ECONOMIC IMPACT OF HEAVY RAINFALL IN SAN JUAN, PUERTO (1987-2016)

Resumen

En este artículo se realiza un análisis de los eventos de precipitación extrema y su impacto económico para la ciudad de San Juan, Puerto Rico en el periodo de 1987 a 2016. En análisis se excluyó las precipitaciones originadas por sistemas ciclónicos (Tormenta y huracanes). Se consideró como precipitación intensa los valores mayores de 50.88 y como muy intensas las precipitaciones mayores de 101.6 mm en 24 horas. En el periodo de 1987 a 2106, la tendencia es positiva. En este último periodo los episodios extremos muestran un aumento de 12%. Con relación al periodo 1957-1986 NWS (2010). El impacto en la economía ascendió a **US $ 179,691,703**, y muestra una tendencia al crecimiento en correlación la frecuencia en aumento del número de eventos extremos. El impacto de algunos eventos no aparece cuantificado, lo que causa una discrepancia entre los daños causados a la economía y los eventos ocurridos. Por otro lado, el crecimiento urbano poco planificado, así como un aumento en pavimentación de los espacios urbanos y una disminución de las áreas verdes, generan un aumento en la escorrentía, contribuyendo a las inundaciones urbanas. Finalmente, la contribución principal de esta investigación a la práctica es que como muestran los resultados, el tiempo atmosférico es una variable que debe ser considerada como parte de la estrategia corporativa ya se requerirá de una inversión importante para lograr tener una empresa resiliente.

Abstract

In this article an analysis of extreme rainfall events and their economic impact for the city of San Juan, Puerto Rico in the period from 1987 to 2016 is made. In this analysis, precipitation caused by cyclonic systems (Storms and Hurricanes) was excluded. The highest values of 50.88 mm were considered as intense precipitation and the highest precipitations of 101.6 mm in 24 hours were considered as very intense. In the period from 1987 to 2106, the trend is positive. In this last period the extreme episodes show an increase of 12% in relation to the period 1957-1986 NWS (2010). The impact on the economy amounted to US $ 179,691,703 and shows a growing trend in correlation with the increasing frequency of the number of extreme events. The impact of some events does not appear quantified, which causes a discrepancy between the damage caused to the economy and the events that occurred. On the other hand, unplanned urban growth, as well as an

increase in the paving of urban spaces and a decrease in green areas, generate an increase in runoff, contributing to urban flooding. Finally, the main contribution of this research to the practice is that as the results show, the weather is a variable that should be considered as part of the corporate strategy and it will require a significant investment to achieve a resilient company.

Key Words. Heavy rainfall, Economic Impact, Puerto Rico.

Introduction

The term "heavy rainfall" refers to instances during which the amount of precipitation experienced in a location substantially exceeds what is normal. What constitutes a period of heavy precipitation, therefore, varies according to location and season. Climate change can result in very heavy or intense precipitation, changes that are often disruptive to the environment and the economy Edward & Owens, (1991); Groissman et al., (2005). Warmer oceans increase the amount of water that evaporates into the air. When more moisture-laden air moves over land or converges into a storm system, it can produce more intense precipitation (e.g., heavier rain and snow storms; Tebaldi et al., (2016). The potential impacts of heavy precipitation include urban flooding, crop damage, soil erosion, and an increase in flood risk due to heavy rains. In addition, runoff from precipitation can impair water quality as pollutants deposited on land wash into water bodies.

Intense precipitation does not necessarily mean that the total amount of precipitation in a location has increased, but the time elapsed during the event is shorter, and the effects can be magnified because the environment has been modified through construction and paving. Changes in the intensity of precipitation, however, when combined with changes in the interval between precipitation events, can also lead to changes in overall precipitation totals (Groisman et al. (2005); Harnack et al., 1999; Konrad, (1997). In the case of San Juan, Puerto Rico, these intense rains frequently turn into flash floods. Climate patterns on the tropical islands of the Caribbean are mainly associated with global oscillations, tropical systems, and Easterly trade winds of the synoptic scale, orographic effects, circulations induced by the ocean, and convective scale instabilities related to intense surface heating Malmgren et al., (1998); Taylor et al. (2002); Comarazamy, (2008).

In the case of Puerto Rico (PR), its geographic and topographic characteristics, in addition to a conditionally unstable atmosphere combined with the sea breeze and the high amount of humidity available at surface level, are the main causes of rainfall on the island. In the same way, we could mention other atmospheric features such as mid- and upper-level trough, cold fronts, and tropical cyclones as potential extreme precipitation sources.

The average precipitation over a 30-year period (1981–2010) is ∼1800 mm/year, and the rainfall has a bimodal pattern with two rainy seasons Méndez- Lazaro et al., (2016). A relatively dry season occurs in the summer months, June and July. The wet season takes place in May and autumn (October and November). Easterly trade winds prevail most of the year over the island, with local winds influenced by the diurnal heating cycle. Average air surface temperatures range from 22 to 28°C Colón, (2009), but maximum air surface temperature and heat index can reach 36 to 38°C under summer's extreme conditions.

According to Van Beusekom et al. (2015), the driest months of the annual dry, early, and late rainfall seasons showed a small increasing trend in the precipitation—around 0.1 mm day^{-1} yr^{-1}. They concluded that components of precipitation had different absolute and percentage trends along an elevation gradient in northeastern PR from 2001 to 2013.

