Evaporation losses as a major factor in determining allowable yield from water supply reservoirs: the case of Botswana's major reservoirs

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Abstract

Reservoirs play an important role in storing water for various uses. This storage is affected by rising demand due to changes in economic pattern and demand distribution. Added to these is the effect of evaporation especially in semi-arid areas with limited suitable reservoir sites. Botswana is one such country with flat terrains, ephemeral rivers with sandy beds and often lacks well defined channels for potential dam sites. These hydrographic factors lead to the development of shallow and large reservoirs, which lose more water due to evaporation. In assessing performance of Botswana's major reservoirs, a modified sequent peak algorithm has been used to study the effects of evaporation on reservoir sizing and operation, and how that affects the yield. The study concludes that evaporation is very critical for reservoir planning in semi-arid regions, because for every storage there exists a range of yield to be supplied. Outside this range, the effects of evaporation are more difficult to control.
Keywords: allowable yield, reservoir capacity, critical period.

1 Introduction

In semi-arid hydrology, evaporation losses are very important since they influence storage capacity of surface reservoirs. The ability to account for evaporation explicitly is thus important in these regions (Adeloye et al, [1]). Accounting for evaporation in reservoir planning can alter the sequence of critical period (CP, a period over which a full reservoir goes into empty without spillage) and hence of the failure periods, when the reservoir is not able to meet the demand. This alteration has been well reported by Montaseri and Adeloye [6] and Adeloye et al, [1]. While most of these studies adequately address the issue of accommodating evaporation losses, and the subsequent effect on the CP, nowhere do they focus on identifying a window of yield to be supplied in order to contain the sequence of CP even with inclusion of evaporation. This study therefore attempts to bridge the gap, by varying yield to be supplied and checking how that affects the sequence and magnitude of the CP for Botswana's reservoirs. The modified sequent peak algorithm (Lele, [2]; Adeloye et al, [1]) is used initially to estimate the desired storage capacities of reservoirs in Botswana to check its performance, and subsequently assess the effects of evaporation on the CP and target yield

2 Sequent Peak Algorithm (SPA)

SPA uses mass balance equation to simulate reservoir performance through sequential deficits from an initially full reservoir (McMahon and Mein, [5]), as given in eqn. (1a) and (1b)

$$K_t = \begin{Bmatrix} K_{t-1} + D_t + E_t - Q_t > 0 \\ 0, otherwise \end{Bmatrix} \qquad (1a)$$

$$K^*_a = \max(K_t), \qquad (1b)$$

where K_{t-1} and K_t are the volumetric deficits at the start and end of time t, respectively; E_t, Q_t and D_t are volumetric evaporation losses, inflows and yield, K^*_a is the exact estimated capacity. For the purpose of this paper, the modified SPA is used in order to explicitly accommodate storage-dependent losses (Adeloye et al, 2001) as summarized below. The algorithm also begins with the basic SPA to compute K_t and the approximate storage capacity, K'_a. Appropriate storage states (S_t) are estimated by subtracting K_t from K'_a; S_t is then used to obtain E_t with eqns. (2) and (3) (Loucks et al., [4]; Lele, [2]; Adeloye et al, [1])

$$A_t = aS_t + b \qquad (2)$$

$$E_t = e_t(A_t + A_{t+1})/2 \qquad (3)$$

where A_t and A_{t+1} are the surface areas at the beginning and end of t, respectively; e_t is the depth of net evaporation; a and b are constants, obtained from storage-height-area relationships at the reservoir site. The resulting backward pass storage, which includes evaporation can be re-written as eqn. 4 below.

$$S_t = \left[S_{t+1}(1+e_t a/2) + D_t + e_t b - Q_t\right]/(1-e_t a/2) \qquad (4)$$

Since the backward pass starts from the end of the CP, then the starting S_{t+1} is known and equal to zero, and the maximum of all S_t is the exact capacity estimate, denoted by K_a^*. This process is repeated until the capacity settles down, using a convergence criterion given by eqn. (5)

$$\left|(K_a - K_a^{'})/K_a\right| \le 0.0001 \qquad (5)$$

where K_a and $K_a^{'}$ are the estimates of the active storage capacity in any two successive iteration, respectively (Adeloye et al, [1]).

3 Reservoirs and data

Reservoirs under study are Gaborone and Bokaa in the southern part of Botswana, Shashe and Letsibogo in the northern part of Botswana. Shashe dam is located on the Shashe River, near Francistown City, while Letsibogo dam is on the Motloutse River, near Selibe-Phikwe town. Gaborone dam is located to the south east of the City of Gaborone on the Notwane River, while Bokaa is on the Metsimotlhabe River north of Gaborone City. A summary of the hydrographic data is presented in Table 1 below:

Table 1: A summary of hydrographic data for the Four Dams used in the study.

