DOI:10.24850/j-tyca-2018-05-07

Articles

Daily precipitation concentration index in the Río Grande de Morelia basin

Abstract

The daily precipitation concentration index (CI) was evaluated as an indicator to characterize the sub-basins in the hydrological basin, which represent different degrees of pluviometric torrentiality. The CI was estimated using the Lorenz curve to evaluate the relative weight of the rainiest days in the series of daily precipitation data, which was recorded in 34 conventional meteorological stations (CWS) in and near the Río Grande de Morelia basin, from its source upstream of the Cointzio Dam, to its mouth in Lake Cuitzeo. The Río Grande passes through the city of Morelia, which has been affected by floods in a cyclical manner, resulting in serious damage: human losses, damage to infrastructure and deterioration in agricultural, livestock and forestry production. A platform was developed in a GIS for the delimitation and characterization of the basin and its 23 sub-basins. The CI for each CWS was calculated, with which isopleths were generated with intervals of 0.01, as well as a raster layer of the CI. The CI average was calculated for the 23 sub-basins and for the basin. Based on the results, a CI torrentiality scale is proposed, such as: Low torrential (0.476-0.515), medium torrential (0.515-0.538), torrential (0.538-0.560) and high torrential (0.560-0.607). Weighted average for the basin resulted in a *CI* = 0.55, which corresponds to a torrential basin, and the CI was related to the climate of the basin.

Keywords: Concentration index, torrentiality, isopleths and basin.

Resumen

Se realizó una evaluación del índice de concentración de precipitación diaria (CI), como un indicador para caracterizar las subcuencas de la cuenca hidrológica, que representan diferentes grados de torrencialidad pluviométrica. El CI se estimó por medio de la curva de Lorenz, para evaluar el peso relativo de los días más lluviosos en series de datos de precipitación diaria, que se registró en 34 estaciones meteorológicas convencionales (EMC), dentro y próximas a la cuenca del Río Grande de Morelia desde su origen, aguas arriba de la presa Cointzio, hasta su desembocadura en el lago de Cuitzeo. El Río Grande pasa por la ciudad de Morelia, la cual se ha visto afectada por inundaciones de forma cíclica, que han dejado como consecuencias graves daños: pérdidas humanas y afectaciones a la infraestructura, así como deterioro en la producción agrícola, pecuaria y forestal. Se elaboró una plataforma en un sistema de información geográfica (SIG), para la delimitación y caracterización de la cuenca, y sus 23 subcuencas. Se calculó el CI para cada EMC, con el que se generaron isopletas con intervalos de 0.01 y una capa ráster del CI; se calculó el promedio del CI para las 23 subcuencas y para la cuenca. Con base en los resultados se propone una escala de torrencialidad del CI, esto es: bajo torrencial (0.476-0.515); medio torrencial (0.515-0.538); torrencial (0.538-0.560), y altamente torrencial (0.560-0.607). El promedio ponderado para la cuenca resultó un *CI* = 0.55, que corresponde a una cuenca torrencial; el CI se relacionó con el clima de la cuenca.

Palabras clave: índice de concentración, torrencialidad, isopletas y cuenca.

Received: 03/07/2017

Accepted: 14/03/2018

Introduction

Some hydrological basins and their sub-basins are affected by hydrometeorological events such as extreme precipitations produced by seasonal rains or migratory atmospheric phenomena such as tropical storms and cyclones, among others. These extreme precipitation events create extraordinary runoff that can produce floods, which cause greater damage to human life and urban and hydro-agricultural infrastructure and deterioration of agriculture, fishing and forestry.

For this reason, we proposed that it is possible to evaluate torrentiality in hydrological basins by estimating the Concentration Index (CI). Thus, the objective of this study was to estimate the CI in the sub-basins and basin of the Río Grande de Morelia, Michoacán, Mexico, to assess the degree of torrentiality.

Martín-Vide (2004) proposed a methodology for estimating the Daily Precipitation Concentration Index by applying the Lorenz curve to evaluate the relative weight of the rainiest days in a series of daily precipitation data, recorded in conventional meteorological stations (CWS). Also, Zubieta, Saavedra, Silva and Giráldez (2016) presented a study on the estimation of torrentiality in a hydrological basin using the Concentration Index (CI) and its spatial distribution in the Mantaro River Basin, Peru.

The studies conducted on CI focus on regionalization of precipitation, which is one of the phases to be considered in the study, such as in Martín-Vide and Estrada-Mateu (1992); De Luis, González-Hidalgo and Sánchez (1996); Martín-Vide and Llasat (2000); Martín-Vide (2004); Martín-Vide *et al*. (2008); Alijani, O'Brien and Yarnal (2008); Zhang, Xu, Gemmer, Chen and Liu (2009); Lana, Burgue, Martínez and Serra (2009); Li, Jiang, Li and Wang (2011); Benhamrouche and Martín-Vide (2011); Vargas, Santos, Cárdenas and Obregón (2011); Velasco-Martínez, Mendoza-Palacios, Campos-Campos and Castillo-Bolainas (2011); Suhaila and Aziz (2012); Cortesi, González-Hidalgo, Brunetti and Martín-Vide (2012); Sarricolea and Martín-Vide (2012); Benhamrouche and Martín-Vide (2012); Zubieta and Saavedra (2013); Espinoza, Herrera and Araya (2013); Shi *et al*. (2014); Meseguer-Ruiz, Martín-Vide, Olcina-Cantos and Sarricolea-Espinoza (2014); Benhamrouche (2014); Sarricolea and Romero (2015); Benhamrouche *et al*. (2015); Huang, Huang, Chen, Xing and Leng (2016); Zubieta *et al*. (2016); Monjo and Martín-Vide (2016); Hamzah, Zainal and Jaafar (2016).

However, in Mexico, no application has been presented using a hydrological approach that allows estimating precipitation torrentiality in hydrological basins using the Daily Precipitation Concentration Index (CI) as an indicator of the degree of aggressiveness or torrentiality of the rain that occurs in the basin and its sub-basins.

In this study, we present the application of the method based on the Daily Precipitation Concentration Index (CI) as an indicator for the estimation of the degree of aggressiveness or torrentiality of a rain event in the hydrological basin and sub-basins of the Río Grande de Morelia, where the city of Morelia is located. The city has been affected cyclically by extraordinary flow of the Río Grande and its tributaries (Conagua, 2016).

Materials and methods

The description of materials includes the location of the study area, the characteristics of the elevation model and information on daily precipitation.

Study area

The study was conducted in the Río Grande de Morelia basin, Michoacán, Mexico, where the urban zone of the city of Morelia is located, from upstream of the Cointzio Dam to where the river empties into the Cuitzeo Lake, an area of 1 748 km^2 (Figure 1).

