7-24-2007

Determination of the Relationship Between Precipitation and Return Periods to Assess Flood Risks in the City of Juarez, Mexico

Héctor Quevedo Urías
Universidad Autonoma de Ciudad Juarez

Humberto Garcia
Instituto Tecnologico y de Estudios Superiores de Monterrey

Jorge Salas Plata Mendoza
Universidad Autonoma de Ciudad Juarez

Abstracts of the presentations given on Tuesday, 24 July 2007, in Session 5 of the UCOWR Conference.

DETERMINATION OF THE RELATIONSHIP BETWEEN PRECIPITATION AND RETURN PERIODS TO ASSESS FLOOD RISKS IN THE CITY OF JUAREZ, MEXICO

[1]Héctor Quevedo Urías (Ph. D.), [2]Humberto García (Ph. D.), [3]Jorge Salas Plata Mendoza (Ph. D.)

Departamento de Ingeniería Civil y Ambiental
Uiversidad Autónoma de Ciudad Juárez
Avenida del Charro 450 Norte, Apartado Postal 32310
Ciudad Juárez, Chihuahua, México
Tel. (656) 6 88-4846

[1]Associate professor. Department of Civil and Envrionmental Engineering (UACJ), Email: hquevedo@uacj.mx.
[2]Associate professor. Instituto Tecnológico de Estudios Superiores de Monterrey (ITESM), Campus Ciudad Juárez, Email: jhg@itesm.mx
[3]Associate professor. Department of Civil and Envrionmental Engineering (UACJ), Email: jsalas@uacj.mx.

Abstract

This hydrology study applied the Hazen plotting position method, to estimate precipitation, return periods and its probability of occurrence, to assess flood risks in Ciudad Juárez, México. The research used the 50 year historical statistical precipitation (period 1957-2006), from the Comisión Nacional del Agua, of Ciudad Juárez. The application of the Hazen method consisted in determining the statistical distribution of the annual precipitation for duration of interest, by calculating the annual precipitation (in cm), the return periods and the probability of being equaled or exceeded. The methodology consisted in placing the annual values in ascending order, by assigning ranks to each value and, by calculating the probabilities (F_a) and the return periods (in years). Afterwards, the method consisted in plotting the annual precipitation amounts, against the probability of recurrence and return periods, on log-normal graph probability paper. Then, using the least squares method, a regression line was drawn through the plotted points, to estimate, through interpolation and extrapolation, the results of precipitation associated with the period of return and its probability of occurrence. The statistical descriptive results showed the sample distribution of annual precipitations is approximately normal, with arithmetic mean equal to 25.42 cm (10.6 inches), median equal to 24.47 cm (9.63 inches), skewness equal to 0.56, 95% and a p value equal to 0.067 using the Anderson-Darling normality test. According to the results, the return periods of the storm of 2006 in Ciudad Juárez was 100 years.

Introduction

The most common means used in hydrology, to show the probability of an event, is to assign a return period or recurrence interval to the event. The return period is defined by Bedient et al. (1948), as an annual maximum event that has a return period (or recurrence interval) of T years, if this value is equaled or exceeded once, on the average, every T years. The reciprocal of T is called the probability of the event or the probability the event is equaled or exceeded in any one year. The function below shows this relationship.

$$P = 1 / T \qquad (1)$$

For example, a 100 year flood has a probability, $P = 1/T = 1/100 = 0.01$ or 1.0 % of being equaled or exceeded in any single year. Here, however, it is important to realize that the return period implies nothing about the actual time sequence of an event. The concept of a return period is usually found by analyzing a series of maximum annual floods, rainfalls, etc. For example, if the return period for a precipitation of 3 hours of a total of 4.0 millimeters for a city in particular, is 25 years, this means that, on the average, a precipitation of 4.0 millimeters over 3 hours occurs in that city every 25 years. Another example is that, if the period of return of a flow of 150 m^3/sec, is 30 years, then, equal flows or greater than that volume would occur on the average, every 30 years.

