1 **Evidence of Equilibrium Peak Runoff Rates in Steep Tropical Terrain on the Island of**
2 **Dominica During Tropical Storm Erika, August 27, 2015**

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7 **ABSTRACT**

8 Tropical Storm Erika was a weakly organized tropical storm when its center of
9 circulation passed more than 150 km north of the island of Dominica on August 27, 2015.
10 Hurricane hunter flights had difficulty finding the center of circulation as the storm encountered
11 a high shear environment. Satellite and radar observations showed gyres imbedded within the
12 broader circulation. Radar observations from Guadeloupe show that one of these gyres formed
13 in convergent mid-level flow triggered by orographic convection over the island of Dominica.
14 Gauge-adjusted radar rainfall data indicated between 300 to 750 mm of rainfall on Dominica,
15 most of it over a four hour period. The result was widespread flooding, destruction of property,
16 and loss of life. The extremity of the rainfall on steep watersheds covered with shallow soils was
17 hypothesized to result in near-equilibrium runoff conditions where peak runoff rates equal the
18 watershed-average peak rainfall rate minus a small constant loss rate. Rain gauge adjusted radar
19 rainfall estimates and indirect peak discharge (IPD) measurements from 16 rivers at watershed
20 areas ranging from 0.9 to 31.4 km² using the USGS Slope-Area method allowed testing of this
21 hypothesis. IPD measurements were compared against the global envelope of maximum
22 observed flood peaks versus drainage area and against simulations using the U.S. Army Corps of
23 Engineers Gridded Surface/Subsurface Hydrologic Analysis (GSSHA) model to detect landslide-
24 affected peak flows. Model parameter values were estimated from the literature. Reasonable

agreement was found between GSSHA simulated peak flows and IPD measurements in some watersheds. Results showed that landslide dam failure affected peak flows in 5 of the 16 rivers, with peak flows significantly greater than the envelope curve values for the flood of record for like-sized watersheds on the planet. GSSHA simulated peak discharges showed that the remaining 11 peak flow values were plausible. Simulations of an additional 24 watersheds ranging in size from 2.2 to 75.4 km² provided confirmation that the IPD measurements varied from 40% to nearly 100% of the envelope curve value depending on storm-total rainfall. Results presented in this paper support the hypothesis that on average, the peak discharges scaled linearly with drainage area, and the constant of proportionality was equivalent to 134 mm h⁻¹, or a unit discharge of 37.22 m³ s⁻¹ km². The results also indicate that after the available watershed storage was filled after approximately 450 to 500 mm of rain fell, runoff efficiencies exceeded 50 to 60 percent, and peak runoff rates were more than 80 percent of the peak rainfall rate minus a small constant loss rate of 20 mm h⁻¹. These finding have important implications for design of resilient infrastructure, and means that rainfall rate was the primary determinant of peak flows once the available storage was filled in the absences of landslide dam failure.

Introduction

The 2015 tropical Atlantic hurricane season was quiet by most measures. However, one particularly devastating counterpoint was the impact of Tropical Storm Erika on the island nation of Dominica. Figure 1 shows the location of Dominica in the eastern Caribbean basin and the approximate path of TS Erika. Even though the center of TS Erika passed more than 150 km north of Dominica, the synoptic scale mid-level flow produced a region of significant convergence in the vicinity of Dominica. Dominica's topography exerts a strong orographic

47 control over rainfall (Smith et al., 2012), and the net effect of regional convergence with
48 topographic interactions on Dominica was over 500 mm of rainfall in 10 hours on 27 August,
49 2015.

50 **<FIGURE 1>**

51 According to the U.S. National Weather Service, on August 27, 2015, the hurricane
52 reconnaissance flight from the U.S. had difficulty identifying the center of circulation. The
53 storm was located in a region of very high precipitable atmospheric water in excess of 60 mm
54 (Votaw et al., 2015). The storm track was difficult to forecast because upper level wind shear
55 caused the predominance of convection to occur east of the center of circulation (Franklin,
56 2015).

57 When torrential rains fell in Dominica in the early morning hours of 27 August, 2015,
58 most people were caught by surprise because forecasters did not predict significant weather from
59 TS Erika. The preceding two weeks were quite rainy, with about 200 mm of precipitation.
60 Unfortunately, Erika produced extreme rainfall that caused the most significant flooding in
61 Dominica since Hurricane David in 1979. There was significant loss of life, and damages to
62 structures near rivers. Many of the bridges on the island were damaged or destroyed. The entire
63 island was impacted except the far northwestern portion. TS Erika also produced significant
64 amounts of rainfall that caused damage in Puerto Rico and Hispanola on August 28.

65 Dominica has the most rugged topography of all the Caribbean islands. The island has
66 two main volcanoes that are both nearly 1,500 m in elevation, as well as ten smaller volcanoes.
67 This makes the topography of the island very steep as over 60 percent of the slopes on the island
68 are steeper than 30 percent gradient (World Bank 2004). As a result, most of the populated areas
69 lie on coastal alluvial fans, and most of the interior of the island is covered by forest that has re-

grown since the massive destruction rendered by Hurricane David in 1979. Finally, the soils in Dominica are of volcanic origin and almost exclusively thin (Rouse et al., 1986). The relatively recent andesitic-dacitic eruptive history has created the condition where variations in rainfall amounts are the main determinant of soil type (Goldsmith et al., 2010) because of different weathering sequences. As a result there are four main clay-rich soil types on Dominica (Rouse et al., 1986). On the western coastal regions where there is a dry season the soils are montmorillonitic and smectitic. Rainforest areas that have a weak dry season have kaolinitic soils. The continuously wet regions on the north and eastern mountain flanks have allophanic latosols. In the highest elevation regions annual rainfall exceeds 7000 mm (Benson et al. 2001), and are dominated by allophone podzolics (Rouse et al., 1986). Rouse et al. (1986) found that the development of saturated soils that initiate landslides occurs during high-intensity rainfall associated with tropical cyclones.

This study was designed to test the hypothesis that the combination of high-intensity rainfall for several hours on small, steep, tropical catchments with uniform land cover and thin saprolitic soils led to runoff conditions that approached equilibrium. The word “equilibrium” is used here in the sense that the peak rate of watershed runoff was well approximated by the peak rate of rainfall input. This hypothesis was tested using weather radar rainfall estimates, indirect peak discharge (IPD) measurements in 16 watersheds, and a two-dimensional process-based hydrological model. Results are compared against the envelope curve (Rodier and Roche, 1984; ICOLD, 2002) for global maximum flood peaks as a function of watershed area.

