Evaluation and Update of Two Regional Methods (ORSTOM and CIEH) for Estimations of Flow Used in Structural Design in West Africa

Sehouevi M. D. Agoungbome[1(✉)], Ousmane Seidou[2], and Moussa Thiam[2]

[1] African Institute for Mathematical Sciences,
Mbour Km 2 Road of Joal, Mbour, Senegal
sehouevi.m.d.agoungbome@aims-senegal.org

[2] Department of Civil Engineering, University of Ottawa,
161 Louis Pasteur Office A113, Ottawa, Canada

Abstract. The ORSTOM and CIEH methods are the most popular methods used in West Africa to estimate the design flow, needed in the design of hydraulic structures. However, these methods, based on hydrological data collected before 1965 and 1983 for ORSTOM and CIEH respectively, showed some shortcomings and deviations in the estimation of the forecasts. This study, therefore, assesses the design flow on data collected from some watersheds in Benin and Niger using a frequency analysis. These estimations are therefore compared with estimations obtained using the ORSTOM and CIEH methods on the same watersheds. As result, we observe an important under-estimation of the flows with the ORSTOM method, whereas the CIEH method gives higher values. The use of the log linear regionalization method, considering the area of the watershed basin and the global slope index, gives very interesting results and good perspectives of estimation on few or no data watersheds basins.

Keywords: Design flow · Watershed · Log linear regionalization

1 Introduction

As any other area in the world, the prosperity of Africa relies on the quality of its infrastructures. Unfortunately, it is very common to witness dams, bridges and communities being destroyed by floods. While flood damages are expected to happen everywhere, the high frequency of destruction points to inadequate design flow calculations. The design flow or project flow is the expected flow resulting from the worst combination of meteorological and hydrological conditions considered to be reasonably characteristics of the concerned region (aquaportail.com). The ORSTOM and CIEH methods are the most popular design flow estimation methods in West and Central Africa. These are regional

C. M. F. Kebe et al. (Eds.): InterSol 2018, LNICST 249, pp. 153–162, 2018.
https://doi.org/10.1007/978-3-319-98878-8_15

methods (not directly based on observed flow on the site) because of the low data availability in most African regions. The ORSTM method was developed using meteorological and hydrological data recorded up to 1965 while the CIEH was developed using meteorological and hydrological data recorded up to 1983 [1]. But it is clear that the climate in Africa and particularly the western part, has shifted since then: a decrease of 15–35% has been reported for rainfall; a 200 km shifted of isohyets to the south has been observed; the streamflows in most watersheds experienced a decrease of 40–60% [2]. Olivry et al. [3] indicated that surface water resources in rivers have declined since the beginning of 1970 and have halved in the 1980s. Therefore, the application of the CIEH and ORSTOM methods in their original proposed form may not reflect the current level of hydrological risk. They should be reassessed and updated in order to prevent damage or financial losses that may result from an over-sizing or under-sizing of hydraulic structures.

The aim of this work is to reassess these two methods and propose an alternative more accurate method that can be used to estimate the design flow.

2 ORSTOM Method

Also called Rodier-Auvray method, it is a deterministic method of flow estimation proposed in 1965 by the ORSTOM's hydrologists ("Office de la Recherche Scientifque et Technique Outre-Mer"). This institution was later replaced with the "Institut Régional pour le Développement" (IRD). The project flow is defined as a flood caused by a rainfall that is equalized or exceeded in average once a decade for a watershed in the Sahelian and tropical dry lands [4]. This method, based on 65 watersheds with surface areas between 10 and 120 km^2, is applied in theory to all the West African's basins, between 150 and 1600 mm in annual rainfall and in the range of some hectares to 1500 km^2 surface area. The study was able to identify the main factors that explain the floods. Those are the height of the generating rainfall, the area of the watershed, the infiltrability of the soil and the relief.

The peak flow of the ten-year flow (m^3/s) is given by the relation:

$$Qr_{10} = m.A.P_{10}.Kr_{10}.\alpha_{10}.S/Tb_{10} \tag{1}$$

where A is the abatement coefficient, m: the coefficient of increasing, P_{10}: the ten-year daily rainfall (m), Kr_{10}: the runoff coefficient corresponding to the ten-year flow (%), α_{10}: the peak coefficient corresponding to the ten-year flow, S: the area of basin (m^2), Tb_{10}: the base time or time of the flood (s).

