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Probable Maximum Flood Estimation Using a Statistical Approach and a Storm Model Approach for a Watershed in Southern St. Vincent

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Probable Maximum Flood Estimation Using a Statistical Approach and a Storm Model Approach for a Watershed in Southern St. Vincent

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by

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Abstract

With the increase in frequency and severity of flooding due to natural events, there is an increased need for flood studies in order to mitigate the effects of flooding. Some of the most vulnerable countries to flooding are Small Island Developing States (SIDS). These countries face many common development challenges, including geographic and economic isolation, limited resources, environmental fragility, high costs of transportation and energy, and vulnerability to climate change and natural disasters. This project focuses on estimating the probable maximum flood (PMF) for a watershed in a SIDS. To find PMF, the probable maximum precipitation (PMP) is needed. Two methods of finding PMP, the Hershfield's statistical method and the inferential method using a storm model approach, were used in this project. The hurricane model produced a more reasonable estimate of 82 inches. Using the Soil Conservation Service (SCS) Curve Number Method, the resulting PMF was 79 inches, which was used to obtain a peak discharge estimate of 61000 cfs.

1. Introduction

Disasters are common in the Caribbean, but there has not been much consideration of the types of actions needed for long term resilience (Wilkinson et al., 2018). Understanding the factors that lead to disasters is critical in finding solutions for mitigating their effects (Wilkinson, 2018). To build resilience to disasters, the following are required: a comprehensive disaster impact assessment, legal and regulatory reforms, a recovery strategy closely linked to existing development and investment plans, and more participatory forms of planning are required. Also required, is a more systematic use of hazard information and climate science in planning decisions (Wilkinson, 2018). This paper presents a PMF study using climate science, which can be used for planning for disasters in the Caribbean country, St. Vincent and the Grenadines.

Literature Review

St. Vincent is the largest and main island of the country St. Vincent and the Grenadines. It is located in the southern Caribbean Sea and is a part of the Lesser Antilles island arc as shown in Figure 1. St. Vincent has a total area of 133 mi^2. The island has a central wooded highland influenced by the active volcano La Soufriere in the northern portion of the island. Numerous spurs and valleys radiate from this central mountainous region; and, due to the island's volcanic nature, the soils of St. Vincent are deep and fertile (Ministry of Agriculture, Industry and Labour, 1995). The climate is Tropical Maritime, with average rainfall ranging from about 60 inches along the coast to 150 inches in the mountainous center of the island. St. Vincent's mountains cause significant uplift of the moisture laden air producing heavy orographic rainfall; so, there is a wet season that lasts from July to December and a dry season for the remainder of the year. St.

Vincent lies within the Hurricane Belt, and there is the risk of hurricanes during the wet season (Ministry of Agriculture, Industry and Labour, 1995).

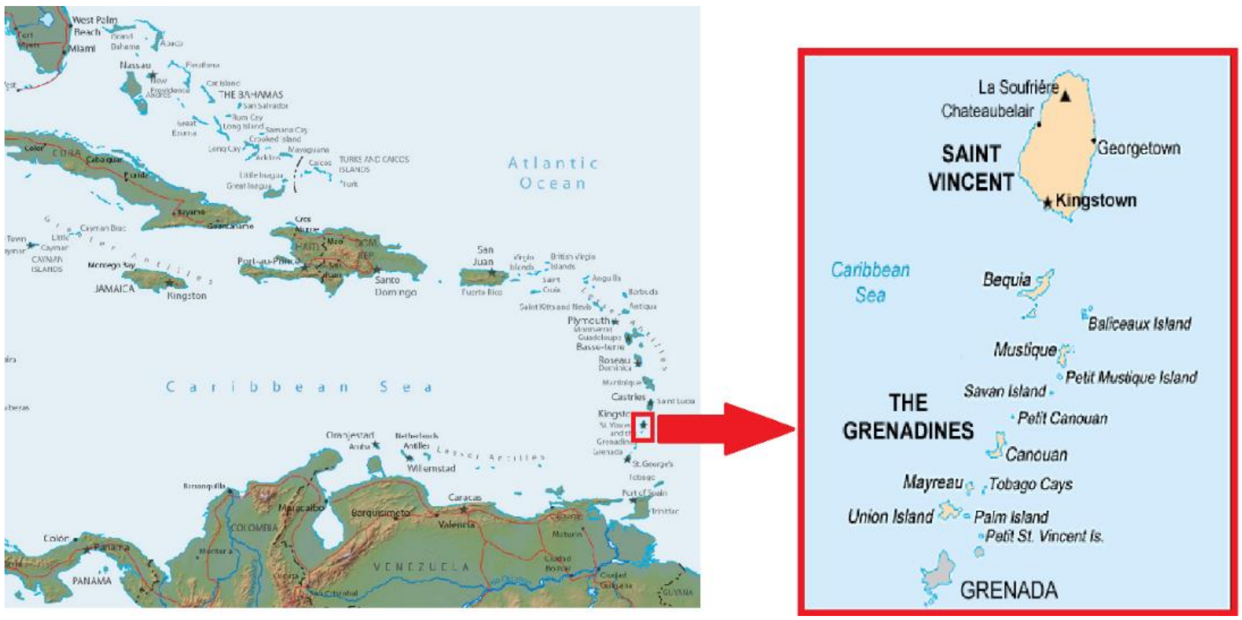

Figure 1. St. Vincent and the Grenadines on the world map (Geographic guide, n.d., Global Affairs Canada, 2012).

This study focuses on a watershed in the south of St. Vincent with an area of about 5.7 mi^2. The study area is outlined in Figure 2. From Jetten, (2016) the soil types found in the study area composes of clay loam (CL), loam (L), clay (C), sandy loam (SL), and sandy clay loam (SCL). From Westen et al. (2016), land use in the study area consists of evergreen forest, semi-deciduous forest, pastures, cultivated land and herbaceous agriculture, woody agriculture and built up area. This area includes Arnos Vale, a rapidly developing area on the island. The E.T Joshua Airport located at Arnos Vale also shown in Figure 2.

