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

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**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 $F(x) = e^{-e^{-(x-u)/d}}$, 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 $P_{\text{return period}} = P(x \leq X) = 1 - (1/T)$, 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 $P(x > X) = 1 - F(x) = 1/T$.

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. |
|---|---|---|---|---|---|
| Climates 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 Chaququina (*) | 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 Cotol | 9 | 31°00' | 71°06' | 1966-2002 | 33 |
| | | Illapel | 10 | 31°38' | 71°10' | 1976-2002 | 27 |
| | | La Tranquilla | 11 | 31°54' | 71°00' | 1962-2002 | 34 |
| | | Los Cóndores | 12 | 32°07' | 71°19' | 1973-2002 | 15 |
| | | Quequén | 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 Lluí-Lluí | 16 | 33°08' | 71°13' | 1979-2002 | 14 |
| | | Lago Peñalol | 17 | 33°09' | 71°33' | 1974-2001 | 21 |
| | | Embalse Rungue | 18 | 33°01' | 70°55' | 1940-2000 | 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 |
| | | Los Quilles | 25 | 35°00' | 70°49' | 1982-1998 | 15 |
| | | Potrer 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' | 1992-1998 | 14 |
| | | Molzal | 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 Digu | 34 | 36°15' | 71°32' | 1988-2002 | 15 |
| | | Embalse Bullileo | 35 | 36°17' | 71°26' | 1982-1998 | 16 |
| | | San Manuel (*) | 36 | 36°21' | 71°59' | 1996-2002 | 14 |
| | | Embalse Coihueco | 37 | 36°35' | 71°47' | 1984-2003 | 20 |
| | | Chillán Viejo | 38 | 36°38' | 72°08' | 1974-2003 | 29 |
| | | Embalse Diguilín | 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 |
| Subhumid humid | Biobío | Lago Calafquén (*) | 42 | 38°15' | 72°40' | 1988-2003 | 16 |
| | | Traiguén | 43 | 38°26' | 71°53' | 1991-2003 | 13 |
| | | Curcautín | 44 | 38°44' | 72°45' | 1989-2003 | 15 |
| | | Puello Nuevo | 45 | 39°16' | 71°58' | 1984-2003 | 20 |
| | | Lago Calafquén (*) | 46 | 39°34' | 72°15' | 1997-2008 | 24 |
| | | Llancahue | 47 | 39°50' | 73°10' | 1977-2007 | 31 |
| | | Puello (*) | 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): \[ I = (k \times T^m) \times D^n \]
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, \(k, m, \text{and } n\) 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 (Liberador 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

