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LATITUDINAL ANALYSIS OF RAINFALL INTENSITY AND MEAN ANNUAL PRECIPITATION IN CHILE

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The study and analysis of precipitation has become a crucial tool in understanding the temporal and spatial behavior of water resources, in terms of availability and impact on extreme events. The objective of this study was to evaluate different rainfall parameters (intensities for 1-h duration D = 1 h and return periods of T = 5 and 100 yr, and mean annual precipitation) for different latitudinal and climatic zones in Chile. We analyzed the information recorded on thousands of pluvial bands and rain gauges for 49 stations; this because it is unclear how rainfall intensities change along the country (though total amounts do), in addition to a lack of literature focused on ranges and amounts on the behavior of rainfall variables. The Gumbel probability distribution function (PDF) and mathematical rainfall intensity formulas were used to develop intensity-duration-frequency (IDF) curves for each station. Maximum and minimum rainfall intensity values for T = 100 yr ranged from 8.79 (hyperarid zone) to 40.17 mm h^{-1} (subhumid-humid zone). Total annual rainfall values ranged between 43.9 (hyperarid zone) and 3891.0 mm yr^{-1} (humid zone). Additionally, the real maximum intensity registered on each station was analyzed, determining its exceedance probability. Likewise, multiple comparisons were made to detect significant differences between the gauge stations and different climatic zones using the Kruskal Wallis test (alpha = 0.05). Differences between maximum and minimum values registered for all stations were as much as 80 times for total rainfall amounts and 4.5 times for rainfall intensities (T = 100 yr). However, maximum rainfall intensities values were similar at different latitudes, suggesting the absence of correlation between maximum rainfall intensity and annual rainfall amount, as the latter variable increased gradually with latitude.

Key words: Precipitation, frequency-duration-intensity curves, IDF curves, rainfall intensity.

Precipitation is often the principal hydrological contribution for a watershed and usually improves the general conditions of drainage. Nevertheless, extreme precipitation events often cause serious problems worldwide, such as flooding and their consequences for human lives and property (Maidment, 1996).

Hydrologic phenomena, such as precipitation, floods, and droughts, are inherently random by nature. These physical processes are not fully understood due to the complexity of the hydrologic cycle; for instance, reliable deterministic mathematical models have yet to be developed. Statistical approaches have been commonly adopted in order to provide useful analyses for design of hydraulic pathways and structures (Grimaldi *et al*., 2011). In this context, rainfall can be characterized in terms of its frequency, duration, and intensity, with intensity being most relevant to the less frequent but more damaging high-intensity events. Using statistical techniques these three variables (intensity, duration, and frequency) can be correlated to create intensity-duration-frequency (IDF) curves, based on maximum precipitation intensities. IDF curves are crucial in the design of storm water management structures (Haan, 2002) and are useful tools for watershed management, such as prediction of water erosion. Such phenomenon has been evaluated using rainfall simulators (Sangüesa *et al*., 2010), that generate rainfall with a known intensity and duration on an erosion plot in a controlled manner, thus making it possible to quantify superficial runoff and soil loss and predict erosion with a high level of detail (Martínez-Mena *et al*., 2001). Artificially generated rainfall in these simulators must be calibrated according to maximum values of rainfall intensity (IDF curves) corresponding to the location of the study site.

Additionally, IDF curves are used to determine design parameters for soil and water conservation practices. According to Pizarro *et al*. (2005), the design must include at least four basic hydrological parameters: a return period, an IDF curves, a runoff coefficient, and soil infiltration capacity. IDF curves can be represented as mathematical functions used to determine rainfall intensity by inputting frequency values (years) and duration (minutes or hours). Furthermore, IDF curves have been widely used by different authors. Willems

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(2000) separated both convective and frontal storms in terms of their peak-over-threshold intensity distributions in Belgium, helping to better understand what factors affect IDF curves and their scaling properties. Bougadis and Adamowski (2006) used traditional techniques to compare the scaling properties of extreme rainfall IDF curves using data collected in Ontario, Canada. The authors concluded that the scale approaches were more efficient and gave more accurate estimates through comparing observed data. Other authors have focused IDF research on analyzing and developing mathematical functions (Veneziano and Furcolo, 2002; Pereyra-Díaz *et al*., 2004; Langousis and Veneziano, 2007), the effects of topography and elevation (Dairaku, 2004), and studying ungauged areas of watersheds (Watkins *et al*., 2005).

IDF curves analyses have been conducted in Vietnam (Minh Nhat *et al*., 2006), Japan (Minh Nhat *et al*., 2008), Mexico (Hallack-Alegria and Watkins Jr., 2007), and many other places worldwide. Pizarro *et al*. (2001) developed IDF curves for the Maule Region in Chile and UNESCO (2007) updated IDF curves for a great portion of the Chilean territory (between Coquimbo and La Araucanía Regions). However, there is no scientific evidence regarding the values and existing differences among the curves developed for the country, including geographical extremes of Chile. Therefore, the objective of this study was to evaluate maximum rainfall intensities (D = 1 h and T = 5 and 100 yr) and mean annual precipitation for different latitudes and climatic zones of Chile, based on information obtained from pluvial bands and rain gauges from 49 stations distributed along the country, in order to determine if a pattern able to explain the behavior of IDF curves at different latitudes (e.g. under different climates) exists.