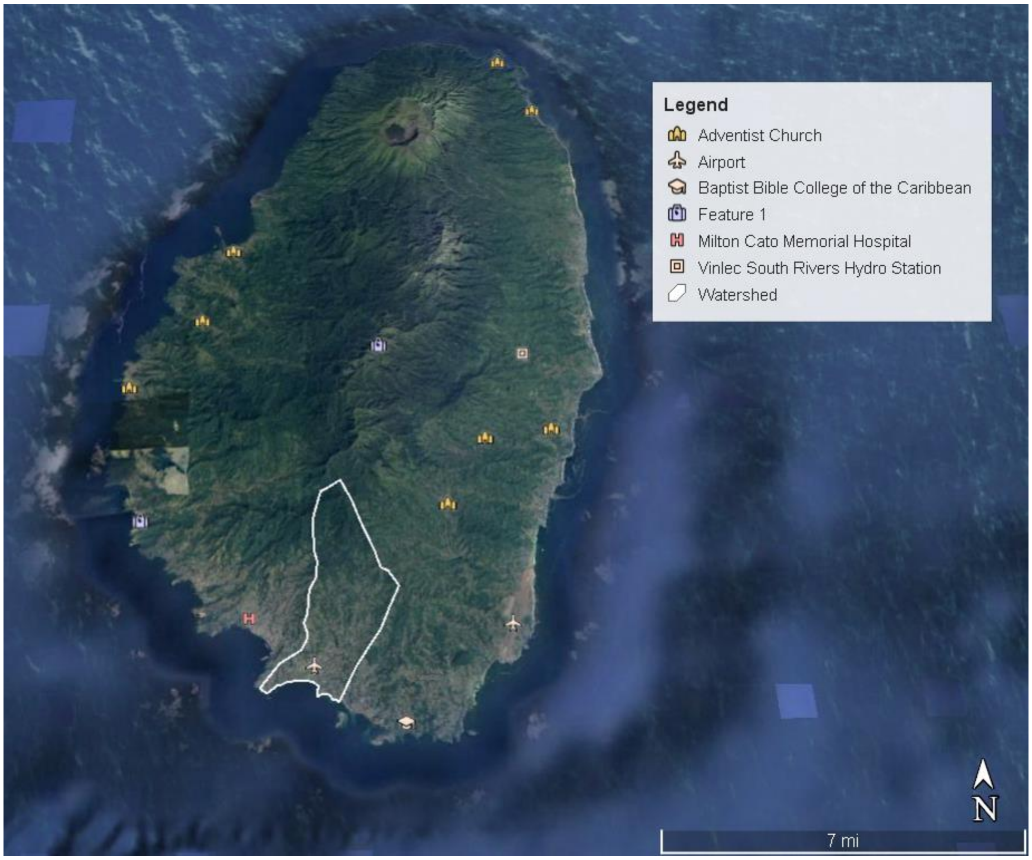

Figure 2. Map showing the watershed of study and location of meteorological station (Google Earth, 2019).

Probable Maximum Flood (PMF)

The probable maximum flood (PMF) is the hypothetical largest flood possible resulting from the prevailing meteorological and hydrological conditions of a specific watershed or drainage area (WMO, 2009). The PMF can be used by engineers for the hydraulic design of high-risk projects to prevent flood induced failure. It is typically used as a design criterion for spillways of large dams and reservoirs (Gorouh et al, 2018). The PMF can be found using different methods depending on the data that is available and the size of the area of interest. Precipitation data for PMF calculation can be found with an estimate of the probable maximum precipitation (PMP).

Probable Maximum Precipitation (PMP)

PMP is the theoretical maximum precipitation for a given duration possible in a specific location considering the meteorological conditions at a particular time of year with no consideration of long-term climatic trends (WMO, 2009). PMP values are referred to as upper physical limits of storms. Due to the physical complexity of the phenomena and limitations in data and the meteorological and hydrological sciences, only approximations of the upper limits of storms can be made (WMO, 2009). Hence, PMP values are not exact but are estimated values, and various methods have been developed to obtain these values.

The methods developed to estimate PMP values depend on factors such as the size of the drainage basin, availability of data and the amount of data recorded (Joos et al., 2005). The types of methods for estimating PMP presented by World Meteorological Organization (WMO) are:

1. local
2. transposition
3. combination
4. inferential,
5. generalized
6. statistical

The most commonly used types are statistical and inferential methods (Chavan and Srinivas, 2015). The statistical method is based on statistical analysis. Whereas, the inferential method generalizes the 3D spatial structure of a storm to generate a simplified physical storm equation or storm model, and it requires meteorological analysis and focus on the conditions for maximum precipitation development (WMO, 2009).

The U.S. Weather bureau used two methods to estimate PMP in U.S. Weather Bureau (1961). One of the methods used by U.S. Weather Bureau (1961) for determining an estimate of PMP is the Hershfield's statistical method, developed from a general frequency equation given by Chow (1951), and it is found using Equation 1.

$$X_t = \overline{X_n} + K_m S_n \qquad \text{Equation (1)}$$

Where,

X_t = Rainfall for return period t

$\overline{X_n}$ = Mean of a series on n annual maxima

K_m = Frequency factor

S_n = Standard deviation of a series on n annual maxima

This method requires at least 20 years of precipitation maxima to obtain $\overline{X_n}$ and S_n. The frequency factor, K_m is derived from the chart by Hershfield (1965), which presents K_m as a function of rainfall duration and the mean of annual series (WMO, 2009). Hershfield's method is used for estimates in small basins and is advantageous in areas such as the Caribbean where other data, such as dew point, are lacking (WMO, 2009).

The other method used by the U.S Weather Bureau (1961) to obtain PMP estimates is the inferential method using a hurricane-storm model approach. A hurricane is a tropical cyclone with sustained winds exceeding 72 mph. A tropical cyclone is the generic term for a non-frontal synoptic scale storm with organized convection and definite cyclonic surface wind circulation that is characterized by low-pressure and high winds (Zehnder, 2018). Hurricanes form over tropical or sub-tropical waters. A tropical depression is a tropical cyclone with sustained winds below 32 mph. With sustained winds of 32 mph to 72 mph, a tropical cyclone is classified as a tropical storm. A hurricane model approach was chosen by U.S Weather Bureau (1961) after it was determined from investigating historical rainfall events globally and for Puerto Rico that the PMP in Puerto Rico will most likely be caused by a hurricane.

The investigation of historical rainfall by U.S Weather Bureau (1961) began with analyzing the recorded maximums for durations under 24-hours for the study area. Only one station provided adequate data for durations under 24-hours and none of the maxima were caused by a tropical cyclone. The 12-hour rainfall listed by Quinones (1953) was the only maxima associated with a tropical cyclone (U.S Weather Bureau, 1961). The meteorological conditions leading to 24-hour maxima for the study area were also analyzed. The recorded maxima caused by tropical cyclones resulted from one of two hurricanes: San Ciriaco of August 1899 and San Filipe II of September 1928. The non-hurricane maxima were associated with cold fronts and troughs. According to U.S. Weather Bureau (1961) many of these stations have short records and may not have experienced the full effect of an intense hurricane, and stations with longer records may have never experienced the full effect of an intense hurricane, because of being fairly sheltered by orographic barriers. Also, hurricane precipitation from rain gages may be significantly less than the actual rainfall because of the wind.

