Effects of Forest Roads on Runoff Initiation in Low-Order Ephemeral Streams

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Deposited 05/18/2021

Citation of published version:
Ramos-Scharrón, C., LaFevor, M. (2018): Effects of Forest Roads on Runoff Initiation in Low-Order Ephemeral Streams. *Water Resources Research,* 54(11).
DOI: https://doi.org/10.1029/2018WR023442

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE
10.1029/2018WR023442

Key Points:
- Runoff thresholds for unroaded catchments depend on a combination of antecedent and total storm rainfall
- Runoff thresholds for road-influenced streams depend on total rainfall, road surface area, and proximity of road drains
- Runoff from road-influenced catchments occurs 2.5 to 3.2 times more frequently than if unroaded

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Citation:
Ramos-Scharrón, C. E., & LaFevor, M. C. (2018). Effects of forest roads on runoff initiation in low-order ephemeral streams. *Water Resources Research*, *54*, 8613–8631. https://doi.org/10.1029/2018WR023442

Received 11 JUN 2018
Accepted 13 SEP 2018
Accepted article online 19 SEP 2018
Published online 5 NOV 2018

Effects of Forest Roads on Runoff Initiation in Low-Order Ephemeral Streams

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Abstract Understanding hydrologic connectivity is essential for managing ephemeral headwater streams where upstream land use influences downstream aquatic habitats. This study relies on a field-based approach to evaluate how precipitation and roads affect runoff generation in low-order ephemeral streams of the U.S. Virgin Islands. Logistic regression analyses show that runoff delivery from unroaded catchments agrees with a water storage conceptual model typical for subsurface storm and saturation overland flow-dominated settings. Without roads, runoff occurs only about 4 times per year in response to 10 and 78 mm of storm rainfall, depending on antecedent precipitation. In contrast, maximum 15-min rainfall intensities are a better predictor of runoff generation on unpaved roads than are total rainfall and antecedent conditions. Intensities surpassing ~10 mm/hr lead to road runoff, and this occurs about 40 times per year. Road-influenced streams represent an intermediate setting for which runoff generation depends on storm and antecedent rainfall, as well as the road surface area captured by drains and flow path distance. In our focus area, roads can provoke streams to deliver runoff to coral bearing waters 10 to 13 times every year as a response to 9.3- to 50-mm storms, depending on antecedent rainfall and road drain characteristics. These results highlight the sensitivity of road connectivity to specific road drain characteristics and display the potential for connectivity as a guiding watershed restoration principle.

1. Introduction

1.1. Road Impacts on Runoff

Runoff on undisturbed, steep forested landscapes occurs through a combination of saturation overland flow (SOF) and subsurface stormflow (SSSF; Dunne, 1978). Even though forest roads tend to occupy a relatively small area of most forested landscapes, they can greatly alter water flowpaths and thus intervene with runoff generation (Luce, 2002; Montgomery, 1994). Research dating to the 1960s has focused on the potential of forest roads to increase peak flows (Harr et al., 1975; Rothacher, 1970) and sediment yields (Beschta, 1978; Megahan, 1972; Megahan & Kidd, 1972). Although tools to mitigate their effects have been developed and implemented (e.g., Cao et al., 2006; Ramos-Scharrón, 2012; Ziegler et al., 2006), unpaved roads remain a primary driver of water quality and aquatic habitat degradation (e.g., Biggs et al., 2010; Jones et al., 2000; Ramos-Scharrón & Thomaz, 2016; Sidle et al., 2006; Wemple et al., 2017).

Unpaved roads typically have saturated hydraulic conductivities and steady state infiltration capacities of less than 5 mm/hr (Ramos-Scharrón & MacDonald, 2007a; Ziegler & Giambelluca, 1997), and this is lower than commonly observed rainfall intensities particularly throughout the tropics (Harden, 1992; Wemple et al., 2017). Hence, roads can regularly generate surface runoff by precipitation excess (Horton) overland flow when adjacent tropical forests are not generating any surface runoff (Ramos-Scharrón, 2018; Ramos-Scharrón & Figueroa-Sánchez, 2017; Rijsdijk et al., 2007). Roads may also intercept subsurface flow, converting it into surface runoff (Luce, 2002; Wemple et al., 1996), and this can be substantial during large rainstorms particularly when soils are near saturation at the beginning of the storm (Negishi et al., 2008; Wemple & Jones, 2003; Ziegler et al., 2001).

While road impacts on runoff response have been studied extensively at the plot and segment scales, their effect at the watershed-scale has been debated (e.g., Jones & Grant, 2001; Thomas & Megahan, 1998). Models suggest that if 1–7% of a catchment is occupied by roads, this can induce a 10–30% peak flow increase in watersheds up to 25 km^2 for discharge rates of roughly 3 mm/hr (Cuo et al., 2006; LaMarche & Lettenmaier, 2001; Storck et al., 1998). However, empirical studies only have found increases for lesser peak flows (0.5–1.3 mm/hr) and smaller watersheds (<1 km^2) containing a high density of roads (>12% of surface area; Harr et al., 1975; Jones & Grant, 1996; King & Tennyson, 1984; Wright et al., 1990; Ziemer, 1981). Only one previous study has examined the extent to which roads affect runoff thresholds beyond the road segment scale but it was limited to a pair of zero-order basins (Woldie et al., 2009).

1.2. Road Impacts on Hydrologic and Sediment Connectivity

Generalized metrics, such as road densities, have proven insufficient in explaining the watershed level impacts of roads on runoff generation and sediment yields. This requires understanding of runoff and sediment connectivity within the stream network (Croke et al., 2005; Sidle et al., 2004; Sosa-Pérez & MacDonald, 2016; Wemple et al., 1996). This study meshes with the concept of terrain connectivity as defined for roads (Bracken et al., 2013), and this refers to the maximum downslope reach of runoff below a road drain. In ephemeral drainage systems, this road runoff could also represent an alteration to runoff initiation thresholds along the stream network. Although not integral to this particular study, we presume similarly to Reid et al. (2007) that the occurrence of a continuous surface flowpath implies some sediment connectivity. Stream crossings are an important and direct cause of road-stream connectivity (Coe, 2006; Lane & Sheridan, 2002; Thomaz et al., 2014; Thomaz & Peretto, 2016) yet other road segments also can contribute runoff and sediment, especially when they are in close proximity to a stream (Sidle et al., 2004). Studies have reported that from 9% to 35% of roads can be connected to streams, with the degree of connectivity increasing with annual precipitation and the abundance of road drainage structures (MacDonald & Coe, 2008).

