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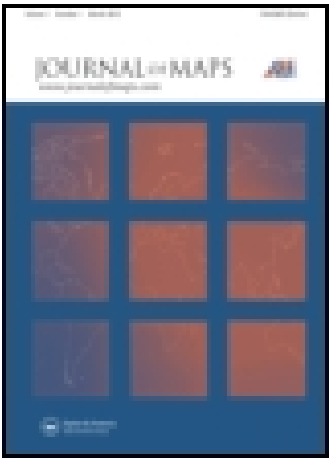

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Extreme rainfall relationship in Mexico

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Extreme rainfall relationship in Mexico

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Precipitation statistics are inherent to the design of water resource systems by the prediction of two aspects of hydrological processes: the extremes and the averages. Extreme rainfall with high temporal resolution (i.e. an hour or less) is necessary for the design of urban drainage systems, as urban areas are generally characterized by their fast response. However, most weather stations only register daily rainfall. The relationship between the hourly intensity of rain and the daily rain intensity is called parameter K. Thus, if extreme daily rainfall data is available, the parameter K allows the estimation of extreme short-duration rainfall intensities. This study offers a map with the regionalization of the relationship between the maximum intensities of precipitation occurring over intervals 1 and 24 hours (parameter K) for the whole country of Mexico, facilitating the description of the geographical variability of precipitation. In this country a high spatial variability of the parameter K was observed, according to the large area studied.

Keywords: Mexico; map; rainfall; extreme rainfall; hydrology; engineering design

1. Introduction

Water has always had, and will continue to have, a controlling influence on the Earth's evolution (Chahine, 1992). Precipitation is one of the most influential climatic elements on the environment (Segura, Zapata-Sierra, & Manzano-Agugliaro, 2013), as it directly affects the distribution of plant and animal species and human activities such as agriculture and forestry (Zapata-Sierra & Manzano-Agugliaro, 2008). Rainfall is one of the most important climatic features that characterizes a geographic area (Zapata-Sierra, Manzano-Agugliaro, & Ayuso-Muñoz, 2009). Precipitation statistics are inherent to the design of water resource systems by the prediction of two aspects of hydrological processes: the extremes and the averages (Němec & Schaake, 1982).

Extreme rainfall events can have severe impact on society, thus possible long-term changes in the intensity of extreme events are of some concern (Koutsoyiannis, 2004). The impact of heavy rainfall events on such aspects as agriculture, engineering structures such as dams, water resource management, the insurance industry and human livelihood is considerable, and therefore the possibility of long-term changes in the intensity of extreme events should be taken into account (Mason, Waylen, Mimmack, Rajaratnam, & Harrison, 1999). The maximum rainfall

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for a given duration follows a probability distribution which can be employed when constructing rainfall intensity-duration-frequency (IDF) curves (Manzano-Agugliaro, Zapata-Sierra, Rubí, & Hernández-Escobedo, 2014). IDF curves are used for the hydraulic design of storm sewers, culverts, drainage structures (Guo, 2006) parking lots, and detention ponds (Guo & Zhuge, 2008); hydrological planning and design (Yang *et al*. 2008), for hydrologic risk analysis (Faiers & Keim, 2008; Vaes, Willems, & Berlamont, 2001).

Extreme rainfall with high temporal resolution (i.e. an hour or less) is necessary for the design of urban drainage systems, as urban areas are generally characterized by their fast response (Nguyen, Nguyen, & Wang, 1998). However, most weather stations only register daily rainfall (Svenson, Clarke, & Jones, 2007). This highlights the need for a tool to predict short-term extreme precipitation from daily records.

The intensity-duration dimensionless law is characteristic of each zone and it is a function of the temporal distribution of its rainfalls. For this reason, this study presents the regionalization of the ratio between the maximum rainfall intensities for 1 and 24 hour intervals (parameter K) for the whole country of Mexico to find out, from daily rainfall records, about the intensity of short-duration rainfall events.