Dam	Catch. Area (Km^2)	Dam Area (Km^2)	Capacity ($x10^6m^3$)	MAR ($x10^6m^3$)	Average Depth (m)
Shashe	3630	18	88	91	20
Letsibogo	7930	16	100	69	20
Gaborone	4300	22	144	35	22
Bokaa	3570	7	18.5	9.7	8

The northern part of Botswana receives relatively higher annual rainfall to the tune of 600mm, compared to 350mm in the southern Botswana. For this reason, northern catchments have higher mean annual runoff (MAR) as shown in Table 1.

4 Data collection

Evaporation data were obtained from Department of Meteorological Services. Capacity curves needed for constants a and b in eqn. (2) and (4) were obtained from Liebenberg and Stander [3] and SMEC [7]. However, since historical streamflow data at all the four sites were small, simulation exercise was undertaken to obtain as large as 64 years of record at each site using Pitman Model (SMEC, [7]).

5 Data presentation and analysis

The SPA results for the four dams are presented in Table 2. Firstly, SPA was used to estimate the capacities of the reservoirs. This was done to test the ability of the method in estimating reservoir capacity. The method returned very good results; 99% for Gaborone, and 100% for the rest, indicating perfect estimation for all the dams.

Table 2: Storage and Yield estimates from SPA.

Dams	Capacity ($x10^6m^3$)	SPA Stor. ($x10^6m^3$)	Effect of evapo (%)	Yield/an. ($x10^6m^3$)	CP (Months)
Shashe	88	88	24	43	85
Letsibogo	100	100	13	35.4	124
Gaborone	144	142	27	17.6	298
Bokaa	19	19	116	2.52	57

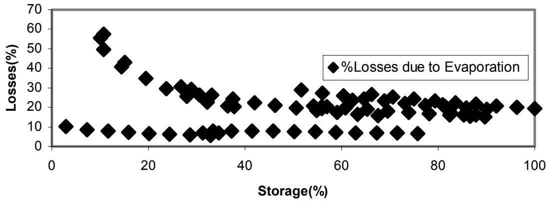

Figure 1: Effect of evaporation as percentage of active storage (Shashe dam).

5.1 Effects of evaporation on storage and allowable yield

Reservoir capacities were determined for specified yield under the cases when evaporation was included and when it was not. It was observed that when including evaporation into SPA method, the desired storage capacities increased, indicating significance of evaporation for the dam in question (Table 2). From these results alone, it is clear that the northern reservoirs have lower evaporation rates compared to their counterparts, with Bokaa dam recording the highest rate of evaporation. It should however be noted that the above conclusions are restricted to inclusion of evaporation on the estimation of reservoir capacity, and as such there is a need to further assess these effects on reservoir performance and the CP under specified yields. Since the effects are much felt within the CP, an assessment of the effects was restricted to this period, though the simulation was based on the entire record length. From Figs 1-4, it is observed that Botswana reservoirs loose more water due to evaporation, with more water lost when the storages are low (i.e. below 50%). Also, these results are in agreement with Table 2, as on average, southern catchments displayed higher evaporation losses of 24%(Gaborone) and 54% (Bokaa), compared to northern catchments, with low rates of 20%(Shashe) and 11%(Letsibogo). It may also be noted that although Letsibogo dam has generally lower rates of evaporation, most of these losses however occur when the dam is 50-75% full, unlike Gaborone and Shashe dams, where the losses are much pronounced below 50% full capacity. Interestingly, Bokaa dam on the other hand tends to display a persistent loss of 50% through all the storage states, most likely due to shallow depth (8m).

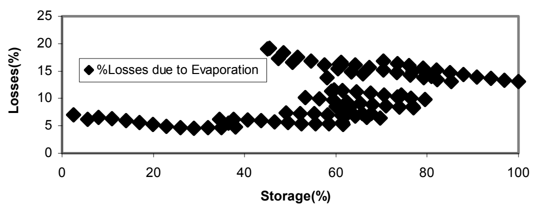

Figure 2: Effect of evaporation as percentage of active storage (Letsibogo dam).

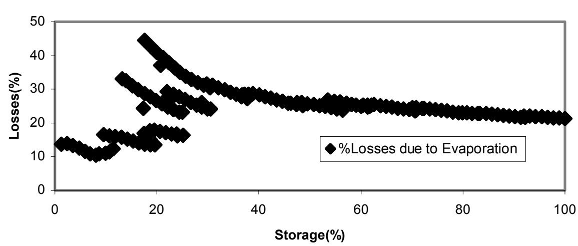

Figure 3: Effect of evaporation as percentage of active storage (Gaborone dam).