The lack of hydrometeorological data in tropical locations (Wohl et al., 2012), and particularly on small islands, limits the ability of engineers to adequately design resilient infrastructure. The development of meaningful rainfall and flood statistics for the Caribbean

islands, particularly the lesser Antilles, is hampered by many sources of complexity (Lumbroso et al. 2012). This storm, with extreme high-intensity rain falling for several hours, offered an opportunity to evaluate flooding resulting from extreme rainfall in a tropical volcanic island setting.

Landslides represent a complicating factor in analyses such as this one because they can create dams that, when breached by overtopping or other failure mechanism, release a torrent of water, increasing the flood peak beyond that which would have occurred had there not been a landslide that formed a dam (Larsen, 2008). Dominica has the steepest topography on average of any island in the Caribbean. This fact coupled with widespread thin soils that are prone to saturation, causes many landslides during extreme rainfall events, and makes Dominica extremely vulnerable to landslides (Costa and Schuster, 1988).

Most landslide dams are small and are overtopped during the rainfall event that caused them. There have been exceptions (Arlington and Serrant, 1997) such as the event of November 18, 1997, when a landslide dam blocked the Layou River and failed after three days, released large quantities of water. On November 25 of that same year, a much larger landslide occurred in the same general area. Similarly this landslide dam also failed after three days and led to catastrophic damages to crops and property along the Layou River. A secondary effect of this large slide was the creation of a dam on the Matthieu River, which is a tributary to the Layou River. The 40 m deep lake formed by this landslide dam persisted for 13 years and 8 months, but disappeared in about 15 minutes when the dam failed on July 27, 2011 (James and de Graffe, 2012).

De Graff et al. (2012) examined the spatial distribution of factors leading to landslides in Dominica, and produced a susceptibility map. On this map, most of Dominica is in the moderate

to high risk of landslide activity. Some small regions of extreme landslide risk were identified in the Layou, Belfast, and Geneva river basins.

Analysis of Radar Observations of TS Erika

The French Meteorological Agency *MeteoFrance* operates two S-band weather radars on the islands adjacent to Dominica in the Lesser Antilles. The S-band radar on Martinique, the island immediately south of Dominica, has a 1.3 degree beam width, but unfortunately experiences significant beam blockage in the direction of Dominica caused by topography on Martinique. The S-band weather radar on Guadeloupe, which is north of Dominica at a range of 75 to 120 km, has a less desirable 2.1 degree beam width, but has an unobstructed view in the direction of Dominica. Data from this radar were used to estimate storm total rainfall.

According to the metadata included in the headers of the data files, the radar on Guadeloupe is sited at 16°18'58"N, 61°20'45"W, at an elevation of 30 m, on a 13 m tall pedestal. Its relatively large 2.1 degree beam width makes it more susceptible to range and beam-filling dependent errors (Sharif et al., 2004). When using weather radar for precipitation estimation, it is important to use data from the lowest elevation angle not contaminated by ground clutter (Battan, 1973). A beam propagation analysis was performed using the methodology of Sharif et al. (2004) to identify the lowest unobstructed beam elevation angle. The atmospheric sounding recorded by a weather balloon launched from Guadeloupe at 12:00 UTC on 27 August, 2015, was used in this beam propagation analysis, and is listed in Table 1. The relative humidity values in this sounding indicate that the atmosphere was very nearly saturated below 605 mb or 4323 m elevation. At the time of this sounding, the precipitable water amount was 67 mm. This is a high amount of precipitable water for the tropics (Vatow et al.,

2015, Figure 6), and indicates that the circulation associated with TS Erika encountered abundant moisture in the vicinity of Dominica.

Figure 2 shows calculated radar beam paths for different antenna elevation angles (degrees). Notice that the 0-degree beam path is completely intercepted by the island of Dominica. The 1.6-degree elevation angle is the lowest one that clears most of the topography given the 2.1-degree beam width. Therefore, data from the 1.6 degree elevation angle were used in this analysis to estimate rainfall rates.

<Figure 2>

The radar reflectivity data were converted into a range versus time plot to identify any data irregularities. On this plot instances of ground clutter appeared as intermittent strong returns at a fixed range against a moving background of returns from rainfall. This plot showed three mountain peaks that were occasional sources of ground clutter during periods of anomalous beam propagation (Battan, 1973). These included the most northward volcano and the two tallest volcanoes on the island. A total of 24 radar pixels where ground clutter occurred in the 1.6 degree elevation angle data were used to create a clutter mask, where radar data were omitted. Radar reflectivity values in these relatively small masked areas were interpolated using inverse distance-squared interpolation from the four nearest radar pixels.

Radar-Rainfall Mean Field Bias Adjustment Using Hourly Rain Gauge Data

The radar reflectivity factor Z is proportional to the sixth moment of the raindrop size distribution (Battan, 1973). For this reason, Z can take on a very wide range of values and is commonly expressed using decibel units (dBZ). The units of Z are $\text{mm}^6 \text{m}^{-3}$ and the conversion between Z and dBZ is: $\text{dBZ} = 10 \log_{10} Z$.

The form of the widely used radar reflectivity factor Z vs. rainfall rate R relation is:

$$Z = \alpha R^{\beta} \quad (1)$$

161 Where:

162 Z = radar reflectivity factor ($\text{mm}^6 \text{m}^{-3}$),

163 R = rainfall rate (mm h^{-1}),

164 α = empirical coefficient, and

165 β = empirical exponent.

166 Published Z - R relations cover many different situations, but in reality the relationship
 167 between radar reflectivity factor and the rainfall rate is non-unique and varies in both space and
 168 time. The “standard” tropical Z - R relation uses parameters $\alpha=250$ and $\beta=1.2$, with the
 169 reflectivity in decibel units (dBZ) limited to 50 dBZ (Rosenfeld et al., 1993). This limit requires
 170 that measured reflectivities greater than 50 dBZ are set to 50 dBZ, and is sometimes called a
 171 “hail cap” as it serves to eliminate hail contamination from the signal. The effect is to limit the
 172 maximum rainfall rate to 147 mm h^{-1} using the standard tropical Z - R relation parameters given in
 173 this paragraph.