K itself indicates how variable the rain is. The highest values of K imply high runoff, therefore it affects hydrological risk. The highest values ($K>12$) (Ferrer-Polo, 1993) usually coincide with short-duration rainfall of high intensity, which is more characteristic of arid and semi-arid regions. By contrast, long-duration rainfall events, which are characteristic of humid regions, usually present a lower intensity and therefore lower values for K ($K\approx8$) (Témez, 1987).

The aim of this study is to calculate and provide a map of Mexico where the K parameter is obtained from rainfall data for 105 automatic weather stations, K is then interpolated for the whole country using a geographic information system (GIS). In this way it is possible to generate IDF curves for the different geographical areas of Mexico when only daily rainfall data are available.

2. Data

In order to build the parameter K for Mexico, records were used from the network of automatic weather stations (EMAs) administered by the General Coordination of National Weather Service (CGSMN) with satellite transmission. The network which was employed has 105 automatic weather stations installed throughout the country. The rainfall records for each EMA were taken every hour (GMT) for the years 2008 and 2009, representing a total of 17,520 data points analyzed for each EMA, giving a total of 1,839,600 records analyzed in this study. The Main Map shows the geographical distribution of EMAS in Mexico.

To enable the identification of those discordant with the remaining stations, the discordance Di is used (Hosking & Wallis, 1997). This allows the identification of 'unusual' stations compared to other stations in the region. For this, it is necessary to calculate the L-moments for each maximum rainfall series obtained in each locality.

The L- moments vector $u_i = (\tau_2{}^{(i)}, \tau_3{}^{(i}, \tau_4{}^{(i)})$ of a given station is a point in three dimensional space, so that the stations will form a point cloud. Those points away from the center of gravity of the assembly will be considered discordant. Numerically the discordance measure Di is defined:

$$\mathrm{Di} = \frac{N}{3} \cdot (u_i - \bar{u})^T \cdot S^{-1} \cdot (u_i - \bar{u}) \qquad (1)$$

With $S^{-1} = \sum_{i=1}^{N} (u_i - \bar{u}) \cdot (u_i - \bar{u})^T$ and $\bar{u} = n^{-1} \sum_{i=1}^{N} u_i$ where u_i is the mean value of the observations, whose total are the whole stations. The critical value for the employed stations

(Di > 15) is 3 (Hosking & Wallis, 1997). Having analyzed all stations, none of them are considered discordant.

3. Methods

The relationship between the hourly rain intensity and the daily rain intensity is called parameter K. It should be noted that the intensity (r) according Chow, Maidment, and Mays (1988), is defined as the rate of precipitation, i.e. the height per unit time (mm h^{-1}), and is expressed as:

$$r = \frac{R}{t} \tag{2}$$

where R is the height of rainfall in mm and t is the duration term commonly given in hours.

The IDF relationship can be described mathematically by means of various expressions (Wenzel, 1982). The most common one, which groups the various intensity–duration curves for different return periods in a single formula, is equation (3), which is applicable to locations with observatories keeping records for rainfall durations between 10 min and 24 h.

$$r_t^T = \frac{aT^b}{t_{d^c} + e} \tag{3}$$

Where r_t^T is the mean intensity (mm h^{-1}) for the duration t_d (min) and the return period T (years), and *a, b, c* and *e* are parameters to be determined by fitting.

In cases where only 24 h rainfall data are available, regional rainfall characterization studies are carried out analyzing the ratios between short-lasting rainfall and rainfall over 1 h and/or 24 h (Bell, 1969; Chen, 1983; Froehlich, 1993, 1995). Using isohyet rainfall maps for large regions of the USA, Chen (1983) obtained a ratio between the rainfall height for 1 h and 24 h, regardless of the return period, ($R_1^T/R_{24}{}^T$), that varies very little according to geographic location, ranging between values of 0.1 and 0.6, with an average value of 0.4.

Since the IDF curves present a degree of similarity, they can be represented by a single dimensionless law, expressing the intensities as percentages of a mean intensity associated with a given reference duration. Figure 1 shows an example of IDF curves for an EMA in Mexico, for the return periods T=2, 5, 10, 25, 50 and 100 years, the rainfall-height values, R_t^T, were obtained for each rainfall duration considered, t_d, and the corresponding intensities, r_t^T.