Road hydrologic and sediment connectivity has been chiefly assessed by tracking the extension and continuity of erosion or depositional features (i.e., rills/gullies, or sediment plumes, respectively) below road drainage points (e.g., Montgomery, 1994; Wemple et al., 1996). The length of rills and sediment plumes depends on road segment size and total sediment produced, in addition to downslope characteristics such as gradient, soil type, and surface roughness (Megahan & Ketcheson, 1996). Another methodology assessed event-by-event travel distances of road runoff (Croke et al., 1999; Lane et al., 2006) and was termed the "volume to breakthrough" concept. The basic precept is that travel distances can be predicted if one can estimate the volume of runoff needed to overcome infiltration and depression losses along the designated flow path (Takken et al., 2008). Although watershed-scale applications have used this approach (Hairsine et al., 2002), it has not been empirically tested beyond a 10-m runoff travel distance or under natural rainfall conditions.

1.3. Objectives

The goal of this study is to document how the presence and layout of roads affect the antecedent precipitation conditions as well as storm size and maximum rain intensity needed to initiate runoff in dry-tropical, low-order ephemeral streams. The specific objectives of this study are to

1). empirically identify and compare the rainfall thresholds for runoff initiation in ephemeral stream channels with and without unpaved roads in the contributing area, as well as at the outlet of a mostly unpaved road segment; and
2). model the effect to which rainfall thresholds are affected by road surface area and the flow distance from a road drainage location to any given point along an ephemeral channel.

1.4. Study Area

The study area is the 10.7-km^2 Coral Bay watershed draining toward a well-enclosed bay on the southeastern portion of the island of St. John in the U.S. Virgin Islands (Figure 1). The watershed encompasses about 15 ephemeral drainages that either flow directly into coastal waters or flow through a coastal wetland before emptying into Coral Bay. Over half of the area has slopes that exceed 30%. Lithology is dominated by lightly weathered volcanic rocks (Rankin, 2002). Soils are predominantly shallow (0.15–0.5 m), moderately permeable, and well-drained Lithic Haplustolls with gravelly loam and gravelly clayey loam textures (U.S. Department of Agriculture, 1995). The climate is dry tropical with several distinct precipitation zones ranging from 1,000 to 1,400 mm/year with the higher values occurring near Bordeaux Mountain, the island's highest peak (Bowden et al., 1970). Average annual rainfall at an elevation of 9 m within Coral Bay is 1,140 mm/year (Station ID: 671790; National Oceanic and Atmospheric Administration (NOAA), 2001). About 57% of the annual rainfall at this station is associated with low-pressure systems between August and December. Monthly potential evapotranspiration exceeds monthly precipitation for most of the year (Bowden et al., 1970). Dry-evergreen forests and shrubs covering the lower portions of Coral Bay transition into moist tropical forest at higher elevations (Woodbury & Weaver, 1987). About 54% of Coral Bay lies

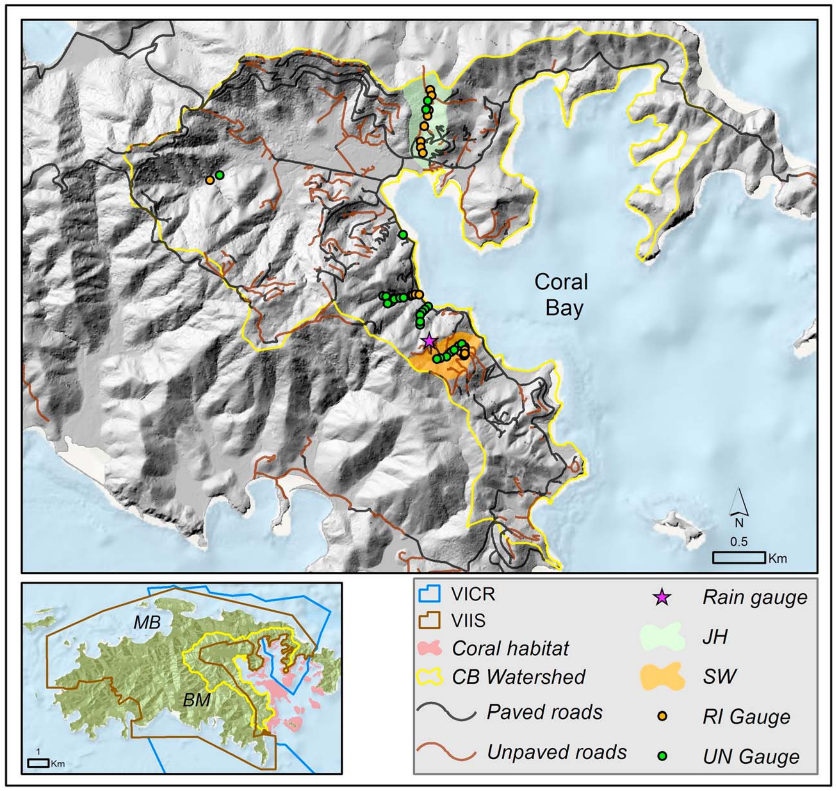

Figure 1. (a) General map of St. John, U.S. Virgin Islands displaying the extent of the Coral Bay watershed, the Virgin Islands National Park (VIIS), the Virgin Islands Coral Reef National Monument (VICR), the Maho Bay area (MB), Bordeaux Mountain (BM), and coral habitat within Coral Bay. (b) Map of the Coral Bay watershed including crest gauges, rain gauge, paved and unpaved roads, and the Johnny Horn (JH) and Shipwreck (SW) catchments.

within the Virgin Island National Park (VIIS; Figure 1), while the land outside the park has been developed for relatively low-density homes since the midtwentieth century (Brooks et al., 2007). Currently there are 64.8 km of roads (6.1 km/km^2), 38% of which are unpaved. Road drain structures include a combination of ditches, swales, and relief culverts.

Almost half of Coral Bay lies within the Virgin Islands Coral Reef National Monument (VICR; Figure 1), and the bay contains a diverse and unique coral assemblage (Rogers, 2009), including endangered *Acropora* species. Live coral cover is about 7.7% (Friedlander et al., 2013), which is in the low end of values reported for the USVI (Rogers et al., 2008). The estimated unpaved road contribution to basin-scale sediment yields into the bay amounts to 330 Mg/year (~30 Mg·km^{-2}·year^{-1}) and this is 4–16 times higher than expected background rates (Ramos-Scharrón, Reale-Munroe, et al., 2012). This plus the very low levels of toxic contaminants (Bargar et al., 2013; Whitall et al., 2015) indicate that fine sediment is the most important terrestrial threat to its coral reefs (Menza et al., 2012). The low coral cover and the perceived threat posed by high sediment yields led the federal and territorial government to declare Coral Bay a priority mitigation area (Territory of the USVI & NOAA, 2010), making a better understanding of road-to-coast connectivity critical to the management of coral reefs locally and throughout the USVI Territory.