174 This standard tropical Z - R relation was applied using the Guadeloupe radar data set and
 175 compared hourly against data from 8 tipping-bucket rain gauges operated by the Dominican
 176 Meteorological Service for the duration of TS Erika. These eight tipping bucket rain gauges
 177 were described by Smith et al. (2012). Rainfall estimated using the standard tropical Z - R relation
 178 was only 57% of the rain gauge accumulations on average, as determined by linear regression of
 179 hourly radar versus rain gauge rainfall.

180 Linear regression of radar versus gauge allowed detection of outliers in the rain gauge
 181 data set. Four hours of data from the Springfield gauge (Smith et al., 2012) were eliminated
 182 from the regression as outliers because this gauge greatly under-measured the rainfall values for

those four hours compared to all other gauges in the network and the radar. The reason for this significant gauge under-measurement is unknown. A partially- or completely-plugged rain gauge funnel is a common cause of under-measured rainfall.

One consideration when using rain gauges to calibrate radar observations for a particular storm is the proximity of the rain gauges to the area of interest. In other words, how representative is the calculated radar-gauge bias at points that are different distances from the gauge? Using 5-years of warm season radar observations and rain gauge data from the Mississippi river basin, Rogalus and Ogden (2013) found that the correlation coefficient between single-polarization radar-rainfall biases computed using at rain gauges separated by less than 25 km was $r^2=0.42$ for storms with duration 4 hours or longer. The relatively small size of the island of Dominica and relatively long duration of the storm both help reduce spatial variability in radar-gauge bias. However, because of the orographic enhancement of the storm, the possibility that there was significant spatial variability of the radar-gauge bias cannot be ruled out.

Following quality control of the rain gauge data, the coefficient α in the Z-R relation (Equation 1) was adjusted to force the slope of the radar vs. gauge regression line to equal 1.0. This procedure is known as mean field bias adjustment (Steiner et al., 1999). After removing the outliers from the Springfield gauge, the value of the coefficient α in Equation 1 was systematically varied until the slope of the regression line between hourly radar and rain gauge rainfall became equal to 1.0. The resulting value was $\alpha=132$. This decrease in α had the effect of increasing the radar-estimated rain rates. The 50 dBZ hail cap with this α value with $\beta=1.2$ represents a rainfall rate of 251 mm h⁻¹. The calibrated hourly radar versus rain gauge rainfall

accumulations are plotted in Figure 3, and the four culled outliers from the Springfield rain gauge are denoted, and were not used in the regression.

Comparing the storm total rainfall for the calibrated relation $Z=132R^{1.2}$ with and without the 50 dBZ hail cap allowed identification of the effect of the hail cap. The largest difference at any point across the island was a 4 percent reduction in storm-total rainfall with the hail cap in effect. It is safe to conclude that the application of the 50 dBZ hail cap had little impact on the radar-rainfall estimation results.

The results shown in Figure 3 indicate that the hourly bias-adjusted radar-rainfall estimates are reasonably accurate ($r^2=0.86$). This is despite the relatively large 2.1-degree radar beam width, 75-120 km range, and the necessity of using a relatively large 1.6-degree elevation angle to avoid topographic contamination of the radar signal.

<Figure 3>

Island-Wide Isohyetal Map for TS Erika

Bias-adjusted and clutter-filtered radar rainfall rates were integrated over the island for the period from 00:00 UTC to 23:59 on August 27, 2015, to produce the rainfall storm-total isohyetal 50 mm contour interval map shown in Figure 4. This figure includes shaded topography with a contour interval of 300 m to illustrate how the topography of the island clearly played a role in triggering precipitation. Precipitation maxima occur on the eastern slopes of several prominences.

<Figure 4>

The temporal distribution of island-wide rainfall from TS Erika is shown in Figure 5. Hourly average island-wide rainfall rates were integrated from the Guadeloupe radar data, with

rainfall rates calculated using $Z=132R^{1.2}$. For three consecutive hours the average rainfall rate over the entire island of Dominica exceeded 80 mm h⁻¹.

Also shown on Figure 5 is the cumulative island-wide rainfall, which totaled 508 mm over the duration of TS Erika, with 400 mm of this rain falling between 08:00 and 12:00 UTC. This estimate was produced from bias-adjusted and clutter-filtered radar rainfall estimates.

<Figure 5>

Indirect Peak Discharge Measurements

A total of 16 rivers were selected for indirect peak discharge (IPD) measurements with the assistance of the Hydrometeorology Working Group of the Government of Dominica. Those rivers are shown on Figure 6 with the watershed area above each measurement point. The actual location of the survey varied in terms of distance from the coast because the suitability of a particular river reach for IPD measurements depends upon local conditions such as access, identifiable high-water marks, post-event changes, channel morphology, and the presence of large woody or other debris. Each river in Dominica ends in an alluvial fan at the coast. Most surveyed cross sections were performed upstream of the head of the fan, in a confined cross section.

<Figure 6>

IPD measurements were made using the U.S. Geological Survey (USGS) Slope-Area Method (Dalrymple and Benson, 1968; USGS, 1994). The essence of the method is that Manning's equation is used based on several surveyed channel cross-sections which provide the cross-sectional area and slope of the water surface. Values for the Manning roughness coefficient were identified based on personal experience using visual clues from the USGS report entitled "Roughness Characteristics of Natural Channels", which is available online

(http://pubs.usgs.gov/wsp/wsp_1849/html/pdf.html). The USGS slope-area program “SAC” was run on the surveyed data sets. This program requires identification of Manning n values for the main channel, as well as the left- and right-overbank areas.

The quality of the IPD measurement is noted in each instance. Factors considered include: agreement of the left- and right-hand high water marks, obvious indications of large changes in the cross-section during the event, uncertainty regarding roughness coefficient values, and the amount of overbank flow. These quality indicators were used to subjectively indicate an uncertainty bound on the indirect peak flow measurement of either $\pm 25\%$, or $\pm 50\%$ as per the recommendation of the U.S. Geological Survey (USGS 1994).