The $r_1^T/R_{24}{}^T$ ratio is independent of the return period; it only depends on the geographic location of the area. Témez (1987) characterizes this law by means of the ratio $r_1^T/r_{24}{}^T$, such that equation (4) becomes

$$r_t^T = r_{24}^T \left(\frac{r_1^t}{r_{24}^T}\right)^{(28^{0,1} - t_d^{0,1})/28^{0,1} - 1} \tag{4}$$

where t_d is rainfall duration in h.

Thus, the K parameter relate rainfall and intensities using equation (5):

$$K = \frac{r_1^t}{r_{24}^T}\frac{R_1^t}{R_{24}^T} \tag{5}$$

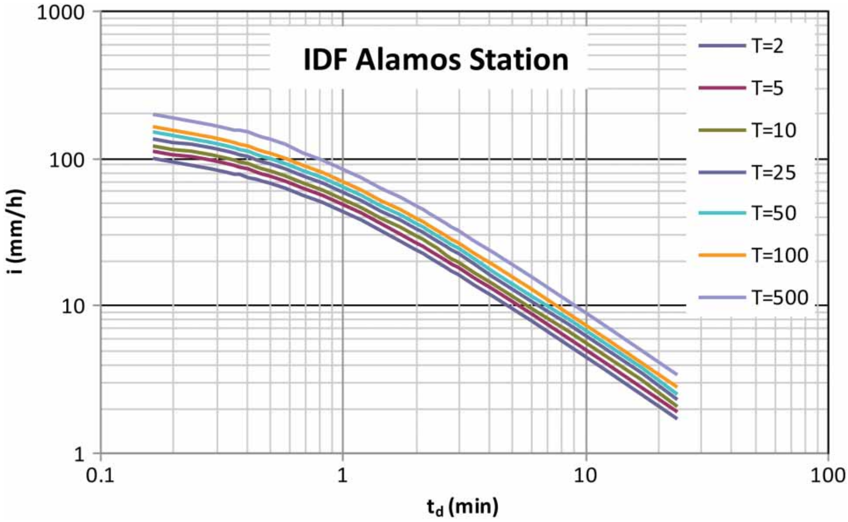

Figure 1. Example of IDF curves for different return periods (T in years) in Alamos (Mexico), *i* is the mean rainfall intensity (mm/h) for a specific duration t_d (min).

4. Results and discussion

For each EMA the values of *K* for each year were averaged to obtain a mean value. The results are summarized in Table 1, in which the dimensionless parameter *K* has been ordered from the minimum to maximum, from 2.6 to 18.2.

A simple analysis of the variance (ANOVA) has been used to determine the statistical differences between the mean values of k:

- obtained in the different EMAs for each year
- obtained in each year for the different EMAs

Statistical significance tests have been performed using Snedecoŕs *F* distribution (critical value of F). All data were analyzed with a 0.05 significance level (α).

Table 1 shows that *K* is practically continuous throughout Mexico. It is observed that the parameter *K* does not exceed the value of 11 in 37% of the stations, while 25% exceed a value greater than 14. These values justify the climate variability that characterizes the country and the torrential nature of the rainfall events that often occur. This is in agreement with Ferrer-Polo (1993) and Témez (1987) who indicate, in the characterization of the parameter *K* in Spain, that high values ($K>12$) denote the existence of areas with a high frequency of torrential rainfall. This usually coincides with high intensity short duration rain, most typical of arid and semi-arid regions. Faiers and Keim (2008) established that arid areas will have higher values of the ratio between the maximum rainfall of short duration and 24 hours; this is due to the fact that these areas do not usually have long-term rainfall. By contrast, long-term rain events are characteristic of humid regions, and therefore have a lower intensity, thus, lower values of *K* are obtained ($K \approx 8$).

With these results, a frequency analysis is possible at each station using the maximum annual rainfall for each of the rainfall durations selected; for example from 10 minutes to 24 hours depending on the hydrological design necessities. Several distributions can be used to fit each series; for example the Gumbel distribution has traditionally been used (Kite, 1977), but the

Table 1. Mean values of *K* at each Automatic Weather Station in México.

