RESERVOIR STORAGE REQUIREMENTS IN ARID AREAS

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Water reservoir storage requirements are a function of demand and variation in inflow. The greater the variation the greater the storage required to meet a specified draft. The selected recurrence interval of failure also affects the storage required. It is found that the variation in flow increases the lower the average flow. Arid countries such as Botswana are therefore more vulnerable to drought than low mean annual flows would indicate. Rainfall and river flow records for Botswana were analyzed to produce maps that show the coefficients of variation (COV's) over the country. Examples of the use of the charts are given. The COV of river flow is significantly higher than for rainfall. This means that it is theoretically more economic to harvest rain than to attempt to store river flow. There is also less evaporation from rain tanks owing to the smaller surface area to depth ratio. However, the scale of storage also affects economics and rain harvesting affects catchment water balance.

Keywords; Botswana rainfall, rivers, reservoirs, storage

1 INTRODUCTION

Arid and semi-arid environments are dry with variable climatic conditions, that is, rainfall patterns are highly inconsistent (exhibit great variability), both in time and space. Also the soil conditions generally do not allow for favourable surface runoff and there are high evaporation and transpiration rates. Arid areas usually have low mean annual rainfall and few perennial rivers if any, thus resulting in limited fresh water resources for people, animals, agriculture, etc. The lack of rain is compounded by high variability. These conditions make management of water resources difficult for many arid and semi-arid nations.

Botswana is especially affected by these factors: it is a landlocked country with a semi-arid climate that has chilly winters and hot summers. It has low rainfall, extremely low runoff and the runoff exhibits high variability.

Most river gauging stations are in the east of the country where rivers run, and those to the west are on international rivers eg the Okovango, making extrapolation difficult. Rainfall stations on the other hand cover the country better. The maps of runoff presented are therefore preliminary and reservoir planning should in practice be supplemented by site gauging.

The objectives of the study are:

- To calculate the value of the coefficient of variation of annual rainfall and of runoff in Botswana
- To compare the coefficient of variations of mean annual runoff and rainfall and illustrate that runoff has greater variation than rainfall.
- To show that variability increases with decrease in rainfall and runoff
- To give guides to calculate storage for areas in Botswana or other areas where COVs are available for rainfall or runoff.

2 MEASURE OF VARIABILITY

The great variability in rainfall and runoff can be explained by the distribution of rainfall since only a small proportion of storms or rain days in the course of the year may provide a disproportionate amount of total rainfall. The variability of rainfall is much greater for areas with low average annual precipitation, where rain may fall only occasionally compared with equatorial regions where rain may fall nearly every day. In addition to rainfall amount, the time intervals between storms is critical as time interval affects the storage requirement and the depletion characteristics of the particular system of interest such as soil moisture or supply reservoirs [1] so runoff variability can be even greater.

Variability is an intrinsic feature of the earth's climate and it is particularly worse in semi-arid countries such as Botswana as the average annual precipitation is low, that is, rain falls occasionally and it does not rain in large satisfying quantities. According to Ward and Robinson [1] point precipitation records exhibit great variation from hour to hour, week to week, and even from year to year. The pattern of precipitation is related to the synoptic weather conditions and the properties of the air masses. Considerable advances have been made using numerical methods to produce digital models of weather systems for forecasting purposes but, in practice, for hydrological purposes, the analysis of rainfall data is often based on the statistical properties of observed rainfall time series.

A time series is a sequence of values arrayed in order of their occurrence, which can be characterised by statistical properties. If the expected value of the statistical parameter is the same for each section, the series is said to be stationary. If the expected values are not the same, the time series is non-stationary.

Stochastic, periodic and secular time series components can be used to describe the types of variations that occur in precipitation records.