| Climatic zone          | Station/Location | Map number | Annual rainfall amount | Maximum rainfall intensity |
|------------------------|------------------|------------|------------------------|---------------------------|
| Hyperarid              |                  |            |                        |                           |
| Hyperarid              | Putre            | 1          | 237.7                  | 7.9                       | 5.75                      | 10.29                    |
| Hyperarid              | Parinacota       | 2          | 394.0                  | 8.5                       | 7.05                      | 10.72                    |
| Hyperarid              | Central Chapiquiña | 3          | 195.5                  | 8.5                       | 6.45                      | 11.04                    |
| Hyperarid              | Iglesia Colorada | 4          | 58.4                   | 7.4                       | 5.73                      | 9.98                     |
| Hyperarid              | Santa Juana      | 5          | 43.9                   | 15.5                      | 8.90                      | 19.62                    |
| Hyperarid              | Albaricoque      | 6          | 84.9                   | 6.6                       | 4.91                      | 8.79                     |
| Arid-semiarid          | Rivadavia        | 7          | 100.1                  | 13.3                      | 7.97                      | 15.38                    |
| Arid-semiarid          | Embalse La Paloma| 8          | 135.4                  | 20.0                      | 19.00                     | 27.49                    |
| Arid-semiarid          | Embalse Cogotof  | 9          | 168.0                  | 20.6                      | 10.82                     | 20.40                    |
| Arid-semiarid          | Illapel          | 10         | 179.6                  | 16.6                      | 9.76                      | 18.36                    |
| Arid-semiarid          | La Tranquilla    | 11         | 251.0                  | 15.0                      | 9.34                      | 17.09                    |
| Arid-semiarid          | Los Cóndores     | 12         | 241.4                  | 15.0                      | 10.07                     | 18.48                    |
| Arid-semiarid          | Queón            | 13         | 300.1                  | 15.6                      | 9.67                      | 16.79                    |
| Semiarid               | Hacienda Pedernal| 14         | 247.5                  | 17.8                      | 12.62                     | 20.22                    |
| Semiarid               | Quillota         | 15         | 361.7                  | 18.6                      | 13.10                     | 22.57                    |
| Semiarid               | Embalse Llu-Llu  | 16         | 571.2                  | 23.4                      | 19.95                     | 31.77                    |
| Semiarid               | Lago Peñuelas    | 17         | 735.6                  | 30.3                      | 22.22                     | 37.41                    |
| Semiarid               | Embalse Runque   | 18         | 372.5                  | 17.0                      | 11.63                     | 18.83                    |
| Semiarid               | Cerro Calán      | 19         | 441.5                  | 19.2                      | 13.58                     | 21.53                    |
| Semiarid               | Los Panguiiles   | 20         | 361.5                  | 14.8                      | 11.04                     | 19.20                    |
| Semiarid               | Pirque           | 21         | 470.1                  | 15.2                      | 11.53                     | 18.42                    |
| Semiarid-Mediterranean | Rengo            | 22         | 563.8                  | 21.5                      | 13.68                     | 21.43                    |
| Semiarid-Mediterranean | Central Las Nieves | 23  | 828.9                  | 16.2                      | 13.68                     | 19.37                    |
| Mediterranean          | Convento Viejo   | 24         | 721.2                  | 19.3                      | 15.04                     | 23.53                    |
| Mediterranean          | Los Queñes       | 25         | 1183.8                 | 25.2                      | 18.89                     | 30.13                    |
| Mediterranean          | Potrero Grande   | 26         | 1103.1                 | 25.7                      | 19.14                     | 30.66                    |
| Mediterranean          | Ponchue          | 27         | 673.0                  | 15.9                      | 12.37                     | 19.15                    |
| Mediterranean          | Talca            | 28         | 661.9                  | 14.3                      | 10.78                     | 16.27                    |
| Mediterranean          | San Javier       | 29         | 767.5                  | 14.2                      | 12.14                     | 18.04                    |
| Mediterranean          | Colorado         | 30         | 1387.4                 | 25.6                      | 17.15                     | 28.23                    |
| Mediterranean          | Melozal          | 31         | 743.3                  | 23.0                      | 13.05                     | 22.68                    |
| Mediterranean          | Embalse Ancoa    | 32         | 1506.4                 | 23.4                      | 12.23                     | 23.39                    |
| Mediterranean          | Parral           | 33         | 968.8                  | 19.3                      | 14.77                     | 23.68                    |
| Mediterranean          | Embalse Digua    | 34         | 1519.8                 | 25.8                      | 20.06                     | 30.91                    |
| Mediterranean          | Embalse Bullileo | 35         | 2157.1                 | 22.4                      | 18.54                     | 25.60                    |
| Mediterranean          | San Manuel       | 36         | 1391.7                 | 23.0                      | 17.62                     | 28.49                    |
| Subhumid humid         | Embalse Colihueco| 37         | 1512.8                 | 36.5                      | 21.93                     | 40.17                    |
| Subhumid humid         | Chillán Viejo    | 38         | 1093.4                 | 22.1                      | 18.33                     | 29.02                    |
| Subhumid humid         | Embalse Diguín   | 39         | 2143.5                 | 30.2                      | 20.28                     | 32.20                    |
| Subhumid humid         | Quilaco          | 40         | 1572.1                 | 26.0                      | 17.62                     | 27.62                    |
| Subhumid humid         | Cerro El Padre   | 41         | 2131.3                 | 28.8                      | 19.83                     | 30.52                    |
| Humid                  | Traiguén         | 42         | 1016.2                 | 20.4                      | 13.87                     | 22.03                    |
| Humid                  | Curcautín        | 43         | 1750.8                 | 15.3                      | 13.98                     | 20.44                    |
| Humid                  | Pueblo Nuevo     | 44         | 1201.5                 | 14.3                      | 13.09                     | 18.62                    |
| Humid                  | Pucón            | 45         | 2154.5                 | 18.9                      | 14.18                     | 21.39                    |
| Humid                  | Lago Calafquén   | 46         | 2113.7                 | 17.8                      | 14.13                     | 19.39                    |
| Humid                  | Llanquihue       | 47         | 1983.1                 | 26.4                      | 17.39                     | 27.05                    |
| Humid                  | Puelo            | 48         | 3891.0                 | 16.1                      | 12.74                     | 20.21                    |
| Cold-semiarid          | Punta Arenas     | 49         | 422.8                  | 13.0                      | 7.59                      | 12.85                    |

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

| Climates zone            | Station/Location     | Map number | Maximum intensity of rainfall (mm h⁻¹) | Year of occurrence | Return period (yr) | Exceedance probability (%) |
|--------------------------|----------------------|------------|----------------------------------------|--------------------|--------------------|----------------------------|
| Hyperarid                | Putre 1              | 7.9        | 2007                                   | 21                 | 4.9                |
|                          | Parinaíca 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                |
|                          | Parque 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                |
|                          | Potroco 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                |
|                          | Melolaz 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 Buillío 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.

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

| 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).

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.](image)

| Climatic zone               | Region              | Station/Location   | Map number | South latitude | Annual rainfall amount | Maximum rainfall intensity T = 100 yr |
|-----------------------------|---------------------|--------------------|------------|----------------|------------------------|--------------------------------------|
| 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                                |
|                             | Metropolitan        | Los Panguiles      | 20         | 33°26’         | 361.5                  | 19.20                                |
| Semiarid-Mediterranean      | Libertador General  | Central Las Nieves | 23         | 34°29’         | 828.9                  | 19.37                                |
| Mediterranean               | O’Higgins           | Curacauín          | 43         | 38°26’         | 1730.8                 | 20.44                                |
| Humid                       | Maule               | Pencahuín          | 27         | 35°23’         | 673.0                  | 19.56                                |
|                             | La Araucanía        | Curacauín          | 43         | 38°26’         | 1730.8                 | 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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