IMPROVED FLOOD ESTIMATION MODEL FOR BRIDGE AND CULVERT DESIGN IN ZIMBABWE

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ABSTRACT

Economics and risk minimization in the design of infrastructure that is vulnerable to flood damage often prove to be non-commensurate objectives. To economically minimize the risk of hydraulic failure of this type of infrastructure is a noble design objective. The hydraulic design of bridges and culverts in Zimbabwe is currently hinged on empirical algorithms of flood estimation. In a changing climate and changing land use environment, the current flood estimation method seems to under-estimate the design floods as evidenced by the increasing number of bridges and culverts being overtopped by floods. This paper discusses the several shortcomings of the current method in use and proposes a new consistent but robust computerized method of flood routing based on historical flow data and statistical analysis techniques. The methodological praxis and resultant design software are intended to substantively improve the flood estimation process, producing a more precisely estimated design flood. From the results obtained, the proposed new model is more conservative than the current method used by the Ministry of Transport (MoT) by an average factor of 1.4. At ungauged sites, or at sites where the stream flow data is inadequate in quantity and quality for Flood Frequency Analysis (FFA), it is recommended that a factor of safety of 1.4 be applied to MoT current flood estimates.

Key words: Extreme Value Theory, Flood Frequency Analysis (FFA), Stationarity Assumption, Model Validation, Model Calibration, Model Testing, Climate Change, Bridges and Culverts

INTRODUCTION

In Zimbabwe, the prediction of flood flows for the design of river bridges and culverts is done using a method incorporating the Mitchell (1974), Rational and Creager formulae. The flood value for a particular return period is obtained from this weighting (MoT 1985):

\[ 0.2(\text{Mitchell} + 2 \times \text{Rational} + 2 \times \text{Creager}) \]

hereinafter referred to as the MoT model. The precision or lack thereof of the MoT model can be construed to spring partly from the weighting itself and partly from the constituent formulae that do not take into account the observed historical hydrological flow data, thereby ignoring an important aspect of hydrological analysis and climate variability. In general, methods based on the analysis of floods are probabilistic by nature and are more suitable for estimating design floods (Smithers, 2012).
The following criteria are used in the design of bridges in Zimbabwe for high flood level (HFL):

i) For the 20 year design flood, there must be a free board of at least 0.8 m,
ii) For the 50 year design flood, there must be a free board of at least 0.2 m,
iii) The 100 year flood must not rise above a level 0.6 m below the finished road level,
iv) The proposed bridge or culvert structure must not raise the level of the 50 year flood by more than 1.0 m above the natural river flow.

With the increased impacts of climate variability compounded by land use changes in Zimbabwe, the increased number of bridges overtopping by floods that are being observed suggests the need to adopt a more conservative design flood estimation method than that currently being used. This may require a paradigm shift with more reliance on statistical methods of Flood Frequency Analysis (FFA) without departing from the current design criteria but bearing in mind that the flood routing algorithms in current use were developed a long time ago and need to be updated or recalibrated to suit the current understanding of hydrological processes. Such activities as deforestation, overgrazing, veld fires, alluvial mining, clearance of vegetative cover for agricultural and residential purposes among other land uses, also affect the conversion of rainfall into run-off and hence flood flows.

It must be stressed that the continued application of empirical methods in their original form, even after decades of additional hydrological data, implies that no change has been observed physiographically, climatologically and hydrologically – a risky assumption. The Rational and Creager formulae that directly depend on run-off coefficients are very subjective in their application. Pilgrim and Cordery (1993) argue that a major drawback in the application of the Rational method is the judgment required in the determination of the run-off coefficient and the variability of the coefficients between different hydrological regimes. The selection of the run-off coefficient is based on the experience of the user (Smithers, 2012). Researchers such as Pilgrim and Cordery (1993) and Alexander (2001) report that the Rational method is widely used throughout the world for small rural and urban catchments. This notwithstanding, current practice in Zimbabwe employs the Rational method even in very large catchments. This highlights the need to improve local practice so that it aligns with international practices.