MATERIAL AND METHODS

The study was done using information on rainfall intensity, obtained from 49 gauge stations distributed along the country (Figure 1A), property of Chile's Water General Direction (Dirección General de Aguas), and installed under the norms and specifications of the World Meteorological Organization (WMO). Stations were located under different climates, varying from hyperarid and semiarid zones to humid and cold semiarid (UNESCO, 2006; 2010), all within the 12 Chilean first-order administrative regions (Figure 1B). Chile's geography is unusual, being the country with the world's largest length-to-width ratio (4300 km to about 177 km in average) (IGM, 2008). But most importantly for this study is to notice the wide heterogeneity of the country's climates, a direct consequence of large latitudinal changes (high and low atmospheric pressure zones), combined with important topographic features, like the presence of Los Andes and La Costa mountain ranges, and the cold Humboldt Current in the Pacific Ocean. Moreover, this north-to-south general climatic variability begins with the extreme aridity of desert zones, ends with cold-rainy climates in the extreme south of the country, passing through temperate-warm climates in central Chile (INE, 2007).

For 86% of the rain gauges IDF curves were obtained using maximum annual precipitation intensities. However, partial time series, as described by Linsley *et al*. (1977) were used for the remaining stations (14%) since were recently established and had less than five years' worth of data. A selection criterion of two or three storm events per year was established to increase the number of data available for analysis. It is also not worthless to mention

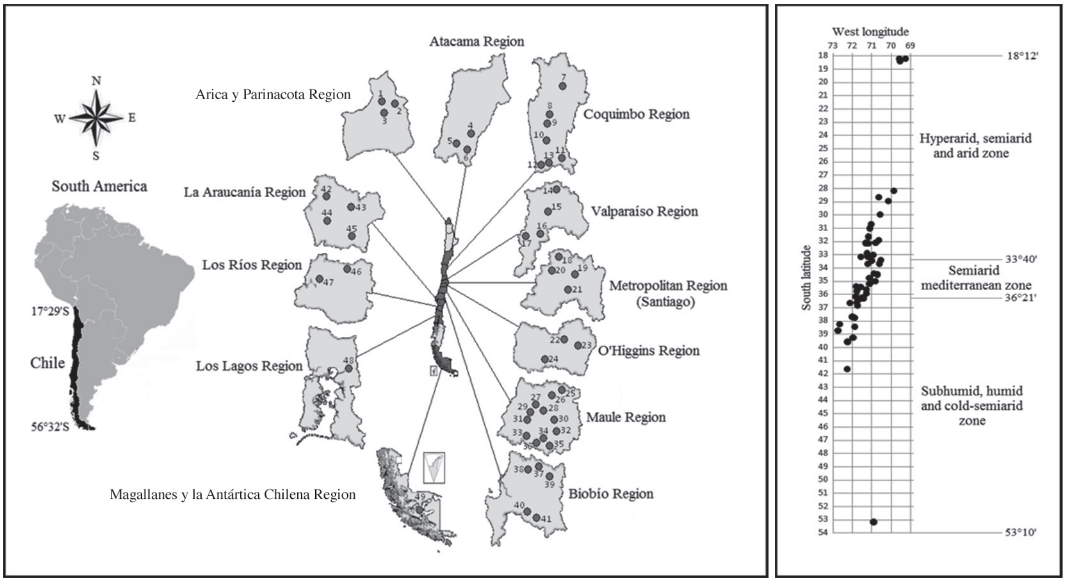

Figure 1. (A) Spatial distribution of the 49 gauge stations on each administrative Region of Chile. (B) Spatial distribution of the 49 gauge stations on each climatic zone of Chile.

that the historical data documented at the analyzed stations were between 10 and 40 records (47% with more than 20 records, 39% between 15 and 19 records, and 14% between 10 and 14 records).

Table 1 lists general information about the gauge stations (number of years on record, administrative region, geographical coordinates, and climatic zone). The Gumbel procedure (Gumbel, 1958) was applied to each data series listed on Table 1 in order to obtain a probability distribution for return periods of T = 5 and 100 yr for each station. The Gumbel probability distribution function (PDF) is expressed as $F(x) = e^{-e^{-d \bullet (x-u)}}$, where *x* is the value of the random variable, *d* and *u* are parameters of the function, and *e* is the Neper constant. Similarly, the probability of occurrence, or the probability for a random variable to have a value equal or lower than a certain number *X*, is given by the probability distribution function defined as $\int_{-\infty} f(x)dx = P\ (x \le X) = 1 - (1/T)$, (where *T* represents the return period in years). The probability of exceedence, defined as the probability for the random variable to exceed a given value, is determined by the expression $P(x > X) = 1 - F(x) = 1/T$. On the same way, it is important to add that the Gumbel function has been used in studies related to extreme meteorological events, and has provided a precise fit to daily and annual hydrological values (Mintegui y Robredo, 1993). Similarly, Stol (1971), cited in Dickinson (1977), states that Gumbel is the best approach in representing extreme annual rainfall. Additionally, the Gumbel function has been cited extensively in related literature due to its ability to fit extreme values (e.g. Linsley *et al*., 1977; Témez, 1978; Pizarro, 1986; Ponce, 1989; Chow *et al*., 1994; Monsalve, 1999).

Table 1. Climatic zone, administrative Region, location, and years of record for each gauge station.