In the island of St. John, road surfaces can generate precipitation excess 10 times more frequently than SOF- and SSSF-driven watershed-scale runoff generation (Ramos-Scharrón & LaFevor, 2016). The ephemeral nature of streams in St. John (Jordan & Cosner, 1973) provides an excellent opportunity to study runoff threshold behavior. Runoff thresholds and road connectivity are poorly understood in dry tropical areas, especially in the Northeastern Caribbean where unpaved roads are a primary source of anthropogenic sediment that may be adversely affecting nearshore coral reefs (Brooks et al., 2015; MacDonald et al., 1997; Ramos-Scharrón, Amador-Gutierrez, & Hernández-Delgado, 2012). Terrestrial erosion control is a focus of ongoing coral reef management programs in the U. S. Virgin Islands (USVI) (Territory of the USVI & NOAA, 2010) and elsewhere (e.g., State of Hawaii & NOAA, 2010; Waterhouse et al., 2017). Previous management actions have assumed that channeling road runoff into low-order ephemeral streams is an effective way to reduce the frequency and severity of runoff delivery. Here we document event-by-event road connectivity with the ultimate goal of identifying individual road segments that frequently deliver sediment to coastal waters during storms when runoff would not occur in the absence of roads.

2. Methods

2.1. Rainfall

Fifteen-minute rainfall data were collected from 25 October 2013 to 30 November 2015 in Coral Bay using a tipping bucket-recording rain gauge with a 0.1-mm resolution located at an elevation of 165 m (Figure 1). Total rainfall (ΣP) and maximum 15-min rainfall intensities (P_{int}) were compiled for every individual rainstorm, where each storm represented a rainfall pulse separated by at least 60 min with no rain. A time-weighed antecedent precipitation index (API; in mm) was also calculated for each storm event (Dunne & Leopold, 1978). API maintains a running sum of daily rainfall totals, but the value at each successive day with no rainfall is updated at the end of that day by multiplying the current index by 0.9^k, where k equals the number of subsequent days without rainfall. The index for each storm event equals the index at the beginning of the day plus any additional rainfall that fell on that day prior to the onset of the storm. Monthly total rainfalls were put into historical context by comparing these values to the longer-term data from the Coral Bay rain gauge located about 1.7 km away (NOAA, 2001).

2.2. Stream Runoff Response

Forty-six peak crest gauges recorded the occurrence of runoff along eight first- and second-order ephemeral stream tributaries in the Coral Bay area (Figure 1). In this study, crest gauges were only used to determine the occurrence or absence of flow (i.e., a binary value). The crest gauges are hollow, cylindrical pipes containing a smaller PVC pipe and powdered cork that adheres to this inner cylinder to mark the highest (peak) stage (Sauer & Turnipseed, 2010). Crest gauges were checked about once every 2 weeks between 25 October 2013 and 31 July 2015 except for crest gauges JH10 and JH11 that were installed on 8 August 2014. Twenty-six of the crest gauges were installed in streams that received no road runoff (unroaded sites, or UN). The location of each crest gauge was marked with a GPS unit (3-m resolution) and local slope was measured with a hand-held clinometer. UN sites represented a range of drainage areas and slopes typical for first- and second-order streams in St. John (2–18 ha and 3.6–53%, respectively; Table 1).

The other 20 crest gauges were all downslope of road drains (road influenced, or RI sites) along Coral Bay's ephemeral stream network. For practical reasons, all but two of the RI crest gages were clustered in four subbasins (Figure 1). Similar to UN sites, RI sites represented a range of drainage areas and slopes (1.6–58 ha and 3.9–52%, respectively). For all RI sites, the nearest upslope drainage point was identified and mapped with a GPS unit. Road drains included cemented swales, ditches, and culverts. The flow distances between the nearest road drain and each crest gauge (R_D) were determined from a 3-m digital elevation model. F_D values ranged from 16 to 493 m. Sketch maps and field measurements used to used to define the length, width, and area of all contributing road segments estimated road area (R_a) values between 284 and 1,470 m^2. Road surface area to flow distance ratios (R_a/F_D) ranged from 16 to 493 m^2/m.

A total of 1,845 measurements were collected from the 46 peak crest gauges. Individual peak crest gauges were checked on average 40 times during the study period. For each crest gauge, we compiled the ΣP, P_{int}, and API values for every storm that occurred when no runoff was noted. If flow was observed, we compiled the same rainfall parameters but only those associated with the storm with the largest ΣP, and then used the P_{int} and API value from that storm. For each storm, we also established the interstorm duration as the elapsed time since the last storm with at least 1 mm of rainfall.

2.3. Measured Runoff From Maho Bay Road

Rainfall and runoff measurements were available for a 230-m-long road segment in the Maho Bay area (Figure 1) from September 1999 to May 2000 (Ramos-Scharrón, 2004). Maho Bay road is mostly unpaved with only 15% of its surface covered by pavement. From these data, we derived a binary variable signaling runoff along with ΣP, P_{int}, and API values for 127 storms. This data set is hereafter referred to as RD. Road runoff for