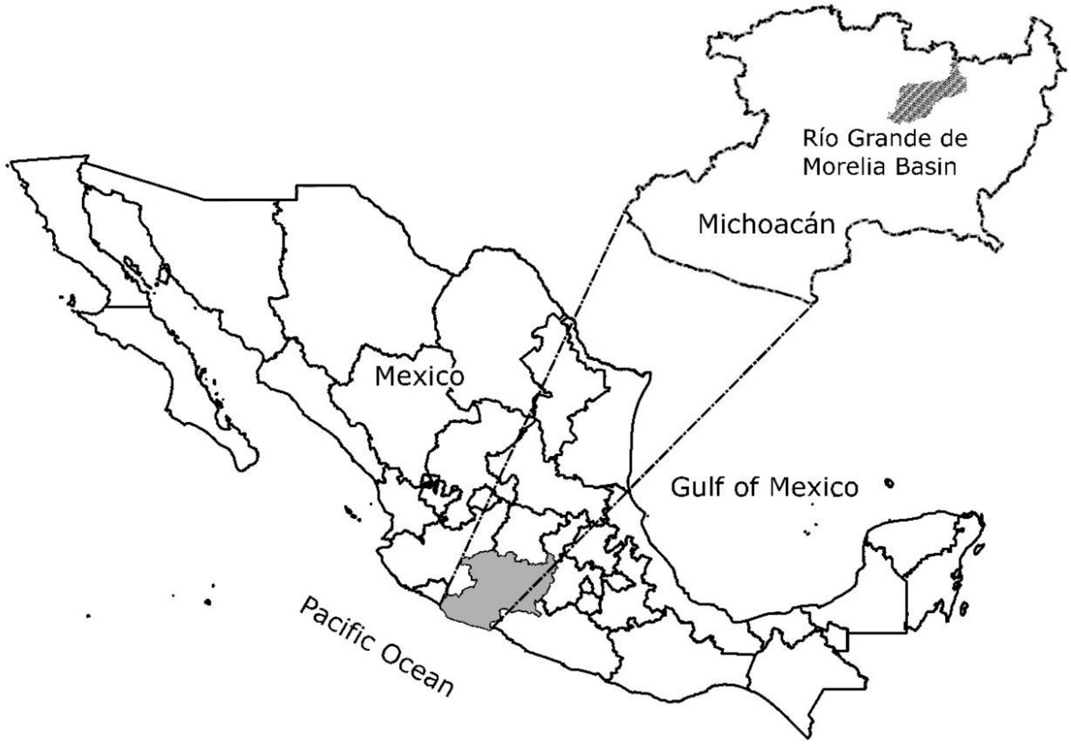

Figure 1. Location of the Río Grande de Morelia Basin, Michoacán, México.

Information used

The digital elevation model (DEM) used has a pixel resolution of 15 m and a scale of 1:50 000 (INEGI, 2013).

The meteorological information used is from the National Weather Service's Conventional Weather Stations (CWS) network (Estaciones Meteorológicas Convencionales del Servicio Meteorological Nacional [SMN, Spanish acronym]). This study included 34 CWS, from which daily precipitation registries from 1923 to 2015 and location were obtained. An average of 0.48% of the data in the series were missing (SMN, 2017).

Methodology

The methodology applied in this study is presented in Figure 2.

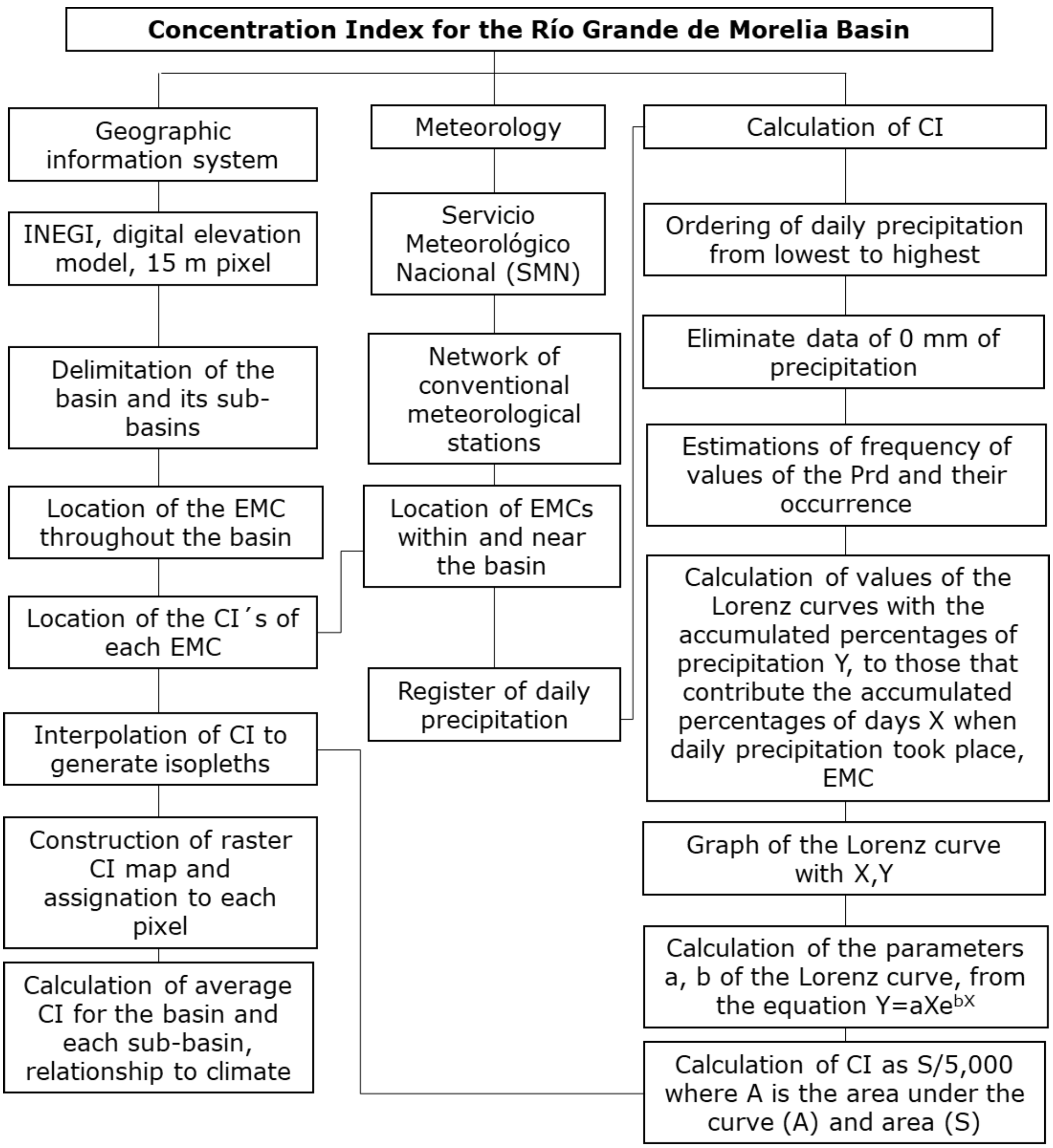

Figure 2. Diagram for calculating the concentration indexes (CI) by sub-basin in the basin of the Río Grande de Morelia.

Delimitation of the hydrological basin

The basins were delimited based on the Continuo de Elevación Mexicano (CEM 3.0) provided by INEGI (2013). The basin of the Rio Grande de Morelia basin was delimited using the extension in the Soil and Water Assessment Tool (Winchell, Srinivasan, Di Luzio, & Arnold, 2013) (Figure 3).