Sometimes, these intense or extreme rain events result in serious impact to the economy and to the safety of the population through loss of human life and damage to public and private property. Flash floods are one of the greatest operational meteorology challenges. Historically, these are the main cause of deaths in natural disasters Staes et al., (1994). The principal challenge for the meteorologists is to forecast the flash flood event in advance and produce the necessary warning for the right areas of impact. Several rapid flood studies have identified numerous factors that contribute to sudden flooding Doswell et al., (1996); Stephenson et al., (2014) and produce various impacts such as landslides and transportation problems Larsen et al., (1993).

For the period 1900-2007, at the 139 stations analyzed by Torres-Valcarcel (2014) in PR, precipitation declined in PR during most of the century and in the ecological life zones of Holdridge, particularly before 1970—a period when the average and monthly mean curves were relatively consistent. Precipitation over urban areas dominates in the Humid Forest while precipitation over nonurban areas dominates in the Dry Forest. This result suggests that, if the positive trend in precipitation is not simply part of a climate cycle, it may be due to increasing urban development and a higher sensitivity or response to urban impacts in wetter areas of PR (e.g., the northeast). Due to the impact of heavy rains in Puerto Rico, specifically in the metropolitan areas, will conduct an analysis of the trend of heavy rains in San Juan, with the objective of quantifying the economic impact of these meteorological phenomena for the period 1987-2016

Historic rainfall was registered at the San Juan airport on July 18, 2013 Votaw et al., (2013). It was estimated that more than US $10,000,000 in property damage resulted from the 50.8 mm to 101.6 mm of rain across most of the area, with a maximum well over 230 mm and around the airport. This is more than a factor of two larger than the mean flash flood damage per event (i.e., about $420k) as reported in the NWS 2006-2016 Local Storm Report Database, shown in Figure 1. In that period, PR had 621 flash flood events with a mean total damage per event of US $42,739. The largest flash flood event in PR resulted in total damage of US $20M in 2008. People lost countless hours as they became stranded by floodwaters, were blocked from going where they needed to, and lost business from flooding.

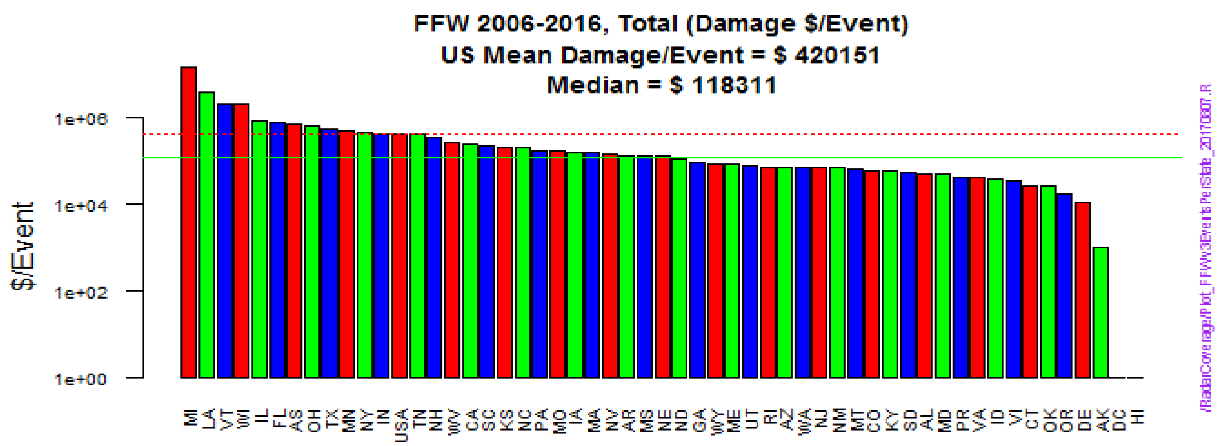

Figure 1. Mean damage per flash flood event per US jurisdiction from the US National Weather Service local storm report database. The mean damage per event in $420k (median $118k) and the mean damage for such events in Puerto Rico is less than $300k per event.

Previous studies Enfield et al (1999), Amador, (2008); Gamble & Curtis, (2008); Wang et al., (2007); Glenn et al., (2015) have documented connections between sea surface temperatures (SSTs) in the Intra-Americas Region (IAR), defined as the geographical region that includes the Caribbean, Mexico, Central America, and parts of North and South America; the IAR is a distinctive region of dynamic climatological processes. The range of regional climatological features includes traveling easterly waves and trade winds, tropical storms and hurricane activities, convective systems, cold fronts from the north reaching tropical regions, the Mid-Summer Drought

(MSD), the Atlantic Warm Pool (AWP), and the Caribbean Low-Level Jet (CLLJ) Amador et al (2008).

The weather and climate of tropical islands is also affected by strong maritime influences as well as synoptic scale phenomena, such the North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO), the Trade Winds, and the Warm Water Pool North Atlantic, as well as the behavior of the Azores anticyclone, called Caribbean Regulators Climate Centers (CRCCs) Mendez-Tejeda et al., (2016). The link between increases in extreme precipitation and climate change is robustly established Folke et al., (2005). As the atmosphere warms, it can carry more moisture. Extreme precipitation events have been found to scale with the moisture-carrying capacity and are projected to intensify by about 6% per °C of warming Lonsdale et al., (2015).

Many articles in the last 15 years have analyzed the episodes of intense rainfall problems, establishing links between tropical and Pacific Atlantic SSTs and precipitation from the Caribbean / Central America; Giannini et al., (2000); Taylor et al., (2002); Stephenson et al., (2008), Alfaro (1998), generally with the aims of understanding regional dynamic drivers and identifying possible seasonal forecasting potential. Changes in daily precipitation and temperature extremes have been considered Peterson et al., (2002) and (2014); Mclean et al., (2015), but this timescale is not considered in this research. During strong storms, it has increased by 33% in the EPA of Puerto Rico 2017, and it is likely that the trend towards increasingly strong storms will continue due to the effect of the (CRCCs) More intense storms can increase floods as inland rivers exceed the highest levels frequently, and more water accumulates in the low areas that drain slowly due to the unplanned urban growth. Larger areas prevent the soil from absorbing the water and, therefore, increase runoff. All this causes major problems for the urban populations, both in transportation and in flash flooding, throughout the metropolitan areas (i.e., San Juan, Carolina, Bayamón and Guaynabo).