Wanielista [2] states, "[because] of the extreme variability and lack of deterministic relationship for

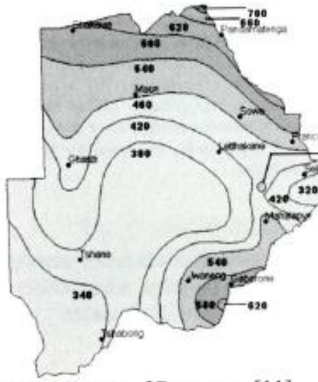

Figure 1 Rainfall map of Botswana [11]

rainfall, runoff and other hydrologic processes, it is frequently necessary to use probability and statistics concepts to aid in defining and predicting these events". Important statistical parameters that represent variability are: mean, standard deviation, range and coefficient of variation. Statistical parameters used in this paper are:

1. Mean annual flow $$\bar{Q} = \sum_{i=1}^{n} Q_i / n \qquad (1)$$

Where:

ΣQ_i = sum of the observations

n = number of observations

The mean annual flow is related to the depth of annual runoff (d), in mm, and catchment area (A), in square meters as follows [3]:

$$\bar{Q} = 0.001d\ (m) \times A\ (m^2) \qquad (2)$$

2. Standard deviation of annual flows

$$s = \sqrt{\{[\Sigma (Q - \bar{Q})^2]/n\}} \qquad (3)$$

3. COV is the coefficient of variation, a measure of variability that is calculated by dividing the standard deviation of annual flows (s) by the mean annual flows ($\bar{Q}$).

Other parameters that shall be used in this paper are $D/\bar{Q}$, $V/\bar{Q}$ and RI. Storage V is a function of draft D, mean annual flows $\bar{Q}$, coefficient of variation COV, and a risk factor t:

$$V = D - \bar{Q}(1 - COV \cdot t) \qquad (4)$$

Dimensionless values of draft and storage can be obtained by dividing the above equation by $\bar{Q}$ hence obtaining $V/\bar{Q}$ as dimensionless storage and $D/\bar{Q}$ as dimensionless draft. For the basis of this paper the above equation translates to [4]:

$$V/\bar{Q} = D/\bar{Q} - 1 + COV \cdot t \quad \text{or} \qquad (5)$$

$$V/\bar{Q} + 1 - COV \cdot t = D/\bar{Q} \qquad (6)$$

The inverse of the probability that a certain flow will occur in any year is referred to as the recurrence interval, RI. It represents a mean time interval in years that the occurrence is equaled or exceeded, based on the distribution of flows over a period of record [5].

Therefore, draft $D/\bar{Q}$, can be plotted against storage $V/\bar{Q}$ with either RI or COV as parameters that can be used in the analysis of the graphs. This allows that for a particular recurrence interval RI for an area with a specific coefficient of variation COV, the draft for any river can be estimated for a selected storage and risk.

3 DATA ANALYSIS FOR BOTSWANA

The Botswana department of meteorology provided the rainfall data, used in this paper, collected from their weather stations. The meteorology department collects rainfall data on a daily basis beginning on the first day of each month until the last day; this is done until the end of the year. Therefore, for convenience, calculations were based on calendar year figures, that is, totals for each month were summed up to give a total for the year. For most of the 23 weather stations data collection commenced in the year 1973, thus, the statistical information was calculated over a period from 1973 to 2000. But, some weather stations have blank spaces for years in which data was not collected. For those stations, the study period was taken as the number of years with data. That is, the statistical information was calculated for these stations using the value of the number of year's data was collected.

