EVALUATION OF FLOOD DISCHARGES IN TSITSA RIVER: SOUTH AFRICA

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Abstract - The design of large hydraulic structures must consider both magnitude and frequency of extreme floods expected in a given catchment so as to minimise risk of structural failure. While probable maximum flood forms the basis of flood evaluation, the choice for the exact magnitude of flood needs to weigh economic factors as well. Flood evaluation for dam design in South Africa entails evaluation by five main methods for return periods ranging from 2 years to 200 years. Flood magnitudes from the five methods are compared against each other based on professional judgment and prior knowledge of the catchment. The design flood is taken as the mean value of the best results. Since most dams have catchments far in excess of 15 km^2, the rational method is used mostly to validate results from the other methods. This study investigated the performance of the rational method, standard design flood, and regional maximum flood. The standard design flood and the regional maximum flood were consistently in agreement for all the return periods considered. The rational method performed satisfactorily for long return periods, but tended to overestimate the flood for shorter return periods.

Keywords - Rational Method, Regional Maximum Flood, Standard Design Flood

I. INTRODUCTION

Although some parts of the world receive high rainfall accompanied by floods in some areas, semi-arid regions are starting to experience varying degrees of water scarcity. South Africa in particular has a semi-arid climate that yields approximately 465 mm of rainfall annually compared to the world average of 860 mm [14]. Annual precipitation varies from 1 500 mm in the eastern costal lands, diminishing to as low as 100 mm on the western side[4]. Harnessing the country's scarce water resources for socio-economic development is thus a strategic goal of the South African government.

The stochastic nature of hydrology renders random behaviour to streamflow in any given catchment. A hydrological system that exhibits no correlation between adjacent observations, in time and space, is described as stochastic and independent. In contrast to daily and monthly records, annual streamflow peaks display the independent behaviour manifesting little or no correlation between the years [2]. Daily and monthly flows on the other hand exhibit higher degrees of serial correlation which weakens the independence property. In a study on estimation of karst spring discharge, Zhong *et al.*[18] developed a General Extreme Value (GEV) model assuming independent and identically distributed flows. Although annual peak flow is generally considered independent for flood analysis, Franks and Kuczera, in a study of influence of secular climate variability, argue that the independence assumption is only valid for long-term flood risk provided the flood record contains different climate periods[6].

The design of large hydraulic structures must consider both magnitude and frequency of extreme floods expected at a given location in order to design for an acceptable risk level. The recurrence frequency of a flood is related to flood magnitude through an empirically fitted probability distribution[10] or through exceedance probability analysis. Alam *et al.*[1]investigated the best-fit probability distributions and return periods for maximum monthly rainfall. In South Africa, flood analysis for dam design is based on evaluation of extreme floods obtained mostly from five methods in common use; namely, the rational method, probabilistic method, standard design flood, regional maximum flood and the unit hydrograph method[16]. The five methods are frequently used in combination to allow comparative analysis of the methods and cross validation. A design flood is selected from the resulting set of discharges based on professional judgement and prior knowledge of the catchment. Flood magnitudes for different applications are evaluated forreturn periods ranging from 1 in 2 years through 1 in 5 years, 1 in 10 years, 1 in 20 years, 1 in 50 years, 1 in 100 years and 1 in 200 years. The 200-year flood (Q_{200}), known as *recommended design flood*, is adopted for sizing the spillway.

Smithers[16] states that the original rational method was developed for catchments not exceeding 15 km^2. Since most dams have catchments far in excess of 15

km^2, the biggest benefit of the rational method in dam design lies mostly in validation of results from the other methods. The rational method, however, has been used successfully to estimate flood discharges in large catchments in South Africa and other regions of the world. In a study to estimate peak flows in ungauged catchments, Kim and Shin[11]successfully applied the rational method in a catchment measuring 1584 km^2 in the eastern part of South Korea. In the present study, the performance of the rational method, standard design flood and regional maximum flood wereinvestigated. The rationale for working with these three methods is explained in section 3 on methodology.