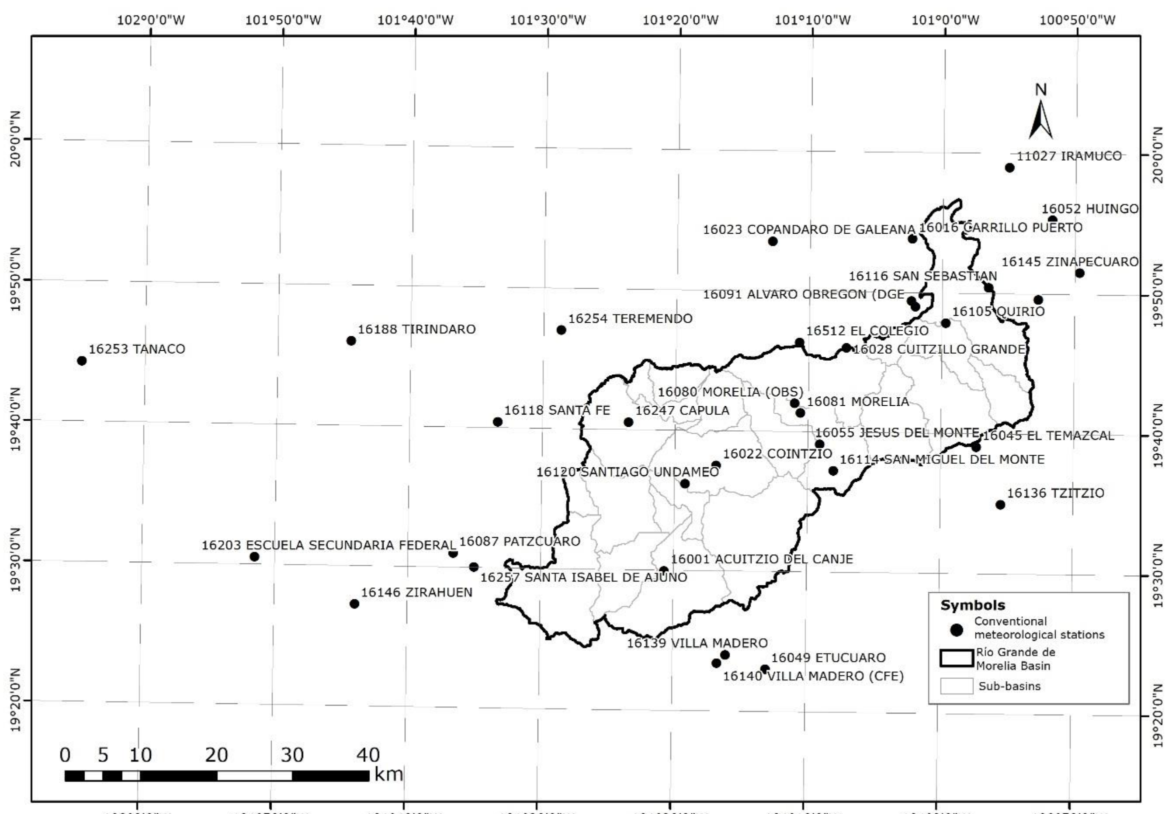

Figure 3. Location of the conventional weather stations in the Río Grande de Morelia basin, Michoacán.

CWS selection, location and georeferencing

The geographic location of each conventional weather station was extracted from the database, using those that are located within and closest to the basin of the Rio Grande de Morelia, as described in Figure 3.

Collection of information on daily precipitation from the CWS registers

The 34 CWSs, their official codes and names, operational condition, georeferencing and length of their registers were identified up to 2015 (SMN, 2017) (Table 1). These CWSs were located in a GIS (Figure 3).

Table 1. General data from the conventional weather stations studied (SMN, 2017).

Num.	Code	Name	Utm (zone 14N)		Altitude (m)	Years registered	% Missing data
			X	*Y*			
1	16001	Acuitzio del Canje	253,909	2,157,711	2 200	1961-2008	0.37
2	16004	Álvaro Obregón (Smn)	287,023	2,192,475	1 846	1964-1986	0.05
3	16016	Carrillo Puerto	286,636	2,201,400	1 840	1969-2006	0.03
4	16022	Cointzio	260,775	2,171,585	2 096	1940-2006	0.11
5	16023	Copandaro de Galeana	268,243	2,201,079	1 840	1969-2001	0.01
6	16028	Cuitzillo Grande	277,931	2,187,050	1 987	1969-2007	0.04
7	16045	El Temazcal	295,018	2,173,989	2 220	1965-2014	0.06
8	16049	Etúcuaro	267,190	2,144,739	1 690	1944-1988	0.01
9	16052	Huingo	305,078	2,203,831	1 921	1941-2012	0.04
10	16055	Jesús Del Monte	274,421	2,174,360	2 180	1935-2014	0.29
11	16080	Morelia (Obs)	271,139	2,179,754	1 913	1986-2014	0.07
12	16081	Morelia	271,880	2,178,484	1 908	1947-2015	0.06

Num.	Code	Name	Utm (zone 14N)		Altitude (m)	Years registered	% Missing data
13	16087	Pátzcuaro	226,111	2,160,051	2 140	1969-2015	0.01
14	16091	Álvaro Obregón (Dge	286,508	2,193,220	1 840	1966-2015	0.12
15	16096	Presa Malpaís	303,216	2,193,364	1 859	1944-2015	0.02
16	16105	Quirio	291,014	2,190,306	1 858	1963-2015	0.11
17	16114	San Miguel del Monte	276,184	2,170,862	1 965	1963-2013	0.24
18	16116	San Sebastián	296 657	2 194 976	1 836	1969-1991	0.00
19	16118	Santa Fe	232 000	2 177 316	2 203	1963-2014	0.04
20	16120	Santiago Undameo	256 661	2 169 179	2 130	1953-2007	0.03
21	16136	Tzitzio	298 196	2 166 418	1 565	1969-2014	12.41
22	16139	Villa Madero	261 961	2 146 652	2 097	1943-1984	0.40
23	16140	Villa Madero (CFE)	260 808	2 145 560	2 182	1943-1984	0.08
24	16145	Zinapécuaro	308 668	2 196 872	1 880	1923-2014	0.48
25	16146	Zirahuén	213 167	2 153 360	2 090	1947-2014	0.03
26	16188	Tiríndaro	212 702	2 187 987	2 002	1973-2003	0.11
27	16203	Escuela Secundaria Federal	199 989	2 159 575	1 387	1975-1982	0.05
28	16221	Fruticultores	310 023	2 198 457	1 986	1980-2005	0.02
29	16247	Capula	249 253	2 177 280	2 097	1981-2007	0.05
30	16254	Teremendo	240 396	2 189 406	2 188	1982-2014	0.42
31	16257	Santa Isabel de Ajuno	228 855	2 158 194	2 250	1982-1988	0.18
32	16512	El Colegio	271 796	2 187 774	1 880	1986-2014	0.14
33	11027	Irámuco	299 457	2 210 784	1 840	1929-1979	0.24
34	16253	Tanaco	177 252	2 185 364	2 140	1982-2014	0.14

Station 18145 (Zinapécuaro) contained the longest registry, with 91 years (1923-2014) and station 16257 (Santa Isabel de Ajuno) had the shortest registry, with 6 years (1982-1988).

