Validation of the modified Témez rational model in the watersheds of Norte de Santander, Colombia

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Abstract. Physics includes the study and investigation of the phases that make up the hydrological cycle, including the estimation of flow rates in river basins, most of which are not instrumented, i.e., they lack historical records of circulating flows. For this situation, the application of hydrological models can allow flow estimates to be made. In the Department of Norte de Santander, Colombia, some watersheds do not have instrumentation for flow measurement or hydrological modeling methodologies appropriate to the site. Therefore, methods such as the modified rational model of Teméz are used, even without knowing the relevance of its applicability to the site conditions. Consequently, for the present research, the Teméz model was validated in watersheds of the Norte de Santander Department to estimate the values of extreme flows with a return period of 100 years. In this sense, 11 watersheds were selected, which contained historical rainfall data greater than 20 years and a drainage network of fewer than 1000 Km². It was found that the Teméz model overestimates the real flows of the 11 hydrological basins, where the climatological parameters used in the application of the Frühling factor and its statistical verification using multivariate regression did not achieve an acceptable correlation.

1. Introduction

Physics includes the study and investigation of the phases that make up the hydrological cycle, including the estimation of flow rates in river basins. Flow records of a river basin are fundamental for planning the use of water resources, in terms of agricultural, industrial, and urban supply activities, as well as for the sizing of physical infrastructure works, such as hydraulic structures [1]. No instrumented watersheds can measure flows allowing them to contain records over time. However, watersheds generally do not have the instruments for flow monitoring, so estimates of these values must be made [2].

The circulating flows of river basins can be estimated by applying indirect methods, one of which is the hydrological model proposed in 1991 by Teméz J, called the modified rational model [3]. This model is widely used for flow estimation in Spain, allowing to obtain the values, even when data on the distribution of rainfall over time are not available [4].

The modified rational model is suitable for estimations in small basins and can be extrapolated for basins with an area of up to 3000 Km². It is based on an ideal event, with constant rainfall intensity and indefinite duration. Therefore, to obtain the maximum discharge it is sufficient that the duration of rainfall is equal to the time of concentration. Teméz introduced a series of modifications that reduce the simplicity of the rational method by considering a concentration period between 0.25 hours and
24 hours, a rainfall uniformity coefficient, based on the concentration-time, and a reducing factor according to the basin area [5].

Currently, the Department of Norte de Santander (DNdS), Colombia, has no instrumented watersheds, a situation that makes it necessary to resort to the application of hydrological models to obtain the values of extreme flows [6]. Therefore, the objective of this research is to validate the modified rational model of Teméz in watersheds of the DNdS, Colombia, to estimate the values of extreme flows with a return period of 100 years.

2. Methodology

Historical rainfall data provided by the hydrological stations (HS), property of the “Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM)”, located in DNdS, were used as the base information for this study. Eleven watersheds were selected from those located under the 40 HS of DNdS. For this purpose, two selection criteria were used among the HS. The first criterion was based on the content of historical data greater than 20 years, and the second criterion consisted of analyzing the drainage area of the monitored watersheds, considering those with a drainage area of less than 1000 Km², according to the applicability of the Teméz model.

Figure 1 shows the delimitations made using ArcGIS® software of the selected watersheds areas. Figure 1 shows the names of each of the 11 watersheds, which are monitored by different precipitation stations. The Campo Seis, La Cabaña, Los Pomarrosos, Cornejo, and Las Vegas watersheds are each provided with two precipitation stations; La Donjuana, Pte. San Miguel and Pte. Abrego watersheds have three stations each; and Pte. Sardinata and Pte. López have four stations per watershed.

To characterize the watersheds, primary characteristics and morphometric indices were determined using ArcGIS® software: watershed area, A (Km²); watershed perimeter, P (Km); Gravelius index, Kc; shape factor, Ks; mean watershed elevation, Z (masl); mean watershed slope, Y (%); main river channel length, L (m); mean channel slope, S (m/m); total channel slope, S₀ (m/m) [4].