The ORSTOM method uses several abacus, tables and graphs with fixed values to estimate those parameters. Estimating each term of this expression independently of each other gives less accuracy on the overall quality of the estimate such that the errors made on each parameter appear as a multiplier of the error on Q_{10} [5].

3 CIEH Method

Proposed by Puech and Chabi-Gonni [5], the CIEH ("Comite Interafricain d'Etudes Hydrauliques") method is based on a statistical multi-regression analysis of the data collected in the collection of Dubreil [6] entitled "Recueil des données de base des bassins representatives et expérimentaux" supplemented by information from the member countries of the CIEH. This study was carried out on a set of 162 small and medium-sized catchments located in 14 West and Central Africa countries [5] and highlighted the main factors which can be quantified without ambiguity.

- Physical factors: area, length, slope, compactness of the watershed;
- Climatic factors: annual and daily precipitation, type of climate, temperatures;
- Soil factors: runoff that depends on pedology, vegetation cover, soil moisture.

The ten-year's peak flow Q_{10} (m^3/s) based on a multiple regression scheme is given by the relation:

$$Q_{10} = a.S^s.Pan^p.Ig^i.Kr_{10}^k.Dd^d \quad (2)$$

with a, s, p, k, d some coefficients to be determined, Pan: annual average precipitation (m), Kr_{10}: the runoff coefficient (%), Ig: the global slope index (m/km), S: the area of basin (km^2), Dd: the drainage density (km^{-1}).

The parameters that have to be included in the model are not limiting, and it may take into account more parameters.

However, recent studies (1994) was carried out using multiple regressions to express more accurately the CIEH formula by defining the most interesting and important factors to consider, by regional climatic groupings and according to the quality (or reliability) criteria. As a result, here is a partial correlation matrix (Table 1) for the following parameters S, L, Ig, Pan, P_{10}, Pm_{10}, Dd, Kr_{10} and Q_{10}.

Table 1. Partial correlation matrix [4]

	Q_{10}	S	L	Icomp	Dd	Ig	Pan	P_{10}	Kr_{10}
Q_{10}	1								
S	0.623	1							
L	0.654	0.963	1						
Icomp	0.151	0.157	0.365	1					
Dd	−0.079	−0.459	−0.383	0.155	1				
Ig	−0.309	−0.693	−0.639	0.076	0.537	1			
Pan	−0.264	−0.103	−0.078	0.098	0.058	0.341	1		
P_{10}	−0.161	0.032	0.047	0.090	−0.112	0.170	0.812	1	
Kr_{10}	0.472	−0.044	−0.041	−0.064	0.064	−0.078	−0.271	−0.168	1

For the purpose of this study, the following parameters with respect to their correlation coefficient r were selected to estimate the project flow:

- The area S (r = 0.623);
- The global slope index Ig (r = −0.309);
- The precipitations Pan and P_{10} The runoff coefficient;
- Kr_{10} (r = 0.472) (which has to be taken into account for better estimates when Pan is greater than 1000 mm in order to reach significant levels).

Considering these parameters, the following mathematical formulation emerges:

$$Q_{10} = a.S^{s}.Ig^{i}. \tag{3}$$

Like the ORSTOM method, the CIEH method requires the estimation of certain parameters in situ. The accuracy of the final result depends, in a large extent, on the precision and accuracy of those parameters. Moreover, these formulations do not take into account the internal heterogeneities of the basin.

4 Frequency Analysis

The statistical treatment of the data in order to estimate the ten-year flow rate was carried out using a frequency analysis which consists in studying past events characteristic of a given process (hydrological or other) in order to define the probability of a future occurrence.

4.1 Return Period

In West Africa, ORSTOM hydrologists based on the relatively small watershed in the tropical and Sahelian regions and available measurements, defined the ten-year return period. It is a statistical estimator which may be observed once in ten years [4].

$$T = \frac{1}{1 - F(x)} \tag{4}$$

with $1 - F(x)$: the probability of overpassing of the event.

4.2 Choice of the Flood Distribution Model

Several models (normal distribution, log-normal distribution, Gumbel distribution, etc.) are used to describe flood phenomena, but the choice is based on some criteria such as the theoretical conditions of the distribution, the asymptotic behavior, some suitability tests, and the use of various diagrams. The most used distribution in hydrology to describe extreme events, such as rainfall and in our case floods, is the Gumbel distribution [7]. It is a double exponential distribution, the limiting form of the distribution of the maximum value of a sample of n values. The Gumbel distribution's cumulative density function is defined as:

$$F(x) = exp\Big[-exp\Big(-\frac{x-a}{b}\Big)\Big] \tag{5}$$

where a $\in \mathbb{R}$ is the location parameter, b: the scale parameter, x: the descriptible variable.