Table 1 lists the most recent world's maximum observed point rainfalls obtained from NOAA (2017), along with whether they were associated with a tropical cyclone. All maxima below 12-hours were not associated with a tropical cyclone. For durations 12-hours and above, all maxima resulted from tropical cyclones except for the 48-hour rainfall. The 48-hour rainfall record occurred in June 1995 in Cherrapunji, India, which is known as one of the wettest places on earth because of strong orographic influences (WMO, 2014). This record of 98.1 inches just slightly exceeds the previous 48-hour record of 97.1 inches recorded on La Réunion in 1958, after the passage of an unnamed tropical cyclone. The 12-hour, 18-hour and 24-hour records were associated with the passage of Tropical Cyclone Denise, and the 72-hour, as well as the 94-hour records were associated with the passage of Tropical Cyclone Gamede (WMO, 2019).

Table 1. World's Maximum Observed Point Rainfalls (NOAA, 2017).

Duration	Amount (in)	Location	Start Date	Tropical Cyclone
1 min	1.50	Barot, Guadeloupe	26 Nov 1970	No
5 min	2.48	Porto Bello, Panama	29 Nov 1911	No
20 min	8.11	Curtea-de-Arges, Romania	7 Jul 1889	No
30 min	11.00	Sikeshugou, Hebei, China	3 Jul 1974	No
60 min	15.80	Shangdi, Nei Monggol, China	3 Jul 1975	No
2 hr	19.30	Yujiawanzi, Nei Monggol, China	19 Jul 1975	No
3 hr	28.50	Smethport, PA, USA	18 Jul 1942	No
6 hr	33.10	Muduocaidang, Nei Monggol, China	1 Aug 1977	No
12 hr	45.00	Foc Foc, La Réunion	7 Jan 1966	Yes
18 hr	62.60	Foc Foc, La Réunion	7 Jan 1966	Yes
24 hr	71.90	Foc Foc, La Réunion	7 Jan 1966	Yes
48 hr	98.10	Cherrapunji, India	15 Jun 1995	No
72 hr	155.00	Cratère Commerson, La Réunion	24 Feb 2007	Yes
96 hr	194.00	Cratère Commerson, La Réunion	24 Feb 2007	Yes

The U.S Weather Bureau’s (1961) rainfall investigation also included analyzing the global recorded maximum precipitations in 1961 for rainfall events of different durations to determine what type of event will cause the 24-hour maximum. It was observed by U.S. Weather Bureau (1961) that all the events with durations below 12 hours were associated with localized cloudbursts of extraordinary intensity, however the stations were inland stations in the middle latitudes, with dense precipitation networks, and meteorological conditions suited for cloudbursts of such magnitudes are more likely in these localities rather than a maritime tropical region. Cloudbursts do occur in tropical climates, but usually not of record magnitudes according to U.S. Weather Bureau (1961). On the other hand, the U.S Weather Bureau observed that the events with durations of 12 hours and above were all associated with a tropical cyclone. From these observations, U.S. Weather Bureau determined that the probable maximum precipitation for durations over 12 hours for the study area will be associated with a tropical cyclone therefore, to estimate PMP, a hurricane model was postulated and tested on hurricane rainfalls for Puerto Rico by U.S. Weather Bureau (1961).

The U.S. Weather Bureau (1961) hurricane model incorporated surface features based on studies by Graham and Nunn (1959) and a vertical structure based on studies by Riehl (1954) and Miller (1958). The surface wind pattern used is illustrated in Figure 3, and it represents the wind field 30 ft above the sea surface for a large radius hurricane, with a central pressure of 906 mb moving at 12 mph just off the east coast of Florida. The winds in the wind pattern enter the cylindrical surface of the bottom 1 km layer of the model at a 25-degree angle with the tangent to the surface at point of entry. The similarity of the climates of Florida and the Caribbean allowed the wind field to be suitable for use for Puerto Rico according to U.S. Weather Bureau (1961). The vertical structure of the hurricane model is shown in Figure 4. The height of inflow was assumed to be equivalent to a 100 mb pressure change, which represents a 1 km change in height. Both Riehl (1954) and Miller (1959) observed that there was little or no outflow until about 6 km and above. As a result, there was the assumption that the model had no inflow or outflow between the 1 km and 6 km levels. Therefore, moist air comes in at the bottom 1 km layer by the radial component of the wind (v_r) which after produces an upward component (v_z) which provides the cooling that causes the air to condense. The outflow above the 6 km layer carries condensation moisture as well as rainfall out of the model.