Table 1
Crest Gauge Site Description and Brief Summary of Field Observations

Crest gauge id	Type	Drainage area (ha)	Local slope (%)	Road length (m)	Road surface area (m^2)	Flow distance (m)	R_a/F_D (m^2/m)	Average road slope (%)	Total obs.	Obs. w runoff	% obs. w runoff	# storms	# storms w runoff	% storms w runoff	# storms no runoff
JH10	UN	2.5	26	—	—	—	—	—	21	2	10%	211	2	0.9%	209
JH11	UN	2.1	49	—	—	—	—	—	21	4	19%	184	4	2.2%	180
NN1	UN	3.6	36	—	—	—	—	—	40	8	20%	328	8	2.4%	320
NN2	UN	6.5	34	—	—	—	—	—	40	8	20%	328	8	2.4%	320
NN3	UN	7.7	51	—	—	—	—	—	40	7	18%	353	7	2.0%	346
NN4	UN	8.3	33	—	—	—	—	—	40	7	18%	353	7	2.0%	346
NN5	UN	9.0	25	—	—	—	—	—	39	7	18%	353	7	2.0%	346
NN6	UN	9.4	28	—	—	—	—	—	44	7	16%	390	7	1.8%	383
SGM1	UN	15.5	39	—	—	—	—	—	40	8	20%	316	8	2.5%	308
SGM2	UN	15.7	30	—	—	—	—	—	40	8	20%	330	8	2.4%	322
SGM3	UN	17.9	35	—	—	—	—	—	40	8	20%	330	8	2.4%	322
SGN1	UN	7.6	41	—	—	—	—	—	40	7	18%	345	7	2.0%	338
SGN2	UN	10.5	24	—	—	—	—	—	40	7	18%	345	7	2.0%	338
SGN3	UN	11.0	27	—	—	—	—	—	40	7	18%	345	7	2.0%	338
SGS1	UN	2.7	41	—	—	—	—	—	40	8	20%	317	8	2.5%	309
SGS2	UN	3.5	41	—	—	—	—	—	40	8	20%	318	8	2.5%	310
SGS3	UN	3.6	50	—	—	—	—	—	40	8	20%	318	8	2.5%	310
SP	UN	16.6	3.7	—	—	—	—	—	47	7	15%	385	7	1.8%	378
SWN1	UN	3.1	37	—	—	—	—	—	39	7	18%	360	7	1.9%	353
SWN2	UN	3.4	36	—	—	—	—	—	41	6	15%	414	6	1.4%	408
SWN3	UN	4.3	30	—	—	—	—	—	39	7	18%	360	7	1.9%	353
SWN4	UN	6.5	30	—	—	—	—	—	40	7	18%	360	7	1.9%	353
SWN5	UN	7.7	53	—	—	—	—	—	40	8	20%	360	8	2.2%	352
SWN6	UN	8.1	46	—	—	—	—	—	41	6	15%	144	6	4.2%	138
SWN7	UN	11.6	19	—	—	—	—	—	40	11	28%	169	11	6.5%	158
UCBS	UN	13.6	3.6	—	—	—	—	—	40	8	20%	344	8	2.3%	336
JH1	RI	1.6	52	81	284	71	4.0	16	42	8	19%	173	8	4.6%	165
JH2	RI	3.3	22	176	563	25	22.5	5	42	19	45%	160	19	11.9%	141
JH3	RI	9.6	11	237	830	81	10.2	19	42	14	33%	295	14	4.7%	281
JH4	RI	13.5	14	95	333	47	7.1	10	42	16	38%	210	16	7.6%	194
JH5	RI	16.6	15	95	333	156	2.1	10	43	16	37%	230	16	7.0%	214
JH6	RI	23.0	3.9	205	1,025	128	8.0	15	42	12	29%	315	12	3.8%	303
JH7	RI	24.1	5	205	1,025	187	5.5	15	42	11	26%	361	11	3.0%	350
JH8	RI	24.5	4.9	205	1,025	246	4.2	15	42	9	21%	375	9	2.4%	366
SGM4	RI	18.2	19	137	548	16	34.3	16	41	9	22%	217	9	4.1%	208
SGM5	RI	18.4	19	137	548	44	12.5	16	40	9	23%	209	9	4.3%	200
SGM6	RI	28.0	6.1	137	548	82	6.7	16	45	10	22%	241	10	4.1%	231
SWM1	RI	14.3	13	358	1,468	116	12.7	16	41	19	46%	325	17	5.2%	308
SWM2	RI	15.1	14	358	1,468	141	10.4	16	41	20	49%	173	20	11.6%	153
SWM3	RI	16.1	3.9	358	1,468	214	6.9	16	46	20	43%	204	20	9.8%	184
SWS1	RI	2.4	44	211	739	24	30.8	23	41	19	46%	178	19	10.7%	159
SWS2	RI	2.8	38	211	739	40	18.5	23	40	20	50%	176	20	11.4%	156
SWS3	RI	3.8	42	358	1,468	24	61.2	16	41	20	49%	148	20	13.5%	128
SWS4	RI	4.0	35	358	1,468	52	28.2	16	41	20	49%	176	20	11.4%	156
SWS5	RI	4.2	34	358	1,468	79	18.6	16	41	20	49%	175	20	11.4%	155
UCBN1	RI	58.4	7.6	230	920	493	1.9	21	38	8	21%	346	8	2.3%	338

all of the rainstorms considered here was solely generated by HOF as field observations confirmed the absence of any upslope contributions or cutslope interception (Ramos-Scharrón & MacDonald, 2007a).

2.4. Defining Rainfall- and Road-Related Thresholds

SOF- and SSSF-driven runoff depends on a series of complex processes controlling soil saturation and lateral subsurface flow (Montgomery & Dietrich, 2002). An overriding assumption of this study was that these complexities could be subsumed under the category of water storage-dependent elements of rainfall (McGrath et al., 2007). This approach presumes that stormflow occurs when a storm exceeds the subsurface water storage capacity of the landscape. Antecedent soil moisture and storm size have proven to be reliable proxies for these storage-based elements (Graham et al., 2010; Scaife & Band, 2017). In contrast, infiltration capacities for unpaved roads are so low that precipitation excess can occur even during short-lived events regardless of antecedent moisture conditions. Therefore, road runoff thresholds are expected to be better explained by rain intensity than by storm rainfall or antecedent conditions. Road influenced streams present an intermediate scenario between unroaded areas and road segments. Therefore, the nature of their runoff thresholds is expected to depend on the road surface area and proximity of individual road drains.

Thresholds are commonly established visually (e.g., Detty & McGuire, 2010) or through piecewise regression analyses (e.g., Oswald et al., 2011; Scaife & Band, 2017). Here were relied on logistic regression to establish rainfall-dependent threshold values for the UN, RI, and RD sites. Six models were developed to test the effects of API and either ΣP or P_{int} using the following format:

$$P_r = 1/[1 + \exp(b0 + b1*(\Sigma P \ or \ P_{\mathrm{int}}) + b2*(API) + b3*(API*\Sigma P \ or \ P_{\mathrm{int}}) \quad (1)$$

where, P_{r} is the probability of runoff occurrence (≥0.5 suggests runoff generation), *b0–b3* are regression coefficients, and all other variables are as previously defined (ΣP and API are in millimeters; P_{int} is in millimeters per hour). Model performance was evaluated by relying on the pseudo-R^2 and level of significance for each variable. The marginal effect of ΣP or P_{int} and API on Pr were evaluated graphically.

The effect of R_{a} and F_{D} on the presence or absence of runoff for the RI sites was evaluated by adding these factors into equation (1):

$$P_r = 1/[1 + \exp(b0 + b1*(\Sigma P \ or \ P_{\mathrm{int}}) + b2*(API) + b3*(R_a) + b4*(F_D) \quad (2)$$

where, all parameters are as described for equation (1), R_{a} is road surface area in square meter, and F_{D} is flow distance in meters. The expectation is that sites with smaller road surface areas and long flow distances (low $R_{\mathrm{a}}/F_{\mathrm{D}}$) would be similar to the unroaded sites, while sites with a large R_{a} and a short F_{D} (high $R_{\mathrm{a}}/F_{\mathrm{D}}$) would behave more similarly to the road data set.

3. Results

3.1. Rainfall Associated to UN and RI Observations

A total of 551 rainstorms generated 1,588 mm of rainfall between 25 October 2013 and 31 July 2015 (Figure 2); this is only 82% of the long-term mean for Coral Bay for the same time period. The mean ΣP was 2.9 mm but ranged from 0.2 to 94.8 mm. Eighty-nine percent of the storms had less than 5 mm of rain and only 2% had more than 20 mm of rain. P_{int} averaged 5.5 mm/hr and ranged from 0.8 to 82 mm/hr. Monthly totals followed the typical wet and dry seasons but exceeded mean monthly values for only six of the 21 months. API averaged 33.4 mm and had a median of 25 mm. API values continuously exceeded 100 mm from 4 November 2013 to 14 January 2014, and briefly in mid-May 2014 and early November 2014. January through July 2015 was particularly dry with only 46% of normal rainfall and a mean API of 9.6 mm.