Calculation of the Lorenz curve

Concentration indexes were determined by calculating and constructing the Lorenz curve as the basis. To calculate the Lorenz curve, *Y* is the accumulated percentage of precipitation, to which the accumulated percentage of days, *X*, contributes, where *X* represents the days that had that precipitation value Martín-Vide, 2004).

Based on this daily precipitation information from each CWS, the following variables are described: i = index of the observed daily precipitation value with value I_i, adimensional, *i* = 1 to NI, number of values defined for the reduced register.

I_i = Assigned daily precipitation values i, mm.

F_i= Frequency of daily precipitation that occurs with the value, I_i in the reduced register.

FA_i = Accumulated frequency of N_i.

$$FA_1 = F_1, \quad \text{for } i = 1 \quad (1)$$

$$FA_i = FA_{i-1} + F_i, \quad \text{for } i > 2 \quad (2)$$

FP_i = Frequency of daily precipitation with which value I_i occurs in the reduced register, %.

FT = Total observed frequencies.

$$FT = \sum_{i=1}^{i=NI} F_i \quad (3)$$

$$X_i = \frac{FA_i}{FT} * 100 \quad (4)$$

P_i = Precipitation that occurs for each value I_i,

$$P_i = I_i * F_i \quad (5)$$

PA_i = Accumulated precipitation in N_i.

$$PA_1 = P_1, \quad \text{for } \quad i = 1 \quad (6)$$

$$PA_i = PA_{i-1} + P_i, \quad \text{fo } \quad i > 2 \quad (7)$$

FP_i= Daily precipitation with which value I_i occurs for the reduced register, %.

Tecnología y ciencias del agua, 9(5), 170-197, DOI:10.24850/j-tyca-2018-05-07

PT = Total observed precipitation.

$$PT = \sum_{i=1}^{i=NI} P_i \quad (8)$$

$$Y_i = \frac{PA_i}{PT} * 100 \quad (9)$$

Calculation of the Daily Precipitation Concentration Index, CI

Martín-Vide (2004) proposed the concentration index, CI, as an approximation of the numerical representation of differences, shown by the Lorenz curves (Figure 4). In this case, it is used to estimate the importance of rainy days relative to the total accumulated rain in a time series and thereby determine the relative impact of daily precipitation to evaluate the weight of the registered daily maximums relative to the total.

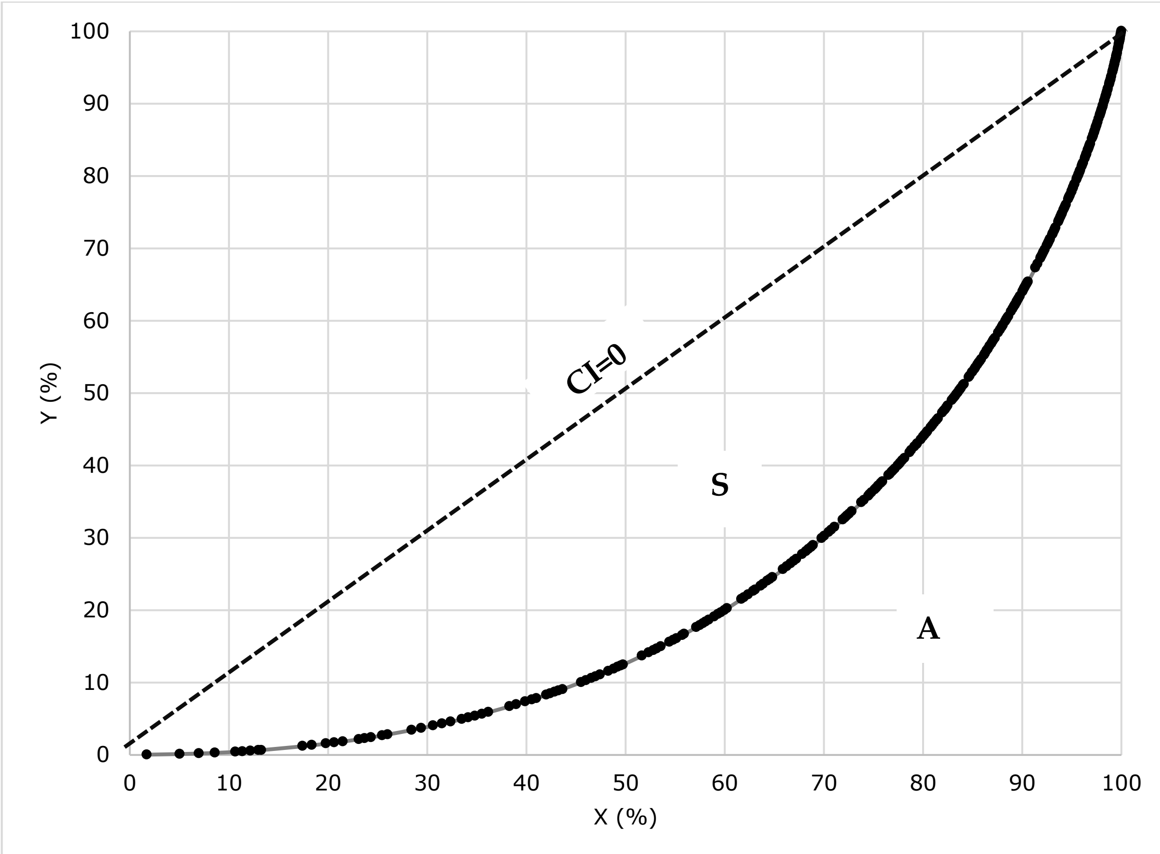

Figure 4. Lorenz curve for the concentration of daily precipitation at the Iramuco Station (1929-1979).

Martín-Vide (2004) associates these curves with exponential type functions:

$$Y = aXe^{bX} \qquad (10)$$

Where *a* and *b* are parameters of the corresponding Lorenz curve.

To determine the values of *a* and *b* in the equation, Martín-Vide (2004) obtained the following relationships:

$$\ln(a) = \frac{\sum X_i^2 \sum \ln Y_i + \sum X_i \sum X_i lnX_i - \sum X_i^2 \sum lnX_i - \sum X_i \sum X_i lnY_i}{N\sum X_i^2 - (\sum X_i)^2} \qquad (11)$$

$$b = \frac{N\sum X_i lnY_i + \sum X_i \sum lnX_i - N\sum X_i \, lnX_i - \sum X_i \sum lnY_i}{N\sum X_i^2 - (\sum X_i)^2} \qquad (12)$$

The integral is the area, *A*, defined by the area under the Lorenz curve between 0 and 100 (Figure 4):

$$A = \int_0^{100} aXe^{bX} dX \quad (13)$$

$$A = \left[\frac{a}{b} e^{bX}\left(X - \frac{1}{b}\right)\right]_0^{100} \quad (14)$$

Area, *S*, is the area under the line of perfect equality (45º) where CI = 0, (100 * 100 / 2 = 5 000) and *A* is:

$$S = 5\,000 - A \quad (15)$$

The concentration index, CI, is defined as the proportion between *S* and the area under the line of perfect equality (Figure 4):

$$CI = \frac{S}{5\,000} \quad (16)$$

The CI are calculated for the 34 conventional weather stations (Table 2 and Figure 5).