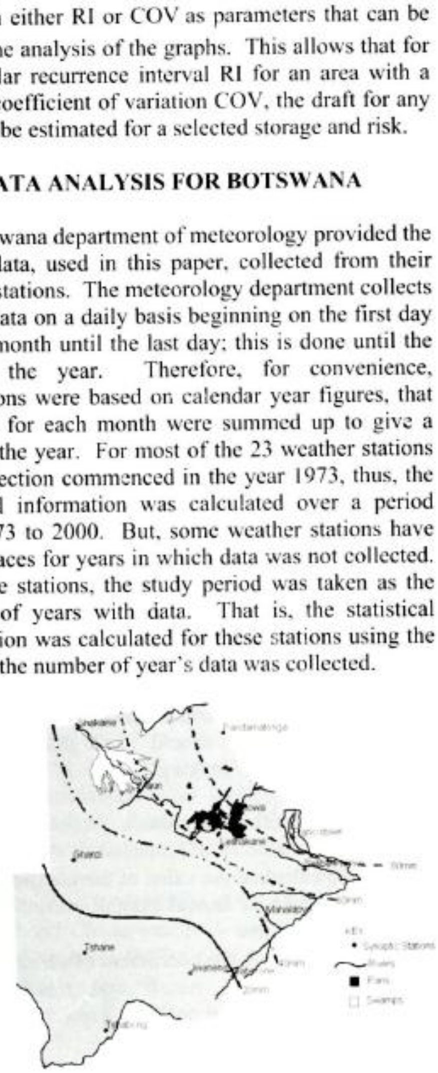

Figure 2 Botswana mean annual runoff in mm

Information on rivers was obtained from the Department of Water Affairs and this data was analysed in a similar manner to that of rainfall. The comparison of the coefficient of variation (COV) of annual rainfall and runoff was achieved by plotting graphs. It must be borne in mind that runoff data is particularly prone to error on reading and the interpolations here are a first approximation.

The data was plotted on maps of Botswana (Figures 1 to 4). The map in Figure 1 and the data plotted on it is a department of surveys and mapping reproduction, whereas, in Figure 2 the data plotted was obtained through the evaluation of equation 2.

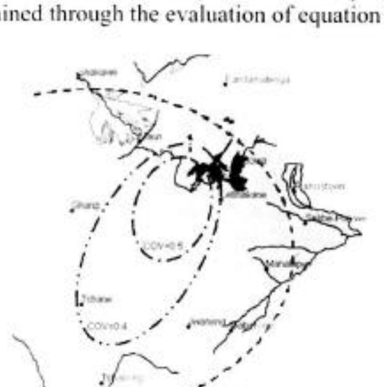

Figure 3 Botswana rainfall COV

Figure 4 Botswana runoff COV

Both rainfall and runoff decrease to the South West, whereas COV's increase in that direction, particularly runoff COV. As can be seen from the maps, there is a concentration of river flow in the Eastern part of the country and very little if any noticeable rivers towards the Western part. The coefficient of variation maps indicate that in general, the COV increases from East to West with storage requirements increasing accordingly.

Two types of statistical evaluations were compared in the assessment of this data; these are the Extreme Value Theory (EVT) and the Normal Distribution method.

Normal Distribution

This method is used when large numbers of observations are made and the range is divided into classes that result in a frequency curve that approximates closely to a standard curve it is known as the normal distribution curve and it has a characteristic bell shaped formation [6]. The method is based on the notion that the probability corresponding to any interval in the range of the variate is represented by the area under the curve within that interval. From a theoretical approach the Normal Distribution curve has an equation, which is a complicated integral that cannot be evaluated by analytical means. Thus, a table [7] containing the values of this integral for different values of the standardised normal variate is used. This table is readily available in any text that deals extensively with normal distribution. The Normal Distribution method actively uses the probability function to calculate the value of the RI. Draft is used to calculate storage (using equation 4) for differing values of COV and standardised recurrence interval. With this, a graph of dimensionless Draft versus Storage is plotted for the different values of RI. Thus, the values of dimensionless draft and COV are assumed and kept constant and those of probability are obtained from the statistical table. The graphs are depicted in Figures 5a and 5b.

Extreme Value Theory

The Extreme Value Theory (EVT) is a branch of applied statistics, which specifically deals with the frequency of extreme events and is frequently applied in hydrology [8]. This theory is also referred to as the Extreme Value Distribution, and according to Stephenson and Petersen [9], for low flows it may be written as:

$$Q_T = \bar{Q} - sK(T) \qquad (7)$$

Where:

$K(T) = \sqrt{6}/\pi(\gamma + \ln(\ln T))$

is referred to as the frequency factor K(T)

γ = Eulers constant, 0.57721

$\bar{Q}$ = mean annual flow

s = standard deviation of annual flows

T = the recurrence interval (RI) of the drought flow being equal to or less than Q_T

In this paper, the graphs of Draft versus Storage were used to determine the value of the Draft/Mean flow for different values of the COV. That is, the values of COV and Recurrence Interval (RI) were kept constant for different values of Storage per Mean Annual Rainfall/Runoff (V/Q=Storage/MAR). With this, a graph was plotted to determine the value of the Draft / Mean Annual Rainfall or Runoff (D/Q=Draft/MAR). Graphs were plotted for RI= 10, 25 and 50 years using COVs from 0.25 to 2 for V/ $\bar{Q}$ values ranging from 0 to

5. This analysis is the one used to draw up the graphs in Figure 6a and 6b. Equations 1 to 5 are used in the assessment of this data.