Climatic zone	Region	Station/Location	Map number	S lat	W long	Registration period	Range (n)
Hyperarid	Arica y Parinacota	Putre (*)	1	18°12’	69°35’	2004-2008	15
		Parinacota (*)	2	18°12’	69°16’	2004-2007	12
		Central Chapiquiña (*)	3	18°23’	69°33’	2005-2008	12
	Atacama	Iglesia Colorada	4	28°10’	69°52’	1988-2008	20
		Santa Juana	5	28°40’	70°39’	1988-2005	17
		Albaricoque (*)	6	28°56’	70°09’	1988-2008	30
Arid-semiarid	Coquimbo	Rivadavia	7	29°58´	70°34´	1976-2001	25
		Embalse La Paloma	8	30°41´	71°02´	1962-2002	40
		Embalse Cogotí	9	31°00´	71°06´	1966-2002	33
		Illapel	10	31°38´	71°10´	1976-2002	27
		La Tranquilla	11	31°54´	70°39´	1966-2002	34
		Los Cóndores	12	32°07´	71°19´	1978-2002	22
		Quelón	13	32°09´	71°10´	1973-2002	27
Semiarid	Valparaíso	Hacienda Pedernal	14	32°06´	70°48´	1978-2001	10
		Quillota	15	32°53´	71°15´	1979-2002	12
		Embalse Lliu-Lliu	16	33°08´	71°13´	1979-2002	14
		Lago Peñuelas	17	33°09´	71°33´	1974-2001	21
	Metropolitana	Embalse Rungue	18	33°01´	70°55´	1984-2000	16
		Cerro Calán	19	33°23´	70°32´	1983-2000	17
		Los Panguiles	20	33°26´	71°00´	1985-2000	15
		Pirque	21	33°40´	70°36´	1984-2000	17
Semiarid-Mediterranean	Libertador General Bernardo O’Higgins	Rengo	22	34°25´	70°53´	1970-2002	26
		Central Las Nieves	23	34°29´	70°42´	1971-2002	27
		Convento Viejo	24	34°46´	71°07´	1972-2002	21
Mediterranean	Maule	Los Queñes	25	35°00´	70°49´	1988-2002	15
		Potrero Grande	26	35°12´	71°07´	1988-2002	15
		Pencahue	27	35°23´	71°48´	1982-1998	17
		Talca	28	35°26´	71°35´	1982-1998	17
		San Javier	29	35°36´	71°44´	1988-2002	15
		Colorado	30	35°38´	71°16´	1982-1998	14
		Melozal	31	35°45´	71°47´	1982-1998	17
		Embalse Ancoa	32	35°54´	71°17´	1988-2002	15
		Parral	33	36°09´	71°50´	1982-1998	17
		Embalse Digua	34	36°15´	71°32´	1988-2002	15
		Embalse Bullileo	35	36°17´	71°26´	1982-1998	16
		San Manuel (*)	36	36°21´	71°39´	1996-2002	14
Subhumid humid	Biobío	Embalse Coihueco	37	36°35´	71°47´	1984-2003	20
		Chillán Viejo	38	36°38´	72°08´	1974-2003	29
		Embalse Diguillín	39	36°50´	71°44´	1965-2003	38
		Quilaco	40	37°41´	72°00´	1965-2003	39
		Cerro El Padre	41	37°46´	71°53´	1976-2003	28
Humid	La Araucanía	Traiguén	42	38°15´	72°40´	1988-2003	16
		Curacautín	43	38°26´	71°53´	1991-2003	13
		Pueblo Nuevo	44	38°44´	72°45´	1989-2003	15
		Pucón	45	39°16´	71°58´	1984-2003	20
	Los Ríos	Lago Calafquén (*)	46	39°34´	72°15´	1997-2008	24
		Llancahue	47	39°50´	73°10´	1977-2007	31
	Los Lagos	Puelo (*)	48	41°38´	72°16´	1997-2008	24
Cold-semiarid	Magallanes y la Antártica Chilena	Punta Arenas	49	53°10´	70°54´	1983-2008	26

(*) Stations in which two or three annual data were considered.

In Chile, the Gumbel function was used by Pizarro *et al*. (2008) to characterize annual precipitation in central Chile. It is also important to add that national experience on recent studies in process of publication demonstrate that the Gumbel function more accurately fits to extreme precipitation and runoff values than other functions, such as Log-Normal or Goodrich and Pearson Type III. However, these latter functions fit more accurately for data in arid and semiarid climates (mostly between south 29° and 32° latitude), where data is more variable. However, Linsley *et al*. (1977) mentioned that although effort has been focused on better defining hydrological data, research suggests that there isn't a unanimously superior distribution. Thus we continued the use of the Gumbel function and validated the results with the Kolomogorov-Smirnov (K-S) Goodness of Fit Test (Massey, 1951), a non-parametric test used on continuous distribution functions F(x), which is based on comparing the absolute value of the maximum difference between the cumulative distribution functions (observed) in the sorted sample Fo(x) and the distribution proposed under the null hypothesis F(x). If the comparison has a sufficiently significant difference between the sample and the proposed distribution function, then the null hypothesis (i.e. the distribution is F(x)) is rejected. One hundred percent of the results applied to intensity data were accepted with this test. The coefficient of determination (R^2) was used to explain the percentage of variation for the dependent variable of the model (Dougherty *et al*., 2000). In this context, most of the obtained R^2 values were over 0.8. In other words, 100% of the results were considered acceptable by this test, with an average value of 0.9, supporting the superiority of the Gumbel function for modeling extreme climatic data.