Changes in heavy rainfall intensity have been reported for various regions of the Caribbean Stephenson et al., (2014). The objective of this study was to fill part of the existing knowledge gap by examining trends in intense rainfall and its economic impact in the metropolitan area of San Juan. The biggest inconvenience that we found was that there is no institution that stores this data; we have had to collect this information from various sources such as the National Weather Service, Statistical Institute of Puerto Rico, Emergency Management Agency, and Municipality of San Juan.

Site Description

Puerto Rico (PR) is an island bordered by the Caribbean Sea to the south, and the Atlantic Ocean to the north. Measuring approximately 180 km by 65 km, it is the smallest island in the Greater Antilles. In truth, Puerto Rico includes several islands, including Vieques and Culebra to the east, and Isla Mona to the west. These islands are densely populated in a small geographic area. Puerto Rico is situated at latitude 18º 31’ N and longitude of between 66º and 67º W. The highest point in Puerto Rico is Cerro de Punta, a mountain peak in the Cordillera Central, at 1,338 meters (4,389 feet) of elevation. Sierra de Luquillo is an isolated range located on the northeast part of the island. This range contains the peak El Yunque, which harbors a rainforest that receives some of the highest rainfall totals on the island Cruz & Boswell, (1997).

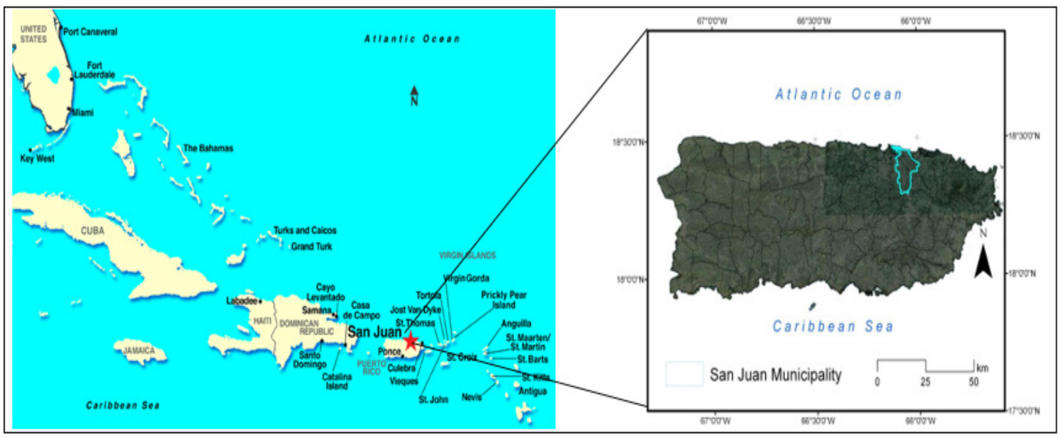

Figure 2. Shows the geographical location of the city of San Juan, Puerto Rico, located in the Caribbean, affected by the Atlantic Ocean and the Caribbean Sea.

The first-order weather station at the airport, operated by the National Weather Service, is an important source of meteorological and climatological information for the Caribbean region. The research data used corresponds to the meteorological station located in San Juan, Puerto Rico at the Luis Muñoz Marín International Airport. The data is validated and supplied by National Climatic Data (NCDC).

Data and Methodology

According to the National Weather Service (NWS), a *heavy rainfall* defined as a significant rainfall of 1 inch (25.4 mm) of rain per hour during 3 consecutive hours Schumacher (2003). To this investigation, the daily rainfall data series of the San Juan weather station were analyzed by counting the following: (a) total days with precipitation greater than 1mm; (b) the total days with precipitation greater than 50.8 mm; and (c) the number of days with precipitation greater than 101.6 mm (See Tables 1).

Contribution to Total Days with Precipitation
1987-2016 (30 years)

Total days	10,958	(100%)
Total days with precipitation	6,142	(56%)
Total days with precipitation above 1mm	4,670	(76%)
Total days with precipitation above 50.8 mm (heavy)	100	(1.63%)
Total days with precipitation above 101.6 mm (very heavy)	11	(0.20%)

Table 1 *Trend Characteristics in the Number of Days with Heavy and Very Heavy Precipitation over the Contiguous San Juan, Puerto Rico (1987-2016)*

Events of Intense Precipitation Occurring from 1987 to 2016

Date of the Event Heavy Precipitation	**Total Cost (US$)**	**Precipitation (mm)**
Apr. 12 1987	1,098,365	98.55
Jan. 05, 1992	2,873,262	95.00
May 15, 1995	1,899,545	100.33
Aug. 23, 2000	1,225,187	61.98
Nov. 6, 2001	5,147,725	97.028
Nov. 22, 2001	4,853,371	69.088
Nov. 23 2003	65,217,483	61.976
Jun. 24, 2004	4,887,408	97.028
Apr. 21, 2005	7,358,275	130.42
Oct. 10, 2005	5,889,678	100.82
Oct. 1, 2008	57,628,531	73.94
Aug. 23, 2011	1,847,409	146.304
Jul. 14, 2011	7,427,467	55.37
Jul. 18, 2013	10,000,000	234.44
Apr. 23, 2016	2,337,997	147.83
TOTAL	**US $ 179,691,703**	

Table 2. Sources: State Agency for Puerto Rico Emergency Management (PREMA), Municipality of San Juan, National Weather Service, Office of Planning of Puerto Rico, Firefighters of Puerto Rico.
*Some events do not appear quantified in the archives of these agencies

In the selection of the data, we have excluded the precipitation produced by cyclonic phenomena (e.g., hurricanes, depression storms). Most of the rain is convective-type, where the sea breeze has a very important role. Some of this precipitation can be caused by the cold fronts that arrive during the winter to the region, especially in November and January.