Alexander (2002), using a longer data series, calibrated the then 150 year old Rational method principally for South African bridge design practice and developed the Standard Design Flood (SDF) method on the premise that many bridges were being swept by floods in South Africa because of not taking into account climate variability. According to (Gorgens, 2002), the SDF produces 50 year floods that are approximately 210% higher than the Log-Pearson Type III (LP III) generated floods and therefore must be seen as a conservative approach. However the use of the SDF in South Africa may result in significant overdesign of some hydraulic structures e.g. dam spillways which render them uneconomical. Knoesen (2011) predicted that design floods are expected to increase in South Africa due to climate change, with the increase in design floods being larger than those for design rainfall. The same can be fairly said for Zimbabwe. The Meteorological Services Department of Zimbabwe’s Climate Application Branch reports that
floods caused by tropical storms have become more frequent and severe, exceeding those observed in more than 50 years (MSD, 2013). Floods experienced in 2000 and in 2013 damaged many bridges in Zimbabwe. UNDP (2000) estimated the total number of bridges damaged by Cyclone Eline as 67. Bridge and culvert structures, such as on the Bullnose-Matowa, Suswe-Chitsungo, Mutoko-Mayo, Nyamasote-Katemere and Rwenya roads, were damaged in January 2013 in Mashonaland East Province of Zimbabwe with an estimated rehabilitation cost amounting to 2.4 million United States dollars.

**FLOOD FREQUENCY ANALYSIS (FFA)**

The commonly used probability distribution functions for flood analysis are the: Log-Normal, Pearson, Log-Pearson, Gumbel, and Weibull. Albeit, the spectrum is relatively wide, it is necessary to select the most suitable and appropriate distribution for design purposes. It must be noted therefore that in choosing from the said available wide spectrum of statistical distributions, hypothesis testing, using say the Chi-squared test, usually needs to be carried out for the goodness of fit of a data set to any particular distribution function. However, since the interest is in designing for the rare and extreme flood events, probability functions that are based on the Extreme Value Theory, which focuses on the occurrence of extreme and rare events, are considered more appropriate.

The asymptotic Weibull Distribution has an upper finite endpoint, generally believed to be characteristic of many hydrological data sets (Cunane, 1989). It must be borne in mind however that floods are a result of a combination of natural phenomena that have no upper boundary and there is no quantifiable upper limit to the magnitude of a flood that might occur at any site (Alexander, 2002). It is therefore not prudent to rely on a probability distribution function that will try to define and fix an endpoint to the input data.

The Gumbel EVI Distribution is unbounded and has an exponential tail thus having the advantage of not fixing an endpoint to climatic data. The Gumbel EVI Distribution is effective for (small) sample sizes less than 50, (Cunane, 1989). The Gumbel EVI Distribution in principle has 2 parameters only: location and scale. Two parameter distributions have smaller standard error compared to 3 or 4 parameter distributions (Cunane, 1989). Data is fit to the Gumbel EVI Distribution using L-Moments which have less bias compared to other techniques, and have been adopted as a standard approach in e.g. the United Kingdom (Smithers, 2012). Furthermore, L-Moments are more robust (less sensitive) to the presence of outliers in the data (Alem, 2011). Thus the distribution is less biased and has small standard error, properties which increase the precision in capturing flood behaviour. Thus the Gumbel EVI Distribution was selected from amongst its family members in the development of the improved flood estimation model for bridge and culvert design in Zimbabwe.

The Log-Pearson Type III (LP III) Distribution (also known as the Gamma Distribution) has two interacting shape parameters (Stedinger, 2007) and also uses the scale and location parameters. This distribution has a low upper bound which is undesirable since it tends to give small
differences between flood values for relatively large differences in return periods. To minimize this effect, the following modifications, as suggested by Jagadesh and Jayaram (2009), have been adopted:

i) Estimates of the recurrence interval $T$ are obtained using the Cunane plotting position formula given in equation (2) as:

$$T = \frac{n + 0.2}{m - 0.4}$$ (2)

where $n$ is the number of years of record and $m$ is the rank obtained by arranging the annual flood series in descending order of magnitude.

ii) A logarithmic system, $y = r(\ln x) + q$, is then used for modelling, where $y$ is the discharge (in m$^3$/s) and $x$ is the return period, given by $T$ in equation (2).