Once the fit was made, the relationships between intensity (mm h^{-1}), duration (1, 2, 4, 6, 12, and 24 h), and frequency (5, 10, 20, 30, 40, 50, 60, 75, and 100 yr) were determined. Finally, a family of nine negative exponential curves (IDF curves) was built for each gauge station, though only a portion of them was considered for use in this study, as is explained later.

IDF curves are often expressed as a function, to minimize errors and avoid graphical reading (Chow *et al*., 1994). Hence, a mathematical equation was developed for each family curve. These equations are based on the model proposed by Bernard (1932): $I = (k * T^m) * D^{-n}$, where I is the maximum rainfall intensity (mm h^{-1}), T is the return period (yr), and D is the duration of the storm (h). Also, k, m, and n are the regression's parameters.

Once the IDF curves and their respective functions were done for each of the 49 stations, we decided to analyze rainfall intensities for a duration D = 1 h (because is the minimum time that human eye can obtain from weekly pluvial bands, being these, the most commonly bands used in Chile), considering return periods of T = 5 and 100 yr. In this context is important to mention that extreme events that generate larger impact are generally associated with short durations, even less than 1 h. Similarly, T = 5 and 100 yr were selected to analyze the two extreme frequencies associated to all the frequencies defined from IDF curves. Additionally, the real maximum intensity registered on each station was analyzed, determining its exceedance probability. Likewise, multiple comparisons were made to detect significant differences between the gauge stations and different climatic zones using the Kruskal Wallis test (alpha = 0.05), a non-parametric statistical test that determines whether samples derive from the same population. This test evaluates the null hypothesis that the means are statistically similar, and is an extension of the Mann-Whitney *U* test for three or more groups (in this case 49) (Kruskal and Wallis, 1952).

A latitudinal analysis of rainfall intensities (D = 1 h, T = 5 and 100 yr) was performed, with the results expressed graphically. The latitudinal distribution of mean annual precipitation was also considered to find possible correlation and trends.

RESULTS AND DISCUSSION

Chile has great climatic diversity, which is explained by its wide latitudinal extension and the presence of four well-defined geographic areas: the Andes mountain range to the east, the La Costa mountain range to the west, the intermountain valley, and littoral floodplains. The location of the country next to the Pacific Ocean, the effects of the Humboldt Current, in addition to the Pacific high-pressure zone, give rise to a wide variety of climates, varying from extreme aridity in the north (Arica y Parinacota, and Atacama Regions), to Mediterranean climates (warm temperate) in the center (Libertador General Bernardo O´Higgins and Maule Regions), and cold rainy climates in the extreme south (Aysén del General Carlos Ibáñez del Campo and Magallanes y la Antártica Chilena Regions) (Errázuriz *et al*., 1998; INE, 2007).

In terms of the length of the analyzed data series, results presented by Ott (1971) show that with the use of 20 yr of data there is 80% probability of overestimating the design runoff, and 45% probability that the overestimated values exceeding real values in more than 30%. Linsley *et al*. (1977) for example recommends avoiding the use of data series shorter than 20 yr. However, the same authors state that if necessary, peak flows can be estimated using 2 or 3 yr of observed data. On the other hand, maximum rainfall intensities documented in Chile do not necessarily correlate to higher rainfall amounts during wet periods. In fact, many high intensity values were recorded during dry periods. Besides, the behavior of rainfall intensities in arid climates responds similarly to those in Mediterranean and humid environments (UNESCO, 2007). From a regional perspective and considering the intensity results given by IDF curves, we can assume that there are differences in the quality of the generated information, as a consequence of the differences in data series. However, such differences are not as significant as the behavior of rainfall intensities within the national territory. If such differences are represented by minimum extreme values, values associated with return periods of 50 or 100 yr would overestimate the maximum recorded intensity in the data series, meaning that there will always be higher values that securely allowed the development of hydrological design. Therefore, the selection of a series to be analyzed and the return periods to be considered will depend on the project's objective, as well as the respective infrastructure costs. Finally, we should mention that when hydrological data are not abundant and historical data series are insufficient for analysis, it is appropriate to develop a Regional Frequency Analysis (RFA), which is designed to solve this type of problem (Linsley *et al*. 1977) and has been used to estimate and map the frequency of droughts in northern Chile. The use of RFA implies the availability of information from stations located in areas with similar rainfall regimes (Paulhus and Miller, 1957), generally separated by distances no larger than 160 km (Ott, 1971).

In this vein, IDF curves were successfully developed for each of the 49 stations, for durations of 1, 2, 4, 6, 12, and 24 h and return periods of 5, 10, 20, 30, 40, 50, 60, 75, and 100 yr. As previously mentioned only D = 1 h and T = 5 and 100 yr were considered (Table 2). The lowest rainfall intensities for 1 h were recorded at Albaricoque station (arid climate) for the two studied return periods. The highest extremes occurred at Lago Peñuelas station (semiarid climate) for T = 5 yr and Embalse Coihueco (subhumid climate) for T = 100 yr. Higher values were in

Table 2. Maximum rainfall intensity (T = 5 and 100 yr) estimated at each gauge station.