There are numerous methods to estimate precipitation, probabilities and return periods, which have been proposed for the plotting of precipitation data. Texts of hydrology call those plotting position formulas, probability plots and goodness-of-fit tests. For example, Maidment (1993) listed several plotting positions and types of probability papers, such as those used by Weibull, Cunnane, Gringorten, Hazen, among others. He said, however, that the Hazen alternative plotting position is a traditional choice, because Hazen, originally, developed probability paper that simplifies the relationship among pluvial events, return periods and probability of occurrence. For example, lognormal paper can be designed by, either plotting the logs of precipitation on an arithmetic scale or, by providing a log scale instead of an arithmetic scale, for the magnitude of the variable, and by using probability scales for the return periods and probabilities of occurrence (Bedient et al. 1948). In fact, in hydrological studies, the return period is one of the most significant parameters that need to be taken into account, when the engineer designs a hydraulic structure, to control flooding, as in the case of spillways dams for flooding control, construction of bridges, etc. On the other hand, Chow (1964) discusses a mathematical method to estimate the relationship between the annual maximum recurrence series (in years) of intervals and the recurrence intervals of annual occurrences and by plotting the results in logarithmic paper. Similarly, Linsley et al. (1958), discuss the corresponding return periods (in years), for partial and annual series. Equally important, other authors of hydrological studies, as Gupta (1989), discuss the application of discrete probability distributions, as the binomial distribution to estimate binary events.

For hydraulic construction purposes, the return period varies as a function of the importance of the hydraulic structure, that is, of the socio-economic, strategic, touristic or the desired goal of flood risk/damage reduction. Moreover, this is as a function of the existence of other alternative ways capable of reducing the damage, and the destruction it would imply, that is, loss of human lives, cost, and time construction, economic and political cost of the bad functioning of the structure, etc. Sometimes, it is necessary to oversize the hydraulic structure to minimize the damage in case of extreme events (this will be more common as the pluvial or climatological events will be even more altered due to the global warming).

The return periods generally accepted for hydraulic works for channeling of pluvial waters in middle and big cities is between 20 to 50 years; however, for small cities the return periods would be between 5 to 10 years. Similarly, for important bridges, an acceptable return period would be 100 years[1]. In some cases, for hydraulic structures, whose failure would mean a very elevated risk of loss of human lives; these return periods are revised using the method of "Maximum Probable Precipitation" (Bedient et al. 1948). Furthermore, these authors, apply discrete probability distributions (as the binomial, Poisson, etc.), and also continuous probability distributions (as the normal, lognormal, gamma, exponential distributions, etc.), to problems in hydrology. In the case of the application of discrete probability distributions, these functions assign probabilities to the number of occurrences of an event, while the continuous probability distributions determine the probability of the magnitude of an event. For example, Bendient et al. (1948) apply the binomial distribution to risk studies and reliability. They define the risk, as the probability of occurrence in *n* events. Therefore, the risk is the sum of the probabilities of 1 flood, 2 floods, 3 floods,….., of *n* floods, which occur during *n* periods of years. According to this procedure, to calculate the risk, the function below is used.

$$\text{Risk} = 1 - (1 - 1/T)^n \qquad (2)$$

Where *n* is the number of events or floods and T is the return period. Similarly, to estimate the reliability the function below is used.

$$\text{Reliability} = (1 - 1/T)^n. \qquad (3)$$

The concepts of risk and reliability are very important in the design of hydrological projects, and can be used to determine the return period required for the life span of a hydraulic project. For example, in the study of a flood critical design, the hydrological engineer may calculate the probability that at least one 50-year flood would occur during the life of a 30 year project. This is simply the failure of risk discussed with function (2). Thus, using equation (2), with $1/T = 1/50 = 0.02$ and with $n = 30$ years, the risk for this project is:

$$\text{Risk} = 1 - (1 - 0.02)^{30} = 0.455$$

However, this risk is too big, and the engineer would have to design the flood control project, for an event of 100 years, in whose case this would give:

$$\text{Risk} = 1 - (1 - 1/100)^{30} = 0.26$$

Under these circumstances, the reliability is estimated using equation (3):

$$\text{Reliability} = (1 - 0.01)^{30} = 0.74$$

Insofar as the application of probability graphs and goodness of fit tests, there are numerous positions of graphical delineations, that is, to estimate return periods or recurrence intervals and probabilities for a given duration of precipitation. One of these methods is the Hazen graphical position, which is precisely the approach used in this study[7]. This method consists in determining the statistical distribution of the amounts of precipitation for the duration of interest. It is done by plotting the distribution data in graph paper with logarithmic and probability scales. This can also be done by plotting the logarithmic data transformed on an arithmetic scale. Then, using the method of the least squares, a regression line is drawn and, from thereon, the precipitation values, the return periods and the probabilities can be calculated through interpolation or extrapolation. Likewise, relying on the general equation for the analysis of hydrological sequences, proposed by Chow, a procedure of the least squares, to fit normal or lognormal distributions was developed by Brakensiek[3].

