack of local evaporation dataset that can be used in reservoir water management and policy making process in the study area and limited research on the reservoir evaporation, this study was undertaken to: (a) estimate evaporation losses from Bontanga reservoir, (b) assess the impact of reservoir evaporation losses on water demand. This information was critically important for guidance on development of more precise and effective water resource management strategies and to satisfy water demands for irrigation, domestic, livestock, fishery and other water uses.

2. Materials and Methods

2.1 Study Area

Bontanga Reservoir is located in the Kumbungu district of the Northern Region of Ghana. The reservoir is located between latitudes 9° 30' and 9° 34' N and longitudes 1° 00' and 1° 03' W. Fig. 1 shows the location of the study area.

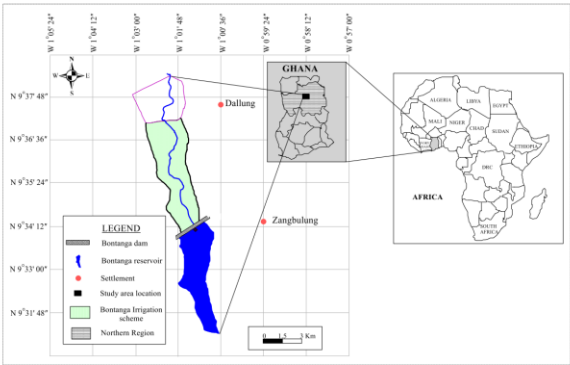

Fig. 1 - Location of Bontanga reservoir

Bontanga reservoir was created by constructing an earthen dam across Bontansi river, a tributary of White Volta in Northern Ghana. Water from the reservoir is used for irrigation, domestic water supply, livestock water use, and fish production [13]. Key technical details of Bontanga reservoir and dam structure are presented in Table 1.

Table 1- Key technical details of Bontanga reservoir and dam structure

Key parameter	Value/specification
Maximum reservoir storage capacity	25 million m^3
Live storage capacity	20 million m^3
Dead storage capacity	5 million m^3
Catchment area	165 Km^2
Maximum reservoir surface area	770 ha
Crest length	1900 m
Crest width	6 m
Maximum depth	12 m
Top embankment level	125.63 m above sea level
Water surface elevation at flooding level	122 m above sea level

Sources: [14]; [15]

2.2 Data collection

33 years climatic data (1990-2023) were obtained from Savanna Agricultural Research Institute (SARI), located at Nyankpala in Northern Ghana. The climatic data included: maximum and minimum air temperatures, solar radiation, sunshine hours, wind speed, and relative humidity.

2.3 Methods of estimating reservoir evaporation losses

2.3.1 Energy Balance Method

According to [16], the energy balance method is based on the conservation of heat energy within a body of water, and the method relies on the assumption that the ratio between the sensible and latent heat fluxes is compatible by means of measurable local microclimatic variables. The rate of evaporation from the reservoir was computed using Equations (1) and (2):

$$E_r = \frac{R_n}{\ell_v \times \rho_w} \tag{1}$$

$$\ell_v = 2.501 \times 10^6 - 2370T \tag{2}$$

Where;
E_r is the rate of evaporation (m/s),
R_n is the net radiation (W/m^2),
ρ_w is the density of water (1000 Kg/m^3),
ℓ_v is the latent heat of vaporisation (j/kg)
T is the mean air temperature (°C)

2.3.2 Aerodynamic Method

The Aerodynamic method is one of the simplest and oldest methods widely applied for estimation of open water surface evaporation because of its simplicity and reasonable

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accuracy [17]. According to [18], Equations (3), (4), (5) and (6) were applied to compute the rate of reservoir evaporation:

$$E_a = B\left[e_s - e_a\right] \quad (3)$$

$$\mathrm{B} = \frac{0.102u_2}{\left\{ln\left(\frac{z_2}{z_0}\right)\right\}^2} \quad (4)$$

$$e_s = 611\ exp\left[\frac{17.27T_{mean}}{237.3+T_{mean}}\right] \quad (5)$$

$$e_a = \frac{RH_{(mean)}}{100}\left[e_s\right] \quad (6)$$

Where;
E_a is the evaporation rate (mm/day),
B is the vapour transfer coefficient (mm/day/pa),
U_2 is the wind speed (m/s) measured at a height of 2 m,
Z_2 is the height at which the wind speed is measured (200 cm),
Z_o is the roughness height above water surface (0.01 - 0.06 cm),
RH_{mean} is the mean relative humidity (%),
e_s is the saturated vapour pressure (Pa),
e_a is the actual vapour pressure (Pa)