The quantile function which is the inverse cumulative distribution x_q is given by:

$$x_q = a - b.ln\big[-ln[F(x)]\big] \tag{6}$$

The Gumbel distribution allows describing the annual maxima of the flow rate on the considered basin.

4.3 Adjustment of the Model

The adjustment of the model to the data set consists of finding the parameters a and b of the above-mentioned distribution. For this purpose, we define a reduced variable u:

$$u = \frac{x-a}{b}. \tag{7}$$

The adjustment or determination of the parameters can be done by the graphical method or the method of the moments.

4.3.1 Graphical Method

In the case of the adjustment according to Gumbel distribution, the graphical method based on the linearity of the expression of a quantile corresponds to a straight line equation ($x = f(u)$). The parameters a and b are then obtained by estimating the coefficients of the regression line (Fig. 1) which fits the most to the points. But, to find the variable u, some expressions are proposed in order to compute an experimental value of $F(x)$. Simulations have shown for the Gumbel distribution that the appropriate expression is Hazen formula which is defined as:

$$F(x_r) = \frac{r-0.5}{n} \tag{8}$$

where r is the rank of the value in the sample; n is the sample size; x is the describe variable.

The data is decreasingly ordered. Each value is assigned its rank and we use Eq. 8 to compute F(x). Then, we deduce the reduce variable u using the Eq. 6:

$$u = -ln\big[-ln[F(x_r)]\big]. \tag{9}$$

Therefore we plot on the same graph the flow x in terms of u and the regression line.

The advantage of this method is that it provides a visual representation and the adjustment of the data, essential aid for the judgment of the adequacy of the chosen distribution and the data processing. Once we have the parameters a and b, we equate the Gumbel formula with the expression of F(x) deduced from the return period formula. This gives us:

$$F(x) = 1 - \frac{1}{T} \text{ and } u = -ln[-ln[\frac{1}{T}]] \tag{10}$$

Hence, we easily compute the ten-year project flow using the Eq. 6.

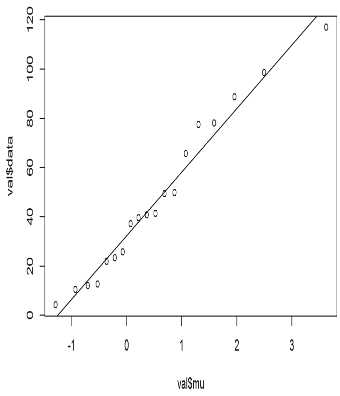

Fig. 1. Regression line. (Aguimo watershed)

4.3.2 Method of Moments

The method of moments consists of equating the sampling moments and the theoretical moments of the chosen distribution.

Let $x_1, \ldots, x_n$ be the sample available and let $\hat{\mu}$ the standard estimators of the mean and $\hat{\sigma}^2$ the variance of the sample. The first two theoretical moments of the Gumbel distribution are expressed in terms of the location and scale parameters as follows:

$$\hat{\mu} = a + b\gamma \text{ and } \hat{\sigma}^2 = \frac{\pi^2.b^2}{6} \tag{11}$$

where

$$\gamma = 0.5772 \text{ (Euler constant).}$$

Therefore, we easily deduce a and b:

$$b = 2.45\frac{\hat{\sigma}}{\pi} \text{ and } a = \hat{\mu} - b\gamma \tag{12}$$

So with a and b, we compute the ten-year project flow using the Eq. 6.

5 Simulations and Results

5.1 Target Watersheds of the Study

All the data, we used in this research has been collected from the database of AMMA-CATCH. It is a hydro-meteorological observatory service, whose aim is to document the long-term climate, hydrological and ecological changes in West Africa.

Seven watersheds are located in the north of Benin between the positions 9.954 N; 1.819 W; 2.399 E; 9.7106 S. They are parts of the big coastal watershed basin of Oueme-Yewa (Benin) [8].

Three basins belong to the Niger watershed located in Niger between the positions: 13.884 N; 2.63 W; 2.7001 E; 13.6445 S. The areas of the watershed vary from 0.048 to 0.16 km^2.