Climatic zone	Station/Location	Map number	Annual rainfall amount	Maximum rainfall intensity	Intensity of rainfall 1 h	
					T = 5	T = 100
			mm	mm h^{-1}	mm h^{-1}	
Hyperarid	Putre	1	237.7	7.9	5.75	10.29
	Parinacota	2	394.0	8.5	7.05	10.72
	Central Chapiquiña	3	195.5	8.5	6.45	11.04
	Iglesia Colorada	4	58.4	7.4	5.73	9.98
	Santa Juana	5	43.9	15.5	8.90	19.62
	Albaricoque	6	84.9	6.6	4.91	8.79
Arid-semiarid	Rivadavia	7	100.1	13.3	7.97	15.38
	Embalse La Paloma	8	135.4	20.0	19.00	27.49
	Embalse Cogotí	9	168.0	20.6	10.82	20.40
	Illapel	10	179.6	16.6	9.76	18.36
	La Tranquilla	11	251.0	15.0	9.34	17.09
	Los Cóndores	12	241.4	15.0	10.07	18.48
	Quelón	13	300.1	15.6	9.67	16.79
Semiarid	Hacienda Pedernal	14	247.5	17.8	12.62	20.22
	Quillota	15	361.7	18.6	13.10	22.57
	Embalse Lliu-Lliu	16	571.2	23.4	19.95	31.77
	Lago Peñuelas	17	735.6	30.3	22.22	37.41
	Embalse Rungue	18	372.5	17.0	11.63	18.83
	Cerro Calán	19	441.5	19.2	13.58	21.53
	Los Panguiles	20	361.5	14.8	11.04	19.20
	Pirque	21	470.1	15.2	11.53	18.42
Semiarid-Mediterranean	Rengo	22	563.8	21.5	13.68	21.43
	Central Las Nieves	23	828.9	16.2	13.68	19.37
	Convento Viejo	24	721.2	19.3	15.04	23.53
Mediterranean	Los Queñes	25	1183.8	25.2	18.89	30.13
	Potrero Grande	26	1103.1	25.7	19.14	30.66
	Pencahue	27	673.0	15.9	12.37	19.56
	Talca	28	661.9	14.3	10.78	16.27
	San Javier	29	767.5	14.2	12.14	18.04
	Colorado	30	1387.4	25.6	17.15	28.23
	Melozal	31	743.3	23.0	13.05	22.68
	Embalse Ancoa	32	1506.4	23.4	12.23	23.39
	Parral	33	968.8	19.3	14.77	23.68
	Embalse Digua	34	1519.8	25.8	20.06	30.91
	Embalse Bullileo	35	2157.1	22.4	18.54	25.60
	San Manuel	36	1391.7	23.0	17.62	28.49
Subhumid humid	Embalse Coihueco	37	1512.8	36.5	21.93	40.17
	Chillán Viejo	38	1093.4	22.1	18.33	29.02
	Embalse Diguillín	39	2143.5	30.2	20.28	32.20
	Quilaco	40	1572.1	26.0	17.62	27.62
	Cerro El Padre	41	2131.3	28.8	19.83	30.52
Humid	Traiguén	42	1016.2	20.4	13.87	22.03
	Curacautín	43	1750.8	15.3	13.98	20.44
	Pueblo Nuevo	44	1201.5	14.3	13.09	18.62
	Pucón	45	2154.5	18.9	14.18	21.39
	Lago Calafquén	46	2113.7	17.8	14.13	19.39
	Llancahue	47	1983.1	26.4	17.39	27.05
	Puelo	48	3891.0	16.1	12.74	20.21
Cold-semiarid	Punta Arenas	49	422.8	13.0	7.59	12.85

general found in Mediterranean and subhumid climates. The highest values on mean annual precipitation were obtained in south-central Chile (humid and mediterranean climates), whereas the lowest amount of rainfall fell, not surprisingly, over stations located in hyperarid climates.

On the other hand, when verifying the relationship between rainfall intensity and elevation, there was no clear trend because similar rainfall intensity values at different elevations (between 0 and 1200 m a.s.l.) were found. Similarly, for some stations, such as Putre, Central Chapiquiña, or Iglesia Colorada, (among others), located in the northern portion of the country (hyperarid climate) have altitudes that surpass 1200 m a.s.l., and have maximum intensities similar to Punta Arenas and other stations located a few meters above sea level, in south extreme of Chile.

A relationship between real maximum rainfall intensities, their corresponding return periods, and their probability of exceeding the maximum-recorded value was made for each station, using the obtained mathematical equations. This analysis allowed the estimation of the probability of surpassing the registered real maximum intensity for each data series, as well as its corresponding return period (Table 3). There was a 15% probability to surpass 23.4 mm h^{-1}, the recorded maximum rainfall intensity at Embalse Lliu-Lliu station (semiarid climate), corresponding to a return period of 7 yr, the lowest registered return period. This large exceedance probability suggests that high rainfall intensities at that location are common. In contrast, a maximum of 23.4 mm h^{-1} was recorded at Embalse Ancoa station (Mediterranean climate). Nevertheless, the probability of

Table 3. Return periods and exceedence probabilities for maximum rainfall intensities recorded on 1 h an each gauge station.