It will be noted by comparing Figs. 5a and 6a that there is similarity of the results for COV=0.5. ie the EV reproduces the normal distribution (which is an approximation to the real distribution anyway). For higher COVs the similarity decreases (compare Figs. 5b and 6b).

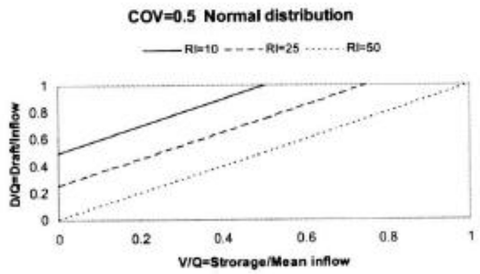

Figure 5a Draft versus storage for COV=0.5 and normal distribution.

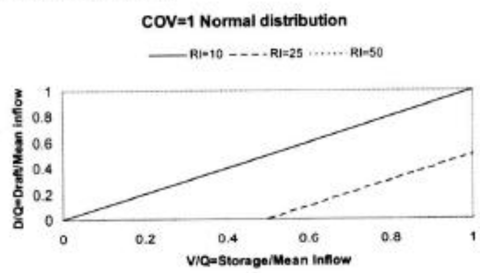

Figure 5b Draft versus storage for COV=1 and normal distribution.

4 USE OF THE GRAPHS FOR STORAGE COMPUTATION

The graphs are used to estimate storage required to supply a community near Rakops with 50% of their water requirements i.e. 30 000 cubic metres per year from rainwater tanks or a dam.

Roof area of the 1000 houses is 100 000 square metres and mean annual rainfall is 0.4m. COV of rainfall is 0.5 and of river flow 1.0. Assume a 10-year RI.

Therefore, Mean Annual Rain is 100000 x 0.4 = 40000 cubic metres. So Draft/MAR=0.75. From Figure 5a storage needed is 0.25 x MAR=10 000 m^3. This is 10 m^3 per house. This storage is large and water may become stagnant and polluted. So other considerations may reduce the dependable yield.

If a nearby stream with a mean annual flow of 40000m^3 was dammed the following storage would be required: Draft/MAR= 0.75. From Fig.5b storage=0.8 x MAR=32 000 m^3. But allowing for evaporation the net yield would be less from the river with greater storage than for rainwater.

5 CONCLUSIONS

The annual river flow variation in Botswana is extreme with COV ranging from 1 to 2 as the area becomes more arid. With regard to rainfall the variation is much less, ranging from 0.2 to 0.5. This means that for most areas in Botswana surface storage is not a practical solution. This reaffirms that Botswana is an arid country that needs to enforce stringent water conservation methods and regular restrictions in use. To harvest rain requires less storage than river flow for the same flow. One way of overcoming droughts is variable draft operation of reservoirs, another conjunctive use of alternative sources [10]

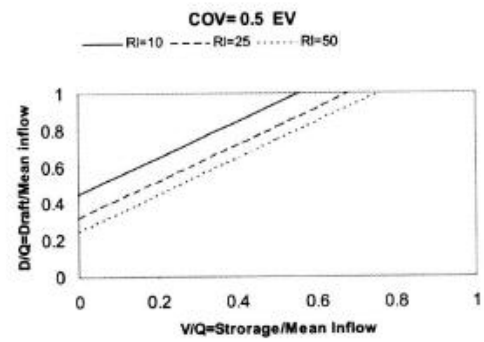

Figure 6a Draft versus storage for COV=0.5 and EV distribution.

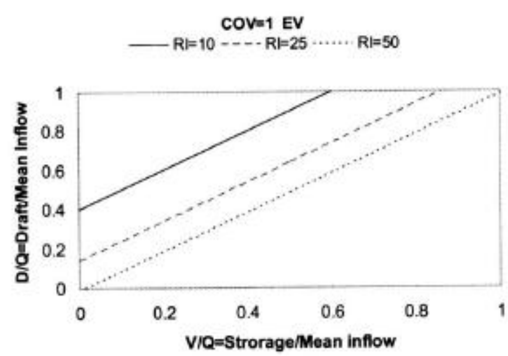

Figure 6b Draft versus storage for COV=1 and EV distribution.

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