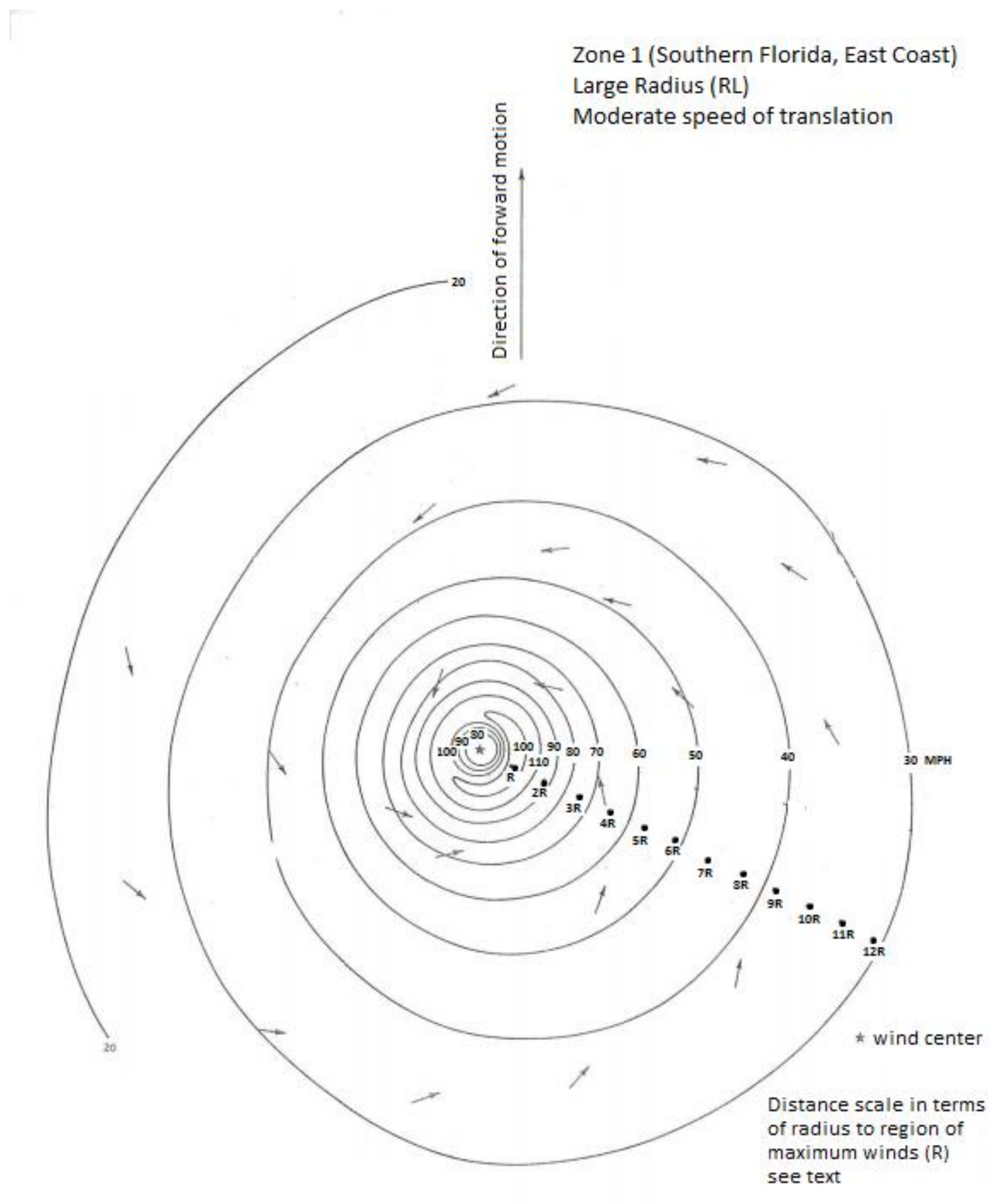

Figure 3. Hurricane model surface wind field from (Graham and Nunn, 1959).

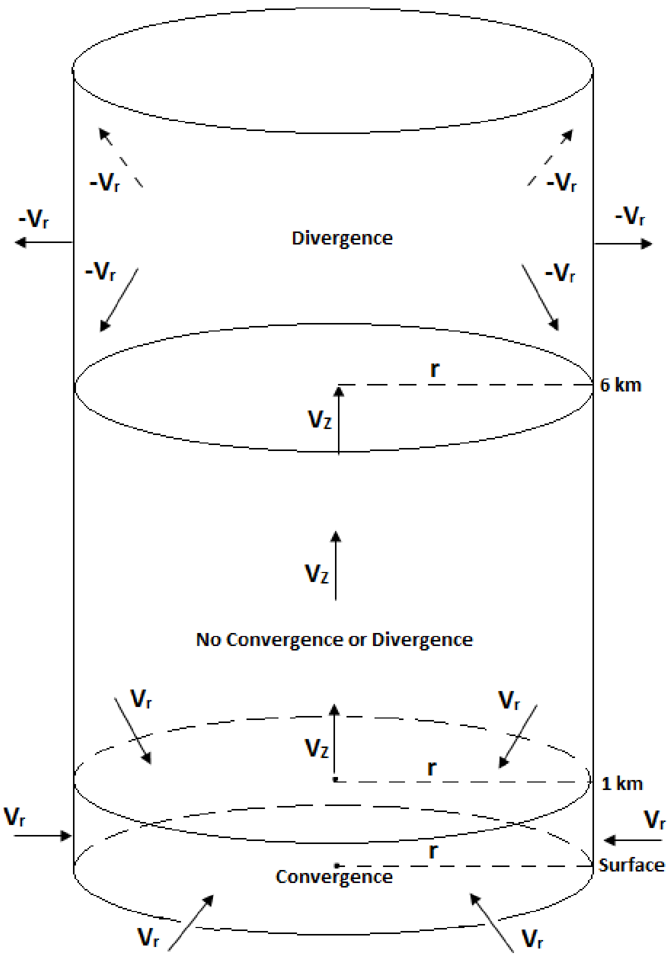

Figure 4. Vertical distribution of convergence and divergence in hurricane model from (U.S. Weather Bureau, 1961).

Several assumptions were made for the model by U.S. Weather Bureau (1961). 1) Although the wind field represents conditions 30 ft above the sea surface, U.S. Weather Bureau (1961) assumed that it would be unchanged overland due to the opposing effects of decreased wind speeds and increased tangential angles caused by surface friction on land. 2) The moisture content of the wind is also an important factor for the wind inflow rate. Vapor content is limited by the temperature of the air; vapor pressure can not exceed saturation vapor pressure. Therefore, U.S. Weather Bureau (1961) assumed that for PMP, saturated air would be going into the model.

3) A relatively constant surface air temperature in hurricanes is generally accepted (U.S. Weather Bureau, 1961). The air in the model was assumed to be 75 degrees Fahrenheit since from the examination of temperature traces of hurricanes, there was little fluctuation from a mean temperature of 75 degrees Fahrenheit. U.S. Weather Bureau (1961) applied these assumptions of meteorological conditions for maximum precipitation to the hurricane model to estimate a convergence component and an orographic component of rainfall, which are combined to find PMP.

Convergence rainfall is the rain the hurricane will produce over a flat land surface, and whenever the wind has an on-slope component, the upward motion of convergence will be supplemented by orographic lifting and an orographic rainfall component produced (U.S. Weather Bureau, 1961). The convergence and orographic components are combined by addition of the rainfall intensities to get the total PMP from the hurricane model. For the model it was determined by U.S. Weather Bureau (1961) that the most critical rainfall intensities will occur along a line eight miles from the center. Therefore, convergence and orographic rainfall intensities were found along a line eight miles from the eye of the hurricane.

The convergence component of the hurricane model was found by U.S. Weather Bureau (1961) using the method suggested by Riehl (1954). Convergence rainfall intensities were found using Equation 2.

$$R = \frac{0.18 V_r w}{r} \qquad \text{Equation (2)}$$

Where,

R = Rainfall intensity (in/hr)

V_r = Mean radial inflow wind component (mps)

w = Average mixing ratio (gm/kg)

r = Radius (mi)

For the orographic component of the model, Equation 3 developed by Showalter's equation presented in U.S. Weather Bureau (1961), was used.

$$R = 0.41 v_f \tan\alpha \qquad \text{Equation (3)}$$

Where,

v_f = On slope wind speed (mps)

α = Angle of slope

Considering these factors, it is reasonable to expect the maximum precipitation from records extending hundreds of years will be caused by a tropical cyclone in the tropics, and the U.S. Weather Bureau hurricane model can presently still be used to estimate PMP.

To validate a PMP estimate, current recorded maxima for the study area must be investigated. The largest recorded 24-hour precipitation amount found for a tropical cyclone in the Caribbean region was 34.1 inches. This rainfall amount was the result of the passing of a tropical depression in Cuba in May 1988 (Cubagua, 2003). This maximum was a reconstructed or observed value with evidence that in reality it is an under estimation. Also, rain gage catch tends to decrease in hurricanes due to the wind associated with the hurricane. The deficiency in the rain gage catch should be significant in the case of hurricane winds, and the true value should be larger than what was recorded.

From observation of 30 years of rainfall data obtained for St. Vincent from 1987 to 2016, the largest maximum recorded rainfall was 9.8 inches. It was caused by a passing tropical depression on August 3rd, 2004, which later formed into Tropical Storm Bonnie (Roth, n.d.). The second largest maximum was about 7.0 inches and was produced by a passing trough system.