Climatic zone	Station/Location	Map number	Maximum intensity of rainfall	Year of occurrence	Return period	Exceedance probability
			mm h^{-1}		yr	%
Hyperarid	Putre	1	7.9	2007	21	4.9
	Parinacota	2	8.5	2005	11	9.0
	Central Chapiquiña	3	8.5	2007	36	2.8
	Iglesia Colorada	4	7.4	1989	9	10.8
	Santa Juana	5	15.5	1997	24	4.1
	Albaricoque	6	6.6	1992	15	6.5
Arid-semiarid	Rivadavia	7	13.3	2000	28	3.6
	Embalse La Paloma	8	20.0	1997	33	3.0
	Embalse Cogotí	9	20.6	1992	53	1.9
	Illapel	10	16.6	1994	30	3.4
	La Tranquilla	11	15.0	1997	47	2.1
	Los Cóndores	12	15.0	1984	29	3.5
	Quelón	13	15.6	1974	34	2.9
Semiarid	Hacienda Pedernal	14	17.8	1983	32	3.1
	Quillota	15	18.6	2000	19	5.2
	Embalse Lliu-Lliu	16	23.4	1984	7	15.0
	Lago Peñuelas	17	30.3	1981	11	8.8
	Embalse Rungue	18	17.0	1990	48	2.1
	Cerro Calán	19	19.2	1986	19	5.3
	Los Panguiles	20	14.8	2000	15	6.6
	Pirque	21	15.2	1996	40	2.5
Semiarid-Mediterranean	Rengo	22	21.5	2001	99	1.0
	Central Las Nieves	23	16.2	1981	16	6.2
	Convento Viejo	24	19.3	2000	33	3.1
Mediterranean	Los Queñes	25	25.2	2000	46	2.2
	Potrero Grande	26	25.7	2000	23	4.3
	Pencahue	27	15.9	1986	26	3.8
	Talca	28	14.3	1987	29	3.4
	San Javier	29	14.2	1999	N/A	N/A
	Colorado	30	25.6	1993	84	1.2
	Melozal	31	23.0	1992	48	2.1
	Embalse Ancoa	32	23.4	2002	36	2.8
	Parral	33	19.3	1993	26	3.9
	Embalse Digua	34	25.8	1992	27	3.7
	Embalse Bullileo	35	22.4	1995	31	3.2
	San Manuel	36	23.0	1998	46	2.2
Subhumid humid	Embalse Coihueco	37	36.5	2000	57	1.7
	Chillán Viejo	38	22.1	2002	19	5.2
	Embalse Diguillín	39	30.2	1974	46	2.2
	Quilaco	40	26.0	1970	54	1.9
	Cerro El Padre	41	28.8	1980	71	1.4
Humid	Traiguén	42	20.4	2003	54	1.9
	Curacautín	43	15.3	1994	10	10.4
	Pueblo Nuevo	44	14.3	1992	9	11.2
	Pucón	45	18.9	1990	45	2.2
	Lago Calafquén	46	17.8	2003	75	1.3
	Llancahue	47	26.4	1984	65	1.5
	Puelo	48	16.1	2004	18	5.6
Cold-semiarid	Punta Arenas	49	13.0	1993	47	2.1

N/A: information not available.

exceeding this value is only 2.8%, associated with a return period of 36 yr. Furthermore, the relationship between the recorded maximum intensity of each data series and its corresponding exceedance probability is illustrated in Figure 2, indicating that the lowest values occurred in the northern regions (hyperarid and arid climates), compared to the other analyzed climate types.

In general, the probability of exceeding a recorded real maximum intensity was less than 10%. However, for the Embalse Lliu-Lliu, Curacautín, and Pueblo Nuevo stations, representing semiarid and humid climates, the recorded maximum intensity was surpassed, which indicates a higher chance of an extreme event exceed the maximum recorded in those areas.

Significant differences between stations and between climatic zones for rainfall intensities were found by the Kruskal Wallis test (Table 4). The largest statistical differences were obtained in the extreme climatic zones, such as hyperarid and cold semiarid climates (Figure 3). However, it is important to point out the fact that stations can reach similar values of maximum rainfall intensity, despite geographic and climatic differences. For example, even though there were significant differences between northern climates (i.e. hyperarid, arid, and semiarid) and central climates (Mediterranean and humid), the largest variability of rainfall intensities happened in arid environments, where higher intensities were common and similar to those recorded in central Chile.

Table 4. Statistical comparison of rainfall intensities among different climatic zones, using the Kruskal-Wallis test.

Type of comparison	Sample	Sample size (n)	P-value	Null hypothesis
Among climatic zones	Hyperarid	106	< 0.05	Rejected
	Arid-semiarid	208		
	Semiarid	122		
	Semiarid-Mediterranean	74		
	Mediterranean	187		
	Subhumid-humid	154		
	Humid	143		
	Cold semiarid	26		

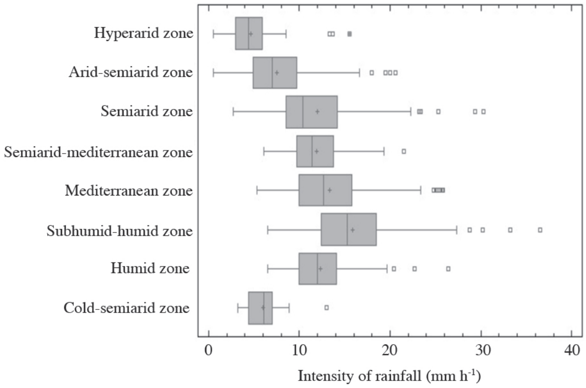

Figure 3. Significant difference on maximum precipitation intensities among climatic zones, after applying the Kruskal-Wallis test (alpha = 0.05).