3.2. Rainfall Associated to RD Observations

Reliable runoff data from Maho Road between September 1999 and May 2000 was associated to 127 individual rainstorms that generated 508 mm of rainfall. The average size of these storms was 4.0 mm with values ranging from 0.25 to 30.5 mm. Maximum 15-min intensities ranged from 1.0 to 83.4 mm/hr with an average of 9.4 mm/hr. API values ranged from 0.0 to 200 mm and averaged 44.4 mm.

3.3. Runoff Observations at UN Sites

On average, runoff was recorded for 18% of the observations across all UN sites, with values for individual crest gauge sites ranging from 10 to 28% (Table 1). The smallest event that triggered runoff at an UN site was 5.6 mm, but this was for just a single-peak crest gauge with wet antecedent conditions (API = 122 mm). In general, runoff tended to occur at UN sites when ΣP exceeded 20 mm under wet conditions (API $>$ 100 mm), while at least 50 mm were required during relatively dry conditions (API $<$ 50 mm). At a representative UN site, crest gauge SWN5, the smallest storm to generate runoff was 22.2 mm and this occurred when API was 179 mm (Figure 3a).

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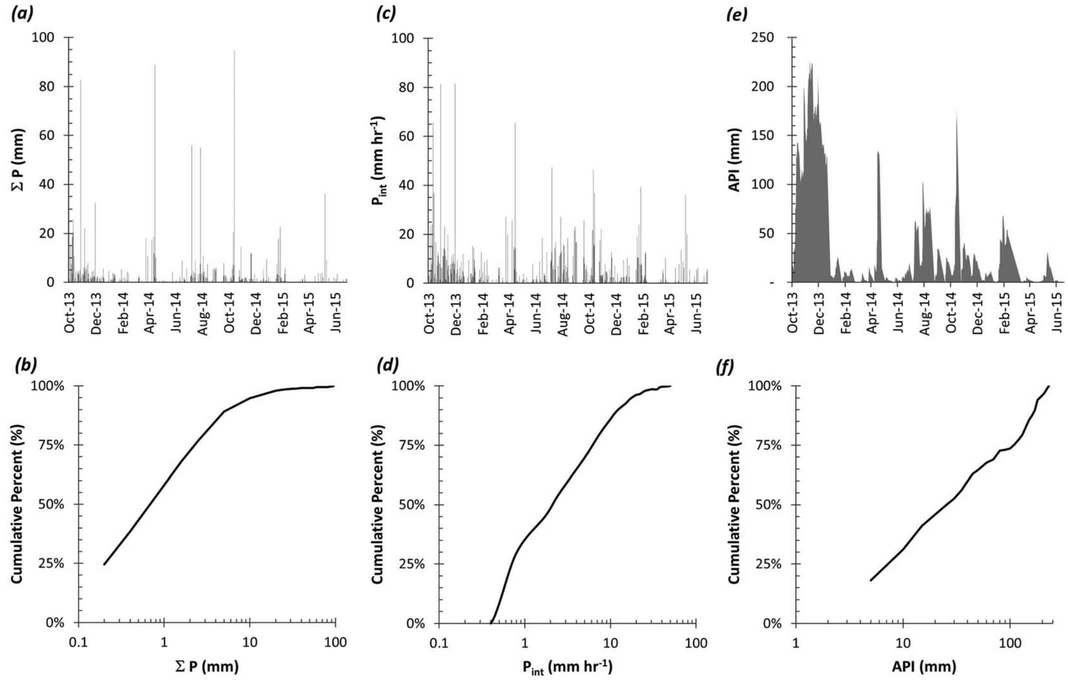

Figure 2. Time series and cumulative percent distribution curves for storm total precipitation (ΣP; a, b), maximum 60-min precipitation intensity (P_{int}; c, d); and antecedent precipitation index (API; e, f) for October 2013 through July 2015.

The majority of events triggering runoff at UN sites had P_{int} values exceeding 16 to 22 mm/hr. However, the smallest P_{int} value inducing runoff from a UN site was 10.4 mm/hr and this surprisingly occurred during dry conditions (API = 7.5 mm). The apparent anomaly might relate to the spatial distribution of rainfall during some storms even though the rain gauge was no further than 2.6 km from any crest gauge. The average interstorm duration for storms generating runoff from UN sites was 16.75 hr or 18% of the 93-hr average for those that did not generate any runoff. The maximum interstorm duration for runoff-triggering events at UN sites was 153 hr. This implies that runoff generation at UN sites tended to be triggered following a series of storms in quick succession that build up API rather than as an isolated rainstorm. For example, at SWN5 no storm with less than 43 mm of API or with an interstorm duration longer than 24.75 hr triggered runoff.

3.4. Runoff Observations at RI Sites

On average, the RI sites recorded runoff about twice as often as the UN sites or for 38% of the observations. The range of values for individual sites ranged from 19 to 50%. The smallest ΣP associated to runoff response from a RI site was 4.8 mm, and in contrast to the UN sites, this occurred during very dry conditions (API $<$ 10 mm). The proportion of RI sites with runoff increased from about one third when ΣP was about 8 mm to more than half when storm precipitation was greater than 15 mm. These proportions varied little regardless of API values. An excess of 9.6 mm/hr of P_{int} was required to generate runoff for most RI sites. However, P_{int} values as low as 3.2 mm/hr were reported to have triggered runoff even during dry conditions (API = 11.6 mm). Heterogeneities in the spatial distribution of rainfall are presumed to affect some of the rainfall parameters during particular storms. Interstorm duration has no apparent effect on the rainfall thresholds for RI sites.

Relationships between API and ΣP, API and P_{int}, and interstorm duration with ΣP for three representative RI sites are displayed in Figures 3b–3d. Sites JH5, SWM3, and SWS3 correspond to three sequential degrees of road influence as defined by their R_a/F_D ratios (2.1, 6.9, and 61.2 m^2/m, respectively). In contrast to UN sites, runoff was observed at all three sites at a wide range of API (0.15 to 207 mm) and interstorm duration values (1.5 to 274 hr). The smallest events triggering runoff at JH5, SWM3, and SWS3 had ΣP values of 7.4, 5.6, and 4.8 mm (respectively), and this is in accordance to the expected lowering of rain threshold with increasing R_a/F_D. In contrast, minimum P_{int} values associated to runoff-triggering events had no evident association to R_a/F_D.