2.3.3 FAO Penman-Monteith Method

FAO Penman-Monteith method (E_{FAO-PM}) is recommended as the standard reference evapotranspiration method for comparison with the results of the other methods [19]. FAO Penman-Monteith equation describes the combined effect of energy and aerodynamic vapor transport. It only requires regularly monitored meteorological data as input, therefore, it is a suitable approach for open water evaporation estimation [20]. The method requires air temperature, humidity, radiation and wind speed data. The CROPWAT 8.0 developed by Land and Water Development Division of FAO was used to compute reference evapotranspiration based on Equation (7):

$$E_{FAO-PM} = \frac{0.408\,\Delta(R_n - G) + \gamma\,(\frac{900}{T_{mean}+273})u_2(e_s - e_a)}{\Delta + \gamma\ (1+0.34u_2)} \quad (7)$$

Where;
E_{FAO-PM} is the estimated reference evapotranspiration (mm/day),
R_n is the net radiation at the crop surface (MJ/m^2 day),
G is the soil heat flux (MJ/m^2 day),
T_{mean} is the average air temperature at a height of 2 m (°C),
u_2 is the wind speed at 2 m height (m. s^{-1}),
e_s is the saturation vapor pressure (kPa),
e_a is the actual vapor pressure (kPa),
Δ is the slope of vapor pressure curve (kPa/°C),
$e_s - e_a$ is the vapour pressure deficit (kPa)
γ is the psychrometric constant (kPa/°C).

According to [21], the reservoir evaporation was computed from the reference evapotranspiration by considering the coefficient for open water surface as indicated in Equation (8):

$$E_{FAO-RESERVOIR} = E_{FAO-PM} \times K_w \quad (8)$$

Where;
$E_{FAO-RESERVOIR}$ is the estimated reservoir evaporation rate (mm/day),
E_{FAO-PM} is the reference evapotranspiration (mm/day),
K_w is the coefficient for open water surface.

According to [22], for reservoir depths greater than 5 m, the K_w value of 1.25 is used. In the case of reservoir depth less than 5 m, the K_w value of 1.05 is used.

2.3.4 Blaney-Criddle Method

The Blaney-Criddle equation correlates evaporation rate with mean air temperature and percentage of day-time hours during the year. According to [23], the reservoir evaporation rates were computed using equation (9)

$$E = 25.4(0.0173T_a - 0.314)T_a\frac{D}{D_{TA}} \quad (9)$$

$$1°\mathrm{F} = (-17.22°\mathrm{C} \times 1.8) + 32 \quad (10)$$

Where;
E is the reservoir evaporation rate (mm/day),
T_a is the average air temperature (°F),
D are the daylight hours,
D_{TA} are the total annual daylight hours.

2.3.5 Performance evaluation of reservoir evaporation estimation methods

ANOVA test was run using GENSTAT 12.1 (Twelfth Edition) to check if reservoir evaporation rates differ significantly when using Energy Balance, Aerodynamic, standard FAO Penman-Monteith method, and Blaney-Criddle method (α = 0.05). Furthermore, the performance of evaporation estimation methods was statistically evaluated using coefficient of determination (R^2), Root Mean Square Error (RMSE), and Index of Agreement (d).

The coefficient of determination (R^2) was used to check the correlation between reservoir evaporation rates from the standard FAO Penman-Monteith method and other methods under assessment. According to [24], a value close to 1 indicates a perfect correlation.

The Root Mean Square Error (RMSE) was used to check if reservoir evaporation rates from other methods fit better with the reservoir evaporation rates from the standard FAO Penman-Monteith method. According to [25], RMSE was computed using Equation (11):

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(E_{FAO-RESERVOIR} - E_A)^2\right]^{1/2} \quad (11)$$

Where;
$RMSE$ is the root mean square error,
n is the number of observations,
$E_{FAO-RESERVOIR}$ is the reservoir evaporation rate from the standard FAO Penman-Monteith method (mm/day),
E_A is the reservoir evaporation rate from the other method under assessment (mm/day).

According to [26], the Index of Agreement is a standardized measure of the degree of method estimation error which varies between 0 and 1. The Index of Agreement value of 1 indicates a perfect match, and 0 indicates no agreement at all. Equation (12) was applied to compute the index of agreement (d):

$$d = 1 - \frac{\sum_{i=1}^{n}(Y_i - X_i)^2}{\sum_{i=1}^{n}[(|Y_i - \bar{X}|) + (|X_i - \bar{X}|)]^2} \quad (12)$$

Where;
d is the Index of Agreement,
Y_i is the estimated reservoir evaporation rate from the examined methods,

X_i is the reservoir evaporation rate from the standard FAO Penman-Monteith method,
$\bar{X}$ is the average reservoir evaporation rate from FAO Penman Monteith method.