The outliers test was applied to each historical series of monthly peak flows and precipitation of the watersheds. The outliers test consists of identifying, using hydrological and mathematical criteria, data points that deviate from the trend of the remaining data [7]. This test consists of identifying, through hydrological and mathematical criteria, data points that deviate from the trend of the remaining data [7].
The method was used to identify which flows and precipitations significantly deviate from the trend, thus avoiding affecting the magnitude of the calculated statistical parameters. For this, Equation (1) was applied to detect major uncertain data, and Equation (2) was applied to detect minor uncertain data, as explained in [7]. Flows and precipitation within the range were selected, and then the probability distribution methods were applied.

\[ Y_H = \bar{y} + K_n S_y \]  
\[ Y_L = \bar{y} + K_n S_y \]  

where, \( Y_H \) is the high outliers’ threshold in logarithmic units, \( Y_L \) the low outliers threshold in logarithmic units, \( \bar{y} \) the mean of the logarithmic values, \( S_y \) the standard deviation and \( K_n \) is the 10% significance level value.

The probability distribution functions normal, Gumbel probability distribution, and Log-Pearson were used, based on the maximum rainfall in 24 hours for each of the watersheds [8-10]. From these functions, rainfall and flow rates with a return period of 100 years were estimated to obtain a value similar to the real value of the flow in the channel.

In addition, the Thiessen polygon method [11] was used to determine average precipitation for each watershed, thus obtaining single precipitation for each hydrological station, since each basin analyzed had more than one precipitation station.

For the application of the modified rational method [3], the concentration time (Equation (3)), uniformity coefficient (Equation (4)), rainfall intensity (Equation (5)), runoff coefficient (Equation (6)), and extreme flow (Equation (7)) were estimated.

\[ T_c = 0.3 \left( \frac{L}{S^{0.25}} \right)^{0.76} \]  
\[ K = 1 + \frac{T_c^{1.25}}{I_T^{1.25} + 14} \]  
\[ I_{T_c} = \left( \frac{I_t}{I_d} \right)^{2^{0.1 - \frac{T_c}{24}}} \]  
\[ Q = \frac{C \times I_x A}{3.6} \]  

where \( T_c \) is the time of concentration (hours), \( L \) is the length of the longest watercourse (Km), \( S \) is the average slope of the main channel (m/m), \( K \) is the uniformity coefficient, \( I \) is the rainfall intensity (mm/h), \( I_{T_c} \) is the average intensity corresponding to the time interval \( t \) (mm/h), \( P_d^* \) is the modified maximum daily rainfall (mm) corresponding to a return period \( T \) (mm), \( I_t \) is the quotient between hourly and daily intensity, \( t \) is the time interval duration of \( I_t \) (hours), \( C \) is the runoff coefficient, \( P_o \) is the runoff threshold and \( A \) is watershed area (Km²).

Additionally, a torrentiality factor was obtained, which is the quotient between the hourly and daily intensity, using as input the actual intensity-duration-frequency (IDF) curves and the precipitation of each watershed of the IDEAM institute. For this, it was necessary to locate the actual IDF curve stations and the closest hydrographic stations to allow a more accurate relationship at the time of interpolation.
The results of the flows calculated by the modified rational method, for the different probability distribution methods, were compared with the actual flows calculated from the maximum monthly flows of the hydrological stations. This made it possible to validate the Témez method concerning the conditions of the basin studied, and to try to calibrate the method to check the uniformity of the data, using Equation (8).

$$f(a) = A^{0.25} (1 - 0.0054),$$

where \( f(a) \) is the Fhrüling factor used in the calibration of the parameters of the modified rational method for to reduce rainfall by watershed spatiality and \( A \) is watershed area (Km\(^2\)).

### 3. Results

The characteristics of the 11 selected watersheds are presented in Table 1. In general, according to the results of the ArcGIS\textsuperscript{®} software and the morphometric characteristics of the 11 watersheds (Table 1), it is observed that the basins reveal an oblong oval to almost rectangular shape, which indicates that there is less probability of instantaneous floods due to their elongated shape. In addition, the average slope in all cases is greater than 5\%, which is natural for mountain rivers [12].