Methodology

The methodology used in this research consisted, first of all, in revising the precipitation data for the supposition of normality. For this goal, the study did a statistical descriptive analysis, which suggests the distribution of the data is normal or approximately normal. For example; one way of revising the normality of the sample distribution was done by analyzing the relation among the values of the arithmetic mean, the median and the mode. In statistics, if these three values are similar, the simple distribution is normal or approximately normal. Certainly, in this particular instance, this was the case. Other functions that give additional information about the uniformity of the population of precipitations are the Anderson-Darling, the Kolmogorov-Smirnov, Lilliefors, etc. These tests also suggested the data came from a normal population.

Afterwards, the study applied the Hazen method to estimate the period of return, the probability, and the annual precipitations of concern, for the historical statistical data of 50 years. This method consisted in assembling the annual precipitations (cm) shown in Table 1 below.

Table 1. Table showing de original data, for 50 years in units of millimeters converted to centimeters, for tthe annual precipitations in Ciudad Juarez, Mexico (Period 1957-2006).

Yr	mm	cm	Yr	mm	cm	Yr	mm	cm	Yr	mm	cm	Yr	mm	cm
1957	162.0	16.20	1967	172.5	17.25	1977	171.5	17.15	1987	216.0	21.60	1997	284.8	28.48
1958	349.5	1.25	1968	323.0	1.10	1978	284.0	1.05	1988	239.5	0.97	1998	187.5	0.87
1959	125.5	0.69	1969	195.0	0.89	1979	190.0	0.87	1989	183.0	0.86	1999	186.0	0.86
1960	209.5	0.92	1970	298.0	1.07	1980	259.0	1.01	1990	376.3	1.17	2000	294.0	1.06
1961	174.0	0.84	1971	119.0	0.67	1981	392.0	1.19	1991	430.5	1.23	2001	177.0	0.84
1962	189.7	0.87	1972	343.5	1.13	1982	249.0	0.99	1992	390.7	1.19	2002	303.5	1.08
1963	193.0	0.88	1973	293.0	1.06	1983	245.0	0.98	1993	244.4	0.98	2003	104.5	0.61
1964	117.0	0.66	1974	449.5	1.25	1984	435.5	1.23	1994	165.5	0.81	2004	300.0	1.07
1965	161.5	0.88	1975	208.8	0.91	1985	243.0	0.98	1995	275.8	1.04	2005	335.5	1.12
1966	283.0	1.05	1976	246.0	0.99	1986	323.0	1.10	1996	202.0	0.90	2006	469.5	1.27

Source: Comisión Nacional del Agua. Gerencia Estatal Chihuahua. Distrito de Riego 009, Valle de Juárez, Jefatura de Operación.

To construct Table 1, the study processed the total annual values (summing the monthly values) using function (4) shown below.

$$\text{Probability } (F_a) = \frac{100\,(2n - 1)}{2\,y} = 100 \,/\, \text{Period of return} \qquad (4)$$

Where:

F_a = Probability of occurence (%)
n = Rank of each event
y = Total number of events
Period of return = $100/F_a$

This procedure was done using equation (4), for the sample size of 50 years, by assigning ranges in ascending order, the precipitations, and the probabilities of occurrences and periods of return, for each year. These calculations are shown in Table 2 below.

Table 2. Table showing ranges, annual precipitations, probabilities of occurrence and return periods for Ciudad Juárez in the period 1957-2006.