Table 2. Calculation of the daily precipitation concentration index and last quartile of the rainiest days at the 34 CWS in the Río Grande de Morelia basin.

Num.	Code	Name	a	b	A	S	CI	Precipitation (25%)
1	16001	Acuitzio del Canje	0.045	0.030	1 964.25	3 035.75	0.607	68.29
2	16004	Álvaro Obregón (SMN)	0.112	0.022	2 431.96	2 568.04	0.514	57.68
3	16016	Carrillo Puerto	0.135	0.020	2 385.37	2 614.63	0.523	62.81
4	16022	Cointzio	0.096	0.023	2 349.57	2650.44	0.530	65.32
5	16023	Copandaro de Galeana	0.079	0.025	2 369.12	2 630.89	0.526	60.37
6	16028	Cuitzillo Grande	0.067	0.027	2 304.40	2 695.60	0.539	61.92
7	16045	El Temazcal	0.085	0.024	2 360.11	2 639.89	0.528	59.65
8	16049	Etúcuaro	0.082	0.025	2 410.67	2 589.33	0.518	59.10
9	16052	Huingo	0.059	0.028	2 286.86	2 713.14	0.543	61.30
10	16055	Jesús del Monte	0.108	0.023	2 604.31	2 395.69	0.479	53.86
11	16080	Morelia (Obs)	0.033	0.034	2 022.81	2 977.19	0.595	67.34

Num.	Code	Name	a	b	A	S	CI	Precipitation (25%)
12	16081	Morelia	0.116	0.020	2 114.08	2 885.92	0.577	65.48
13	16087	Pátzcuaro	0.049	0.030	2 137.12	2 862.89	0.573	64.09
14	16091	Álvaro Obregón (Dge)	0.058	0.028	2 257.55	2 742.45	0.548	62.75
15	16096	Presa Malpaís	0.059	0.028	2 279.18	2 720.82	0.544	61.52
16	16105	Quirio	0.042	0.032	2 133.01	2 866.99	0.573	64.95
17	16114	San Miguel del Monte	0.077	0.026	2 481.04	2 518.96	0.504	57.18
18	16116	San Sebastián	0.061	0.028	2 272.03	2 727.97	0.546	62.33
19	16118	Santa Fe	0.083	0.025	2 481.03	2 518.97	0.504	55.10
20	16120	Santiago Undameo	0.071	0.026	2 239.28	2 760.72	0.552	63.10
21	16136	Tzitzio	0.049	0.030	2 175.95	2 824.05	0.565	64.88
22	16139	Villa Madero	0.064	0.028	2 319.12	2 680.88	0.536	60.34
23	16140	Villa Madero (Cfe)	0.061	0.028	2 272.03	2 727.97	0.546	60.46
24	16145	Zinapécuaro	0.081	0.025	2 430.13	2 569.87	0.514	57.22
25	16146	Zirahuén	0.097	0.024	2 622.23	2 377.78	0.476	52.44
26	16188	Tiríndaro	0.051	0.029	2 176.01	2 823.99	0.565	64.77
27	16203	Escuela Secundaria Federal	0.063	0.029	2 569.25	2 430.75	0.486	57.44
28	16221	Fruticultores	0.044	0.032	2 375.23	2624.77	0.525	60.62
29	16247	Capula	0.061	0.028	2 312.15	2 687.85	0.538	61.57
30	16254	Teremendo	0.093	0.024	2 501.80	2 498.21	0.500	55.78
31	16257	Santa Isabel De Ajuno	0.048	0.030	2 248.28	2 751.72	0.550	63.70
32	16512	El Colegio	0.045	0.031	2 108.32	2 891.68	0.578	66.15
33	11027	Irámuco	0.044	0.031	2 185.41	2 814.59	0.563	63.53
34	16253	Tanaco	0.067	0.028	2 434.76	2 565.24	0.513	58.26

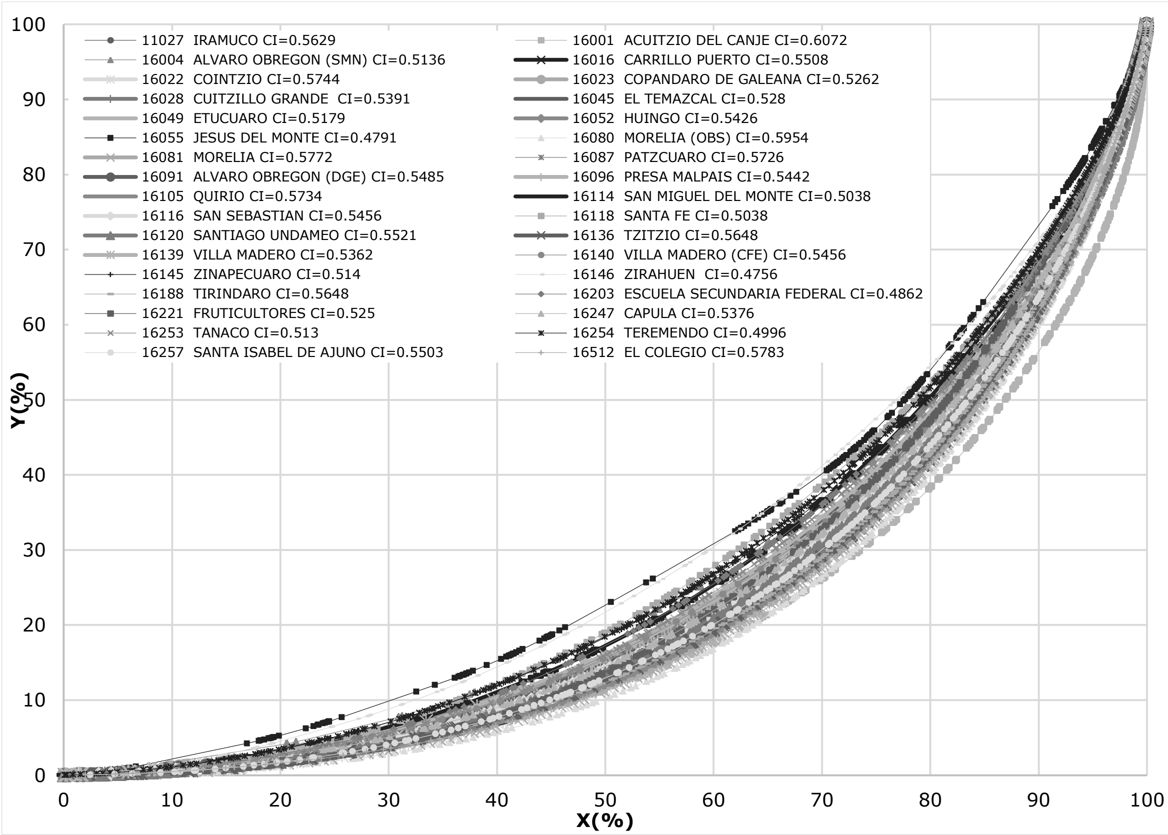

Figure 5. Daily precipitation concentration curves for 34 CWS in the Río Grande de Morelia basin, Michoacán.