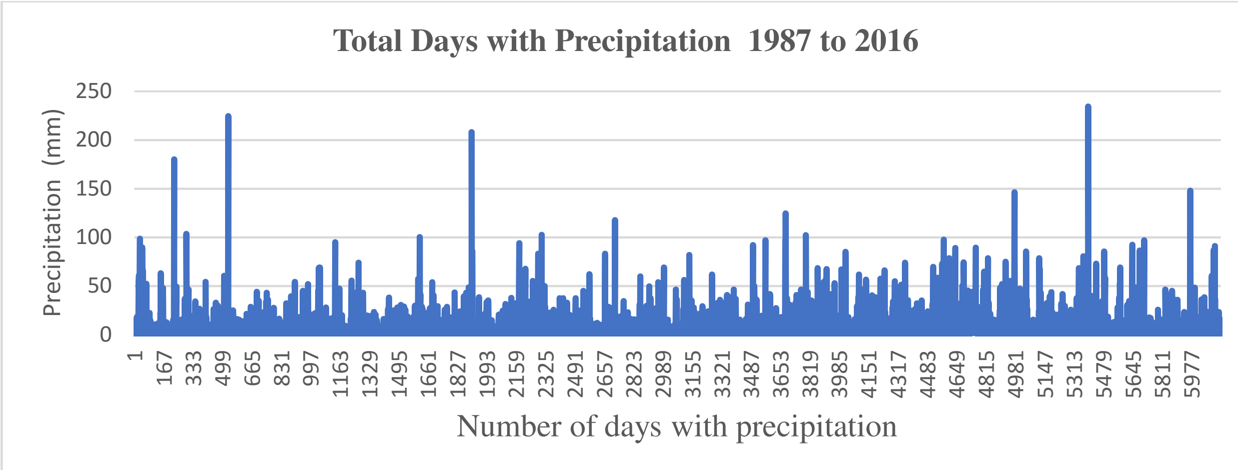

Figure 3. Total daily with precipitation for the Station of San Juan, Puerto Rico (1987-2016).

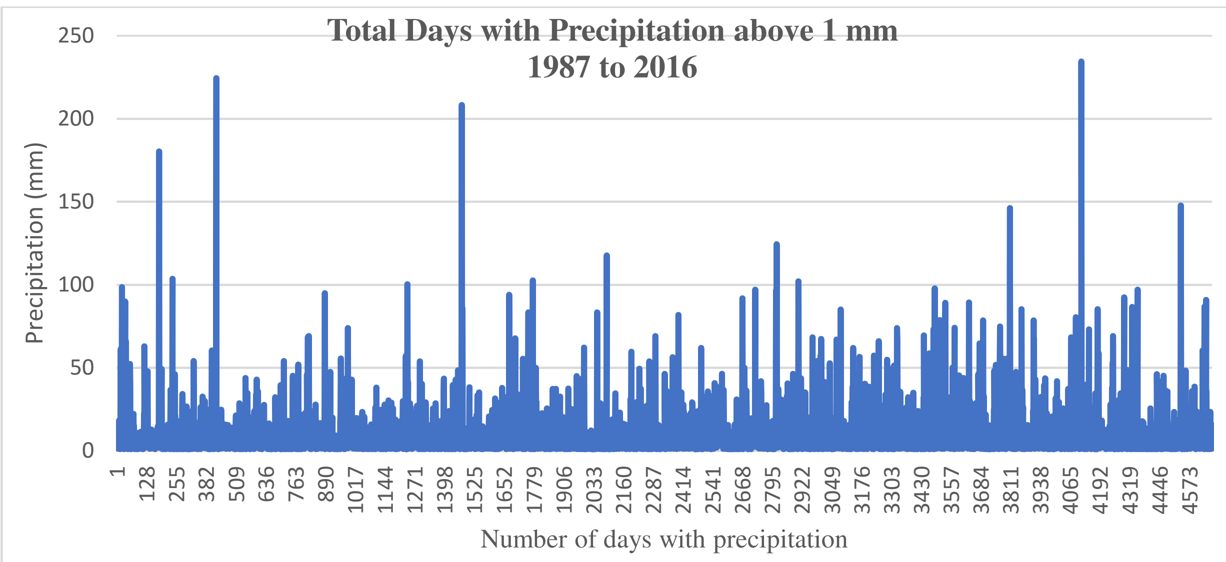

Figure 4. Total daily with precipitation above 1 mm for the Station of San Juan, Puerto Rico (1987-2016).