Range	Annual precipitation (cm)	Probability (F_a)	Period of return (years)	Range	Annual precipitation (cm)	Probability (F_a)	Period or return (years)
1	46.95	1	100.00	26	24.44	51	1.96
2	44.95	3	33.00	27	24.30	53	1.87
3	43.55	5	20.00	28	23.95	55	1.82
4	43.05	7	14.28	29	21.60	57	1.75
5	39.20	9	11.11	30	20.95	59	1.69
6	39.07	11	9.09	31	20.88	61	1.64
7	37.63	13	7.69	32	20.20	63	1.59
8	34.95	15	6.66	33	19.50	65	1.54
9	34.35	17	5.88	34	19.30	67	1.49
10	33.55	19	5.26	35	19.00	69	1.45
11	32.30	21	4.76	36	18.97	71	1.41
12	32.30	23	4.35	37	18.75	73	1.37
13	30.35	25	4.00	38	18.60	75	1.33
14	30.00	27	3.70	39	18.30	77	1.30
15	29.80	29	3.45	40	17.70	79	1.27
16	29.40	31	3.23	41	17.40	81	1.23
17	29.30	33	3.03	42	17.25	83	1.20
18	28.48	35	2.86	43	17.15	85	1.18
19	28.40	37	2.70	44	16.55	87	1.15
20	28.30	39	2.56	45	16.20	89	1.12
21	27.58	41	2.44	46	16.15	91	1.09
22	25.90	43	2.33	47	12.55	93	1.07
23	24.90	45	2.22	48	11.90	95	1.05
24	24.60	47	2.13	49	11.70	97	1.03
25	24.50	49	2.04	50	10.45	99	1.01

By using Hazen plotting position, the methodology of this study consisted in the plotting of the 50 year data values of precipitations (cm), return periods and probabilities of occurrences on log-probability graph paper, for the dependent variable (log annual precipitations in centimeters), and probability scales for the dependent variables, that is, periods of return and probability of occurrence. Finally, using the least squares method, a regression line that fitted the data was drawn, for the purpose of interpolating or extrapolating any desired calculation. Figure 1 shows the graphical relationship of these three variables.

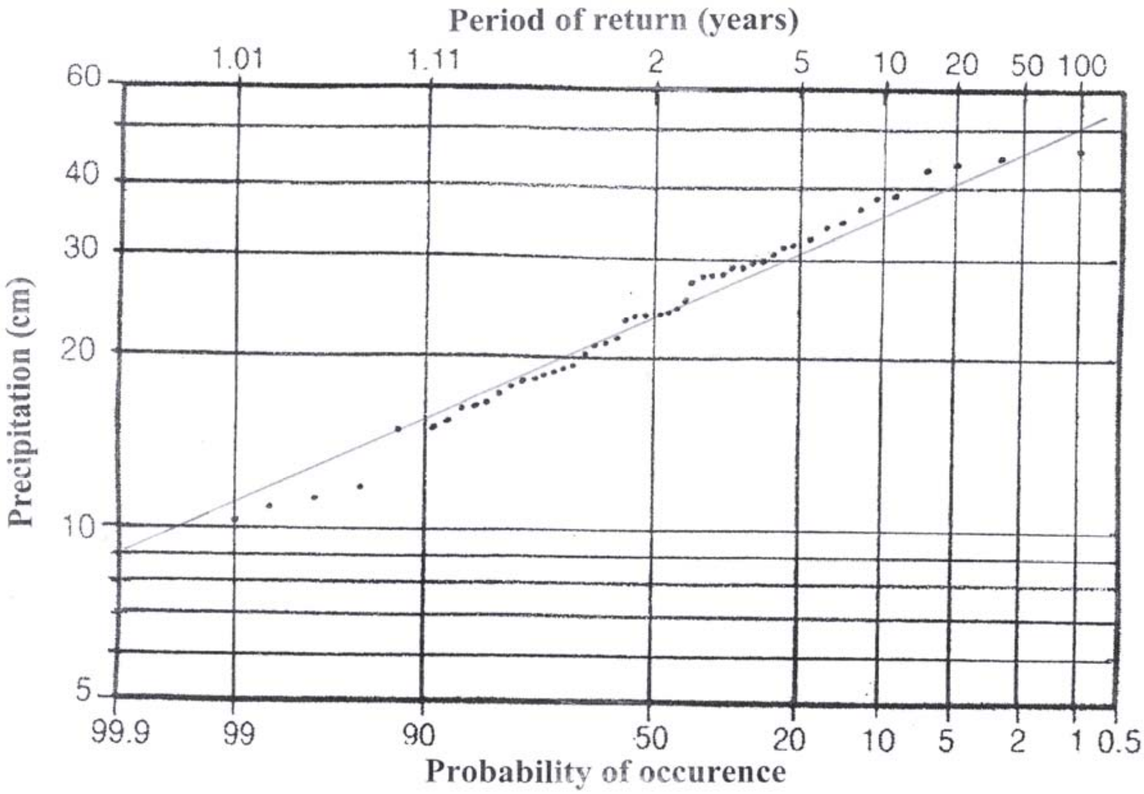

Figure 1. Graph paper used by plotting the logs of precipitation (cm) on an arithmetic scale and the return periods (years) and the probability of occurrence (%), on probability scales.

