Flooding threshold rainfall events in Bermuda

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Introduction

Bermuda is a small oceanic island with low rising relief in the western North Atlantic Ocean (Figures 1(a) and (b)). In recent years, the societal profile of flooding events in Bermuda has been increased by the ready availability of photographs and commentary on news websites and social media. These flooding events are highly localised, with primarily what may be deemed ‘nuisance impacts’; most widely reported are the instances of disruption to traffic flow, parking and potential vehicle damage. In some cases, the subsequent impacts, such as localised landslides or property flooding (Bell, 2014) may cause disruption, and major infrastructure damage is reported to have resulted from phenomena related to heavy rainfall events (Finighan, 2014). In particular, flooding issues have recently become more topical as businesses and property owners in Pembroke Parish look for a means to end the frequent flooding they experience (Johnston-Barnes, 2015). A recent digital elevation model of Bermuda shows that this area is at the bottom of a valley, mostly near sea level at around 64°48′00″W, 32°18′00″N (Figure 1(b)).

Case study – 5 January 2017

On 5 January 2017, a rainfall event brought rainfall totals widely in excess of 100mm across Bermuda, with reports of flooding in several areas. A deep long-wave upper level trough over eastern North America moved eastwards on Thursday morning, allowing a cold front to advance towards and across Bermuda (Figure 2(a)). Deep-layered flow out of the tropics allowed significant moisture transport across Bermuda. The frontal system, supported by upper level dynamics, was able to deposit that moisture in the form of an active band of heavy showers and thunderstorms (Figure 2(b)) that slowly progressed across the island, with a trailing region of light to moderate precipitation.

Rain totals for the meteorological day (0600–0600 UTC) at the Bermuda Weather Service (BWS) far exceeded several records, with 136mm of rain; 5 January 2017 constituted the 5th wettest day on record in Bermuda (Figure 2(a)). Deep-layered flow out of the tropics allowed significant moisture transport across Bermuda. The frontal system, supported by upper level dynamics, was able to deposit that moisture in the form of an active band of heavy showers and thunderstorms (Figure 2(b)) that slowly progressed across the island, with a trailing region of light to moderate precipitation.

Rainfall thresholds

Flooding threshold rainfall events in Bermuda are episodic and tend to occur in the period from June to October. The heat map in Figure 3(a) reveals that, in general, rainfall events are highly intermittent and of relatively low intensity, with a maximum daily event of 197mm recorded on 1 June 1996. ‘Rain days’ are also defined here as days on which measurable rain occurred in the record. Peñate de la Rosa (2015) concluded that events with the highest rainfall amounts are episodic and tend to occur in the period from June to October. This feature is also noted in the values of the average year, shown in Figure 3(b), which suggest the existence of a seasonal pattern of flooding extremes.

In the plot of the time series of rainfall in Bermuda shown in Figure 4, we note an upward trend in rainfall accumulations and rain days over the period 1949–2016. The coefficients of determination ($r^2$) indicate a high degree of variability and no statistical significance at the 95% confidence interval; this precludes adequate predictability of annual rainfall or numbers of rain days from a linear regression. Given the somewhat stochastic
nature of rainfall event occurrence in Bermuda (Peñate de la Rosa, 2015), this is unsurprising. However, any increases in rain rates and rain days through the time series may be broadly consistent with an expected response to warming of average surface temperatures globally (Berg et al., 2013). Given that Bermuda's rainfall is entirely from a marine source region, it is expected that this be consistent with local observations of upper ocean temperature increases in the last several decades (Palmer et al., 2007; Trenberth, 2008; Bates et al., 2012).

Rainfall and flooding events
Bermuda has no riverine systems, so it is unsurprising that there are no published flood measurements or flood watershed analyses locally. An assessment of local flash flooding potential requires the use of anecdotal data to develop inferences about the frequency of events. The flooding described in this study excludes seawater inundation and/or tidal influences on local hydrogeology features, and is intended to inform the reader on freshwater flooding events induced entirely by localised instances of above-average rainfall.

Methods
A catalogue of severe weather reports for the period 2005–2015 was created. Reports were sourced from the monthly and event reports from BWS, and the local news media. While somewhat short, this timeframe was selected to allow for inclusion of Doppler radar analyses at BWS, (Bermuda’s Doppler weather radar was installed in 2005), personal weather station measurements, and frequent online news articles.

The catalogue contains the date, description, and category of each event. For this period of record, most events were of one day’s duration. However, in the cases that were more than one day in duration, the first day of the event was recorded. The event categories recorded are flooding, hail, damaging wind, and tornadoes/waterspouts. Flooding reports were subdivided by whether they were due to rainfall, storm surge, unusual tides, or some combination of those. In addition, information was included on the geographic location of each reported event and which sources reported each event.