2.4 Assessment of the impact of reservoir evaporation losses on water demand

In this study, the water balance approach was applied to visualize the status of water demand from the multipurpose Bontanga reservoir. The water balance approach was applied as presented in Equation (13):

$$\text{Inflow} = \text{Outflow} + \text{change in storage} \qquad (13)$$

In reference to Equation (13), the reservoir evaporation losses formed part of the outflow components of the reservoir-based system. Other outflow components comprised water demands for irrigated agriculture, domestic water use, and livestock water use. The amount of water remaining in the reservoir as storage was targeted for fishery water demand.

Based on the status of water demand components of the multipurpose reservoir, ANOVA test was run using GENSTAT 12.1 (Twelfth Edition) to check if reservoir water demand components differed significantly at 5% level of significance.

3. Results and Discussion

3.1 Performance of reservoir evaporation estimation methods

Fig. 2 shows reservoir evaporation rates during the study period under various evaporation estimation methods:

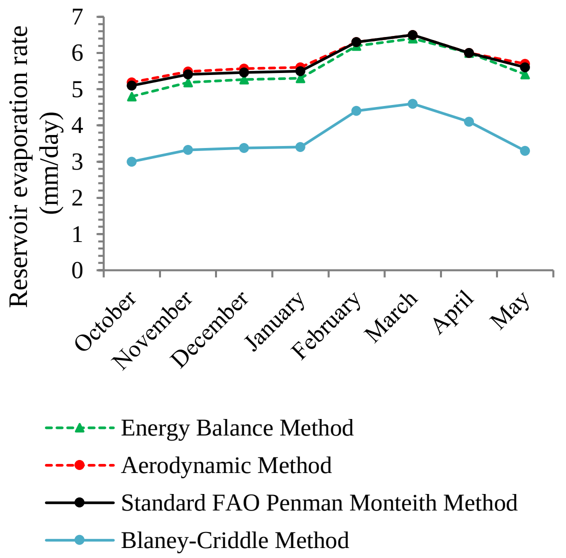

Fig. 2 - Reservoir evaporation rates during the irrigation season (October, 2022 to May, 2023)

During the irrigation season, the peak reservoir evaporation rates were observed in March (6.5, 6.5, 6.4, 4.6 mm/day) for Aerodynamic, standard FAO Penman-Monteith, Energy balance, and Blaney-Criddle methods, respectively. During the peak reservoir evaporation, the minimum temperature, maximum temperature, wind speed, radiation, and relative humidity were 22 ^{0}c, 37.8 ^{0}c, 2.4 m. s^{-1}, 18.5 MJ/m^2/day, and 48 %, respectively.

The summary of multiple comparison analysis results is shown in Table 2.

Table 2 - Multiple comparison analysis results of reservoir evaporation estimation methods

Reservoir evaporation estimation method	Mean	P-value
Aerodynamic	5.98^a	
Standard FAO Penman Monteith	5.88^a	
Energy Balance	5.78^a	<0.001
Blaney-Criddle	3.94^b	

ANOVA results ($p < 0.001$) showed that reservoir evaporation rates differed between some of the methods under assessment at 5 % level of significance. Based on multiple comparison test, there were no significant differences on reservoir evaporation rates from Aerodynamic, Energy balance and the standard FAO Penman-Monteith method. [27] reported an average reservoir evaporation rate of 5.0 mm/day from small reservoirs in the study region. However, Blaney-Criddle method underestimated reservoir evaporation rates and its values differed significantly from all other methods.

Table 3 - Statistical performance indicators of evaporation estimation methods

Evaporation Method	R^2	RMSE	d
Aerodynamic	0.97	0.08	0.97
Energy balance	0.95	0.16	0.96
Blaney Criddle	0.62	2.45	0.18

R^2 is the Coefficient of determination, RMSE is the Root Mean Square Error (RMSE), and d is the Index of Agreement

When compared to the standard FAO Penman-Monteith method, the Aerodynamic method performed well and was ranked first (1). Though the method slightly overestimated reservoir evaporation rates, its results were consistent during the study period. The results are in conformity with the findings of [28] who also reported that Aerodynamic method provides best estimates of reservoir evaporation and further stated that the method demands less climatic data (air temperature, wind speed, and relative humidity).

The Energy balance method also performed well and was ranked second (2). The method slightly underestimated the reservoir evaporation rate. The results are in similarity with the findings of [29] who also found out that combination methods provided the best comparisons with the energy balance method in terms of estimating evaporation rates.

Despite being the simplest approach in estimating evaporation rate, the Blaney Criddle method performed poorly and was the least method. It underestimated the reservoir evaporation rates throughout the study period. The method only relies on air temperature and daylight hours.