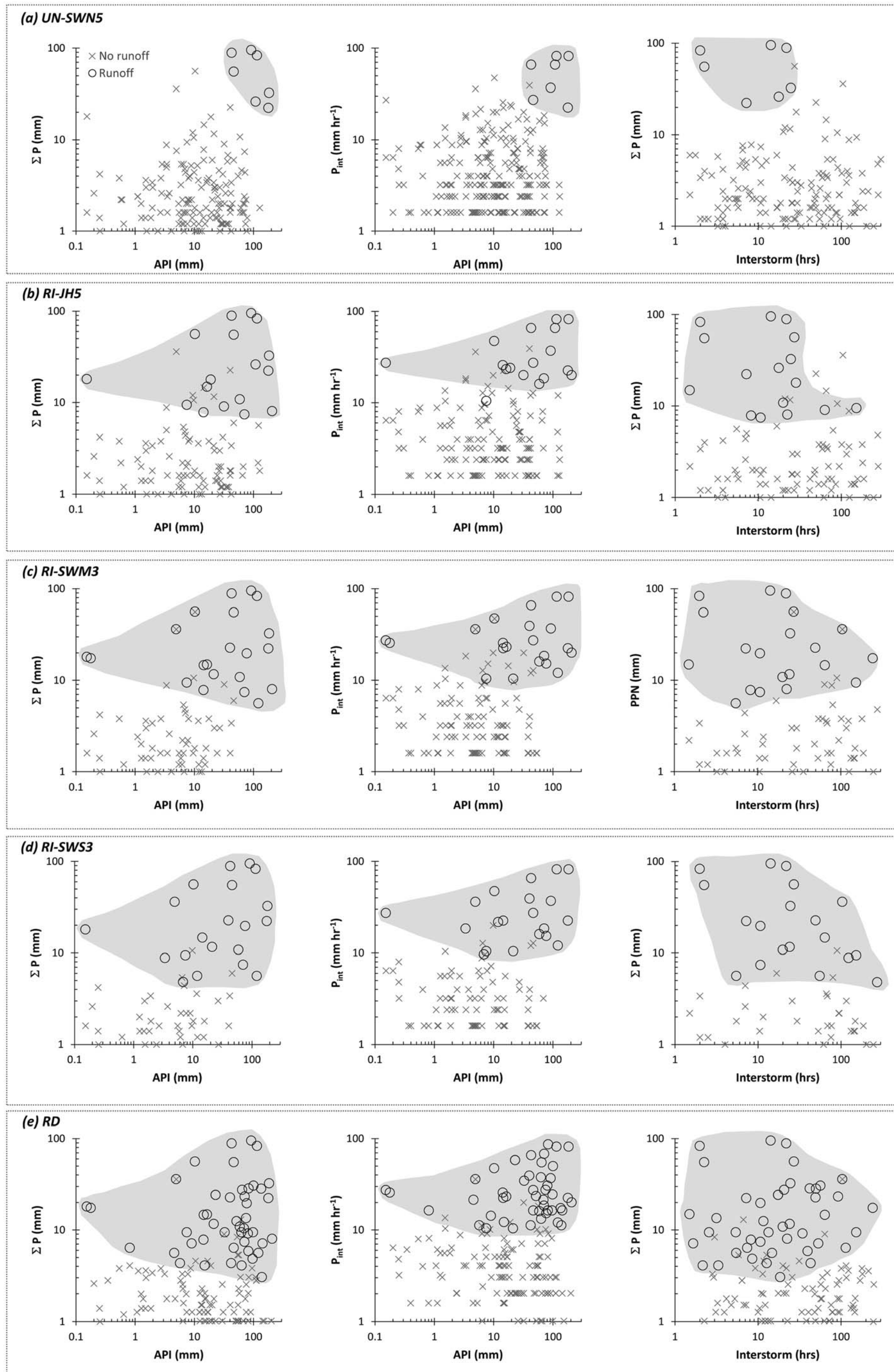

Figure 3. Presence (open circles) or absence (x's) of streamflow as a function of Σ*P*, API, and interstorm duration for crest gages UN-SWN5 (a), RI-JH5 (b), RI-SWM3 (c), RI-SWS3 (d), and Maho Road-RD (e). Gray-shaded areas roughly delineate the extent of observations indicating the presence of runoff. API = antecedent precipitation index.

3.5. Runoff Observations for RD Site

Runoff from the RD site occurred during 20% of the 127 rainstorms. The minimum amount of rain needed to generate runoff was slightly less than the RI sites, with a minimum of 3.1 mm during wet conditions (API = 140 mm) and only 4.3 mm during drier conditions (API = 5.8 mm; Figure 3e). Road runoff was generated at a wide range of interstorm duration values ranging from 1.5 to 241 hr. The minimum P_{int} required for runoff generation at the RD site consistently was 10.4 mm/hr for a wide range of API values. These findings