It was found that the LP III when so modified, is in close agreement with the MoT model, a property to be utilized in the calibration of the new model. It is for this reason that this member of the Pearson Distributions, the LP III, was selected from amongst its family members in the development of the improved flood estimation model for bridge and culvert design in Zimbabwe.

It is interesting to note that in South Africa, both the LP III (data fit using Weighted Moments) and the Gumbel EVI Distributions are applicable (Van der Spuy and Rademeyer, 2010).

**MODEL VALIDATION**

The new proposed flood estimation model for bridge and culvert design in Zimbabwe utilises three inputs: observed hydrological flood flows, flood flows generated from the Gumbel EVI and the modified Log-Pearson Type III Distributions. The Gumbel EVI and LP III disparate modelling approaches are checked for any significant correlation at 50 year return period. A correlation is considered significant if the difference between the two results does not exceed the Least Observed Value (L.O.S) i.e. the value with a 100% probability of having a 1 year return period in both the Gumbel EVI and LP III distributions. If such a correlation exists, the values from the two results should be averaged, otherwise the Gumbel EVI result is taken, preferably since the task at hand is construed to consist in answering probabilistic and statistical questions related to the occurrence of very high floods from a given domain of stochastic processes.

Any significant correlation between the value adopted from the FFA (Gumbel EVI and modified LP III analysis) and that from the Mitchell (1974) formula (which was developed from local experience and is based on catchment area only) is checked. Such correlation is considered significant if the difference between the two values does not exceed the Least Observed Value and if so, the average is taken, otherwise the FFA result is used. The result from this procedure is called the Validated Result. In this role, the Mitchell (1974) formula is used only as a check to the FFA value, which role the South African National Transport Commission (NTC, 1981) would recommend as it advises that empirical formulae must be used only for checking other
methods. Cordery and Pilgrim (2000) also argue that the use of empirical formulae is risky and must be avoided especially if they are not calibrated from the catchment in question.

It can be inferred from the foregoing that the use of the Least Observed Value will always ensure that the result from averaging the Gumbel EVI and the modified LP III models will not ‘significantly exceed or fall short of’ that obtained in the individual model for the particular return period. A flood value shall ‘significantly exceed or fall short of’ the required flood if, after averaging, it is realized that it equals a flood value at that return period plus or minus 2 years, which can be fairly considered to be a high degree of precision.

**DESIGN FLOOD OPTIMIZATION AND MODEL CALIBRATION**

If the flood estimation result from using the modified LP III is in agreement with the MoT model by a factor between 1.0 and 1.2, it can acceptably replace the latter in optimizing the design flood and calibrating the new model. This is beneficial since the model error shall be less than that commensurate with using the MoT model which would bring with it its own assumptions and errors (and/or omissions) resulting in a very high uncertainty associated with the new model. In this regard, the new model proposed herein will only be sensitive to two parameters only: catchment area and flow data.

The Validated Result is optimized subject to the constraints that it shall not exceed the 50 year flood but should be higher than the 20 year Gumbel EVI flood, and that it shall be higher than the 50 year modified LP III flood, among other trivial constraints. The result obtained from such a procedure is the recommended 50 year design flood.

In calibrating the model for computing the 20 year flood, the percentage difference between the modified LP III 50 and 20 year floods is calculated and the same percentage assigned to be the difference (percentage) between the 50 year and 20 year floods for the new model. The same is done for the 100 year flood. The model so calibrated will exhibit differences in flood magnitudes comparable to the differences in the MoT model. This warrants the legitimate application of the new model for bridge and culvert design without departing from the current design criteria.