These recorded maxima for St. Vincent and the surrounding region will be compared to the results obtained for PMP.

The methods presented by WMO (2009) for estimating PMP have been compared by other researchers, and PMP estimates between the different models have varied significantly. Gorouh et al. (2018) compared the standard and a revised Hershfield's statistical method to an inferential method using the storm model approach to estimate PMP in northern Iran. PMP from both statistical methods were higher than the PMP using the storm model. Also, the PMP from the revised statistical method was closer to the PMP from the storm model than the PMP from the standard statistical method. Chavan and Srinivas (2015) compared the inferential method, also using the storm model approach, with the Hershfield's statistical method for PMP estimates in Mahanadi river basin. The comparison revealed that the statistical method resulted in larger estimates of PMP than the PMP obtained from the storm model. From these comparisons between different methods for finding PMP, it is evident that the different methods produce disparate results. Therefore, more than one method should be tested to select the method that gives the most logical result for PMP in order to find the PMF.

After PMP is determined, PMF of a watershed can be found. There are multiple methods used to determine PMF. One of these methods, the SCS curve number method is a simple, widely used and efficient method that estimates direct runoff from storm rainfall (NEH-630, 2004). The SCS curve number method was developed mainly for agricultural watersheds between 10 and 1000 acres in size, and gives the area's total runoff depth, then peak flow can be calculated using Equation 4 using the precipitation of an event and the curve number (CN). Curve number depends on hydrologic soil group (HSG), cover type, treatment, hydrologic condition, and antecedent moisture conditions (USDA-SCS, 1986). The unit peak discharge is found by SCS rainfall distribution charts and the time of concentration. The following equations are used to find time of concentration and peak discharge:

$$q_p = q_u \cdot Q \cdot A \qquad \text{Equation (4)}$$

$$S = \frac{1000}{CN} - 10 \qquad \text{Equation (5)}$$

$$I_a = 0.2\ S \qquad \text{Equation (6)}$$

$$Q = \frac{(P-0.2\ S)^2}{P+0.8S} \qquad \text{Equation (7)}$$

$$T_s = \frac{0.007}{P_{2-24}^{0.5}} \left[\frac{nL_s}{S^{0.5}}\right]^{0.8} \qquad \text{Equation (8)}$$

$$T_{sc} = \frac{L_{sc}}{3600 * KS^{0.5}} \qquad \text{Equation (9)}$$

$$T_{ch} = \frac{L_{ch}}{3600 * V_{ch}} \qquad \text{Equation (10)}$$

Where,

q_p = peak discharge (cfs)

q_u = unit peak discharge (csm/in)

Q = total runoff depth (in)

A = area (mi^2)

Q = total runoff depth (in)

P = precipitation depth obtained from PMP estimations (in)

S = total retention (in)

I_a = initial abstraction (in)

CN = SCS curve number

T_s = time of concentration for sheet flow (hr)

P_{2-24} = 2-year, 24-hour event rainfall (in)

n = Manning's roughness coefficient

L_s = length for sheet flow (ft)

S = slope

T_{sc} = time of concentration for shallow concentrated flow (hr)

L_{sc} = length for shallow concentrated flow (ft)

K = coefficient

T_{ch} = time of concentration for channel flow (hr)

L_{ch} = length for channel flow (ft)

V_{ch} = channel velocity (ft/s)

Peak Discharge

Ogden (2016) performed indirect peak discharge measurements on 10-20 rivers impacted by Tropical Storm Erika in August 2015 for the purpose of providing flow data to aid in design of replacement bridges. The USGS Slope-Area method was employed to calculate indirect peak discharges, and radar-rainfall estimates were obtained from observations by the MeteoFrance Le Moule weather radar on Guadeloupe. The U.S. Army Corps of Engineers Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) model was used as a diagnostic tool to 1) detect landslide-affected peak flows, and 2) reconstruct plausible runoff hydrographs. After analyzing 16 indirect peak discharges, it was revealed that five of them were severely affected by landslide failure, producing peak flows that were significantly greater than the envelope curve values for the flood of record for identically-sized watersheds on the planet (Ogden, 2016). The largest peak discharge found was about 47000 cfs for the Belfast River, which has a drainage basin area of about 5.3 mi^2.

The aims of this study are:

1. to use Hershfield's statistical method and the inferential method using a hurricane-storm model approach to estimate PMPs in a drainage basin in southern St. Vincent.

2. to select the most reasonable PMP and find the PMF and peak discharge using the SCS method.

2. Methodology

The Hershfield's statistical method and the inferential method using the hurricane model postulated by U.S. Weather Bureau (1961) were used for this study to determine PMPs for St. Vincent. The statistical method was chosen because more than 20 years of rainfall maxima were available to use the model. By observing current maximum point rainfall records, it was determined that the hurricane model by U.S. Weather Bureau is still valid and can be used to determine PMP for this study. This hurricane model was also chosen because Puerto Rico and St. Vincent have similar climates. The results from these two methods were compared to determine a PMP to estimate PMF. The SCS method was chosen for this study to determine PMF. This choice was made considering the size of the study area and data available.

First, the Hershfield's statistical method was used to estimate a PMP. 30 years of 24-hour rainfall maxima data were obtained from the St. Vincent and the Grenadines Meteorological Service and used. The meteorological station where rainfall amounts were obtained was at the E.T Joshua Airport located at Arnos Vale. These values were adjusted for error due to gage catch deficiencies by adding to the maximum half of the maximum of the adjoining days. The mean of the adjusted annual maxima for these 30 years was 4.6 inches with standard deviation 1.9 inches, and the frequency factor used was 14.7. PMP was found from Equation 1.

Next, a second PMP was found using the storm model presented by U.S. Weather Bureau (1961). The lowest recorded hurricane pressure recorded in the area is 882 mb for Hurricane Wilma in 2005 (Pasch, R. et al., 2006), and was used as the pressure at the base of the hurricane model. The convergence rainfall intensities (R_1) resulting from Equation 2 was found for different distances along the radius, 8 miles from the eye of the hurricane. Equation 3 was used to determine the orographic rainfall intensities with a max slope of approximately 25 degrees that was found from the island's contour map. Orographic rainfall intensities (R_2) were found also at different distances along the radius, 8 miles from the eye of the hurricane. The total rainfall intensity (R_T) was found by simply adding the convergence and orographic rainfall intensity components. After PMP estimates were obtained from the statistical and inferential methods, the results were analyzed and tested with past events. The most reasonable PMP was chosen, and the PMF was found using the SCS method.