With these results it is possible to discuss the spatial variability of precipitation in Chile, in terms of the proportion between maximum and minimum values for both intensity and total amounts. Maximum values for rainfall intensity (subhumid zone) were as much as 4.5 times the minimum documented values (hyperarid zone), for T = 5 and 100 yr. However, maximum values for total rainfall (humid zone) surpass by more than 80 times the minimum recorded values (hyperarid zone). This allowed us to verify the differences in amplitude for rainfall

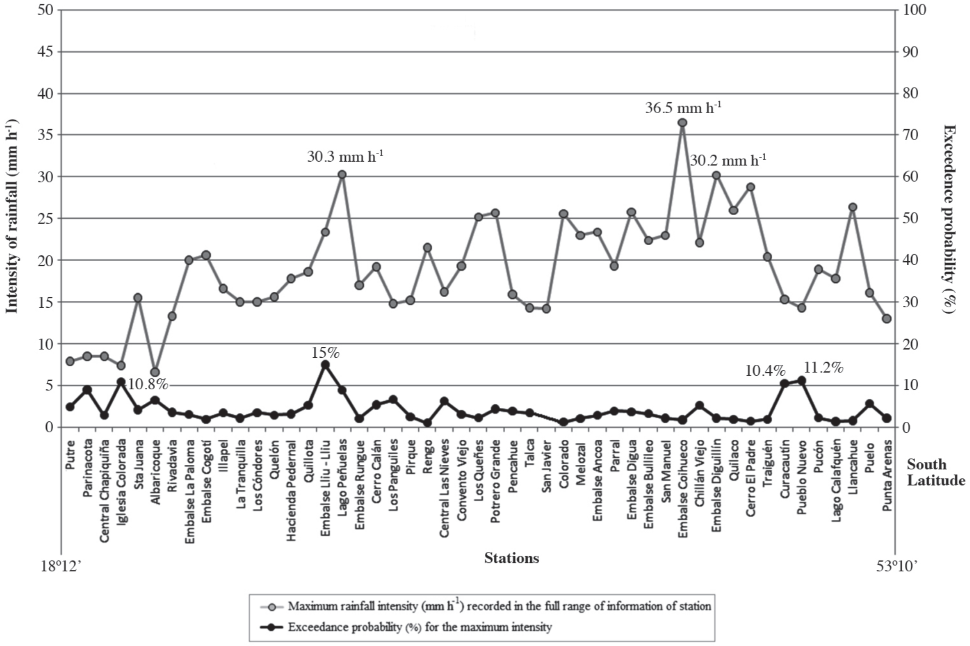

Figure 2. Probability of exceeding the maximum-recorded rainfall intensity at each station.

intensity and total annual precipitation, showing a much larger contrast in the range of the latter variable.

Although some studies have been done in Chile, they were all focused on the behavior of precipitation. Falvey and Garreaud (2007), Verbist *et al*. (2010), and Barrett *et al*. (2011), for example, did not consider variables used in this research. Besides, most of the studies in Chile are based on demonstrating the interannual variability of precipitation in the central portion of the country, which is associated with the El Niño and La Niña phenomena (Rutllant and Fuenzalida, 1991). Furthermore, Garreaud and Aceituno (2001) concluded that the number of rainy days increases during El Niño, particularly moderate (10-20 mm d^{-1}) and extreme (50 mm d^{-1}) intensities. However, no significant differences were found during La Niña, which means that the number of rainy days during this phenomenon does not necessarily decrease during that particular year.

The analysis of these authors, as well as most of the parametric climate studies developed in Chile, focused on the behavior of total rainfall amounts as they relate to atmospheric phenomena at different spatial scales. However, rainfall intensity is not well understood in Chile. It is more relevant to move forward using IDF curves and expand on the few available studies, mostly because recent statistical analyses show changes in rainfall intensity, in the form of higher rainfall intensity values for shorter lapses; thus, design guidelines on hydraulic structures as well as soil and water conservation works should be modified.

Finally, the relationship between rainfall intensity (D = 1h, T = 5 and 100 yr), mean annual precipitation, and latitude (Figure 4) shows no correlation between maximum rainfall intensity and mean annual precipitation in Chile (Table 5), since similar rainfall intensity values were found throughout the country. However, mean annual precipitation gradually increases with latitude, showing a decrease in the extreme south.