Daily rainfall data were obtained from three main sources. Official data came from the National Climatic Data Center (NCDC) for the period 1949–2016 for the station with the identifier 78016. These data are measurements recorded by USNAS for 1949–1995 and, subsequently, BWS from 1995 to present. A gap in USNAS data from January 1968 to June 1970 was filled with measurements by A&F at the Botanical Gardens, about 10km away. Weather Underground (WU)

Table 1
Records broken with the rainfall accumulations of 5 January 2017, with reference to single, meteorological day records for the period 1949–2016 at USNAS/A&F/BWS.

(a) Bermuda rainfall accumulation records broken on 5 January 2017

<table>
<thead>
<tr>
<th>Type of Record</th>
<th>Previous Record</th>
</tr>
</thead>
<tbody>
<tr>
<td>Record wettest for the date 5 January</td>
<td>39.12mm (5 January 1994)</td>
</tr>
<tr>
<td>Record wettest January day</td>
<td>101.35mm (11 January 1986)</td>
</tr>
<tr>
<td>Record wettest winter (December–January–February)</td>
<td>101.35mm (11 January 1986)</td>
</tr>
</tbody>
</table>

(b) Summary of top 5 Bermuda rainfall accumulation records

<table>
<thead>
<tr>
<th>Rank</th>
<th>Accumulation</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>197.36mm</td>
<td>1 June 1996</td>
</tr>
<tr>
<td>(2)</td>
<td>171.96mm</td>
<td>13 October 2016</td>
</tr>
<tr>
<td>(3)</td>
<td>157.73mm</td>
<td>31 August 1982</td>
</tr>
<tr>
<td>(4)</td>
<td>140.21mm</td>
<td>14 July 1980</td>
</tr>
<tr>
<td>(5)</td>
<td>135.64mm</td>
<td>5 January 2017</td>
</tr>
<tr>
<td>(6)</td>
<td>133.10mm</td>
<td>29 October 1967</td>
</tr>
</tbody>
</table>

*Hurricane Nicole.

Figure 2. (a) BWS synoptic chart for 0600 UTC on 5 January 2017, and (b) local IR satellite imagery, Doppler rainfall and lightning display for the same time. (c) Observations around Bermuda indicate that daily rainfall totals of 100–150mm were widespread, with isolated areas seeing >150mm. (Data sources: Weather Underground (2016), WeatherLink (2017), and Bermuda Weather Service (2017)). Note that shaded areas on this map with fewer reports are less reliable.
Rainfall and flooding in Bermuda was the main source of additional unofficial reports from personal weather stations for the period 2012–2015, to help confirm the nature of heavy rain events in terms of their duration, intensity, and spatial distribution. Additionally, descriptive detail was obtained from the BWS climate pages, which are available for the period 2000–2015.

Using the severe weather catalogue, a value by which ‘heavy’ rain events can be defined was determined. This value was defined as the mean amount of rain that fell on the meteorological day that coincided with a flood report. The mean value was chosen as a compromise, knowing that there are several flood reports associated with very local heavy rain events that resulted in little official accumulation at the airport, and that there are some unreported flood events of comparable magnitude to those reported. The local character of these rain events was confirmed using personal weather station and radar analyses.

This threshold was then used to examine the number of heavy rain events by year and month. These statistics were then compared to the number of flood reports over the period of record of the severe weather catalogue.

A recurrence interval is then computed using the entire period of record of rainfall data from 1949 to 2015 as follows:

\[ RI = \frac{n + 1}{m} \]  

where \( RI \) is the recurrence interval, \( n \) is the number of years in the period of record, and \( m \) is the rank of each rainfall measurement where ties are assigned the highest common rank (1 is the highest). This was used to estimate the recurrence interval of a ‘heavy’ rain event. The calculated values were fitted to a function with the best \( r^2 \) value. This best fit was determined by comparing that of the linear, second and third order polynomial, and natural log fits.

**Results**

The summary of severe weather reports using this method returned 32 counts of flooding reports exclusively due to heavy rainfall, three counts due to combined storm surge and rainfall, and two counts due to unusually high tides. The heavy rainfall threshold was found to be 39.3mm (Figure 5), and the results turned up several areas that flooded on multiple accounts. These areas are mainly low-lying parts of Pembroke Parish, including areas within the City of Hamilton.

Figure 6(a) suggests that there is some relationship between the number of heavy rain days per year and the number of flood reports and 24hr rainfall (2005–2015). The mean (39.3mm) is used as the threshold for defining a ‘heavy rain day’.
Rainfall and flooding in Bermuda

of flood reports due to rainfall. However, that relationship is less clear on a monthly comparison (Figure 6(b)). Furthermore, these figures indicate some inter-annual variability in heavy rain events. Lower counts of both flood reports and heavy rain days are noted for 2009–2011, while the other years have much higher counts (Figure 6(a)).