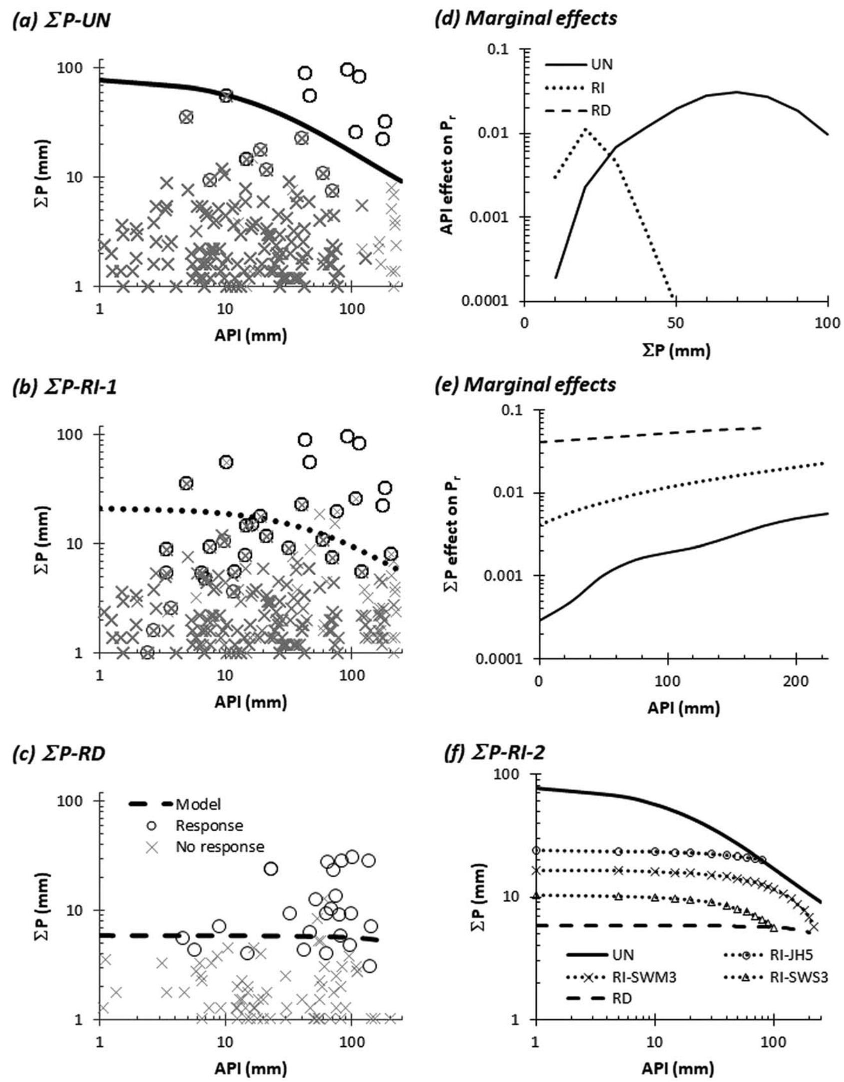

Figure 4. Presence (open circles) or absence (x"s) of streamflow at all 46 crest gages as a function of ΣP and API for (a) unroaded sites; (b) road-influenced sites; and (c) Maho Bay road segment. Lines in each graph indicates the threshold value predicted by logistic regression analyses based on equation (1). (d) The marginal effects of API on the probability of runoff by controlling for ΣP for three logistic regression models based on equation (1) (ΣP-UN, ΣP-RI-1, and ΣP-RD, respectively). (e) The marginal effects of ΣP while controlling for API for the same three regression models. (f) Compares models ΣP-UN and ΣP-RD to ΣP-RI-2 (equation (2)) for conditions at crest gage sites JH5, SWM3, and SWS3. API = antecedent precipitation index.

indicate that, like the RI sites, antecedent moisture and interstorm duration had little effect on either the minimum ΣP or P_{int} needed to generate runoff.

3.6. Logistic Regression—Runoff Response as a Function of ΣP, API, R_a, and F_D

A logistic equation developed for the UN sites (ΣP-UN in Figure 4) shows that ΣP, API, and the ΣP*API interaction term were all statistically significant and the model was successful in separating crest gage readings with and without runoff (pseudo R^2 of 0.91; Table 2). ΣP-UN predicts a decline from 78 to 10 mm in the ΣP needed for runoff generation for API values of 1 and 200 mm, respectively. The marginal effects of the ΣP-UN model for API were much higher than those for ΣP, and these peaked at ΣP values of 70 mm. This indicates that API is particularly important in defining runoff generation from UN sites for all storm sizes of less than 70 mm and that runoff is likely generated by larger storms regardless of API.

In contrast to model ΣP-UN, equation (1)-based logistic regression analyses on the RI data set indicated that only ΣP was statistically significant (ΣP-RI-1 in Figure 4). In addition, this model had a relatively lessened

Table 2
Summary of Logistic Regression Analyses Based on Equations (1) and (2)

Model	Obs.	Pseudo R^2	Int.	ΣP	P_{int}	API	ΣP*API	P_{int}*API	R_A	F_D
ΣP-UN	8,399	0.91	**−7.29** (0.413)	**0.090** (0.012)	—	−0.010 (0.010)	**0.0040** (0.003)	—	—	—
ΣP-RI-1	4,769	0.64	**−4.73** (0.233)	**0.222** (0.054)	—	−0.003 (0.008)	0.003 (0.002)	—	—	—
ΣP-RD	127	0.59	**−5.496** (1.234)	**0.937** (0.285)	—	0.0177 (0.014)	−0.0028 (0.003)	—	—	—
ΣP-RI-2	4,769	0.64	**−7.082** (0.418)	**0.330** (0.018)	—	**0.016** (0.002)	—	—	**0.003** (0.0003)	**−0.0106** (0.0017)
P_{int}-UN	8,399	0.84	**−7.580** (0.323)	—	**0.123** (0.014)	−0.003 (0.008)	—	**0.002** (0.0002)	—	—
P_{int}-RI-1	4,769	0.64	**−5.547** (0.243)	—	**0.194** (0.018)	−0.003 (0.009)	—	0.001 (0.0007)	—	—
P_{int}-RD	127	0.82	**−9.549** (3.331)	—	**0.756** (0.293)	0.023 (0.039)	—	−0.012 (0.003)	—	—
P_{int}-RI-2	4,769	0.66	**−8.362** (0.457)	—	**0.266** (0.013)	**0.017** (0.002)	—	—	**0.003** (0.0003)	**−0.010** (0.001)

Note. Statistically significant parameters are shown in bold font.

capacity to distinguish between runoff versus nonrunoff readings (pseudo R^2 of 0.64). The model suggests that about 21 mm of rain are required to generate runoff during dry conditions (API of 1 mm) and this is 27% of that required for UN sites. Predicted threshold ΣP values for wet conditions (API ~ 200 mm) are about 6.3 mm or 63% of those predicted by ΣP-UN. The marginal effects of both API and ΣP for ΣP-RI-1 are relatively minor compared to ΣP-UN (Figures 4d and 4e).

Similarly to ΣP-RI-1, logistic regression following equation (1) on the RD data set showed that only ΣP was significant (model ΣP-RD in Figure 4). ΣP-RD also had a poorer ability to differentiate runoff versus nonrunoff events than ΣP-UN (pseudo R^2 of 0.59). ΣP-RD suggests that only 4.1 to 5.9 mm of rainfall are required to generate road runoff with the lower values associated to wetter antecedent conditions. The marginal effect of API for ΣP-RD was very small (Figure 4e). In contrast to both ΣP-UN and ΣP-RI-1, the marginal effect of ΣP for the ΣP-RD model was considerable throughout the entire range of API values (Figure 4d).

When the logistic regression analyses on the RI data included ΣP, API, R_a, and F_D (equation (2)), all parameters were found to be statistically significant (model ΣP-RI-2 in Figure 4). However, ΣP-RI-2 had a lessened certainty in differentiating runoff versus nonrunoff storms than ΣP-UN (pseudo R^2 of 0.64). Application of the ΣP-RI-2 model for conditions represented by RI crest gauge sites JH5, SWM3, and SWS3 demonstrate how the model predicts a reduction in API and ΣP threshold combinations with increasing R_a and decreasing F_D (Figure 4f). This means that the smaller the road surface area and the longer the flow distance, the less likely it is that a road will be able to initiate streamflow. For the JH-5 site and for API values greater than 80 mm, the ΣP-RI-2 model predicts ΣP threshold values that are higher than predicted for UN. This suggests that for a storm exceeding ~20 mm of rainfall and 80 mm of API, runoff at this site (R_a = 333 m^2 and F_D = 156 m) would most likely be initiated by processes controlling runoff generation at unroaded catchments rather than from the contributing road segment.

3.7. Logistic Regression—Runoff Response as a Function of P_{int}, API, R_a, and F_D

The P_{int}-based logistic regression model for UN sites following equation (1) (P_{int}-UN in Figure 5) had a slightly poorer, but still strong ability to discern between runoff and nonrunoff observations than ΣP-UN (pseudo R^2 of 0.84; Table 2). P_{int} and P_{int}*API were both statistically significant in model P_{int}-UN. Similar to ΣP-UN, the marginal effects of API were notably more important than for P_{int} (Figures 5d and 5e). P_{int}-UN suggests that P_{int} must exceed 60 mm/hr for runoff to be generated in unroaded streams during antecedent dry conditions (API = 1 mm) and that P_{int} values exceeding 15 mm/hr are expected to trigger runoff during wet conditions (API = 200 mm).