| Table 1. Morphometric characteristics of the river basins. |
|-----------------|---|---|---|---|---|---|---|---|
| Watershed       | A (Km\(^2\)) | P (Km) | \( K_c \) (-) | \( K_f \) (-) | Z (masl) | Y (%) | L (Km) | S (m/m) | \( S_p \) (m/m) |
| Campo Seis      | 314.6 | 95.9 | 1.51 | 0.48 | 517.0 | 36.0 | 25.7 | 0.1241 | 0.0067 |
| La Cabaña       | 530.8 | 136.6 | 1.66 | 0.34 | 1712.4 | 31.1 | 39.4 | 0.0637 | 0.0092 |
| Los Pomarrosos  | 101.0 | 50.4 | 1.40 | 0.32 | 2149.4 | 67.2 | 17.8 | 0.1951 | 0.0034 |
| Cornejo         | 460.8 | 142.1 | 1.85 | 0.17 | 1614.2 | 45.8 | 51.5 | 0.1171 | 0.0363 |
| Pte Sardinata   | 909.9 | 161.5 | 1.50 | 0.27 | 1871.7 | 50.6 | 58.2 | 0.1270 | 0.0401 |
| Campo Tres      | 706.2 | 156.4 | 1.65 | 0.22 | 637.7 | 34.8 | 56.5 | 0.0839 | 0.0089 |
| Las Vegas       | 69.8 | 46.9 | 1.57 | 0.25 | 2083.6 | 36.1 | 16.8 | 0.1367 | 0.0545 |
| Pte López       | 834.1 | 163.9 | 1.59 | 0.46 | 3287.5 | 38.1 | 42.6 | 0.1527 | 0.0341 |
| La Donjuana     | 422.7 | 126.7 | 1.73 | 0.28 | 2000.2 | 45.3 | 38.8 | 0.0933 | 0.0322 |
| Pte San Miguel  | 410.5 | 112.0 | 1.55 | 0.28 | 347.2 | 19.9 | 38.6 | 0.0455 | 0.0044 |
| Pte Abrego      | 367.4 | 109.3 | 1.60 | 0.44 | 2200.8 | 40.7 | 28.9 | 0.0816 | 0.0198 |

#### 3.1. Application of statistical data adjustment

As an example, the maximum monthly flows were calculated in logarithmic units for the Campo Seis hydrology station, and the values of the outliers are shown in Table 2. Based on Table 2, the outliers’ thresholds are obtained: \( YH = 3070 \text{ m}^3/\text{s}, \ YL = 43.7 \text{ m}^3/\text{s}, \) flow greater than 1532 \text{ m}^3/\text{s}, and flow less than 61.3 \text{ m}^3/\text{s}, therefore, for this station, there are no doubtful data.

| Table 2. Application values of questionable data from the Campo Seis station. |
|-----------------|---|---|---|
| Average         | 2.56 | n | 39 |
| \( K_p \)       | 2.671 | Desiation | 0.345 |

#### 3.2. Probability distribution

For the application of the Normal, Gumbel, and Log-Pearson distribution methods in the example of the Campo Seis basin, on the Tibú precipitation station, the following was obtained: mean of the precipitation (P) of 113.8 mm; mean of the logarithms of the precipitation (Log P) of 2.0457; standard deviation of precipitation (\( S_p \)) of 25.14; standard deviation of logarithms of precipitation (\( S_{\text{Log} P} \)) of 0.0983; coefficient of asymmetry (\( C_s \)) of \(-0.3204\); and K of \(-0.0534\).

Since each watershed had more than one precipitation station, the Thiessen Method was applied to determine for each watershed single average precipitation for the distribution functions at a 100-year
return period [13], the uniformity coefficient (K) and simultaneity coefficient (Kₐ) was determined, as presented in Table 3. The modified maximum daily precipitation (Pₑ) was determined using the distribution methods, as presented in Table 4.

| Watershed      | Tₑ (hours) | K     | Kₐ  |
|----------------|------------|-------|-----|
| Campo Seis     | 5.26       | 1.36  | 0.83|
| La Cabaña      | 8.26       | 1.50  | 0.82|
| Los Pomarrosos | 3.64       | 1.26  | 0.87|
| Cornejo        | 9.02       | 1.53  | 0.82|
| Pte Sardinata  | 9.74       | 1.55  | 0.80|
| Campo Tres     | 10.31      | 1.57  | 0.81|
| Las Vegas      | 3.74       | 1.27  | 0.88|
| Pte López      | 7.42       | 1.47  | 0.81|
| La Donjuana    | 7.60       | 1.47  | 0.83|
| Pte San Miguel | 8.66       | 1.51  | 0.83|
| Pte Abrego     | 6.23       | 1.41  | 0.83|

Table 3. Time of concentration, coefficient of uniformity and simultaneity.