The recurrence interval calculations were conducted for the period of record 1949–2015. The day with the most precipitation was 1 June 1996, with 197.4mm (7.77in) of rain. The best fit to the empirical recurrence intervals is a log function:

$$\text{rain} = 17.51578 \times \ln(\text{RI}) + 73.53217$$

where $\text{rain}$ is the amount of rain that fell in a meteorological day in mm and $\text{RI}$ is the recurrence interval in years. The recurrence interval for a heavy rain day (at least 39.3mm) is found to be approximately 0.174 years (2.09 months) using the recurrence interval from observations (Equation 1), and 0.142 years (1.70 months) using the best fit (i.e. the ‘LN’ model; Equation 2), and this is illustrated in Figure 7. It should be noted that the natural log function underestimates the recurrence interval at both extremes.

Figure 8 shows the percentage of daily rain accumulations meeting or exceeding the heavy rain day threshold (39.3mm$^{-1}$) for climatological 30-year periods every five years, starting with 1951–1980 and ending with 1986–2015. It is interesting to note that the climatological proportion of rainfall events which can currently produce flooding in Bermuda is not unprecedented, and that perhaps the ability of the modern urban environment to mitigate heavy rain-fall events has diminished through recent decades. This may be due to less soil permeability/higher soil moisture content in flood-prone areas, or impedance of drainage in the built environment, exacerbated at low elevations by sea level rise.
Conclusions
The methodology presented here shows the utility of using anecdotal evidence for flood-prone locales, such as small islands/non-riverine environments, in the absence of flood depth measurements. We show that there is some relationship between reported flood events and daily rainfall in our relatively short catalogue. When flooding events induced by non-rainfall causes (e.g. tidal, storm surge) were removed from the catalogue, there were no instances of flooding detected which were unexplained by an underlying phenomenon.

The results of this study show that heavy rain days occur more than once every 2 months. This daily accumulation amount may be interpreted as a contemporary threshold for potential flooding and utilised in the development of flood guidance in conjunction with forecasts of precipitation.

The threshold for a heavy rain day estimated in this study is suspected to be low-biased. This is because rainfall is not always evenly distributed around the island, and this study uses rainfall measured in a location that doesn’t necessarily always represent the rainfall that causes each flood event. It should be reiterated that non-meteorological factors will influence the likelihood of flood occurrence. For example, the state of and changes to flood alleviation and drainage schemes are not accounted for in this study. Additionally, the respective roles of changes in land use and antecedent soil moisture conditions are neglected, primarily due to an absence of data.

Additionally, while there are extensive digitised archives of news reports (into the 1700s), the flood reports are not consistent through that record. There are known unreported events of similar magnitude to events that have been reported – even within our period of interest. An attempt was made to account for these limitations of the flood report database by using the mean daily rainfall rather than a percentile that captures the majority of the events. Furthermore, the personal weather station rainfall rates on flood days suggest that many of the flood reports are from short-duration high-intensity rain events. Using guidelines of the United States National Weather Service, many of these events would likely be classified as flash floods because of their rapid onset following or during heavy rain and the short duration of the flooding.

One drawback of our methodology is therefore the neglect of the duration of rainfall events. An analysis of rain rates at a higher temporal resolution (e.g. mmh⁻¹) would be preferable; however, only daily rainfall accumulations are available for the duration of historical record, so a long climatology of rain rates is limited to units of mm day⁻¹. Numerical simulation of rainfall mechanisms, coupled with watershed modeling, may reveal more detailed flood processes in Bermuda.

Bermuda rainfall occurrence and amounts have limited predictability in space (Penate de la Rosa, 2015), so we cannot hope to predict exactly when floods will occur, but this study provides insight into the conditions under which they may arise. This may in turn provide the backdrop against which a flood forecasting tool may be developed, given the availability of accurate predictions of rainfall amounts.

Finally, annual variability of annual rain days and annual rainfall accumulations is very high. Although both exhibit an upward trend in time, they depend greatly on the period chosen, and a linear regression fit does not yield statistical significance at the 95% confidence interval. Future challenges resulting from rainfall extremes that Bermuda may expect to incur will likely be compounded by any reduction in resilience to flooding in the urban environment.

Acknowledgements
This study was funded through the Bermuda Institute of Ocean Sciences, by the Bermuda Program internship, and the Bermuda Risk Project of the Risk Prediction Initiative. The authors thank Andres Cianca of Plataforma Oceánica de Canarias and Germán Rodríguez of the Universidad de Las Palmas de Gran Canaria for their invaluable assistance and advice on rainfall data and statistics. Rainfall data for this study was provided on behalf of the Government of Bermuda Department of Airport Operations by the Bermuda Weather Service operated by CP Aviation, formerly by BAS-Serco Ltd. Support was also provided by the Agencia Estatal de Meteorología (AEMET).

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© 2018 Bermuda Institute of Ocean Sciences doi:10.1002/wea.3096