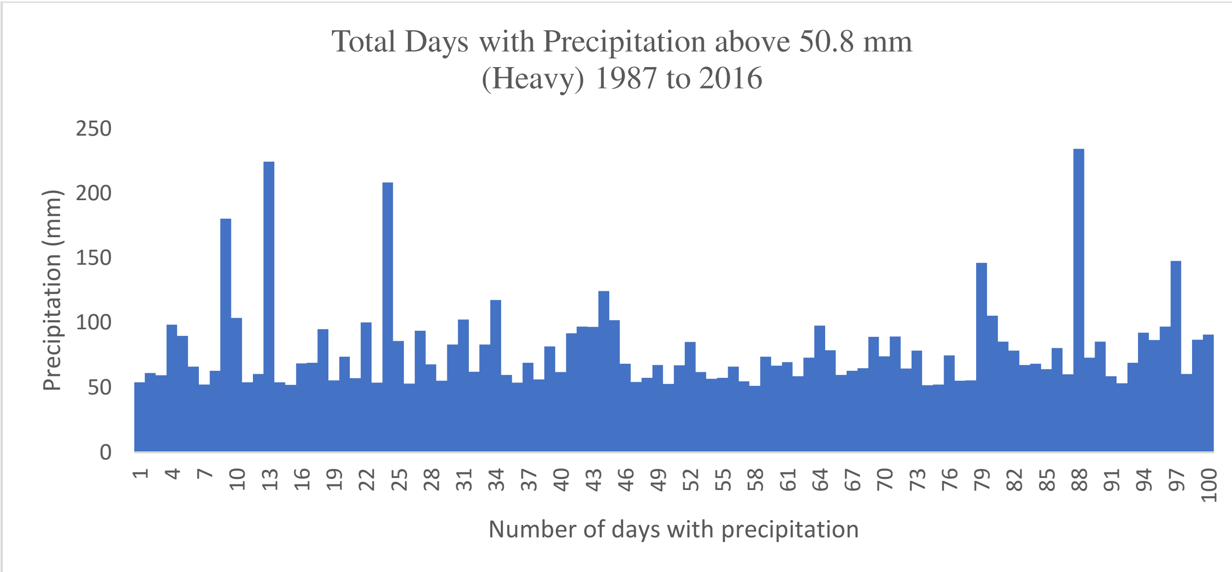

Figure 5. Total daily with precipitation above 50.8 mm for the Station of San Juan, Puerto Rico (1987-2016).

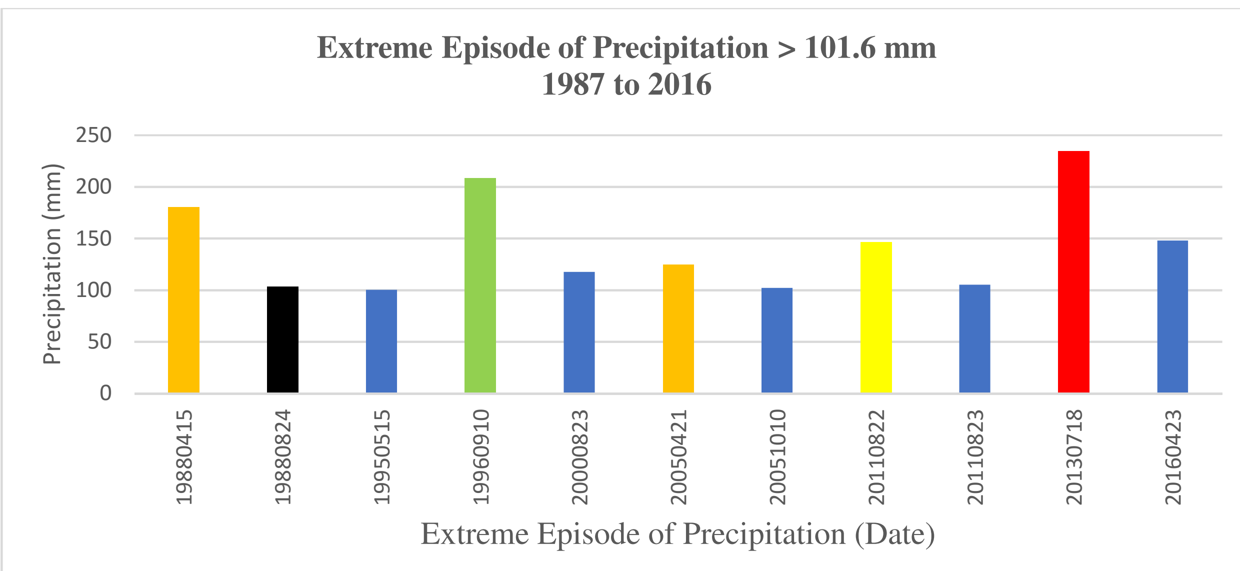

Figure 6. Total daily with precipitation greater 101.6 mm (episode extreme) for the Station of San Juan, Puerto Rico (1987-2016).