**STATIONARITY ASSUMPTION AND CLIMATE CHANGE**

This study was motivated by the need for a safe, conservative but economic hydrologic assessment in bridge and culvert design in Zimbabwe taking cognizance of the climate change and climate variability impacts. Bates et al. (2008) report that climate change will result in some areas experiencing increased runoff, while others will have less runoff and trends in runoff do not necessarily follow the trends in precipitation. This model will capture the trends in runoff, quite importantly since it is the runoff (flood) that is designed for, and not precipitation. Smithers (2012), Beven (2000), and Schulze (1989) hold that using observed data in flood frequency estimation assumes that the data are stationary and therefore the fitted distribution does not explicitly take into account any changes in the runoff generation processes. On the other hand, Lins (2012) argues that stationarity is a property of an underlying stochastic process, not of
observed data. The point being made here is that the assumption of stationarity relates to the runoff generation processes, and not to the resultant data, so much so that while the future will not necessarily repeat the past, its properties can be inferred therefrom. ‘Climate change’ implies that runoff generation processes are non-stationary but as Lins (2012) states, it is important to acknowledge that all of the variations in the observed and historical records of hydro-climatic processes can also be represented with stationary stochastic models, since stationarity does not mean static. The assumption of stationarity is made so that stochastic simulation can be performed.

How then can probability laws and models be used for making risk based design decisions in a changing climate? One can always rely on the concept of hydrologic uncertainty to simplify matters, i.e. fewer assumptions are made as to how hydrology will unfold in the future than those needed for non-stationarity, thereby permitting the invocation of the laws and theories of probability in developing optimal flood estimation models. It can be said therefore that the thrust must be placed on improving the current system of methods to be sufficiently optimal, capturing the extremes that have been experienced historically, rather than losing concentration and focusing on theories which do not have empirical proof, and about which expert opinion diverges. Villarini et al. (2009) point out with respect to flood peaks that it may be easier to claim non-stationarity than to prove it through analyses of actual data. Since a finite realization from a stationary stochastic process is not tightly constrained, and that it can appear indistinguishable from a non-stationary deterministic process, and can exhibit excursions and trends that persist for decades or centuries (Cohn and Lins, 2005), then stationary stochastic models are suitable in a changing climate. For all practical purposes, stationary stochastic models, with an appropriately selected distribution, will give optimal and conservative flood estimates sufficient to inform the design process to the extent feasible or otherwise prudent from an engineering perspective in the context of climate change.

APPLICATION EXAMPLE: MANYAME RIVER BRIDGE HYDRAULICS FOR THE HARARE-MASVINGO HIGHWAY DUALIZATION AT HOUGHTON PARK, HARARE

The annual peak discharge data series obtained from the Research and Data Division of the Zimbabwe National Water Authority [ZINWA] for Gauge Station C3 on the Manyame River upstream of the Manyame bridge site was used.

Table 1 gives results from discharge formulae in current use. Table 2 compares results from the proposed new model with the MoT model. It can be inferred from Table 2 that the proposed model is more conservative than the current practice by the MoT by an average factor of 1.4.

Figure 1 shows screenshots of the graphical representations of the data modelled by the software.

<table>
<thead>
<tr>
<th>Return Period T (years)</th>
<th>Creager Q (m$^3$/s)</th>
<th>Rational Q (m$^3$/s)</th>
<th>Mitchell Q (m$^3$/s)</th>
<th>Gumbel Q (m$^3$/s)</th>
<th>LPIII Q (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>422</td>
<td>393</td>
<td>558</td>
<td>702</td>
<td>460</td>
</tr>
</tbody>
</table>
Table 2: Comparison between MoT and Proposed new Flood Design models

<table>
<thead>
<tr>
<th>Return Period (T years)</th>
<th>MoT Design Flood (Q m³/s)</th>
<th>Proposed New Design Flood (Q m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>438</td>
<td>587</td>
</tr>
<tr>
<td>50</td>
<td>552</td>
<td>759</td>
</tr>
<tr>
<td>100</td>
<td>645</td>
<td>888</td>
</tr>
</tbody>
</table>