To find the runoff depth using the SCS method, first a curve number was found. A soil map was obtained from the CHaRIM Project St. Vincent National Flood Hazard Map Methodology and Validation Report that shows the soil types in St. Vincent (Jetten, 2016), and the soil types in the study area were identified. Ranges for assumed saturated hydraulic conductivity were obtained from the report from Saxton et al. (1986). With these assumed values and knowing that there are deep, fertile soils on the island, hydrologic soil groups were determined using the criteria for assignment of hydrologic soil groups table by USDA-SCS (2009). A land use map was also obtained based on land cover mapping carried out by the British Geological Survey (Westen et al., 2016). The study area was further divided into soil groups and percentage estimates of land use. Curve number estimates for areas divided by soil groups were determined using the tables for runoff curve number by USDA-SCS (1986). A weighted average curve number was calculated, then total retention, initial abstraction and total runoff depth were found using Equations 5, 6 and 7 respectively.

Finally, peak flow was determined using the SCS method by equation 4. To determine the unit peak discharge, time of concentration was calculated. It was found by adding the times for sheet flow, shallow concentrated flow and channel flow. For sheet flow, Equation 8 was used. $P_{2\text{-}24}$ of 3.6 in was found using the Weibull method for the 30 years of rainfall maxima obtained for the study area. A Manning's n of 0.6 was assumed by finding the average for woods with light and dense underbrush. The slope used was 0.47 from contour maps and the maximum length of sheet flow, 100 ft, was used. To find the time for shallow concentrated flow, a K value was found from Iowa DOT (2015). K was selected as 2.4 from a cover description of forest with heavy ground litter, and slope was 0.47. Equation 9 was used to find the shallow concentrated flow velocity, then this was divided by the maximum shallow concentrated flow length 300 ft to get a time. For channel flow, velocities at two different points in the channel were used from previous measurements. The velocities were 1.5 ft/s and 2.5 ft/s. A channel length of 22640 ft was obtained from direct measurement off a map with defined channels ("St. Vincent Map", n.d.). The assumption was made that half of the channel would have a velocity of 1.5 ft/s and the other half 2.5 ft/s. Half the total channel length was divided by both velocities and the results added to find a total channel flow time. Then, the times calculated for sheet flow, shallow concentrated flow and channel flow were added to get a total time of concentration. Unit peak discharge was found using the time of concentration and coefficients for type III rainfall distribution obtained from I_a/P_{24}. Type III was chosen as the most suitable distribution because of the similarities in climate and topography of that region with the study area. Ultimately the peak discharge was estimated for an area of 5.7 mi^2 using Equation 4. The peak discharge obtained was compared to values obtained in Ogden (2016) to determine if it is acceptable.

3. Results/discussion

The PMP using the statistical method was found to be 31.8 in. The results obtained from the inferential method using the hurricane model for the convergence rainfall (R_1), the orographic rainfall (R_2) and the total rainfall (R_T) intensities are found in Table 2 and Figure 5. These total rainfall intensities using the hurricane model produced a PMP of 82.4 in.

Table 2. Rainfall intensities for the hurricane model

r_8 (mi)	r (mi.)	v_{r8} (m/s)	v_{f8} (m/s)	R_1 (in/hr)	R_2 (in/hr)	R_T (in/hr)
-125.26	-125	2.71		0.08		0.08
-100.32	-100	3.22		0.13		0.13
-75.43	-75	3.99		0.21		0.21
-50.64	-50	5.30		0.41		0.41
-40.79	-40	6.46		0.62		0.62
-26.25	-25	8.42		1.25		1.25
-21.54	-20	9.55		1.73		1.73
-17.00	-15	10.53		2.42		2.42
-12.81	-10	11.90		3.62		3.62
-9.43	-5	16.25	0.00	6.72	0.00	6.72
8.00	0	18.89	33.00	9.21	3.11	12.32
9.43	5	15.93	44.37	6.59	4.18	10.77
12.81	10	11.90	44.07	3.62	4.15	7.78
17.00	15	10.53	39.31	2.42	3.70	6.12
21.54	20	9.55	34.22	1.73	3.22	4.95
26.25	25	8.78	30.04	1.30	2.83	4.14
40.79	40	6.63	20.38	0.63	1.92	2.56
50.64	50	5.56	16.29	0.43	1.53	1.96
75.43	75	4.42	12.00	0.23	1.13	1.36
100.32	100	3.64	9.49	0.14	0.89	1.04
125.26	125	3.13	7.93	0.10	0.75	0.85

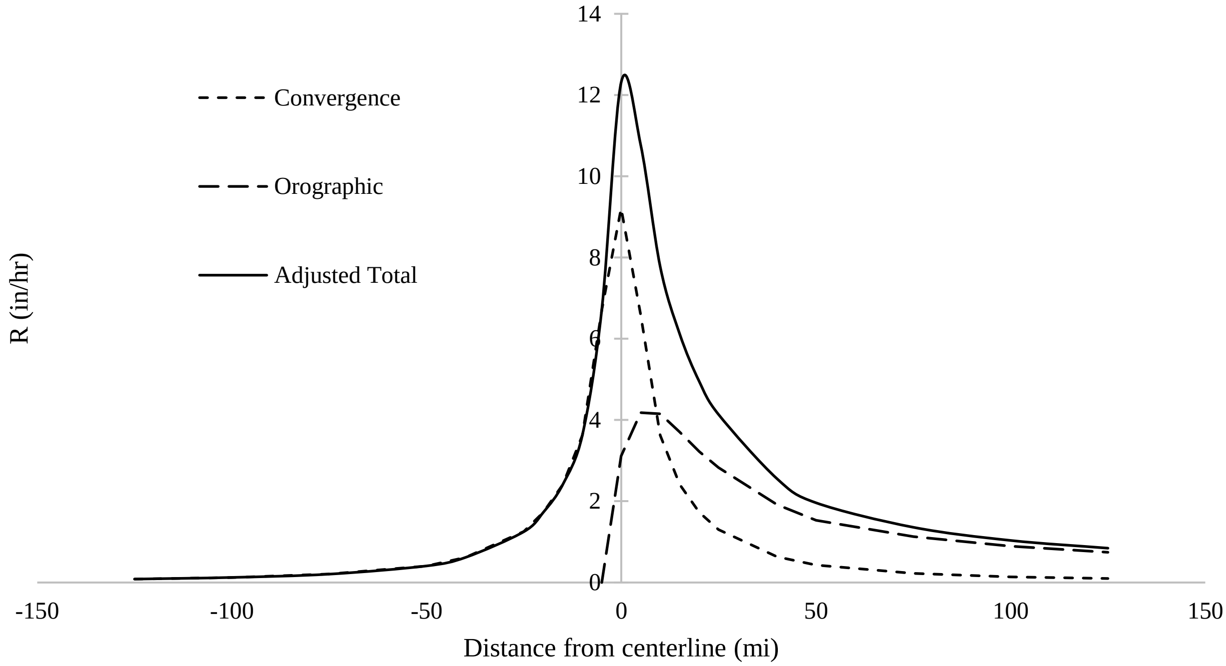

Figure 5. Storm model rainfall intenities.