Automatic Weather Station	Latitude (°)	Longitude (°)	*K*
Peñitas	−93.4577778	17.4450000	2.60
Moctezuma	−109.6533889	29.6788889	3.00
Ocotepec	−93.1597222	17.2250000	4.12
Sanalona	−107.1498333	24.8144167	4.80
Santo Domingo	−93.0563889	16.4525000	5.65
Rómulo Calzada	−93.5516667	17.3538889	6.11
Sayula	−93.3319444	17.4022222	6.64
Mazatepec	−97.4467500	19.9608889	7.20
Nevado de Toluca	−99.7666667	19.1166667	7.31
Acapulco	−99.7488889	16.7633333	7.81
Presa La Cangrejera	−94.3313889	18.1058333	7.82
La Villita	−102.1813889	18.0469444	7.82
Sian Ka an	−87.4655556	20.1277778	7.88
Sierra Morena	−93.5911111	16.1522222	8.12
Presa Emilio López Zamora (Ensenada)	−116.6033333	31.8913889	8.33
Cozumel	−86.9069444	20.4769444	8.51
Oviachic	−109.8878889	27.8220278	8.64
Los Palillos	−102.5350000	19.5394444	8.80
Cancún	−86.7758333	21.0750000	8.92
27 de Septiembre	−108.5758611	26.5094722	8.95
El Caracol	−99.9833333	17.9833333	9.05
Alvarado	−95.6325000	18.7150000	9.20
San Cristóbal de las Casas	−92.6030556	16.7272222	9.25
Malpaso	−93.6047222	17.1994444	9.28
Bacurato	−107.9254444	25.8708611	9.37
Papalutla	−98.8883333	18.0208333	9.58
Huites	−108.3688056	26.8455833	9.58
Paso Nácori	−109.0860556	29.4196111	9.58
Angostura	−92.7777778	16.4008333	10.00
Cerro Catedral	−99.5191667	19.5419444	10.00
San Quintín	−115.8375000	30.5316667	10.07
Arteaga	−102.2897222	18.3550000	10.19
Presa Abelardo L. Rodríguez (Tijuana)	−116.9083333	32.4472222	10.51
Colorines	−100.2183333	19.1755556	10.61
Palenque	−91.9902778	17.5258333	10.72
Chetumal	−88.3277778	18.5005556	10.78
Huejutla	−98.3686111	21.1547222	10.89
Infiernillo	−101.8938889	18.2711111	10.89
Humaya	−107.3915833	25.1017778	10.99
Cd. del Carmen	−91.8225000	18.6480556	11.01
Aguamilpa	−104.8028611	21.8427222	11.02
Cabo San Lucas	−109.9263889	22.8811111	11.02
Altamira	−97.9255556	22.3875000	11.11
Cristóbal Obregón	−93.4669444	16.4413889	11.12
Panches	−102.2219444	18.8833333	11.28
Novillo	−109.6428333	28.9773333	11.29
Atenango del Río	−99.1047222	18.1069444	11.44
Caimanera	−100.8911111	18.4633333	11.44
El Cubil	−109.2363056	29.2324167	11.46
Mocúzari	−109.1040556	27.2246667	11.50
Puerto Ángel	−96.4972222	15.6711111	11.62
Centro de Previsión del Golfo	−96.1113889	19.1427778	11.63
Basaseachi	−108.2088889	28.1991667	11.64

(*Continued*)

Table 1. Continued.