The results suggest that, in addition to the standard FAO Penman Monteith method, Aerodynamic and Energy balance methods can be used to precisely determine the rate of evaporation from Bontanga reservoir. However, in terms of ranking, Aerodynamic method should be prioritized because

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of its level of precision as revealed by statistical parameters.

3.2 Status of reservoir water demands

In order to maximize water usage from the reservoir, it was very important to keep tracking reservoir water storage, water abstraction, and extent of reservoir water losses. The water balance provided information about all inflows and outflows within a defined boundary while taking into account the multiple uses of water within the system. The status of seasonal reservoir water demands is properly visualized in Fig. 3.

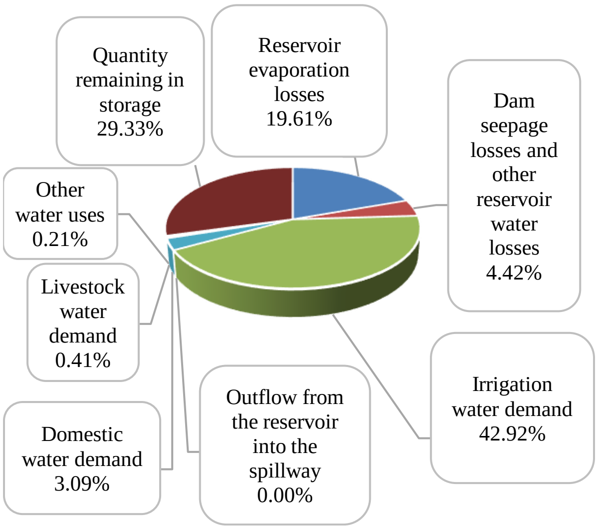

Fig. 3 - Seasonal Reservoir Water Demands

During the study, the estimated reservoir capacity was 19,550,000 m^3. The results showed that 70.67 % of the estimated reservoir capacity aimed at meeting seasonal irrigation water demand, livestock water demand, domestic water demand, reservoir water losses and other water uses as summarized in Fig. 3.

ANOVA results ($p < 0.001$) showed that the seasonal water demands from multiple users differed significantly at 5 % level of significance. Irrigation formed the largest seasonal water demand from the reservoir (42.92 %), this is in conformity with the findings of [30] who also found out that dry season irrigation formed a major water share from the reservoir. The domestic and livestock water demands only accounted for 3.09 % and 0.41 %, respectively. Other water uses e.g construction formed the least seasonal water demand (0.21 %). The multiple comparison analysis results of reservoir water demand are shown in Table 4:

Table 4: Multiple comparison analysis results of reservoir water demand

Reservoir water demand component	Percentage (%)	P-value
Irrigation water demand	42.92^a	
Reservoir evaporation losses	19.61^b	
Dam seepage and other reservoir water losses	4.42^c	
Domestic water demand	3.09^d	<0.001
Livestock water demand	0.41^e	
Other water uses e.g construction	0.21^f	

3.3 Impact of reservoir evaporation losses on water demands

The seasonal reservoir evaporation loss was 3,834,576.20 m^3, representing 19.61 % of the reservoir capacity during the study period. The volume of reservoir evaporation loss represented 0.46 times the seasonal irrigation water demand and 6.3 times the domestic water demand. With the exception of the irrigation, reservoir evaporation losses exceeded the domestic, livestock and other water demands in the system. These results are important for reservoir water management planning. It is therefore necessary to focus on effective reservoir water management interventions in order to reduce water losses and meet water requirements of multiple users. One practical approach is to minimize reservoir evaporation losses by intensifying afforestation on the reservoir's catchment area. The vegetation around the reservoir will act as a wind break, as well as reduce air temperature, hence reducing the reservoir evaporation rate.

4. Conclusions

In addition to the standard FAO Penman Monteith method, the study has demonstrated that Aerodynamic and Energy balance methods can accurately estimate the rate of evaporation loss from Bontanga reservoir. The peak and average reservoir evaporation rates were 6.5 mm/day and 5.88 mm/day, respectively. The study has also revealed that the seasonal evaporation loss from Bontanga reservoir represented 19.61 % of the reservoir capacity and formed a significant part of the Bontanga reservoir water balance. The reservoir evaporation losses significantly affected water demand. Long-term programmes, such as catchment afforestation should be promoted in order to reduce water losses through evaporation. This approach will reduce the wind speed since the established vegetation will act as a wind-break, as well as reduce air temperatures. Once such measures are adopted, further research focusing on the effect of catchment vegetation restoration on reservoir evaporation and sedimentation could be undertaken.

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Conflict of interest

The authors have declared that there is no any conflict of interest regarding the publication of the paper.

Data availability

Data will be made available on request.

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