Equation 17 was used to calculate precipitation for the last quartile (25%) (Table 3) of rainiest days, $Ppd_{25\%}$, as a percentage, where:

$PT_{25\%} =$ is the volume in mm that 25% of the rainiest days contribute, and PT is the total in mm of observed rain (Equation 8).

$$Ppd_{25\%} = \frac{PT_{25\%}}{PT} * 100 \qquad (17)$$

Table 3. Calculation of the Lorenz curve, Station 11027 (Iramuco), Michoacán, Mexico.

i	I_i	F_i	FA_i	F_i	$X_i = FAi/FT * 100$	$P_i = I_i * F_i$	PA_i	P_i	$Y_i = PA_i/PT * 100$
	mm	Freq. in I_i	Freq. Accum in I_i	Freq. in I_i %	Freq. Accum. in I_i %	Prec. in I_i mm	Prec. Accum. in I_i mm	Prec. in I_i %	Prec. Accum. in I_i %

1	0.1	66	66	1.72	1.72	6.6	6.6	0.02	0.02
2	0.2	127	193	3.31	5.03	25.4	32.0	0.09	0.11
3	0.3	75	268	1.96	6.99	22.5	54.5	0.08	0.18
4	0.4	61	329	1.59	8.58	24.4	78.9	0.08	0.26
5	0.5	80	409	2.09	10.66	40.0	118.9	0.13	0.40
6	0.6	27	436	0.70	11.37	16.2	135.1	0.05	0.45
...	...	...	...	...	...	...	...	...	...
352	60.0	1	3 833	0.03	99.92	60.0	29 598.9	0.20	99.30
353	65.0	1	3 834	0.03	99.95	65.0	29 663.9	0.22	99.52
354	65.9	1	3 835	0.03	99.97	65.90	29 729.8	0.22	99.74
355	77.2	1	3 836	0.03	100.00	77.20	29 807.0	0.26	100.00
	Sum	3 836	1 078 505	100.00				100.00	

Results and discussion

The results are presented under the following sub-headings: Calculation of the Lorenz curve for each CWS, calculation of the daily precipitation Concentration Index for each CWS, classification of the sub-basins by the CI, classification of torrentiality according to the CI in the basin and the association between CI and climate.

Calculation of the Lorenz Curve for each CWS

The process is illustrated with daily precipitation data registered at Station 11027 (Iramuco), which began recording on September 1, 1929; the last record was August 31, 1979, and a total of 15 709 data were recorded.

The daily precipitation data were arranged from lowest to highest; data of no precipitation (zero or not available) were excluded. What resulted was a reduced register of Daily Precipitation, $Prdr_j$, in which j = 1 is the minimum value and j = NJ is the maximum.

To estimate the frequency of $Prdr_j$ in I_i, values were assigned to Ii, namely, I = 1 for its minimum value and I = NI for its maximum value. In this case, I_1 = 0.1 and I_{NI} = 72.2, respectively (355 values). In the reduced register of the station, a value of 0.1 mm of precipitation is presented in 66 days, a value of 0.2 mm occurs 127 days, and so on until reaching a value of 77.2 mm, which occurs only once. The calculation of the Lorenz curve for CWS 11027 (Iramuco) is presented in Table 3 and the curve in Figure 4.

This calculation was performed for the 34 conventional weather stations; each station has its own Lorenz graph (Figure 5).

Figure 5 presents the Lorenz curves for the 34 weather stations. If we analyze the elements of areas A, S and CI, we find that they are the same elements as those presented by Sarricolea and Martín-Vide (2012).

Calculation of the Daily Precipitation Concentration Index, CI, for each CWS

By applying the variables from Equations 16 and 17 for each conventional weather station, we obtain the following results (Table 2).

Parameters a and b varied from a maximum of 0.134 to a minimum of 0.033 and from a maximum of 0.034 to a minimum value of 0.020, respectively. This range of values is also presented by Espinoza *et al*. (2013), Martín-Vide (2004), and Benhamrouche and Martín-Vide (2012). The values of A ranged from 2 622.2 to 1 964.3, those of S from 3 035.8 to 2 377.8 and of CI from 0.48 to 0.61. If we compare these values with those obtained by Monjo and Martín-Vide (2016), we observe a value of CI = 0.6 for the latitude 19º 42’, presented in world maps and where the region of Morelia, Michoacán, is located. The values of precipitation of 25% of the rainiest days varied from 52.44% to 68.29%.

In the concentration curves, Station 16146 (Zirahuen), with a CI = 0.4756, is the curve that is closest to the line of perfect equality where

CI = 0, while Station 16001 (Acuitzio del Canje), with *CI* = 0.6072, is the farthest from the line, where CI = 1.

The CI was compared with the precipitation of 25% of the rainiest days, and a linear relationship was found (Figure 6).

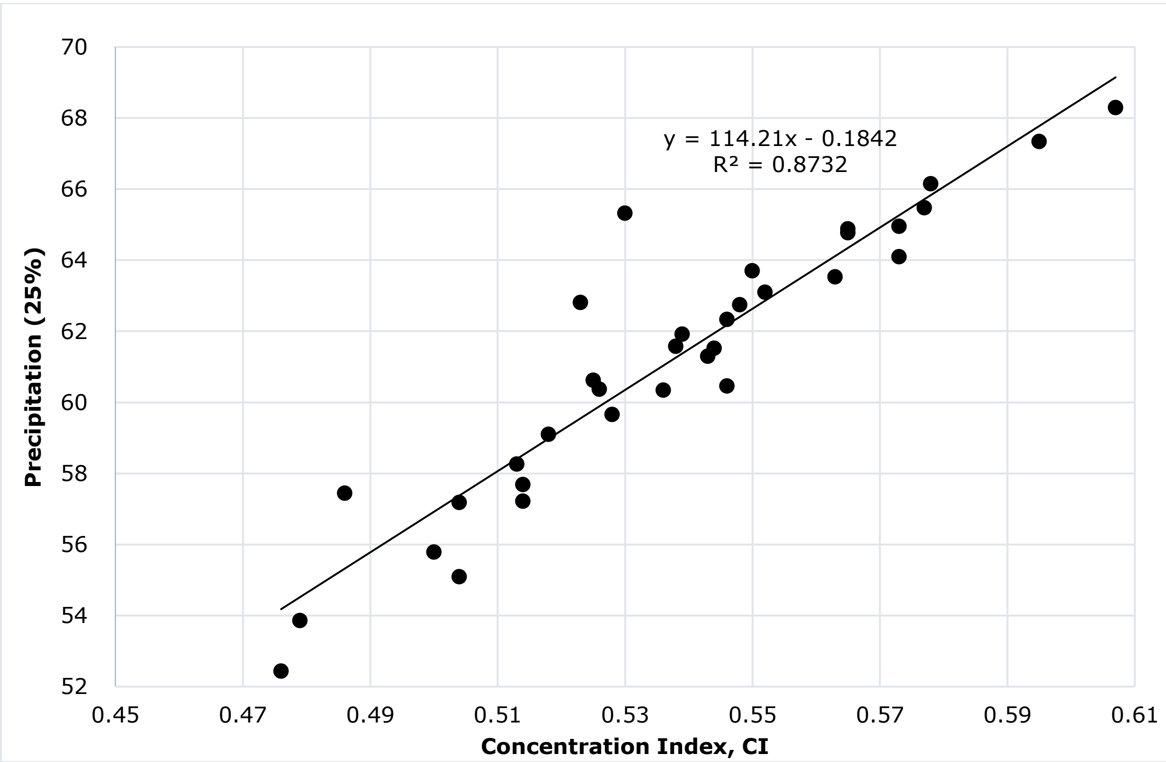

Figure 6. Relationship between concentration index and precipitation of 25% of the rainiest days.