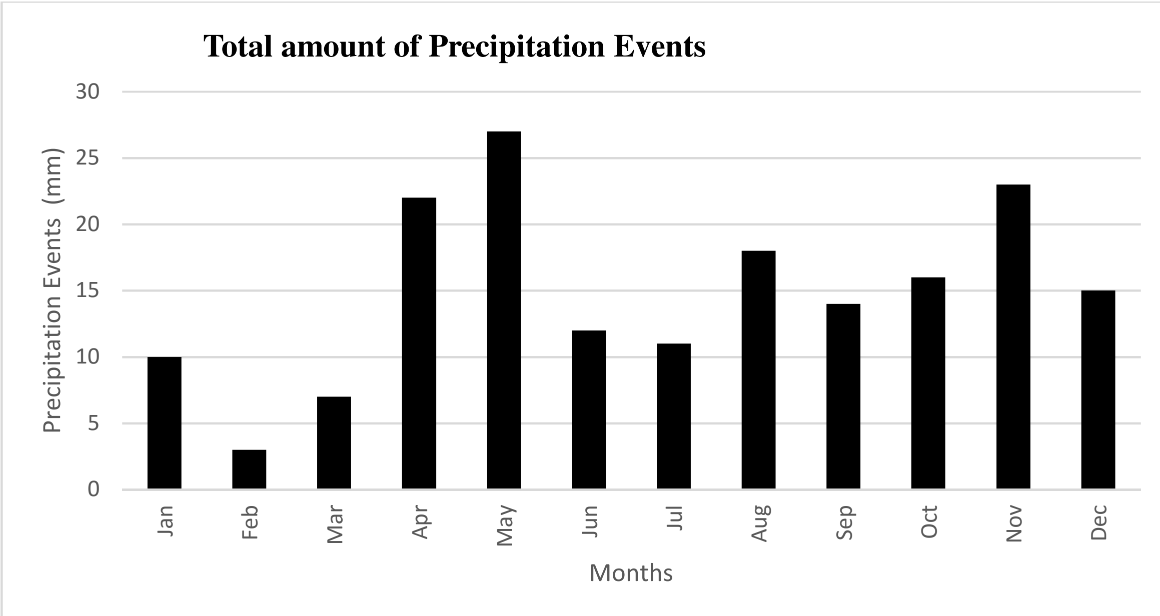

Fig 7. shows the behavior of heavy precipitation events per month for the 30-year series (1987-2016). The impact of some of these events has not been quantified.

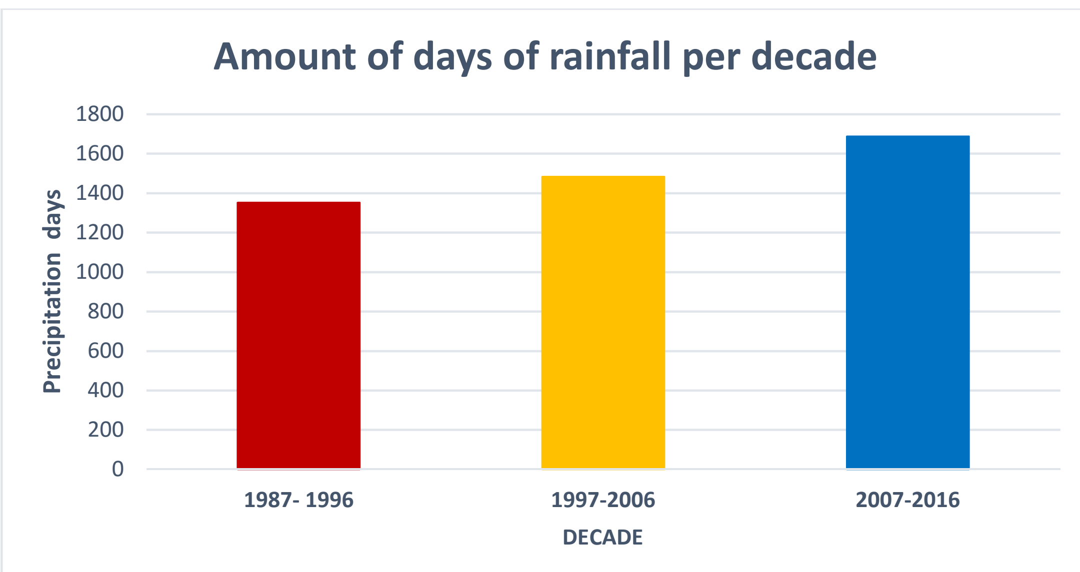

Figure 8. Total of events (days of precipitation) by decades (mm)