5.2 Result Using ORSTOM and CIEH Methods

All the simulations were performed using the software R Studio. For the ORSTOM method, the obtained results are in the range of [0.67–63.24 m^3/s]. The smaller design flows are obtained in the region of Niger, with the smallest one in Wankama-amont watershed. The relatively bigger ten-year flow are in Benin region with the biggest ten-year flow obtained in Sani-a-sani basin.

The results obtained using the CIEH method, are in the range of [3.3–101.1524 m^3/s]. The smaller design flows are obtained in the region of Niger, with the smallest one in Wankama-amont watershed. The relatively big ten-year flows are in Benin region with the biggest project flow obtained in Sani-a-sani basin.

5.3 Flood Peak Estimation Assuming a Gumbel Distribution

A plot of the histogram and the density of the data are presented in Fig. 2. The choice of Gumbel distribution is based on the samples distribution of our data which is left skewed with skewness 0.56 and platykurtic with kurtosis -0.88. It belongs to the Gamma distribution's function.

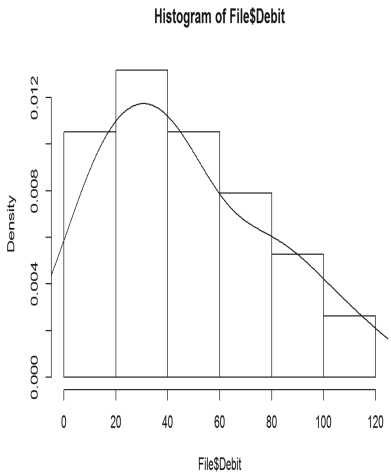

Fig. 2. Sample distribution. (Aguimo watershed)

The available data varies from a watershed to another. It varies from 4 years to 19 years according to the accessible data we got from AMMA-CATH DB. The results obtained with this statistical analysis are in the range of [0.3–122.5 m^3/s]. The biggest value is obtained on Donga-pont watershed whereas the smallest one is obtained on Tondikiboro-amont.

5.4 Discussion

The following table summarises all the results obtained from the frequency analysis (FA), ORSTOM and CIEH methods (Table 2).

Table 2. Summary of simulations

Location	Station	Area (km^2)	FA (m^3/s)	ORSTOM (m^3/s)	CIEH (m^3/s)
Benin	Aguimo	368.77	90.6	45	84.2
Benin	Sani-a-sani	743.3	43.8	63.24	101.15
Benin	Tebou	529.86	87.86	53.94	95.28
Benin	Wewe	276.55	64.7	39.91	77.45
Benin	Ara-pont	10.93	12.8	12.31	21.75
Benin	Donga-pont	586.95	122.5	57.02	96.85
Benin	Donga-route-kolokonde	101.783	41.6	39.95	56.2
Niger	Tondikiboro-amont	0.16	0.3	1.3	4.2
Niger	Wankama-amont	0.048	1.3	0.67	3.3
Niger	Wankama-ZeAmont	0.062	1.6	0.87	3.7

As shown, we clearly see that for almost all the stations, the ORSTOM method estimations are less than what we could expect using the frequency analysis. We noticed some differences in the range of [0.14–20]. The CIEH method as the ORSTOM, doesn't give better estimation of the project flow. We notice for almost all the stations an increasing of the flow Q_{10}.

The smallest mean square error is observed for the CIEH method (21.26) whereas the mean square error, using ORSTOM is a bit bigger (29.18). Then we clearly see that we make less error with the CIEH method. So, as projected, ORSTOM and CIEH methods based on the data we have, and the analysis we made on it, are both no more accurate like in the time there were built. The ORSTOM method under-estimates the design flow whereas the CIEH method over-estimates the design flow. This result confirms the same observation made on some watersheds basins in Burkina Faso [1].

Therefore, the need of their updating is urgent in order to ovoid problems as describe in the introduction caused by an under-estimation or over-estimation of the design flow. At this stage, it is important to find an alternative method.

6 Alternative Method

Adequate estimation of extreme hydrological variables is essential for the rational design and operation of a variety of hydraulic structures, due to the significant risk associated with these activities. Local frequency analysis is commonly used to estimate extreme hydrological events on sites where adequate amount of data is available. In practice, it frequently happens that little or no stream flow data is available on a site of interest (where a dam is going to be erected for example). In such cases, hydrologists use a regional flood frequency procedure, relying on data available from other basin with a similar hydrological regime or region [9].