To determine the better PMP, the PMPs for each model were compared to events that have occurred to know how reasonable they are. It is expected that there should not be a past historical event that has higher precipitation than the PMP. The precipitation for PMP using the statistical method is therefore not reasonable in this case since there was a largest 24-hour rainfall recorded in Cuba in Cubagua (2003) that is larger than the result obtained. These results may have been affected by the fact that only 30 years of data was used to determine PMP, also these values were based off one weather station. On the other hand, the PMP estimate of 82.4 inches using the hurricane model was not exceeded by any past recorded 24-hour precipitation. The model was further tested using data from Hurricane Tomas in St. Lucia. Hurricane Tomas produced a max 24-hour precipitation on St. Lucia of 26.3 inches at Desraches. The pressure in this location was about 982 mb (Pasch et al., 2011). The maximum slope in the area was measured to be about 20 degrees. Applying this data to the model produced the rainfall intensities shown in Figure 6. The total precipitation was found to be 41.5 inches. This value however is based on a wind speed of 110 mph at eight miles from the hurricane eye and was adjusted for the wind speed of about 70 mph for Hurricane Tomas. After this adjustment the precipitation using the Hurricane Model for Hurricane Tomas was found to be 26.4 inches. This value was only 0.1 inches higher than the recorded value. Since the PMP from the statistical method is not logical, and the hurricane model tested well for a past event, the PMP from the inferential method was chosen as the PMP for this study.

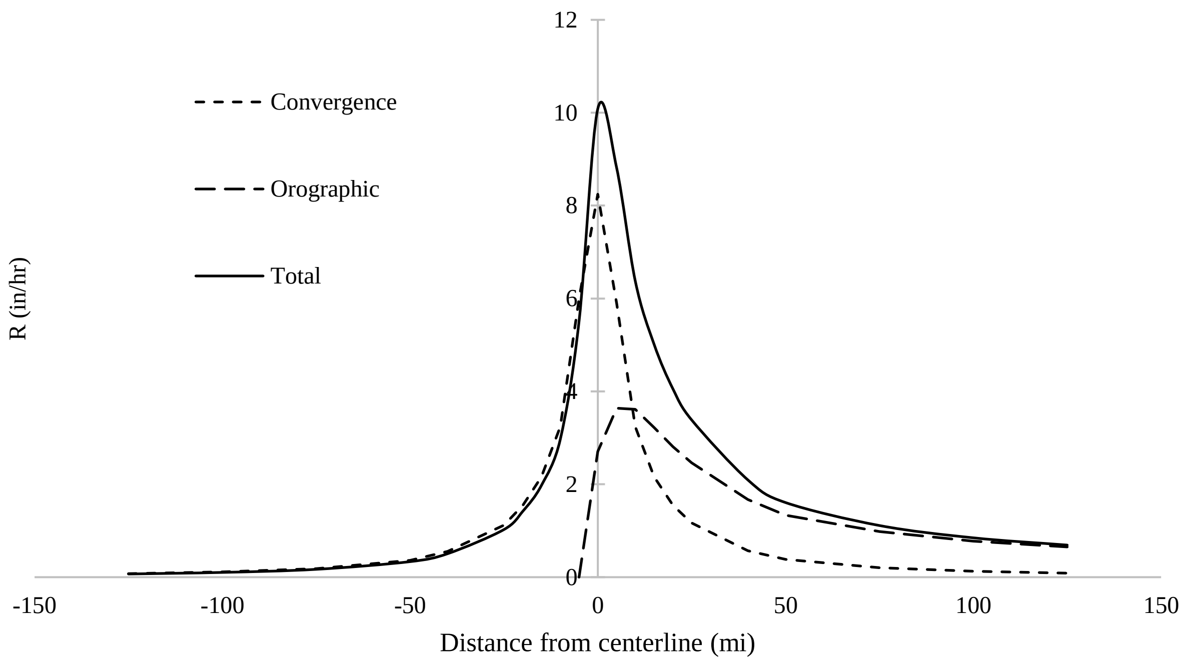

Figure 6. Hurricane Tomas -St.Lucia rainfall intenities.

PMF was found using the PMP from the hurricane model. The next step towards finding PMF was to find a curve number. The curve number obtained for the entire watershed was 77. Table 3 shows a summary of how the CN was found. Next, the total retention was found to be 3 inches, and initial abstraction 0.6. Using the PMP of 82.4 inches. from the Hurricane model resulted in a total runoff depth of 79.0 in. The times for sheet flow, shallow concentrated flow and channel flow found were 0.13 hours, 0.05 hours and 3.4 hours respectively. Time of concentration resulted to be 3.6 hours and the resulting unit peak discharge was 136 csm/in. Peak discharge approximation for the PMP was determined as 61000 cfs. The peak discharge compared to discharges obtained in Dominica in Ogden (2016) was acceptable for the peak discharge resulting from PMF.

Table 3. Weighted CN

Estimated area (mi^2)	**HSG**	**% Land use**	**Land Use**	**CN**	**CN**
3.5	B	60	Pasture/ Agriculture (Contoured, straight row)	72	
		10	Residential 1/2 acre	70	
		30	Woods- grass (good)	58	
					68
0.29	B	75	Pasture/ Agriculture (Contoured, straight row)	72	
		25	Residential 1/2 acre	70	
					72
1.62	C	35	Residential 1/3 acre	81	
		15	Commercial	94	
		30	Pasture/ Agriculture (Contoured, straight row)	81	
		20	Woods- grass (good)	72	
					82
0.22	A	100	Developing urban		77
0.29	B	100	Developing urban		86
Watershed Weighted CN					77

4. Conclusion and limitations

PMP values using the statistical method and an inferential method using a hurricane model were found successfully. The estimated values were 32 inches and 82 inches respectively. It was determined that 82 inches, obtained from the hurricane model by the inferential method, was the more reasonable value for PMP. The resulting runoff depth and peak discharge estimates were 79 inches and 61000 cfs respectively.

The statistical method was limited by the fact that the 30 years of rainfall data was recorded from only one rain gage. A better result may have been achieved by having a larger network of rain gages in favorable locations. The hurricane model estimation was a very rough estimate, and there can be many improvements made. The model failed to correct for unprecipitated moisture escaping at the top of the model. However, because of the close results when the storm model was applied to Hurricane Tomas in St. Lucia, not accounting for this loss may be a compensating factor for an unknown deficiency in the model. More modern methods of predicting hurricane rainfall have also been developed in more recent years. These may be utilized instead of this model to predict a PMP from a hurricane.

Despite the model's limitations, the PMP obtained was reasonable. The PMP seems to be much larger than observed rainfall but this does not mean that the estimated PMP is excessive. Measurements of rainfall are usually very deficient due to the strong winds. Also, the records of rainfall measurements are very short compared to the history of hurricanes. It should also be noted that the most intense rainfall in a hurricane affects a small area, and the chance that a single rain gage would sample this intensity is low. Hence, PMP estimates may appear to be excessive.