The global envelope curve for maximum observed flood peaks (ICOLD, 2002) in watersheds with area less than 300 km^2 published by the International Congress on Large Dams is given by Equation 2. This envelope represents the largest flood peaks Q for natural floods not due to dam failure observed for a watershed of area A , anywhere on the planet.

$$\frac{Q}{Q_1} = \left(\frac{A}{A_1} \right)^{1 - \frac{E}{10}} \quad (2)$$

with:

A = watershed area [km^2]

$Q_1 = 10000 \text{ [m}^3 \text{ s}^{-1}\text{]}$

$A_1 = 300 \text{ [km}^2\text{]}$

$E = 2.1 \text{ [-]}$

Indirect Peak Discharge Results

The results of IPD measurements are listed in Table 2. This table also lists the subjective uncertainty associated with each measurement. Furthermore, this table compares the IPD

271 measurements against the global maximum envelope curve (ICOLD, 2002; Rodier and Roche,
272 1984) for instantaneous peak flood flows ($\text{m}^3 \text{s}^{-1}$), as a function of watershed area (km^2). This
273 comparison provides an indication of the appropriateness of the magnitude of the IPD
274 measurements. Values of peak flow in excess of the envelope curve are either erroneous, or the
275 result of failure of a landslide dam above the measurement site. The IPD measurement is also
276 listed as a ratio of the envelope value. Ratios in excess of 1.0 are most likely affected by
277 landslide dam failure, or possibly by uncertainties in the IPD measurement.

278 Rivers in Dominica are among the steepest in the world. The quality of the high water
279 marks in the surveyed reaches varied considerably. The Belle Fille, Castle Bruce, Melville Hall,
280 and Rosalie Rivers all had well defined high water marks, flows confined to one main channel,
281 and a reasonably straight channel reach. For these reasons, indirect peak flow measurements in
282 those channels are given 25% uncertainty. In contrast, large differences in left and right bank
283 high water marks are possible in steep channels with supercritical flows, particularly with the
284 large sediment sizes and braided channels seen in Dominica. The high water elevations
285 identified on the left and right banks of the Hampstead River below Chaudier's Pool, Malabuka
286 River, and Rosalie River each showed about 2.0 m difference. The uncertainty of the peak flow
287 measurement in those rivers is given as 50%.

288 IPD measurements from this study are plotted in Figure 7 as blue triangles, together with
289 the flood peaks reported in ICOLD (2002) shown as filled black circles. The IPDs from
290 Dominica during TS Erika above the envelope curve shown in Figure 7 are almost certainly
291 affected by landslide dam failure. Peak discharges below the envelope curve range from 23% to
292 94% of the envelope value for each given watershed area, with a mean value of 59%. It is not
293 possible to assign a probability of exceedance to this percentage of the envelope curve value,

because it depends on a host of factors that are not well understood such as climate and runoff generation mechanism, as well as the period of record (Castellarin et al., 2005). It is safe to say that 23% to 94% of the envelope peak discharge is an extreme event, as demonstrated by the extent of the destruction produced by the flooding that resulted from TS Erika.

<Figure 7>

The results in Table 2 show that the Malabuka watershed (1.63 km²) was most severely affected by landslide dam failure. The measured IPD was more than 7 times the maximum envelope curve peak discharge. In the Dubuc (0.9 km²) and Geneva (7.26 km²) rivers the measured IPDs were over 2 times the envelope maximum peak discharge. In the case of the previously mentioned Belfast River, the IPD was 152% of the envelope curve value. It is noteworthy that portions of the Belfast and Geneva river basins were identified by De Graff et al. (2012) as at extreme risk of landslides. In both the Geneva and Dubuc rivers, landslide dams were noted as having had occurred in our interviews with local residents during our field survey.

Hydrologic Modeling for Landslide Dam Failure Identification

While the flood peaks shown in Figure 7 above the ICOLD envelope curve were almost certainly affected by landslide dam failure, it is possible that some of the flood peaks below the ICOLD envelope were significantly increased by landslide dam failure. This happens when naturally occurring landslides block the channel, fill with water, then fail. This failure releases a torrent of water that represents a larger flood peak than what would have occurred due solely to rainfall-runoff processes.

On 27 August, 2015, many landslides occurred in Dominica. We observed many small and a few large landslides during post-event field investigations. This provides strong evidence

316 that enough rain fell to fill most of the pore space in tropical saprolitic soils, because soil
317 saturation is associated with the occurrence of landslides (Rouse et al. 1986). The Gridded
318 Surface/Subsurface Hydrological Analysis (GSSHA) model was used to detect possible landslide
319 affected flood peaks below the ICOLD envelope. GSSHA is a process-based numerical
320 hydrological model (Downer and Ogden, 2006) developed and maintained by the US Army
321 Corps of Engineers for engineering hydrology studies and hydraulic design (Fatichi et al., 2016).

322 GSSHA can simulate infiltration-excess runoff using an infiltration equation. It can also
323 simulate saturation excess runoff with the addition of groundwater flow solution that is coupled
324 to the surface using Richards' equation. Simulations using Richards' equation are much more
325 computationally demanding. Using hillslope scale rainfall-runoff data from the Panola
326 Mountain, Georgia (USA) research site, Ameli et al. (2015) compared rainfall and runoff data
327 with the performance of models that simulated either rapid subsurface stormflow or surface
328 runoff generation mechanisms. They found that both models were able to simulate observations
329 using realistic parameter values. This finding supports the notion that in general, it is possible
330 with the GSSHA model to simulate a range of soil or land-use dependent hydrologic behaviors
331 assuming infiltration-excess runoff generation. GSSHA was previously shown to be quite
332 sensitive to the soil hydraulic conductivity, overland and channel roughness coefficients,
333 retention storage and plant interception of rainfall (Senarath et al., 2000). The sensitivity of
334 GSSHA to initial soil moisture values can be mitigated by performing continuous simulations, as
335 the influence of the initial guess diminishes after the first significant rainfall event (Senarath et
336 al. 2000), or by using measured soil moisture values (Hendrickx et al. 2015). However, in the
337 case of extreme rainfall with more than a few cm of rain, the effect of the initial soil moisture

state is negligibly important because as cumulative infiltration increases, the infiltration rate rapidly goes towards the limiting value of infiltration, K_{sat} .