For low CI values (0.476), the percentage of precipitation of the last quartile of the rainiest days is low (52.4%). In contrast, for high CI values (0.607), values of 25% of the rainiest days are high 68.29%. This permits determining torrentiality in a physical sense, since 25% of the rainiest days contributes 68.29% of all the rain registered. Javier Martín-Vide (2004) did this analysis with the CI and 25% of the rainiest days; he found better contrast in regionalization and in data analysis.

Classification of the Sub-basins using CI

First, each sub-basin was delimited. The CI isopleths were then generated, and the CI was calculated by sub-basin.

Delimitation of the Sub-basins

The sub-basins were delimited with the elevation model, using a minimum area of 500 ha; 23 sub-basins resulted (Figure 3).

Generation of CI Isopleths

Using the CI results for each conventional weather station, the data were imported in a GIS and a map was constructed by interpolating, in order to obtain the spatial distribution of CI, with a separation of CI = 0.01, with which a raster-type layer of the micro-basins is generated (Figure 7).

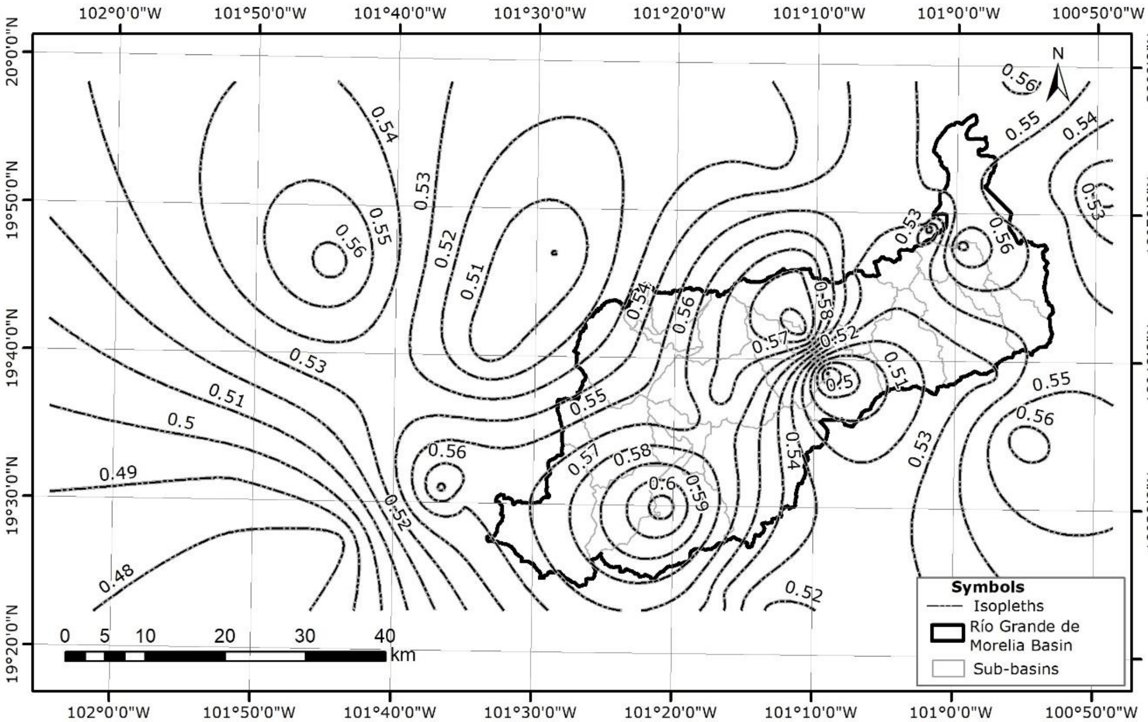

Figure 7. Isopleths of daily precipitation concentration index, CI, for the Río Grande de Morelia basin.

Calculation of CI by Sub-basin

With ArcMap (ESRI, 2016) software, the statistical zone tool was used. Input data included the sub-basins layer and the data raster of the interpolated CI grid, and an average value of CI was obtained for each sub-basin (Figure 8).

Tecnología y ciencias del agua, 9(5), 170-197, DOI:10.24850/j-tyca-2018-05-07

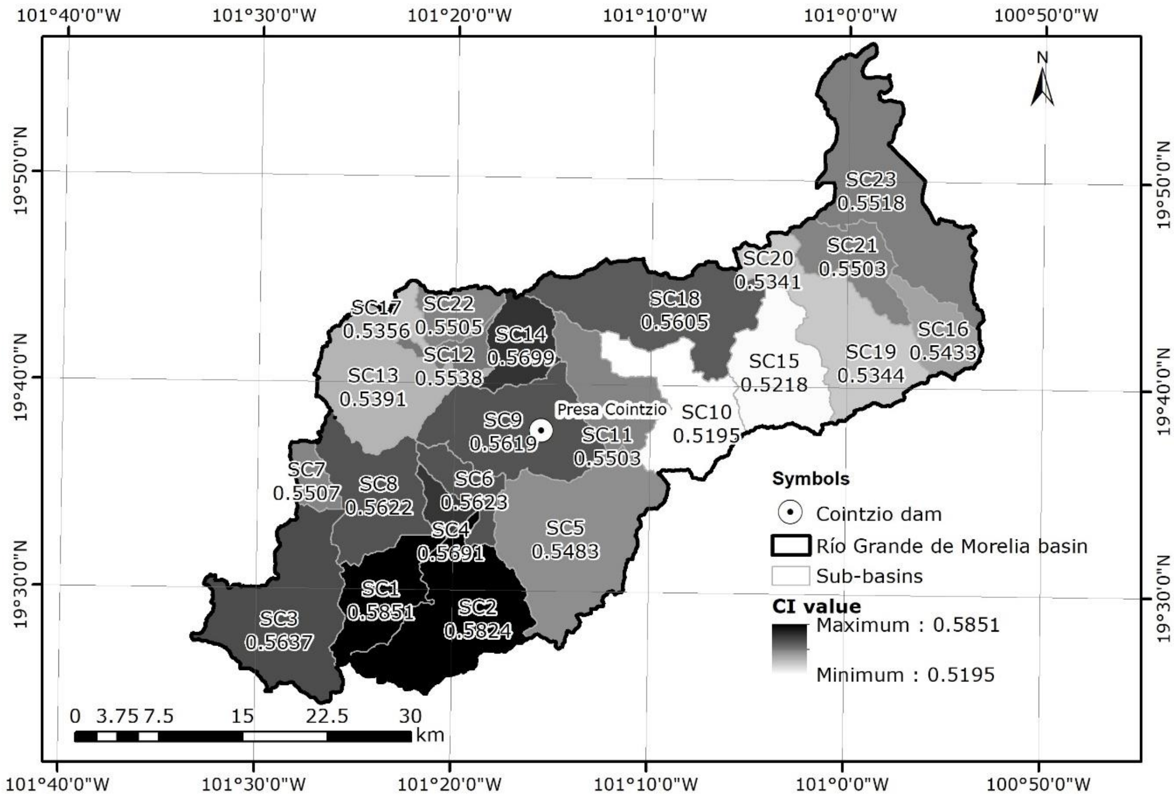

Figure 8. Average CI values by sub-basin for the Río Grande de Morelia Basin.