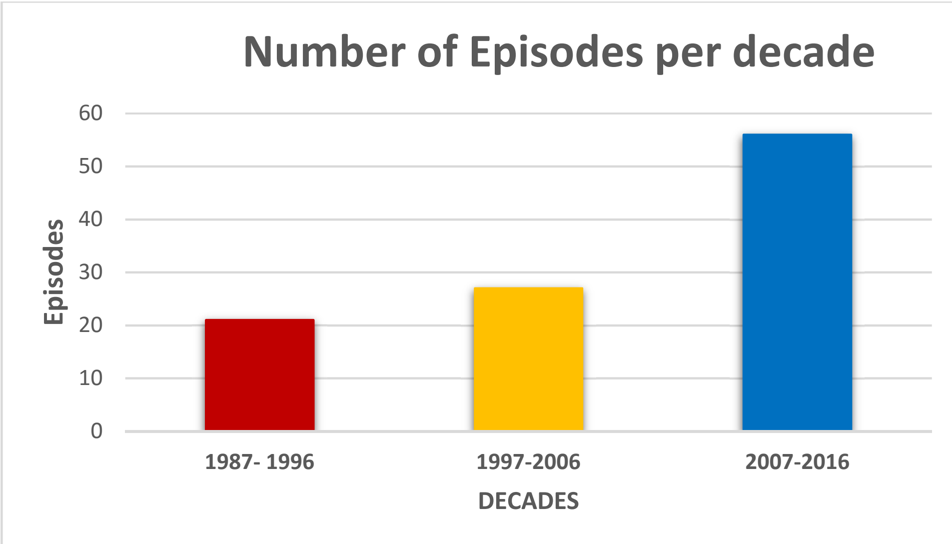

Figure 9 Total Extreme Episodes for every decade

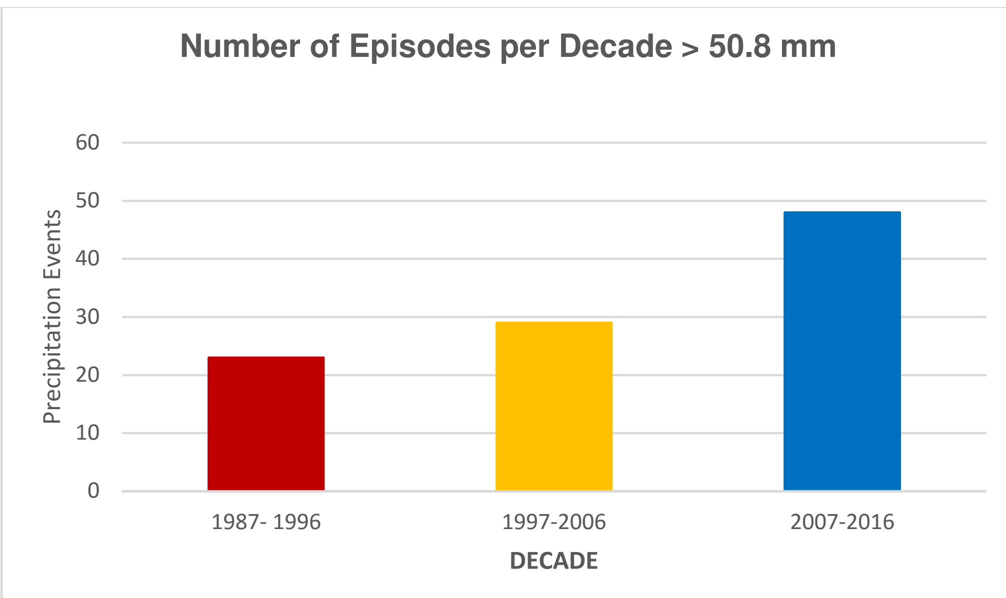

Figure 10. Total amount of precipitation events above 50.8 mm for each decade.