Interception of rainfall by vegetation was neglected. Numerous studies have found that tropical forests intercept about 17 percent of rainfall (Niedzialek and Ogden, 2012) regardless of total rainfall. This is possible because rainfall evaporates off the leaves before falling to the ground as throughfall. However, in truly extreme events such as TS Erika, it was highly unlikely that 17 percent of rainfall evaporated during the event because the lower troposphere was very nearly saturated with water vapor as indicated by the sounding in Table 1. Interception was most likely greatly reduced during TS Erika.

Infiltration was simulated using the Green & Ampt with Redistribution method (Ogden and Saghafian, 1997), assuming that the soil matrix saturated hydraulic conductivity $K_s=2.0$ cm h^{-1} , (Hassler et al., 2011), the Green and Ampt soil capillary head parameter $H_c=10$ cm, pore distribution index $\lambda=0.234$, residual saturation $\theta_r=0.015$, field capacity $\theta_f=0.30$, wilting point water content $\theta_w=0.15$, and effective porosity $\theta_e=0.50$. Because over 200 mm of rain had fallen in the two weeks preceding Erika, the initial soil moisture content was assumed everywhere $\theta_i=0.45$, representing 90% saturation.

Land use effects were not considered because most of the watersheds simulated are predominantly a mixture of old and secondary forest that has regrown since Hurricane David in 1979. There is low intensity suburban development upstream from Roseau. This includes a few traditional housing developments in flatter areas near streams, but otherwise development consists of houses constructed at uneven spacings adjacent to sparse roads. There are very few roads inland. Ogden et al. (2011) found that the effect of imperviousness on flood peaks

diminishes with increasing rainfall amounts as soil infiltration capacity becomes overwhelmed, masking the effects of imperviousness.

The Watershed Modeling System interface was used to set up the GSSHA models using a 30 m digital elevation model (DEM) using the TauDEM software (Tarboton, 2001). Channels were identified using a channel initiation threshold of 0.1 km² in watersheds greater than 3 km² in area and 0.04 km² in smaller watersheds. The identified channel network was trimmed to eliminate short channels and edited to eliminate reaches with adverse slope, which can arise because of DEM errors. The channels were assumed trapezoidal in section with side slope of 1.0 H:V and channel bottom widths b (m) assigned based on the contributing area A (km²) using the following equation that fit the survey cross-section data:

$$b = 16.7A^{0.3} \text{ (m)} \quad (3)$$

Model Results

GSSHA was run on the 16 watersheds with IPD measurements shown in Figure 7, using parameters previously described and the mean-field bias-adjusted radar-rainfall estimates as forcing. If the model did not produce a peak discharge larger than the indirect measurement, then it is likely that the peak was influenced by landslide dam failure. Those simulation results are shown in Table 3.

Landslide dam failure most likely affected peak flows if the relative difference between the GSSHA simulated peak discharge and indirect peak measurement was more negative than -25 percent in Table 3. Using this criterion, six of the 16 watersheds simulated were identified as obviously landslide affected. These watersheds include all portions of Dominica that were identified as having high to extreme landslide risk (De Graff et al., 2012).

The sign of the relative difference in Table 3 is positive if the GSSHA peak flow rate was greater than the indirect measurement. The average difference of the simulations tabulated in Table 3 that were not landslide affected is 27%, while the average absolute difference is 32%. These differences are less than the 25% nominal IPD measure uncertainty in four of the 11 watersheds. These results indicate that the GSSHA model has some skill in predicting peak discharges using soil parameters from the literature, radar-rainfall estimates, and geomorphologically-estimated channel cross-section properties.

GSSHA was used to simulate 24 additional watersheds shown in Figure 8 to estimate peak discharges in those watersheds due to TS Erika. The same watershed parameters were used as in the simulations of the 16 watersheds with IPD measurements. The results of those simulations are given in Table 4.

<Figure 8>

The results in Table 4 show that simulated runoff efficiencies varied from a low of 40 percent in the case of the Gillon watershed, to a high of 66 percent in the Macoucherie river watershed. The GSSHA simulated peak discharge values from the 24 watersheds listed in Table 4 plus the 16 watersheds listed in Table 3 are plotted vs. drainage area in Figure 9. This figure also includes the ICOLD peak discharge envelope for watersheds less than 300 km² in area. The best fit line through the simulated flood peaks has a slope of 0.998 on log-log axes with a coefficient of determination $r^2=0.93$.

Six of the watersheds in Figure 9 (Macoucherie, Hampstead, Castle Bruce, Rosalie, Malabuka, and Geneva) are also in the set of 16 watersheds where IPD measurements were made. While most of the IPD measurements were made some distance from the coast, the simulation results reported in Table 3 represent hydrographs predicted at a point very near the

coast, and represent a significantly larger catchment. For example, the IPD measurement on the Castle Bruce River was made at a drainage area of 13.46 km² (Table 2) while the simulation on the same river reported in Table 3 was performed at a watershed area of 44.07 km².

<Figure 9>

Scaling of flood peaks is an active area of research. The slope of the regression equation through the peak discharges in Figure 9 is very nearly 1.0, which indicates that the peak discharges increased linearly with drainage area for this event. In this case the leading coefficient of the regression equation given in Figure 9 is analogous to a rainfall rate. That rainfall rate is 134 mm h⁻¹, which is equivalent to a unit discharge of 37.2 m³ s⁻¹ km⁻². The results in Figure 9 provide an indication that the GSSHA simulations of ungauged basins with soil hydraulic parameters previously given provide plausible peak discharges relative to the ICOLD maximum discharge envelope. This linear response is likely influenced by the relatively small sizes of the watersheds and the relatively uniform distribution of rainfall across the island (Figure 4). Furthermore, the smaller watersheds simulated tended to be nearer the coast where the storm total rainfall was less than in the interior of the island.

Analysis of Peak Runoff Extremity

Truly extreme runoff events can approach a condition where the peak rate of flow leaving the watershed is very nearly the rate of water entering the watershed as rainfall less some constant loss rate. This is one physical justification behind the concept of the peak runoff rate envelope curve. In smaller catchments, the envelope limit is reached when the atmosphere provides the maximum possible rainfall rate for a long enough time that the entire watershed area contributes to runoff. The 300 km² break in the ICOLD envelope curve might be hypothesized to represent the approximate upper limit of the areal extent at which atmosphere can produce

427 torrential rainfall. Above this 300 km² limit, the likelihood that torrential rainfall covers the
428 watershed becomes diminishingly small.