II. STUDY AREA

2.1 Location and Topography

Ntabelanga is a dam site in South Africa situated at coordinates 31° 7'1.40"S, 28°40' 20.45"E on the Tsitsa Riverwithin quaternary catchment T35E. The watershed draining into Ntabelanga reservoir is estimated to have a catchment area measuring 1 967 km^2. From its headwaters, the Tsitsa River flows for a distance of 114.9 km with an average slope of 0.005 m/m before reaching the Ntabelanga site. The distance to centroid of the catchment is 61.29 km and the time of concentration is 19.52 hours. Based on the method of the Drainage Manual[17] the coefficient of run-off was calculated to be 0.556. The calculated runoff coefficient is a weighted average that accounts for the effect of ground slope, soil permeability and vegetation cover across quaternary catchments. The Ntabelanga catchment was selected for a comparative analysis of the rational method, standard design flood and regional maximum flood which are some of the flood evaluation methods used in South Africa.

2.2 Climate

The Tsitsa River catchment is a relatively high rainfall region compared to other parts of South Africa. The catchment receives an estimated mean annual precipitation of 780 mm producing runoff at Ntabelanga site of 428.5 x 10^6 m^3 per annum. Mean daily temperature in the catchment hovers around 16^{o}C, relative humidity is an average of 65% and evaporation records a minimum of 51 mm during the coldest days of winter and a maximum of 170 mm in summer.

2.3 Land Use

The impact of land use on streamflow is recorded to be very low due to depressed economic activity in this poor region of South Africa. Commercial forestry occupies an area measuring 148 km^2 while 41 km^2 of land have been colonised by invasive alien vegetation that is cleared regularly whenever funding is available. There is little irrigation taking place in the catchment, with only 20 km^2 of land under irrigation. A number of small farm dams with a combined surface area of 0.618 km^2 have been constructed over the years to support commercial agriculture in the catchment. Livestock grazing, rain-fed maize cropping and vegetable production occupy large areas, mainly in the communal parts of the region[5].

III. METHODOLOGY

The subject of this paper arose from PhD research by the corresponding author on 'Optimising hydropower potential by utilising flood energy'. Since the doctoral research investigated hydropower potential at 145 selected dam sites across South Africa it was necessary to select a flood evaluation method which required data readily accessible from government institutions responsible for weatherservices and water resource management. Although reliable data for evaluation of the regional maximum flood were more readily available, to use the method with confidence it was necessary first to review its performance in comparison with the other methodson a dam site where data was available for all the methods.Flood discharge at Ntabelanga site on the Tsitsa River was thus evaluated at different return periods using the rational method, standard design flood method and regional maximum flood method. The discharges obtained from the three methods were compared to assess reliability of each method.Thethree flood evaluation methods are briefly outlined in the paragraphs that follow.

3.1 Rational Method

Although the original unmodified *rational method* is limited to small catchments not exceeding 15 km^2, the method has been used successfully in South Africa in combination with other methods[16]. It is particularly useful as a tool for validating flood discharges obtained from the other methods in a particular catchment. Equation (1)is the rational method formula as it is used in South Africa[11].

$$Q = CiA \quad (1)$$

Where Q is flood discharge (m^3/s), C is run-off coefficient, i is precipitation intensity (m/s) and A is catchment area (m^2).

Precipitation, in turn, is calculated from(2), (3) and (4).

$$i = regional\ factor \times MAP\ factor \times frequency\ factor \quad (2)$$

$$MAP\ factor = \frac{18.79+0.17\times MAP}{100} \quad (3)$$

$$Regional\ factor = \frac{217.8}{(1+4.164\times t)^{0.8832}} \quad (4)$$

Where i is precipitation (mm/h), MAP is mean annual precipitation (mm/year), and t is storm duration (hours). Table 1 gives frequency factors application

to different rainfall return periods. The above formulae produce point precipitation which needs to be converted to uniform areal precipitation over a given quaternary catchment since the rational method is predicated on uniform precipitation over a given catchment. According to Alexander[13], the areal reduction factor (ARF) definedby (5) is used to convert point precipitation to areal precipitation. According to Svensson and Jones[15], conversion to areal precipitation is achieved using (6).

$$ARF = \left(90\,000 - 12\,800\,lnA + 9\,830\,lnt\right)^{0.4} \quad (5)$$

$$ARF = \frac{P_{area}}{P_{point}} \quad (6)$$

Where ARF (%) is areal reduction factor applied to point precipitation estimates, t (min) is time of concentration,A (km^2) is catchment area, P_{area} (mm) is the areal storm rainfall, and P_{point} (mm) is the maximum point rainfall at the storm centre.