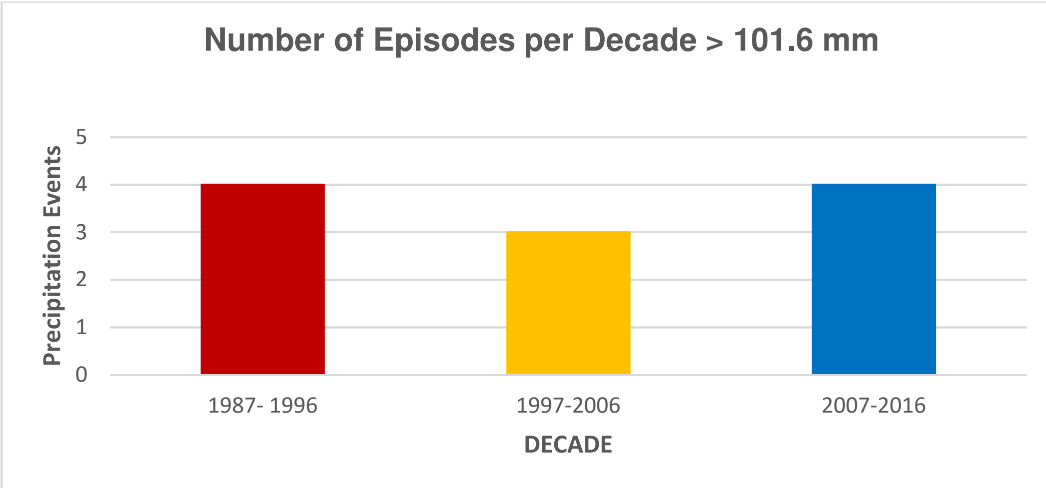

Figure 11. Events with total precipitation > 101.6 mm per decade

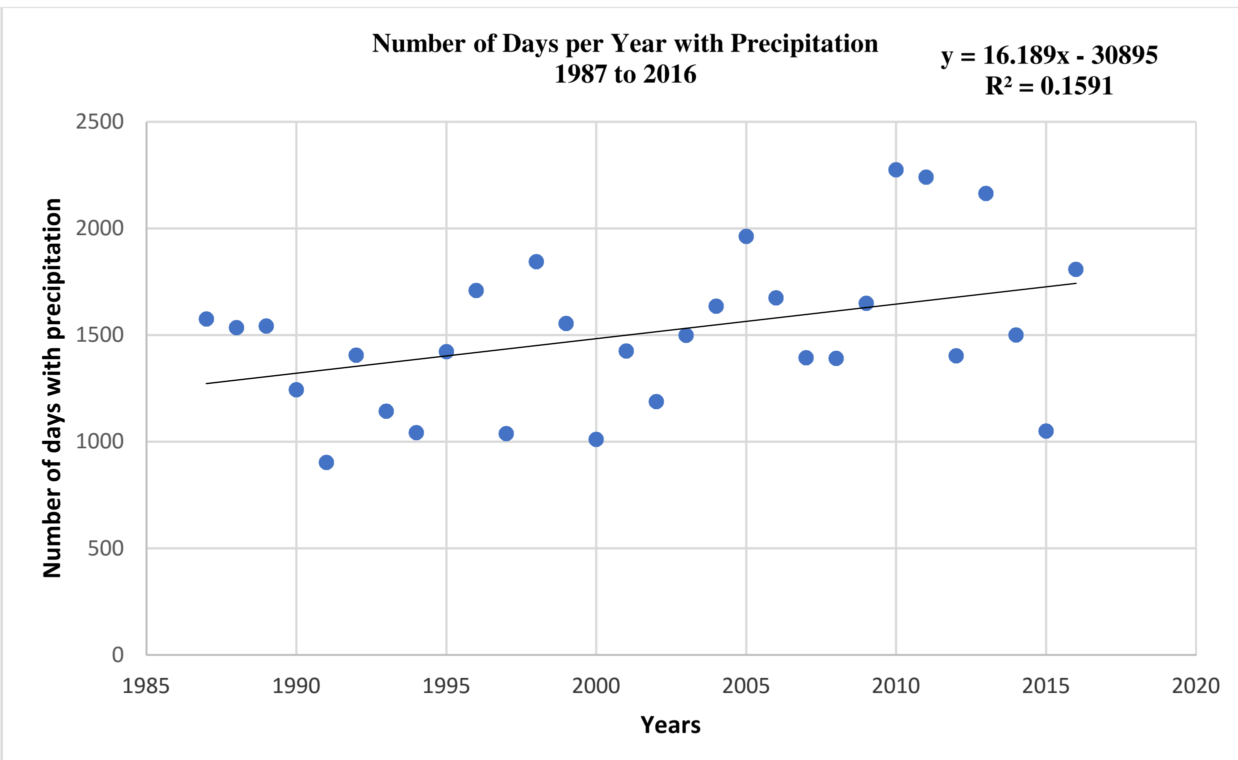

Figure 12. Total days per year (annual) of non-zero precipitation for the period from 1987 to 2016 show a slight decrease in precipitation-days with time. Index of determination is 0.084.

Economic Impact of Intense Rainfall

In the case of the metropolitan area and, especially, the Municipality of San Juan, floods have caused severe damage almost every year. Recurrent drainage problems exacerbate problems in urban areas. The increase of runoff waters and the consequent floods due to both poor drainage and unplanned urban development, as well as the increase in sudden rains, cause the warning time to be very short—1 or 2 hours (see Table 2)—thus increasing the risk of loss of lives and property. According to the Multi-Risk Mitigation Plan of the Autonomous Municipality of San Juan (SJ; 2015), of all the natural hazards to the Municipality, floods are the greatest problem since they affect a substantial percentage of the residents. The economic impact of these events in the period 2000 to 2016 totaled US $ 179,691,703, the combined cost of public assistance and individual assistance, source Puerto Rico Emergency Management (PREMA). More than half (31.14 km^2) of the total area of the municipality (60.63 km^2) is susceptible to flooding (51.4%), SJ (2015). It is estimated that in the metropolitan area, more than 160,000 families live in flood zones. Of these, there are 14,500 families and 55,000 inhabitants living in areas at maximum risk of flooding (see Table 2).

Discution and Conclusion

The probability of these extreme events has been estimated in Technical Paper 42 (1961), and was determined based on the occurrence of past events that caused sliding and flooding in the area. According to this probability determination, these extreme rainfall events must occur every 100 years or in a period of 500 years; however, with the increase of 2.24°C in temperature Mendez-Tejeda, (2017) and the manifestation of global warming, these events are more frequent.

During the period 1957-1986 in figure. 4, the trend is maintained for those days with precipitation greater than 1.0 mm; however, in episodes of extreme rainfall > 101.6 mm/day, no clear trend is observed (figure 5). The most relevant episode (figure 6) of 234.44 mm (red bar), occurred on July 18, 2013—a historic rainfall at San Juan, PR (9.23 inch = 234.44 mm in 24 hr. maximum rainfall).

The trends for the entire period from 1987 to 2016 show that the months of May and November form two peaks of precipitation events (figure 7), which coincides perfectly with the bimodal behavior of precipitation in PR, according to the findings of Colon 2009. Sin However, this figure does not agree with Table 2, because some phenomena have not been quantified by government agencies. This same behavior is present in annual events greater than 50.8 mm and greater than 101.6 mm (see figure 4 and 5). On the other hand, in Figures 8 and 9 an increase in precipitation event frequency per decade can be observed. In the case of the 2007-2016 decade, there has been a very high increase in the last seven years of this decade (2010 to 2016), although in this decade one of the most extreme drought episodes of the last 30 years occurred, when compared to the drought period of 1967 and 1994 (DRNA, 2016).

Some publications, such as Glenn et al., (2015) and Martinez (2015), report an increase in humidity as of 2008, except for the period 2013 to 2015. When the results of Table 1 are compared with the findings of Mendez et al (2018), the number of episodes with precipitation greater than 508 mm (0.28%), representing an increase of 12% compared to the first period. In terms of the most extreme precipitation (> 101.6 mm), there was an increase of 65% compared to the first period with 35%. This increase coincides with an increase in surface temperatures in PR Méndez-Tejeda, (2017).

When analyzing the behavior for decades, we can conclude that the number of episodes of intense precipitation (> 50.8 mm) per decade shows a growth trend in the three decades studied (figure 10), while for episodes of very intense precipitation (> 101.6 mm), increases for the first decade, it decreases in the second decade, to increase again in the third decade (figure 11).

The economic impacts and damage to properties due to flash floods have reached the amount of US $ 179,691,703. In the analysis, the authors have been able to include the data reported by the various agencies and government departments (see table 2). Some expenses have been impossible to quantify due to lack of official reports. Finally, the figure 12, shows that in the analyzed period of 30 years (1987 to 2016), the number of precipitation events has increased by 3% in relation to the results of Mendez-Tejeda (2017), for the period of 1957 to 1986, with a R^2 = 0.1591.

The increase in the impact of heavy rains is increasing every year due to the expansion in the construction of the island that has occurred especially in the period from 1990 to 2005, a period that coincides with great economic growth, especially in the construction. There was huge economic growth and construction of the large urbanizations and squares, paving large areas of land, which increases the runoff in the city. Better planning and cleaning of sewage systems could help to reduce these impacts. The main contribution of this research is to the practice since the data show that the weather variable must be considered as an integral part of the corporate strategy.

Extreme events due to climate change will continue to occur more frequently, so the investment needed to be a resilient organization is part of the very subsistence of the company This analysis is important for any industry but especially for industries sensitive to changes in weather such as the agricultural industry. Where if they fail to adapt can generate a food crisis.

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