5.1.1 Alteration of the critical period due to evaporation

By studying relationship between the allowable yield that a reservoir can support, and the CP, Figs 5-8 have shed more light; that each storage has a range of yield that it can supply without altering the CP. The CP is not offset if it stays on the zero line indicating that the effects of evaporation are contained within that specific range of releases (i.e. for CP lag and CP movement plots). In all the dams, it can be seen that outside the preferred range of yield, the CP either moves to a completely different location within the data record, or its length is altered. A summary of these yields is given in Table 2, with the plots shown in Fig. 5-8. Also, the CP is affected when the yield is increased, that is the storage being put under pressure to release more water than it has been designed for, hence displaying a mixture of positive and negative shift (early CP and late CP, respectively). In this scenario, the demand for water coupled with effects of evaporation make the reservoir more prone to failures. This can be a problem during drought periods when inflows into the reservoirs are much lower.

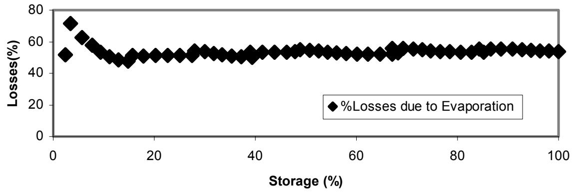

Figure 4: Effect of evaporation as percentage of active storage (Bokaa dam).

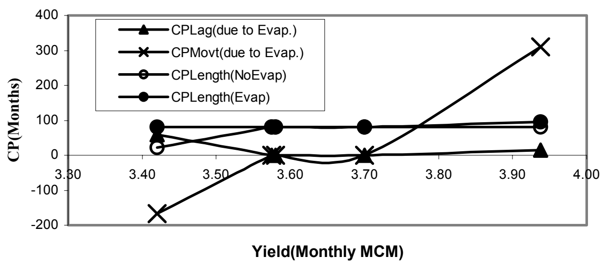

Figure 5: Effect of evaporation on allowable yield (Shashe dam).

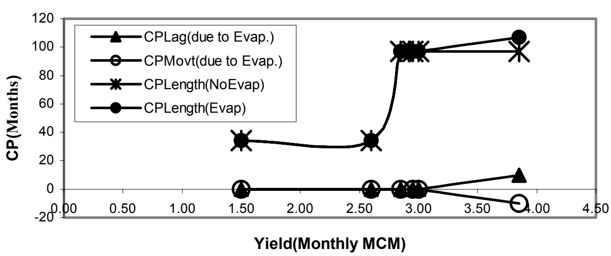

Figure 6: Effect of evaporation on allowable yield (Letsibogo dam).

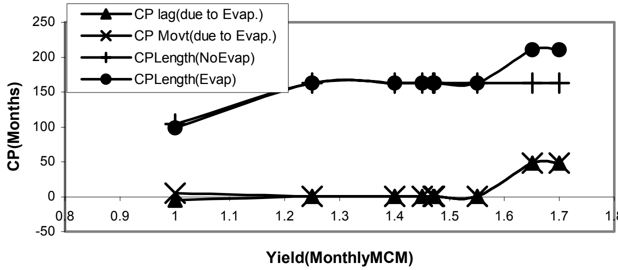

Figure 7: Effect of evaporation on allowable yield (Gaborone dam).

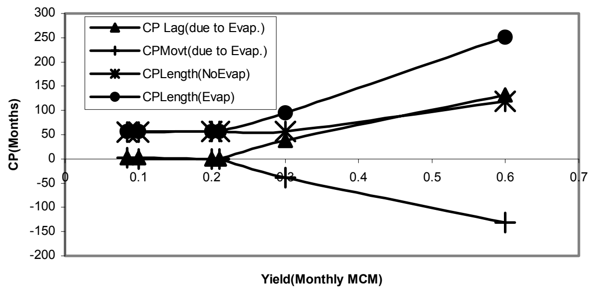

Figure 8: Effect of evaporation on allowable yield (Bokaa dam).

6 Conclusions

The paper's objectives were to determine effects of including evaporative losses on reservoir sizing and operation, and how that affects the yield to be supported by each dam. From the four dams studied, it has been established that evaporation is very critical not only during reservoir sizing but also throughout its operation. Furthermore, it has been found that for each of the reservoir capacity estimates, there exists a window of allowable yield, within which the effects of evaporation can still be contained. The CP then become sensitive as soon as the dam is stressed to release more water than it has been designed for. When considering the significance of evaporation across Botswana dams, it can be concluded that the southern dams are much susceptible to effects of evaporation than the northern dams. From these four, Bokaa showed highest rates, no wonder it is used as a transfer station into the Gaborone dam through the North-South water transfer scheme. While there are several factors contributing to high evaporation rates in Botswana dams, most of these can be attributed to topographic characteristics of catchments (flat terrain and lack of suitable sites), and shape of dams (shallow and wide dams).

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