| Watershed      | Maximum rainfall in 24 hours (mm) for T=100 yr. |
|----------------|----------------------------------------------|
| Campo Seis     | 189.50 214.10 204.00 |
| La Cabaña      | 88.00 100.60 96.60 |
| Los Pomarrosos | 157.00 176.60 165.20 |
| Cornejo        | 130.50 150.00 142.30 |
| Pte Sardinata  | 116.50 135.80 135.70 |
| Campo Tres     | 150.00 167.50 129.20 |
| Las Vegas      | 111.70 128.00 122.10 |
| Pte López      | 58.90 69.20 67.00 |
| La Donjuana    | 85.10 97.10 90.90 |
| Pte San Miguel | 144.60 162.30 140.20 |
| Pte Abrego     | 113.30 133.60 122.80 |

Table 4. Modified maximum daily precipitation.

3.3. Validation of the modified rational method

The maximum flow (Qₑ) was determined by the Teméz model for the distribution functions, and a comparison was made between the flows calculated and the actual flows calculated from the maximum monthly flows of the hydrological stations, as shown in Table 5.

| Watershed      | Qₑ (Teméz Model) | Qₑ (Frequency analysis) |
|----------------|-------------------|--------------------------|
| Campo Seis     | 3358 3642 3586    | 1199 1452 1469           |
| La Cabaña      | 1916 2174 2145    | 538 673 802              |
| Los Pomarrosos | 1225 1310 1264    | 196 246 534              |
| Cornejo        | 2525 2872 2777    | 598 726 878              |
| Pte Sardinata  | 3835 4505 4656    | 589 702 726              |
| Campo Tres     | 3665 4066 2979    | 1114 1320 1283           |
| Las Vegas      | 522 577 578       | 167 209 346              |
| Pte López      | 1851 2180 2163    | 334 396 279              |
| La Donjuana    | 1338 1516 1434    | 191 231 253              |
| Pte San Miguel | 2337 2594 2256    | 526 612 660              |
| Pte Abrego     | 2155 2497 2353    | 245 287 263              |

Table 5. Comparison of peak flows (m³/s) between the Teméz model and actual flows.

The values obtained by the modified rational model [3] as shown in Table 5, overestimate the flows measured by the hydrological stations. Therefore, the parameters of the Témez model were calibrated by first applying the Fhrüling factor (Factor C) to reduce the rainfall per basin spatiality, as shown in Table 6. However, as seen in Table 6, the Fhrüling Factor does not allow for data uniformity, which is essential for flow regionalization [6,14]. This may be due to the high overestimation provided by the Témez method [3] for the 11 wathersheds, which are characterized by being in a site of varied topography different from the conditions considered in the modified rational method.

Figure 2 shows the regression graphs according to each characteristic considered, for the regionalization of climatological parameters. Given the results using Figure 2, the R² value (< 0.5) shows that there are limitations of the Témez model. These values are unsatisfactory as it is determined in [6], for employing the hydrologic model on wathersheds.
Tabla 6. Fhrüling’s factor for watersheds.

| Watershed         | A (Km²) | Factor C |
|-------------------|---------|----------|
| La Cabaña         | 530.8   | 0.44     |
| Los Pomarrosos    | 101.0   | 0.73     |
| Cornejo           | 460.8   | 0.44     |
| Pte Sardinata     | 909.9   | 0.31     |
| Campo Tres        | 706.2   | 0.34     |
| Las Vegas         | 69.8    | 0.75     |
| Pte López         | 834.1   | 0.39     |
| La Donjuana       | 422.7   | 0.49     |
| Pte San Miguel    | 410.5   | 0.47     |
| Pte Ábrego        | 367.4   | 0.54     |

Figure 2. Multivariate regression between morphometric characteristics of the watersheds and the values calculated by the Fhrüling factor; (a) area of the basin vs. Factor C; (b) average slope of the basin vs. Factor C; (c) length of the main channel vs. Factor C.

4. Conclusions
The modified rational model proposed by Témez overestimates the real flows of the 11 watersheds in the Department of Norte de Santander, in which none of the climatological parameters are used in the Fhrüling factor and the multivariate regression, achieved an acceptable correlation. Therefore, in the framework of this study, the modified rational model is not valid for watersheds not instrumented in the Department of Norte de Santander. The proposed methods for estimating peak flows based on rainfall should be validated in other regions.

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