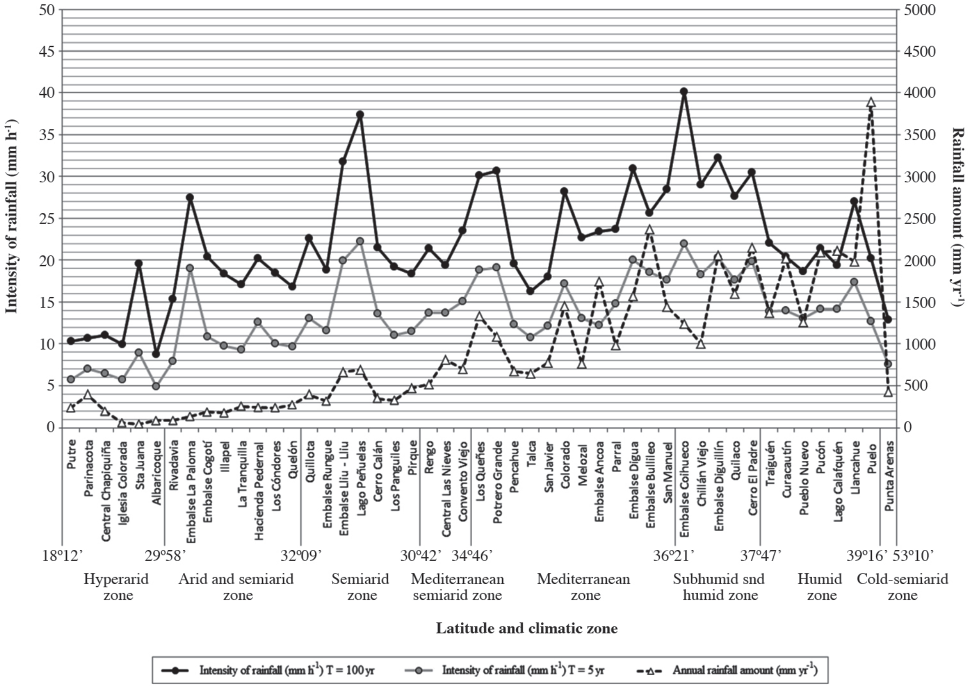

Figure 4. Maximum rainfall intensities (T = 5 and 100 yr) and mean annual precipitation at different latitudes in Chile.

Table 5. Annual precipitation and maximum one-hour rainfall intensity (T = 100 yr) for different climatic zones in Chile.

Climatic zone	Region	Station/Location	Map number	South latitude	Annual rainfall amount	Maximum rainfall intensity T = 100 yr
					mm	mm h^{-1}
Hyperarid	Arica y Parinacota	Santa Juana	5	28°40'	43.9	19.62
Arid-semiarid	Coquimbo	Embalse Cogotí	9	31°00´	168.0	20.40
Semiarid	Valparaíso	Hacienda Pedernal	14	32°06´	247.5	20.22
	Metropolitana	Los Panguiles	20	33°26´	361.5	19.20
Semiarid-Mediterranean	Libertador General Bernardo O'Higgins	Central Las Nieves	23	34°29´	828.9	19.37
Mediterranean	Maule	Pencahue	27	35°23´	673.0	19.56
Humid	La Araucanía	Curacautín	43	38°26´	1750.8	20.44
	Los Ríos	Lago Calafquén	46	39°34´	2113.7	19.39
	Los Lagos	Puelo	48	41°38´	3891.0	20.21

CONCLUSIONS

The highest values of rainfall intensity (D = 1 h, T = 5 and 100 yr) in Chile are present in subhumid zones (36° S lat), and total annual precipitation values are higher in humid zones (39° S lat). Precipitations in Chile have a high amount of spatial variability, a consequence of the wide latitudinal extension of the country. Differences in annual precipitation are noticeable; maximum values that can reach more than 80 times minimum values were observed. However, rainfall intensity does not change with latitude along the country in general, reaching a difference of only 4.5 times between maximum and minimum values.

Finally, we suggest that maximum rainfall intensities distributed in Chile behave similarly throughout the country. However, minimum D = 1 h values were documented at the latitudinal extremes of the country (north and south). Similarly, there was no correlation between elevation and rainfall intensity. As indicated previously, Chile has a large variety of climates, in which annual precipitation gradually increases from north to south. However, such pattern has nothing to do with the way rainfall intensities behave, that is, mean annual precipitation does not predict rainfall intensity in Chile.

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Análisis latitudinal de la intensidad de lluvias y precipitación media anual en Chile. El estudio y análisis de las precipitaciones se ha convertido en una herramienta vital para conocer el comportamiento temporal y espacial del recurso hídrico, tanto en términos de disponibilidad, así como de los posibles impactos asociados a los eventos extremos. El objetivo de esta investigación fue evaluar las intensidades máximas (duración D = 1 h y períodos de retorno T = 5 y 100 años) y los montos anuales de precipitación para diferentes latitudes y zonas climáticas de Chile, analizando la información de miles de bandas pluviográficas y la pluviometría anual de 49 estaciones de medición. Ello, porque aún no es claro que las intensidades de precipitación difieren latitudinalmente en el país, así como lo hacen los montos anuales de las lluvias. Asimismo, no hay evidencia científica de los rangos y montos de ambas variables. Así, se utilizó la función de Gumbel y fórmulas matemáticas para desarrollar las curvas intensidad-duración-frecuencia (IDF) de cada estación. Los valores mínimos y máximos de intensidad de precipitación registrados para T = 100 años, fueron 8,79 (zona hiperárida) y 40,17 mm h^{-1} (zona subhúmeda-húmeda). Respecto al monto anual de precipitaciones, los valores mínimos y máximos fueron 43,9 (zona hiperárida) y 3891,0 mm $año^{-1}$ (zona húmeda) respectivamente. Adicionalmente, la intensidad máxima real registrada en cada estación fue analizada para determinar su probabilidad de excedencia. Asimismo, se realizaron comparaciones múltiples para detectar diferencias significativas entre las estaciones de medición y las diferentes zonas climáticas, mediante el test no paramétrico Kruskal Wallis (alfa = 0,05). Las diferencias entre los valores máximos y mínimos registrados en la totalidad de las estaciones analizadas pueden superar las 80 veces, para el caso de los montos anuales de las lluvias, y pueden llegar hasta 4,5 veces para el caso de las intensidades de precipitación (T = 100 años). Sin embargo, se encontraron valores máximos similares de intensidad de precipitación en diferentes latitudes y altitudes del territorio nacional. Por tanto, se concluye que un mayor monto anual de lluvia no necesariamente involucra una mayor intensidad de precipitación.

Palabras clave: Precipitaciones, curvas intensidad-duración-frecuencia, curvas IDF, intensidad de precipitaciones.

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