429 Three dimensionless parameters were used to evaluate the extreme nature of the runoff
430 generation process. The first was the runoff efficiency, ρ , which is the ratio of the storm total
431 depth of runoff R_{tot} [mm] to the integrated total depth of rainfall over the area of the watershed,
432 I_{tot} [mm]:

$$\rho = \frac{R_{tot}}{I_{tot}}, \quad (4)$$

433

434 The second parameter was the peak dimensionless runoff rate, r_p^* , which represents the peak rate
435 of runoff normalized by the peak rate of rainfall minus the saturated hydraulic conductivity of the
436 soil K_{sat} . The radar-rainfall estimated watershed-average peak rainfall rate is i_p [mm h⁻¹] and the
437 peak runoff rate from GSSHA simulations is r_p [mm h⁻¹], and therefore the dimensionless peak
438 runoff rate r_p^* was calculated using:

$$r_p^* = \frac{r_p}{i_p - K_{sat}} \quad (5)$$

439 The third parameter is the ratio of the peak discharge Q_p [L³ T⁻¹] to the envelope curve
440 peak runoff ratedischarge Q_{env} [L³ T⁻¹]. This parameter indicates the severity of the flooding
441 relative to the ICOLD envelope curve. By Equation 2, Q_{env} that is assumed to be solely a
442 function of watershed area A . The envelope peak discharge ratio to produce a dimensionless
443 peak discharge Q_p^* : was calculated using:

$$Q_p^* = \frac{Q_p}{Q_{env}(A)} \quad (6)$$

444

Q_p^* is plotted versus r_p^* in Figure 10 for the 16 watersheds with IPD measurements to determine if the modeled peak discharge in any of the watersheds approached equilibrium conditions during TS Erika. The use of modeled hydrograph properties in this graph removes the effects of landslide dam failure. Those watersheds in the upper right-hand portion of the figure were most severely affected with $Q_p^* > 0.8$, which include the Macoucherie, Coulibistrie, and Hampstead rivers. A second group with $0.5 < Q_p^* < 0.8$ include the Belfast, Belle Fille, Boeri, Check Hall, Colihaut, Geneva, Melville Hall, Roseau, and Rosalie rivers. Those watersheds with Q_p^* less than 0.5, the Castle Bruce, Dubuc, Malabuka and Pointe Ronde, received less rainfall than the other watersheds and the GSSHA models had peak flow values less than half of the envelope value for equivalent watershed areas.

The results in Figure 10 in terms of dimensionless runoff rate divided by peak observed rainfall rate, r_p^* , are not entirely conclusive. While there is a tendency for watersheds with Q_p^* near 1.0 to have r_p^* near 1.0, there were other watersheds with r_p^* near 1.0 but with $0.3 < Q_p^* < 0.8$. This result indicates that for extreme rainfall events in steep tropical watersheds with thin saprolitic soils, the rainfall rate can be a primary determinant of peak discharge, even in cases where Q_p^* is significantly less than 1.0.

<Figure 10>

One example of a watershed where equilibrium runoff rates were approached is the Macoucherie river, which was one of the worst affected. The watershed-average rainfall rate and modeled runoff rate (mm h^{-1}) are plotted together in Figure 11, together with the ICOLD envelope and the IPD measurement. Results on Figure 10 indicate that the peak rate of runoff was very nearly the same as the peak rainfall rate. The simulated peak runoff rate from GSSHA was 208 mm h^{-1} , while the radar estimated peak watershed-average rainfall rate was 234 mm h^{-1} .

The difference is only 26 mm h^{-1} , which is only 6 mm h^{-1} more than the simulated K_{sat} of 20 mm h^{-1} . This indicates that for the Macoucherie Watershed and others with Q_p^* values near 1.0 on Figure 10, in the case of this event that was near the envelope curve maximum value, the maximum peak discharge was at least strongly affected or, at most, determined by the maximum observed rainfall rate.

<Figure 11>

The dimensionless peak runoff rates r_p^* and the runoff efficiencies η are plotted against storm total rainfall [mm] in Figure 12 for all watersheds considered. Symbols are used to differentiate between the 16 watersheds where IPD measurements were made and the other 24 GSSHA simulation points. The results shown in Figure 12 show an increasing trend in both r_p^* and η with increasing storm total rainfall. These results also suggest that when the storm-total rainfall exceeded 450 mm, the runoff efficiencies reached a maximum value of around 0.6. When the storm total rainfall exceeded 500 mm, the dimensionless peak runoff rates mostly exceeded 0.8. These results indicate that between 450 and 500 mm of storm total rainfall the available storage in the watershed filled, and the peak runoff rate was closely tied to the peak rainfall rate.

<Figure 12>

Conclusions

There are few detailed studies of extreme hydrological events in Caribbean island settings. This paper presents results of a detailed hydrometeorological analysis of Tropical Storm Erika that impacted Dominica on August 27, 2015, causing loss of life and significant

489 damages to personal property and public infrastructure, particularly bridges. Bias-adjusted radar
490 rainfall estimates using S-band weather radar observations from Guadeloupe, indicate that this
491 storm produced from between 300 to 750 mm of rainfall on the island of Dominica, with most of
492 the rain falling during a four hour period. This extremely intense rainfall produced flooding very
493 nearly as severe as naturally possible in some watersheds in the absence of landslide dam failure.
494 This was particularly true in the Macoucherie, Melville Hall, Roseau, and Rosalie rivers.
495 Indirect peak discharge measurements performed in 16 rivers indicated that with some
496 uncertainty, the peak flows resulting from the extreme rainfall associated with TS Erika were
497 near the ICOLD (2002) envelope of maximum flood events recorded anywhere on the planet.

498 In six of the 16 watersheds the failure of landslide dams led to peak flows considerably
499 above the ICOLD (2002) envelope. The IPD measurements also showed that none of the rivers
500 emanating from watersheds greater than 10 km² area, with the exception of the 13.6 km² Belfast
501 River, experienced enhanced peak flows due to the catastrophic failure of landslide dams. The
502 effect of landslide dam failure on peak discharge was not a factor in larger watersheds because
503 large landslide dams that can store enough water to alter peak flows in large watersheds are rare.
504 They do happen, as occurred in the Layou river watershed in 1997 (James and Serrant, 1997;
505 James and De Graff 2012), but did not occur during this event.