Automatic Weather Station	Latitude (°)	Longitude (°)	K
Bahia de los Ángeles	−113.5602778	28.8963889	11.94
Pinotepa Nacional	−98.0525000	16.3497222	12.14
El Devanador	−100.8263889	19.3838889	12.16
San Antonio	−101.7502778	18.2736111	12.16
Santa Rosalía	−112.2694444	27.3380556	12.22
Comedero	−106.8068056	24.5702500	12.24
Jalapa	−96.9247222	19.5297222	12.33
Tizapan	−103.0438889	20.1694444	12.39
Chicoasén	−93.1008333	16.9413889	12.52
Cd. Alemán	−96.0975000	18.1891667	12.54
Urique	−107.9169444	27.2155556	12.62
Jocotepec	−103.4163889	20.2830556	12.63
Gustavo Díaz Ordaz	−113.4575000	27.6427778	12.67
San Cristóbal	−100.4786111	18.1719444	12.68
Presa Allende	−100.8247222	20.8483333	13.07
Matamoros	−97.5186111	25.8858333	13.15
Mexicali	−115.2908333	32.6669444	13.22
El Fraile	−98.4047222	18.1872222	13.48
Presa El Cuchillo	−99.3208333	25.7330556	13.50
Izucar de Matamoros	−98.4519444	18.6166667	13.56
Ixcamilpa	−98.7200000	18.0397222	13.58
Atlacomulco	−99.8697222	19.7916667	13.58
IMTA	−99.1569444	18.8822222	13.81
Guachochi	−107.0730556	26.8136111	13.85
Zacatecas	−102.5061111	22.7466667	13.94
Tantaquin	−89.0472222	20.0302778	14.00
Tuxpan	−97.4169444	20.9600000	14.09
San Juan	−99.5166667	17.9200000	14.11
Cd. Constitución	−111.6633333	25.0097222	14.44
Agustín Melgar	−104.0661111	25.2633333	14.60
Celestun	−90.3830556	20.8580556	14.67
Río Tomatlan	−105.1336111	19.9986111	14.77
Chapala	−103.2016667	20.2902778	14.91
Calakmul	−89.8925000	18.3650000	14.98
Maguarichi	−107.9944444	27.8583333	15.02
Alamos	−108.9377778	27.0216667	15.05
Tezontle	−99.0997222	19.3852778	15.20
ENCB	−99.1711111	19.4536111	15.29
Río Lagartos	−88.1602778	21.5711111	15.37
Chinipas	−108.5363889	27.3927778	15.52
Campeche	−90.5072222	19.8361111	15.69
Los Colomos	−103.3927778	20.7066667	15.77
Mérida	−89.6516667	20.9463889	15.78
Santa Rosa	−103.7056111	20.9093889	15.84
Pachuca	−98.7141667	20.0969444	15.86
Presa Madin	−99.2680556	19.5244444	16.03
UTT	−97.7216667	18.8663889	16.55
Servicio Meteorológico Nacional	−99.1969444	19.4036111	16.56
Chinatu	−106.7705556	26.2294444	16.70
Huimilpan	−100.2836111	20.3902778	16.83
Huamantla	−97.9500000	19.3833333	18.06
Angamacutiro	−101.7225000	20.1252778	18.21

GEV distribution is also widely used (Gellens, 2002; Overeem, Buishand, & Holleman, 2008; Mirhosseini, Srivastava, & Stefanova, 2013). Figure 2 shows an example of the probability of extreme rainfall, both measured and fitted series, for several rainfall durations at the Agustin Melgar station.

The main map shows the spatial distribution of *K* in Mexico. This map has been overlain onto the current state limits of Mexico in order to identify the different geographical areas better. The lower values of the parameter *K* are found in the northwest and southwest areas of the country, as they are known for their humid climate. The higher values of *K* are found in those areas with torrential rain. This happens in the extreme of the Gulf of Mexico, in the inland southern states, in the northeast of the state of Baja California Sur and in southern Chihuahua State. The large differences in mean values of the parameter *K* across the country clearly indicate large contrast in rainfall characteristics of the different areas of the country, closely related to its topography and the distribution of atmospheric circulation (García-Amaro, 2003).

Some authors believe that the use of altitude as an auxiliary variable improves the spatial interpolation of monthly rainfall data (Szolgay, Parajka, Kohnová, & Hlavčová, 2009). However, no definite relationship between the two variables has been found in this study. This can be justified by the diversity of determinants involved in the development of torrential rainfall; altitude is not a significant factor. Carrera-Hernández and Gaskin (2007) argue that the relationship between rainfall and altitude is of little use when interpolating daily rainfall data. In our study, data are of even shorter duration, which is in agreement with both of the aforementioned studies.