T (years)	2	5	10	20	50	100	200
Freq.factor	0.47	0.64	0.81	1.00	1.30	1.60	-
Y_T (-)	0	0.84	1.28	1.64	2.05	2.33	2.58

Table 1: Frequency and Return Period Factors[9]

3.2 Standard Design Flood

The *standard design flood* is another flood evaluation method used in South Africa for designing large hydraulic structures such as dams and bridges. This method is an improvement upon the traditional rational method and does not suffer from the catchment size limitation[16]. The main inputs include runoff coefficient, point precipitation, return period factor, precipitation intensity and catchment area. The runoff coefficient used in the standard design flood calculation was obtained from (7), according to Gericke and du Plessis[8].

$$C_T = \frac{C_2}{100} + \left(\frac{Y_T}{2.33}\right)\left(\frac{C_{100}}{100} - \frac{C_2}{100}\right) \quad (7)$$

In (7)C_T is total runoff coefficient, C_2 is runoff coefficient for a 2-year return period, C_{100} is runoff coefficient for a 100-year return period and Y_T is return period factor as given in Table 1.C_2 and C_{100}coefficients have been evaluated for different hydrological regions of South Africa.

The Hershfield equation (8) is used to calculate point precipitation for storm durations less than 6 hours while the Adamson method is used for durations of one day or longer[7]. The Adamson method refers to storm durations developed by the South African Department of Water and Forestry for various hydrological regions of the country. For storm durations ranging between 6 hours and one day, precipitation is calculated by linear interpolation.

$$P_{t,T} = 1.13(0.41 + 0.64lnT)(-0.11 + 0.27lnt)(0.79M^{0.69}T^{0.2}) \quad (8)$$

$P_{t,T}$ = point precipitation depth (mm)
t = time of concentration (min)
T = return period (years)
M = mean of the annual daily maxima (mm)
R = average days per year on which thunder was head (days)

Various M and R values have been computed for different hydrological regions of South Africaas reported by Alexander[3]. The standard design flood, Q (m^3/s), is calculated from (9), where C_T is evaluated by (7).

$$Q = C_T iA \quad (9)$$

C_T = run-off coefficient
i = precipitation intensity (m/s)
A = drainage area (m^2)

Precipitation depth obtained from (8)is converted to precipitation intensity by diving with storm duration, to conform to the rational method philosophy.

3.3 Regional Maximum Flood

The flood evaluation method originally developed by Francou-Rodier, relating historically observed flood maxima with effective catchment area, has been adapted for Southern African conditions[12] to calculate the *regional maximum flood*. Empirical factors have been developed for converting regional maximum flood (Q_{RMF}) to flood magnitudes of wide-ranging return periods (Q_T). Regional maximum flood is calculated by (10).

$$Q_{RMF} = xA_e^y \quad (10)$$

Q_{RMF} is regional maximum flood (m^3/s), A_e is effective catchment area (km^2),x is a regional coefficient, and y is a regional exponent. Values of x and y are available for the different hydrological regions of South Africa. Ntabelanga site lies in region 5 with a regional coefficient of 100 and regional exponent of 0.50. Effective catchment area was estimated to be 1 967 km^2.

IV. RESULTS AND RECOMMENDATIONS

The flood discharges obtained by the three methods are presented side by side in Table 2 for ease of

comparison. For the rational method, flood discharges range from 921 m^3/s to 3529 m^3/s for the 2-year and 200-year return periods respectively. The 2-year flood for the site is slightly higher than double the mean annual runoff recorded as 428.5 x 10^6 m^3 per annum. This comparison provided a useful validation because, as an average figure, 2MAR is bound to be lower than the 2-year peak flood.