In conclusion, the PMF obtained by finding a PMP using a hurricane model by the inferential method and SCS Curve Number method can be used to obtain design parameters for peak hydrological conditions. Although there are other methods available, this method is simple, cheap, and does not require large amounts of data. By utilizing these methods, SIDS may have better hydrological designs and therefore greater resilience to disasters.

5. References

Chavan, S. and Srinivas, V., 2015. Probable Maximum Precipitation Estimation for Catchments in Mahanadi River Basin. Aquatic Procedia, 4, p. 892-899.

Chow VT., 1951. A General Formula for Hydrologic Frequency Analysis. Transactions American Geophysical Union 32, p. 231-237.

Cubagua, 2003. Integrated Water Management - General characteristics of the factors of the hydrological regime of Cuba. Retrieved from https://web.archive.org/web/20131105222344/http://www.hidro.cu/hidrologia1.htm

Geographic Guide. Physical Map of Central America and The Caribbean. Retrieved from http://www.geographicguide.net/america/caribbean-map.htm

Global Affairs Canada, 2012. Map- Saint Vincent and the Grenadines. Retrieved from https://www.international.gc.ca/cil-cai/country_insights-apercus_pays/map-carte_vc.aspx?lang=eng

Google Earth, 2019. St. Vincent Map.

Gorouh, Z., Bakhtiari, B., & Qaderi, K., 2018. “Probable Maximum Precipitation Estimation in a Humid Climate,” Natural Hazards and Earth System Sciences, 18(11), p. 3109-3119.

Graham, H. E., and Nunn, D.E., 1959. “Meteorological Consideration Pertinent to Standard Project Hurricane, Atlantic and Gulf Coasts of the United States,” National Hurricane Research Project Report No. 33, U.S. Weather Bureau.

Hershfield, D. M., 1961. “Estimating the Probable Maximum Precipitation,” Proc. ASCE, Journal Hydraulic Div., 87(HY5), p. 99-106.

Hershfield, D. M., 1965. “Method for Estimating Probable Maximum Precipitation,” Journal American Waterworks Association, 57, p. 965-972.

Iowa DOT, 2015. “Using the Rational Method to Determine Peak Flow,” Design Manual, Chapter 4, Drainage, p. 7-8.

Jetten, V., 2016. CHaRIM Project St Vincent National Flood Hazard Map Methodology and Validation Report, p. 21-25.

Joos, B., Darakhani, J., Mouvet, L., Mehinrad, A., 2005. An Integrated Probabilistic Approach for Determining the Effects of Extreme Hydrological Events on a Flood Evacuation System.73rd annual meeting of ICOLD, Tehran, Iran, 2005.

Miller, B. I., 1958. “The Three-Dimensional Wind Structure Around a Tropical Cyclone,” National Hurricane Research Project Report No. 15, U.S. Weather Bureau, p. 12-21.

Ministry of Agriculture, Industry and Labour, 1995. St. Vincent and the Grenadines: Country Report to the FAO International Technical Conference on Plant Genetic Resources (Leipzig,1996). Retrieved from http://www.fao.org/fileadmin/templates/agphome/documents/PGR/SoW1/americas/SAIN SAIN.pdf

NEH, 2004. National Engineering Handbook, chapter 10, Estimation of Direct Runoff from Storm Rainfall. Retrieved from https://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/NEHhydrology/ch10.pdf

NOAA, 2017. World Records-HDSC/OWP. Retrieved from https://www.nws.noaa.gov/oh/hdsc/record_precip/record_precip_world.html

Pasch, R., Blake E., Cobb, H., Roberts, D, 2006. Tropical Cyclone Report Hurricane Wilma. Retrieved from https://www.nhc.noaa.gov/data/tcr/AL252005_Wilma.pdf

Pasch, R., Kimberlain, T., 2011. Tropical Cyclone Report Hurricane Tomas. Retrieved from https://www.nhc.noaa.gov/data/tcr/AL212010_Tomas.pdf

Quinones M. A., 1953. High Intensity Rainfall and Major Floods in Puerto Rico. Proceedings American Society of Civil Engineers, 79, p. 35.

Riehl, H., 1954. Tropical Meteorology, Mc-Graw Hill Book Co. Inc. New York, p. 293-295.

Roth, D., Tropical Storm Bonnie - August 10-14, 2004. Retrieved from https://www.wpc.ncep.noaa.gov/tropical/rain/bonnie2004.html

Saxton, K. E., Rawls W. J., et al., 1986. Estimating generalized soil-water characteristics from texture. Soil Science Society of America Journal, 50(4), p. 1031-1036.

St. Vincent Map. Retrieved from https://www.planetware.com/i/map/STV/saint-vincent-map.jpg

USDA-SCS, 1986. Urban Hydrology for Small Watersheds. Technical Release No. 55 (TR-55)

U.S. Weather Bureau, 1961. Generalized Estimates of Probable Maximum Precipitation and Rainfall-Frequency Data for Puerto Rico and Virgin Islands, Cooperative Studies Section, Hydrologic Services Division, U.S. Weather Bureau for Engineering Division, Soil Conservation Service U.S. Department of Agriculture, 1961.

Westen, C.J., Jordan, C., Grebby, S., Dijkstra, T., Dashwood, C., Cigna, F., Sijmons K., 2016. Saint Vincent and the Grenadines: Land Cover Map.

Wilkinson, E., 2018. Towards a more resilient Caribbean after the 2017 hurricanes. Report from roundtable discussions, 30 January 2018. Retrieved from https://www.odi.org/sites/odi.org.uk/files/resource-documents/12114.pdf

Wilkinson, E., Twigg, J. and Few, R., 2018. Building back better: a resilient Caribbean after the 2017 hurricanes, ODI Briefing Paper. London: Overseas Development Institute. Retrieved from https://www.odi.org/ publications/11037-building-back-better-resilient-caribbean-after-2017-hurricanes

WMO, 2009. Manual on Estimation of Probable Maximum Precipitation (PMP), World Meteorological Organization, WMO-No. 1045.

WMO, 2014. New Record for Two-Day Rainfall. Retrieved from https://public.wmo.int/en/resources/meteoworld/new-record-two-day-rainfall USDA-SCS, 2009. Part 630 Hydrology National Engineering Handbook, Chapter 7, Hydrologic Soil Groups, p. 7-4.

WMO, 2019. World Meteorological Organization's World Weather & Climate Extremes Archive. Retrieved from https://wmo.asu.edu/content/world-meteorological-organization-global-weather-climate-extremes-archive

Zehnder, J., 2018. tropical cyclone | Definition, Causes, Formation, and Effects. Retrieved from https://www.britannica.com/science/tropical-cyclone