According to the previous work done by CIEH and ORSTOM hydrologists, and based on the partial correlation matrix (Table 1), they revealed that the ten-year flow is a parameter which highly depends on the area of the watershed and the global slope index and in some extent on the precipitation and the runoff coefficient. Thus, we will use a regression approach which will take into account those four parameters. The regression method is simple, fast and allows using different distributions for the different sites of the region. It is also non-sensitive to the heterogeneity that may exist in the region [9,10]. Then, a logarithmic transformation of the variables is introduced in order to linearize the relation of the power type. Therefore, the equation below is deduced:

$$Log(Q) = a_1.log(S) + a_2.log(Ig) + a_3.log(Pm_{10}) + a_4.log(Kr_{10}) \quad (13)$$

where S is the area of the watershed (km^2), Ig: the global slope index (m/km), P_{10}: the average ten-year daily precipitation (mm), Kr_{10}: the runoff coefficient (%).

The model doesn't give better results. The mean square error obtained with this estimation is 16.87. Then we compute the correlation matrix which shows that the more expressive parameters of the design flow are the area and the global slope index which confirm the previous updating work done by CIEH and ORSTOM hydrologists in 1994.

Hence, we divide the dataset into two, according to the two regions (Benin and Niger). Therefore, we obtain the best results; with a mean square error of 0.96. The result is reported in Table 3.

Table 3. Log linear model results

N	Station	Flow (m^3/s)	New flow (m^3/s)
1	Aguimo	90.6	90.09
2	Tebou	87.86	89.69
3	Wewe	64.7	63.65
4	Ara-pont	12.8	12.97
5	Donga-pont	122.5	123.39
6	Donga-route-kolokonde	41.6	41.63
7	Tondikiboro-amont	0.3	1.36
8	Wankama-amont	1.3	0.97
9	Wankama-ZeAmont	1.6	0.37

7 Conclusion

This work aims to re-evaluate the two most popular methods of design flow estimation in West Africa (ORSTOM and CIEH methods). Ten watershed basins have been considered, seven in Benin and three in Niger. The frequency analysis using Gumbel distribution gives the observable ten-year design flow considered as the true values which were compared to the ten-years flow estimated with the ORSTOM and CIEH methods. The error made using these formers methods in terms of mean square error, is respectively 21.26 and 29.18 for the CIEH and ORSTOM method.

Then, it appears obviously that these two methods are no more accurate in project flow estimation.

An alternative method for updating was proposed based on the regional log linear model. The model takes as parameters the watershed area and the global slope index. It gives better estimation when we identify and divide the dataset into two different regions, with 0.96 mean square error.

References

1. Bambara, T.: Contribution à la révision des normes hydrologiques au Burkina Faso, 2iE (2011)
2. Mahé, G.: Variabilité pluie-débit en Afrique de l'Ouest et Centrale au 20èeme siècle, Changements hydro-climatiques, occupation du sol et modélisation hydrologique. Université des Sciences et Techniques Momtpellier 2 (2006)
3. Olivry, J.C., et al.: Vers un appauvrissement durable des ressources en eau de l'Afrique humide. In: Hydrology of Warm Humid Regions, vol. 216, pp. 67–78, July 1993
4. FAO: Crues et apports: manuel pour l'estimation des crues décennale et des apports annuels pour les petits bassins versants non jaugés de l'Afrique Sahélienne et tropicale sèche. Bulletin FAO et de Drainage, 54 (1996)
5. Puech, C., Chabi-Gonni, D.: Méthode de calcul des débits de crue décennale pour les petits et moyens bassins versants en Afrique de l'Ouest et Centrale. Bulletin CIEH (1983)
6. Dubreuil, P., Chaperon, P., Guiscafré, J., Herbaud, J.: Recueil des donnees de base des bassins representatives et expérimentaux. ORSTOM (1972)
7. Musy, A.: Analyse fréquentielle École polytechnique fédérale de Lausanne (2005)
8. FAO: Profil du bassin versant de l'ouémé et caractérisation des sites pilotes (analyse des données). Rapport FinalFAO (2009)
9. Ouarda, T.B.M., et al.: A review of recent developments in regional frequency analysis of hydrological extremes. Revue des sciences de l'eau **21**(2), 219–232 (2008)
10. Martel, B.: Comparaison de méthodes d'analyses fréquentielle régionale appliquées aux crues automnales du Québec. Université du Québec (2009)