506 The IPD measurements show that the GSSHA model has some skill in predicting peak
507 flows for TS Erika using the bias-adjusted radar-rainfall inputs from the Guadeloupe weather
508 radar. In addition to the sixteen watersheds with IPD measurements, GSSHA runoff simulations
509 of an additional 24 watersheds produced a broader picture across the entire range of watershed
510 sizes present on Dominica. The simulated peak discharges in the absence of landslide dam

failures were on average, proportional to watershed area. The constant of proportionality was 134 mm h⁻¹, which represents a unit discharge of 37.22 m³ s⁻¹ km⁻².

The study described in this paper tested the hypothesis that during extreme rainfall events in steep, mountainous, tropical forested watersheds less than about 30 km² in area, with thin volcanically-derived soils, the peak discharge in streams can in some instances be determined by the rainfall rate less a small constant loss rate. The findings of this study suggest that this did happen in a number of watersheds that approached equilibrium runoff conditions. The results in this study indicate that the available storage was filled after approximately 450 mm of rainfall over approximately a four hour period, and produced runoff efficiencies in excess of 50 percent, a remarkably high value for the humid tropics. When the storm-total watershed-average rainfall exceeded 500 mm, the dimensionless peak runoff rates exceeded 80 percent of the peak rainfall rate minus a small constant loss rate of 20 mm h⁻¹. This information might prove useful for design of resilient infrastructure on tropical volcanic islands in the Caribbean and elsewhere.

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538 [v=WOA0lF30oms](https://www.youtube.com/watch?v=WOA0lF30oms)

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643

Figure Captions

Figure 1. Map of the eastern Caribbean basin showing the location of Dominica and the approximate path of TS Erika at the start of the day shown in the center of the tropical storm symbol, August, 2015. Inset map shows topography of Dominica, contour interval 300 m.

Figure 2. Beam path analysis for MeteoFrance radar on Guadeloupe, at an azimuth of approximately 180-degrees. Shown on the figure is the spine of the island of Dominica.

Figure 3. Radar vs. rain gauge comparison with 17 hourly rainfall accumulations at 8 rain gauges during tropical storm Erika, with four hourly values from the Springfield rain gauge removed as outliers as shown. 50 dBZ limit applied.

Figure 4. Isohyetal map for TS Erika rainfall (mm) over the island of Dominica, August, 27, 2015. Topography denoted with color contours (300 m). Note two maxima near the highest mountains on the island. Rainfall isohyetal contour interval 50 mm. Rainfall estimated using radar data from S-band radar on Guadeloupe, with calibrated relationship $Z=132R^{1.2}$ and applied hail cap of 50dBZ.

Figure 5. Temporal distribution of radar estimated island-wide average rain rate and cumulative rainfall from TS Erika on 27 August, 2015.

Figure 6. Watersheds where IPD measurements were made.

Figure 7. Global peak flood discharge envelope curve (solid line) (ICOLD, 2002), and supporting data points (black). The blue triangles represent Dominica watersheds during TS Erika based on IPD measurements from Table 3.

664 **Figure 8.** The 24 watersheds simulated with watershed outlet near the coast. The area simulated
665 is listed in Table 4.

666 **Figure 9.** Simulated peak discharges using GSSHA with soil saturated hydraulic conductivity
667 $K_s=2.0 \text{ cm h}^{-1}$ driven by TS Erika radar-rainfall on 16 watersheds where IPD measurements were
668 made plus the 24 ungauged watersheds shown in Figure 8 (40 total).

669 **Figure 10.** Simulated peak discharge normalized by the envelope peak discharge (Q_p^*) versus
670 the peak observed runoff rate normalized by the peak instantaneous excess rainfall rate (r_p^*).
671 Both quantities are dimensionless. Watersheds with larger Q_p^* values were worst affected.
672 Effects of landslide dam failure not included.

673 **Figure 11.** The 12.15 km² Macoucherie River Watershed neared equilibrium conditions during
674 TS Erika, with the GSSHA simulated runoff rate nearing rainfall rate during the time of peak
675 flow. Error bars on IPD measurement represent ± 25 percent. Error in time of peak discharge
676 unknown.

677 **Figure 12.** Dimensionless peak runoff rates r_p^* and runoff efficiencies η for all watersheds
678 considered plotted versus storm-total watershed-average rainfall (mm).

Figure 1

Figure 2

Figure 3

Figure 4

Mountain Peaks
P1– elev. 1414 m
P2– elev. 1380 m
P3– elev. 1156 m

Legend
August 27, 2015
Rainfall isohyets
contour interval
50 mm
Topography
shaded contour
interval 300 m

Scale
10 km

Coordinates
Latitude: 15°35'N, 15°30'N, 15°25'N, 15°20'N, 15°15'N, 15°10'N
Longitude: 61°30'W, 61°25'W, 61°20'W, 61°15'W

The map displays a mountainous region with topographic contours and rainfall isohyets. The topographic contours are shaded and labeled with values such as 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 750, and 800. The rainfall isohyets are labeled with values such as 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, 1000, 1050, 1100, 1150, 1200, 1250, 1300, 1350, 1400, 1450, 1500, 1550, 1600, 1650, 1700, 1750, 1800, 1850, 1900, 1950, 2000, 2050, 2100, 2150, 2200, 2250, 2300, 2350, 2400, 2450, 2500, 2550, 2600, 2650, 2700, 2750, 2800, 2850, 2900, 2950, 3000, 3050, 3100, 3150, 3200, 3250, 3300, 3350, 3400, 3450, 3500, 3550, 3600, 3650, 3700, 3750, 3800, 3850, 3900, 3950, 4000, 4050, 4100, 4150, 4200, 4250, 4300, 4350, 4400, 4450, 4500, 4550, 4600, 4650, 4700, 4750, 4800, 4850, 4900, 4950, 5000, 5050, 5100, 5150, 5200, 5250, 5300, 5350, 5400, 5450, 5500, 5550, 5600, 5650, 5700, 5750, 5800, 5850, 5900, 5950, 6000, 6050, 6100, 6150, 6200, 6250, 6300, 6350, 6400, 6450, 6500, 6550, 6600, 6650, 6700, 6750, 6800, 6850, 6900, 6950, 7000, 7050, 7100, 7150, 7200, 7250, 7300, 7350, 7400, 7450, 7500, 7550, 7600, 7650, 7700, 7750, 7800, 7850, 7900, 7950, 8000, 8050, 8100, 8150, 8200, 8250, 8300, 8350, 8400, 8450, 8500, 8550, 8600, 8650, 8700, 8750, 8800, 8850, 8900, 8950, 9000, 9050, 9100, 9150, 9200, 9250, 9300, 9350, 9400, 9450, 9500, 9550, 9600, 9650, 9700, 9750, 9800, 9850, 9900, 9950, 10000. The map also shows three mountain peaks: P1 (elevation 1414 m), P2 (elevation 1380 m), and P3 (elevation 1156 m). The map includes a legend, a scale bar, and a list of mountain peaks.