Figure 1: Left: Gumbel EVI Modeling. Right: LP III Modeling

MODEL ACCURACY

While it is noted that the calibration of the flow gauging stations may not be very robust, results obtainable from this new model are useful for design purposes. Albeit, the Mitchell (1974) formula is used in the model validation procedure, it is here clarified that this does not mean or imply that it can be used for testing this model. Its use in the validation procedure rather implies that if the physiographical, climatological, and meteorological characteristics at any site closely approximate the average conditions used in the development of the formula, then it must closely approximate the statistical analysis result. The recommended test of this model rather consists of a visual inspection of the Gumbel EVI graph to see its approximation to a straight line and arithmetical verification procedures, i.e. test is site specific. It must be noted therefore that the accuracy of this model is dependent upon the accuracy of the Gumbel EVI modeling, not on the LP III modeling. Independence and identical distribution of the data supplied shall be ensured by the user, and the program is limited to this. It is hereby recommended that the discharges be the annual instantaneous maxima observed in hydrological and not calendar years to ensure independent distribution (Chow et al., 1988). Homogeneity (identical distribution) requires that
floods should have occurred under the same type of conditions, and in this case only floods due to rainfall, excluding other factors due to, for example, a dam failure, which will violate the assumption of homogeneity.

A possible criticism to the proposed new flood estimation model might arise due to the fixing of the sample size for FFA to 35. A 35 data series is sufficient for efficient FFA given that authorities like USGS (1982) state that streamflow records of at least 10 years duration are of sufficient length to warrant statistical analysis. Besides, most catchment areas in Zimbabwe do not have long data series. Designers having lengthy gauged records will need to sort the data in descending order of magnitude and use the first highest 35 from the array. For most stations, this will ensure zero flows are left out of the series for FFA, however if zero values still appear, conditional probability adjustments are required. It must be noted that the logarithm of zero is negative infinity, invalid for LP III modeling.

Possibilities of a regionalization approach to FFA in Zimbabwe need to be investigated to see if data from similar and nearby locations can be used. Alexander (1990) argues that regional statistical analyses provide a basis for improving the estimates of the parameters of the distribution at both gauged sites with short records and at ungauged sites, while Cordery and Pilgrim (2000) feel that regionalization is the only sure basis for flood prediction. This is an area requiring urgent research in Zimbabwe.

Critics still holding that goodness of fit tests must always be used for selecting the statistical distribution should consider that floods are a succession of natural events that do not fit any one specific known statistical distribution and a probability distribution is assigned to make the problem of defining flood probabilities tractable (USGS, 1982). Several distributions can give acceptable fits but yielding different results when extrapolated (Beven, 2000). The selection criteria used in the development of this model will address this problem giving the practitioner confidence in the interpretation of its results.

**CONCLUSIONS AND RECOMMENDATIONS**

It is concluded that the proposed methodology and resultant software for estimating design floods for bridges and culverts in Zimbabwe in a changing climate and changing land use environment works well especially in addressing the disparities often encountered when dealing with very large catchments which receive relatively small amounts of rainfall since the software will then recommend a design flood based on observed flow data, thereby guarding against potential overdesign or underdesign. In relatively large catchments, it can be shown that the Mitchell (1974) formula has a tendency to overestimate and suits dam design applications, while the weighted formula has a tendency to underestimate. It is thus recommended that in Zimbabwe, the assessment of design floods for bridges and culverts be based on this new model which takes cognizance of observed flows whilst optimizing the flood estimation through a more rigorous FFA method.
The proposed new model will always produce the same results for the same data sets even if used by different users, i.e. it is independent of the user’s judgment and/or experience and is therefore consistent. Alexander (2002) and Smithers (2012) point out that consistency is an important requirement in flood estimation. Furthermore, this model is robust and can be used for any catchment of any size in Zimbabwe.

From the results obtained, albeit from one example cited, the proposed new model appears more conservative than the current practice by MoT by an average factor of 1.4. At ungauged sites, or at sites where the stream flow data is inadequate in quantity and quality for Flood Frequency Analysis (FFA), it is recommended that the proposed new model be applied in the hydrology and flood frequency analyses to facilitate comparisons. In the event that the results of the proposed new model give a higher design flood than the current MoT model, it is recommended that the former results be adopted for reasons earlier given.

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The User’s Guide and Software for use of this proposed new model are available on disk, obtainable from the Department of Civil Engineering, University of Zimbabwe. Academic as well as commercial user licenses are available.

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