Results

To test for the normality of the frequency distribution, the study performed a descriptive statistics obtaining the following: arithmetic mean equal to 25.54 cm (10.06 inches), median equal to 24.47 cm (9.63 inches), mode equal to a 32.3 (12.72 inches), standard deviation equal to 9.17 (3.61 inches), skewness equal to 0.56 and 95% confidence interval 25.542±1.297 cm.

Insofar as the application of the probability graphs and goodness-of-fit, the selected graphical position was that of Hazen, because of its simplicity. For this goal, the study used the results of the return periods, the probabilities and the precipitations of Figure 1. For example, if it is desired to calculate the precipitation corresponding to a period of return of 20 years, by interpolation from Figure 1 this corresponds to about 40.0 cm with a probability of occurrence of 5 %. This means that in a given year, there is a probability of occurrence of 0.05 that there will be more than 40 cm of rain based on this data. Similarly, if it is desired to calculate the precipitation corresponding to a return period of 50 years, by interpolation using the regression line this would be equal to about 46 cm with a probability of 0.02 or 2.0%.

Conclusion and Recommendations

It is recommended to check for the assumption of normality of data before it is attempted to process the frequency distribution values. This is important, because if the data is skewed, then, by performing logarithmic transformation to the data, this problem can be mitigated. Of the entire existing alternative plotting positions, as those of Weibull, Cunnane, Gringorten, Hazen, etc., to estimate return periods, probabilities and precipitations, this paper recommends Hazen´s graphical position for being the traditional one.

On the other hand, the return period used to dimension a hydrological structure, is as a function of the construction, that is, of the socio-economic, strategic or touristic interest. Moreover, the return period is as a function of other alternative ways capable of the replacement of the hydraulic structure, and of the damage that its failure would imply, as the loss of human lives, cost and duration of the reconstruction, cost construction malfunctioning of the construction, etc. To avoid such situations, sometimes it is recommended to oversize the hydraulic work, to prevent overflowing, whose peak discharge is unexpected. In this way, it is recommended to oversize the works, but without incurring in additional costs, that is, by concentrating the efforts in some defined parts, as vital or essentials and by adopting constructive actions to minimize the damage in case of extreme events, as those caused by the warming of the earth, which is causing climatic changes. This is because global warming is altering the precipitation patterns causing extreme events (drought and flooding). This being so, extreme events are going to be even more common, as global temperatures increase (due to the concentration of greenhouse gases as CO_2, CH_4, water vapor, etc.). To confront these situations, the engineer needs to oversize the water works to minimize damages and water risks, to cope up with extreme events. It is recommended that control water works have effectiveness relative to return period, for which they have been calculated. For example, if the return period, for which the dike height has been calculated, is 20 years, it is understood that, on average, each 20 years a flood will occur that surpass the dike. This does not mean that the event will not happen afterwards the water work construction is concluded. This is especially true, due to the global climatic change, which has distorted rain patterns (alternating floods and drought), high frequencies of hailstorms, winter storms, precipitation storms, tornados, hurricanes, etc. It is concluded that the challenge the hydraulic engineer will have is to develop ways to face exceptional or extreme hydrological events, that is, by designing hydraulic works more adequate, safe and less costly.

Bibliography

1. Bedient & Huber. *Hydrology and Flooding Analysis*. Addison Wesley Publishing Co (1948).
2. Maidment, David R. *Handbook of Hydrology*. McGraw-Hill, Inc. 1993.
3. Ven TE Chow. *Handbook of Applied Hydrology* (1964). McGraw-Hill Book Co.
4. Linsley, R. K. and J. B. Franzini. *Hydrology for Engineers* (1958). Mc. Graw-Hill Series in Water Resources.
5. Gupta, R., *Hydrology and Hydraulic Systems*, 1989. Waveland Press, Inc.
6. http://es.wikipedia.org/wiki/Per%C3%ADodo_de_retorno
7. *Environmental Hydrology*. Edited by Andy D. Ward y William J. Elliot. Lewis Publishers, CRC Press, Inc. (1995).