Extreme rainfall is still a matter of concern to society due to public safety and the potential for huge economic expenditure. Vörösmarty et al. (2013) reported that South American cities have

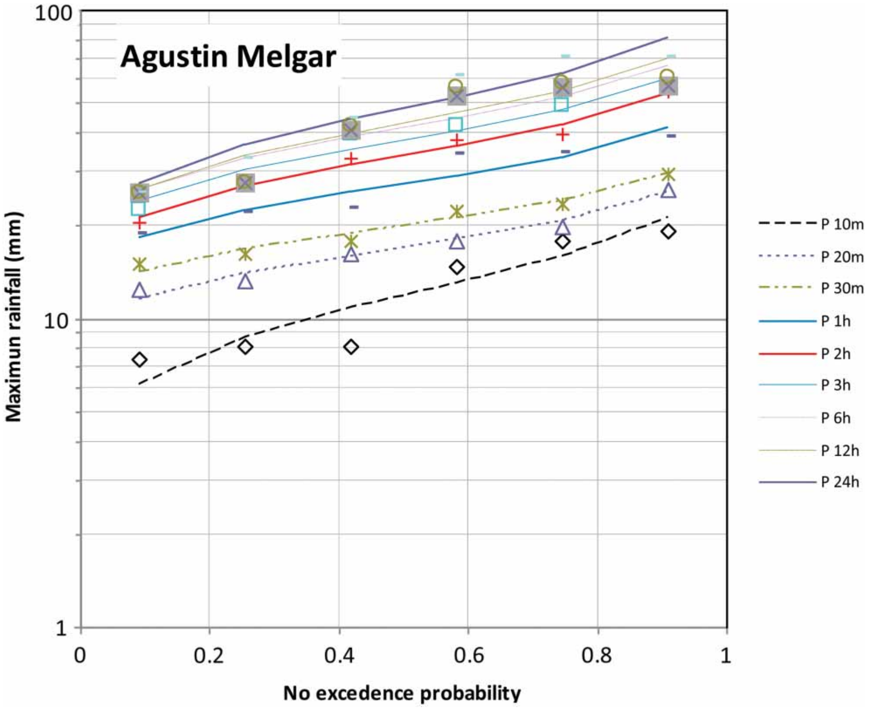

Figure 2. Example of probability of extreme rainfall showing the measured and fitted series for several rainfall durations in Agustin Melgar (Mexico); P_t is the precipitation for a t duration (m = minutes, h= hour). The dots indicate the measured values and the lines show the statistical series.

experienced a doubling of risks associated with extreme rainfall from 1960–2000. While rural populations have the greatest relative sensitivity to extreme rainfall, urban settings show the highest rates of increasing risk. In the coming decades, rapid urbanization will make Mexican cities the focal point for future climate threats, however this situation will also favor an opportunity to reduce vulnerability, for example taking into account maps as those put forward, which show the risk of runoff through parameter K. At this point in time the studies of extreme rainfall cover small geographical areas, such as Mexico City, where the findings show a noticeable increase in runoff in 2000 when compared to 1980, so the increased precipitation and resulting runoff increase flood risk in the city, particularly given the existing drainage system (Baker, 2012). The main innovation in this study is the large geographical area covered, and the fact that it provides valuable georeferenced information regarding location of the relationship between the maximum intensities of precipitation occurring over intervals of 1 and 24 hours (parameter K) for Mexico. Thus it identifies areas where parameter K should be carefully taken into account. Institutionally, this study could be of help in identifying possible shortcomings in the current operational framework for issues on hydrological risk management.

5. Conclusions

This study puts forward a map showing the regionalization of the relationship between the maximum intensities of precipitation occurring over intervals of 1 and 24 hours (parameter K) for Mexico. A high spatial variability of the parameter K was observed across the country. These values were between 2.6 and 18.2, showing more torrential rainfall in those areas in which higher values of K are reached ($K > 12$). Furthermore, the regionalization of the parameter K makes it possible to clearly identify the different climatic zones; this can then be applied to the geographical identification of precipitation. The parameter K allows the estimation of short-duration rainfall intensities from daily rainfall data. Consequently, this opens up new perspectives for environmental research and it should be useful for civil engineering design when only daily rainfall data are available.

Software

The software used for production of the map in this study is Esri ArcGIS 10. All statistical studies were performed using Microsoft Excel.

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