Values in the sub-basins ranged from 0.519 to 0.585. Values in the same range of 0.6 were obtained by Monjo and Martín-Vide (2016). The highest CI values were found in the basins upstream from the Cointzio dam and the lowest near the Río Chiquito micro-basin, which according to the nomenclature used, is basin SC10 (Table 4).

Table 4. CI values by sub-basin for the Río Grande de Morelia Basin.

Num.	Code	Area (km^2)	CI	Level
1	SC1	62.08	0.585	Highly torrential
2	SC2	122.14	0.582	Highly torrential
3	SC3	133.28	0.564	Highly torrential
4	SC4	16.61	0.569	Highly torrential
5	SC5	159.40	0.548	Torrential
6	SC6	28.88	0.562	Highly torrential
7	SC7	17.76	0.551	Torrential

Num.	Code	Area (km^2)	CI	Level
8	SC8	81.77	0.562	Highly torrential
9	SC9	111.09	0.562	Highly torrential
10	SC10	85.52	0.520	Mediumly torrential
11	SC11	61.65	0.550	Torrential
12	SC12	18.09	0.554	Torrential
13	SC13	99.62	0.539	Torrential
14	SC14	43.74	0.570	Highly torrential
15	SC15	80.83	0.522	Mediumly torrential
16	SC16	37.86	0.543	Torrential
17	SC17	74.22	0.536	Mediumly torrential
18	SC18	124.48	0.561	Highly torrential
19	SC19	96.10	0.534	Mediumly torrential
20	SC20	19.01	0.534	Mediumly torrential
21	SC21	50.01	0.550	Torrential
22	SC22	73.82	0.551	Torrential
23	SC23	150.99	0.552	Torrential

Classification of sub-basin torrentiality by CI

To give the physical context of the CI values in the sub-basins and the basin itself, from the results of the CI values reported in the literature, such as Monjo and Martín-Vide (2016), which range worldwide from 0.38 to 0.87, and those of our study, we propose a manner to compare torrentiality levels within a basin, that is, to determine which is more torrential. Using the concentration index obtained for each sub-basin, a histogram was constructed to identify the distribution of CI in the basin. A normal distribution was obtained, and a normality test (Shapiro Wilks) was applied. The test indicator showed a significant difference of nearly 1; thus, its normal distribution is acceptable and the p-value obtained is higher than the alpha of 0.005 tables. Considering the normality of the data, we propose four levels of torrentiality in the Río Grande de Morelia basin based on the CI value. To this end, we used the quantiles 0%

(0.476), 25% (0.515), 50% (0.538), 75% (0.560) and 100% (0.607), which correspond to the boundaries of each class (Table 5).

Table 5. Classification of the concentration index to determine the degree of torrentiality in the Río Grande de Morelia basin.

Concentration index	Level of torrentiality
0.476-0.515	Low torrentiality
0.515-0.538	Medium torrentiality
0.538-0.560	Torrential
0.560-0.607	High torrentiality

The weighted average was calculated for the Río Grande de Morelia basin, obtaining CI = 0.5524; according to the proposed classification, it is of the torrential type.

Association between CI and Climate

To determine the behavior of the sub-basins, it is necessary to relate it to the climate that predominates in the study region. The average CI values in the 23 sub-basins range from 0.5195 to 0.5851. The highest CI values occur in the sub-basins in the upper part of the basin upstream from the Cointzio dam. These sub-basins have a C(E)(w_2)(w) climate, which is cool subhumid, the most humid of the subhumid, with summer rains. The months with the highest precipitation are May to October, with more than ten times more rain than the driest month of the year. The percentage of winter rain is < 5% of the annual total; precipitation in the driest month is < 40 mm and mean annual temperature ranges between 5 and 12 º C.

The CI values are between 0.60 and 0.55 in sub-basins downstream from the Cointzio dam, with C(w_2)(w) climate type, temperate subhumid, the most humid of the subhumid, with summer rains. The months with the highest rainfall are May to October, when precipitation is at least ten times more than in the driest month of the year. The percentage of winter rain is < 5%, precipitation during the driest month is < 40 mm, with a mean annual temperature that ranges between 12 and 18 ºC.

The lowest CI values, between 0.55 and 0.52, occur in the climate type $C(w_1)(w)$, temperate subhumid with medium humidity and summer rains. The highest precipitation occurs from May to October when rainfall is at least ten times that of the driest month of the year. The percentage of winter rain is <5% and precipitation in the driest month is < 40 mm; mean annual temperature ranges between 12 and 18 ºC.

The lowest CI values, between 0.52 and 0.50, are found in the climate type $C(w_0)(w)$, which is temperate and less humid than the subhumid climates with summer rains. Rainfall is highest from May to October when it rains at least ten times more than in the driest month of the year. The percentage of winter rain is < 5% and precipitation in the driest month is < 40 mm; mean annual temperature ranges between 12 and 18 º C (INEGI, 2000).

Conclusions

By calculating the daily precipitation concentration index (CI) in the Río Grande de Morelia basin, it is possible to determine the torrentiality level of the rainfall.

By applying this procedure, it is possible to describe how rainfall is distributed across a basin based on geographic information systems.

Immediate applications that can be obtained from this research are identifying the sub-basins that are more torrential than others and proposing basin instrumentation (hydrometric stations).

Given the CI values obtained in this study, we propose a quartile scale to classify the aggressiveness, or torrentiality, of the precipitation in basins and sub-basins in the Río Grande de Morelia basin.

The CI value obtained in the Río Grande de Morelia basin was CI = 0.55, which indicates a torrential type, according to the proposed classification. It is therefore a basin in which extraordinary events can take place and cause flooding in the lower parts, such as those that have been recorded throughout its history and that which occurred in

2015, creating serious problems in the urban area of Morelia (Conagua, 2016).

In the case of the sub-basins, the average CI values in the 23 sub-basins range from 0.52 to 0.59. The highest CI value was found for the sub-basins in the upper part of the basin upstream from the Cointzio dam, which are located in climate types C(E)(w_2)(w) cool subhumid and C(w_2)(w) temperate subhumid. The lowest CI values are located in climate types C(w_1)(w) and C(w_0)(w), which are temperate, but in the classification of those that are less sub-humid.

The purpose of this procedure is to have a tool that contributes to the hydrological analysis of basins that are susceptible to flooding, and which can be an indicator of rainfall aggressiveness or torrentiality in basins and tributary sub-basins that in the end results in extraordinary runoff.