Likewise, the standard design flood ranges from 114 m^3/s for the 2-year return period up to 4 436 m^3/s for the 200-year return period. The regional maximum flood (Q_{RMF}), calculated as 4335 m^3/s, is the probable maximum flood attainable in this catchment, produced by probable maximum precipitation. This maximum flood was converted to flood discharges at various return periods to provide a range of design floods to suit the desired risk level for a given problem. The 200-year regional flood, for instance, was estimated to be 3 006 m^3/s.

For longer return periods, the three methods produced flood discharges that are consistently in agreement, and should all be evaluated for rigorous flood analyses normally required for the design of large hydraulic structures. An interesting observation is the close agreement between the regional maximum flood at 4335 $m^3/s$and the 200-year standard design flood at 4436 m^3/s. As shown in Fig. 1, for small return periods the standard design flood plots below the other two discharges but switches position at about 1 in 25 years return period. The rational flood and regional maximum flood, on the other hand, move in tandem as return period increases, displaying a great deal of consistency. Although the rational method tends to overestimate the flood at smaller return periods the flood tracks a middle position of the other two estimates from around 1 in 25 years and higher return periods, indicating normal behaviour of the other methods. Based on this observation, an average of the regional maximum flood and standard design flood would represent a reasonable flood estimate for the Ntabelanga site.

Where flow records are scanty and risk aversion is required, a conservative approach may be to adopt the largest of the three estimates. Structures that can tolerate high risk of flooding such as temporary diversion works on dam construction sites are generally designed for smaller return periods, typically 1 in 20 or 1 in 10 years. Except on small catchments, the rational method is not recommended for these temporary structures as this may result in uneconomical designs.

For the purpose of evaluation of flood at the 145 dam sites investigated in the above-mentioned PhD study, the regional maximum flood was considered the more reliable estimate because it varied consistently with the rational method. The standard design flood tended to depart increasingly as return period increased. Furthermore, by plotting below the other two graphs, the regional maximum flood provided a conservative estimate for the hydropower potential at the dam site.

Flood Method	Flood Discharge (m^3/s) at given return period						
	2 years	5 years	10 years	20 years	50 years	100 years	200 years
Rational Method	921	1 255	1 588	1 961	2 549	3 137	3 529
Standard Design Flood	114	677	1 217	1 840	2 782	3 582	4 436
Regional Maximum Flood	377	940	1 300	1 636	2 084	2 529	3 006

Table 2: Comparison of Flood Discharges

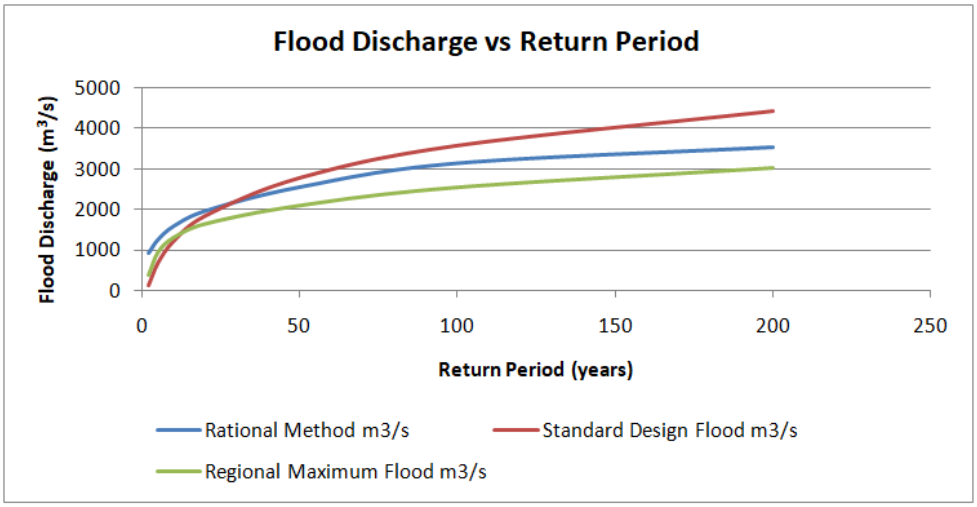


Figure 1: Flood Discharge versus Return Period

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