Figure 5

Figure 6

Peak Discharge (m s^{-1})

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Table 1

Table 1. Atmospheric soundings from Station 78897, La Raizet, Guadeloupe, 12:00 UTC 27 August 2015. [Data source: Atmospheric Science Dept., University of Wyoming]

Pressure	Height	Temperature	Relative
(hPa)	(m)	(C)	Humidity (%)
1008	11	25	95
1000	73	24.8	95
929	719	21.6	96
856	1428	18.3	97
817	1828	16.4	97
739	2672	10.3	98
700	3123	8.6	98
660	3609	7.2	99
636	3914	6.4	99
605	4323	4.2	99
546	5152	-0.2	83
529	5405	-2.1	78
500	5850	-5.7	84
464	6433	-9.5	92
400	7570	-15.7	85

Table 2. IPD Measurements and Comparison with Global Envelope Curve with IPD measurement uncertainty.

River Name	Watershed Area A (km ²)	Indirect Peak Discharge measurement	Unit Discharge	Envelope Curve Q_{env} (m ³ s ⁻¹)	Ratio Q_p/Q_{env} (-)	Uncert. $\pm$ (%)
		Q_p (m ³ s ⁻¹)	Q_p/A (m ³ s ⁻¹ km ⁻²)			
Belfast	13.60	1320	97	868	152	25
Belle Fille	24.18	656	27	1368	48	25
Boeri	16.19	574	35	996	58	25
Castle Bruce	13.46	201	15	861	23	25
Check Hall	6.18	163	26	466	35	25
Colihaut	5.88	218	37	448	49	25
Coulibistrie	7.35	855	116	534	160	25
Dubuc	0.90	243	270	102	239	25
Geneva	7.26	1220	168	529	231	25
Hampstead	18.68	677	36	1115	61	50
Macoucherie	12.12	742	61	793	94	25
Malabuka	1.63	1287	790	162	792	50
Melville Hall	27.01	1196	44	1493	80	25
Pointe Ronde	6.16	232	38	464	50	25
Rosalie	22.82	1233	40	1307	71	50
Roseau	31.38	923	39	1680	73	25

Notes on Table 2: The global maximum envelope curve peak discharge values as a function of drainage basin area were calculated using Eqn. 3 (ICOLD, 2002) for watersheds less than 300 km² in area. Differences in high water mark elevations on left and right banks of Hampstead, Malabuka and Rosalie rivers were greater than 2 m.

Table 3

Table 3. Peak flow results of GSSHA simulations with soil saturated hydraulic conductivity $K_s=2.0$ cm h^{-1} on 16 watersheds compared with IPD measurements.

Watershed name	GSSHA				
	Drainage	Indirect peak	simulated peak	Relative	Obviously
	area	discharge	discharge	difference	landslide dam
	km^2	$\text{m}^3 \text{s}^{-1}$	$\text{m}^3 \text{s}^{-1}$	(%)	affected? (Y/N)
Belfast	13.62	1320±330	561	-58	Y
Belle Fille	24.22	656±160	827	26	N
Boeri	15.96	574±140	634	10	N
Castle Bruce	13.49	201±50	363	81	N
Check Hall	6.19	163±40	245	50	N
Colihaut	5.89	218±55	341	56	N
Coulubistrie	7.37	855±214	465	-46	Y
Dubuc	0.90	243±61	36	-85	Y
Geneva	7.26	1220±305	306	-75	Y
Hampstead	18.71	677±340	936	38	N
Macoucherie	12.15	742±190	705	-5	N
Malabuka	1.62	2876±1438	62	-98	Y
Melville Hall	27.05	1196±300	1168	-2	N
Pointe Ronde	6.16	232±60	201	-13	N
Rosalie	22.48	1233±617	870	-29	Y
Roseau	31.44	923±230	1222	32	N

Table 4

Table 4. Modeled runoff for 24 additional watersheds around Dominica shown in Figure 8.

Watershed name	Area km ²	Q_p (m ³ s ⁻¹)	Rainfall (mm)	Runoff (mm)	Runoff eff. (%)	Q_{env}	$Q_p Q_{env}^{-1}$ (%)
						ICOLD	
						(m ³ s ⁻¹)	
Layou	75.40	2495	564	348	62	3358	74.3
Macoucherie	19.12	1061	630	416	66	1136	93.4
Batali	14.20	905	654	427	65	898	100.78
Dublanc	7.45	338	514	270	53	539	62.71
Pointe Ronde	8.12	246	405	206	51	577	42.63
Picard	12.41	382	501	262	52	807	47.34
Blenheim	18.91	863	442	252	57	1126	76.64
Hampstead	19.54	931	534	291	55	1155	80.61
Penton	5.85	266	527	340	65	445	59.78
Mamelabou	10.81	522	529	318	60	724	72.1
Woodford Hill	5.59	240	585	368	63	430	55.81
Toulaman	16.52	722	591	330	56	1012	71.34
Pagua	38.11	1319	625	362	58	1959	67.33
Castle Bruce	44.07	855	483	263	54	2197	38.92
St. Sauveur	7.13	211	459	244	53	521	40.5
Rosalie	29.87	987	494	272	55	1616	61.08
Toberi	8.27	221	478	255	53	586	37.71
La Ronde	3.20	88	468	247	53	276	31.88
Boetica	2.23	75	499	274	55	208	36.06
Mulatre	20.70	739	567	317	56	1209	61.12
Malabuka	2.96	111	512	298	58	260	42.69
Geneva	22.92	724	491	258	52	1311	55.23
Soufriere	4.77	121	399	174	44	379	31.93
Gillon	3.36	89	366	146	40	287	31.01