The P_{int}-based, RI site model (P_{int}-RI-1 in Figure 5) has the exact same pseudo R^2 value of 0.64 as the ΣP-based model (ΣP-RI-1). P_{int} is the only statistically significant parameter of the P_{int}-RI-1 model and the marginal effects of API are only of importance when P_{int} ranges from 20 to 40 mm/hr (Figure 5d). P_{int}-RI-1 predicts runoff for P_{int} values of 28 mm/hr for pre-existing dry conditions, and this is about half of that predicted by P_{int}-UN. The P_{int} threshold for runoff during wet conditions is 13 mm/hr and this is just shy of the 15 mm/hr predicted by P_{int}-UN.

The P_{int}-based model for the RD site (P_{int}-RD in Figure 5) shows an enhanced capacity to predict runoff generation relative to ΣP-RD (pseudo R^2s of 0.82 and 0.59, respectively). P_{int} was the only statistically significant parameter in P_{int}-RD, and it had marginal effects of notable importance for all API values. The P_{int} threshold for road runoff generation according to P_{int}-RD is 13 mm/hr for preexisting dry conditions, which is about half and 22% of those for RI and UN sites, respectively. The P_{int} road runoff threshold during wet antecedent conditions is 10 mm/hr and this is 77% and 66% of those predicted for RI and UN sites, respectively.

P_{int}, API, R_a, and F_D were all statistically significant according to logistic regression analyses of the RI data based on equation (2) (P_{int}-RI-2 model in Figure 5). The resulting model, P_{int}-RI-2 proved to have a moderate capacity to differentiate runoff versus nonrunoff observations similar to model ΣP-RI-2 (pseudo R^2 of 0.66 and 0.64, respectively). P_{int}-RI-2 predicts that the likelihood of runoff increases with decreasing F_D and increasing P_{int}, API, and R_a. P_{int}-RI-2 estimates a 100 m increase in F_D for every 3.8 mm/hr increase in P_{int} past the threshold intensity value regardless of API and R_a. The model also suggests a 100 m increase in F_D for every 360 m^2 increase in R_a (~72 m in road length) regardless of ΣP and API.

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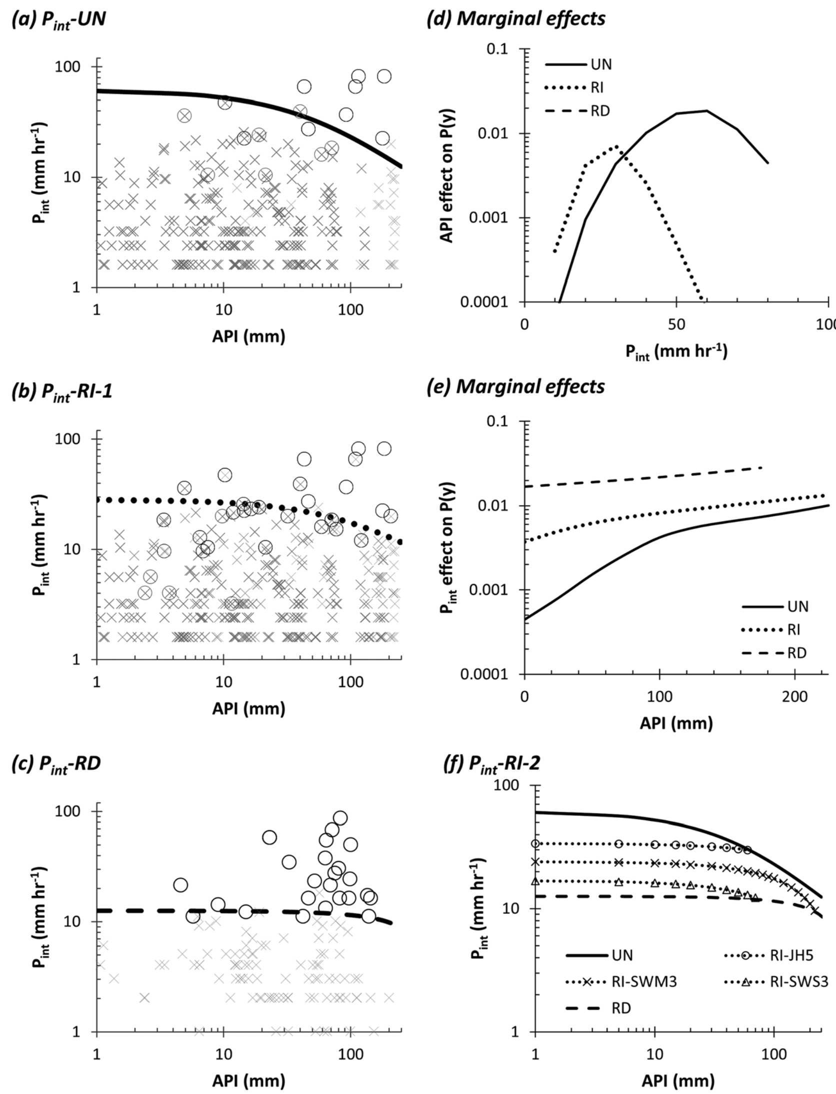

Figure 5. Presence (open circles) or absence (x's) of streamflow at all crest gages as a function of P_{int} and API for (a) unroaded sites; (b) road-influenced sites, and (c) Maho Bay road segment. Lines in each graph indicate the threshold value predicted by logistic regression analyses based on equation (1). (d) The marginal effects of API on the probability of runoff by controlling for P_{int} for each of the three logistic regression models based on equation (1) (P_{int}-UN, P_{int}-RI-1 and P_{int}-RD, respectively). (e) The marginal effects of P_{int} while controlling for API for the same three regression models. (f) Compares models P_{int}-UN and P_{int}-RD to P_{int}-RI-2 (equation (2)) for conditions at crest gage sites JH5, SWM3, and SWS3. API = antecedent precipitation index.

Application of P_{int}-RI-2 to crest gage site JH-5 suggests a lower P_{int} threshold than for UN sites for all API values less than 60 mm (Figure 5f). This suggests that at JH-5, runoff would be generated by the contributing road prior to being generated by UN conditions for all events with API values of less than 60 mm. For API values exceeding 60 mm, any runoff would be more likely generated under UN conditions than by upslope road runoff contributions.

4. Discussion

4.1. Rainfall-Driven Thresholds for Runoff Development

A goal of the present study was to evaluate whether antecedent and storm precipitation conditions can reliably predict runoff generation from unroaded ephemeral streams. Results described here confirm that a parsimonious storage-based model consistently predicts the rainfall-driven thresholds of runoff generation within low-order unroaded catchments in an ephemeral, dry-tropical climate setting. A model relying on

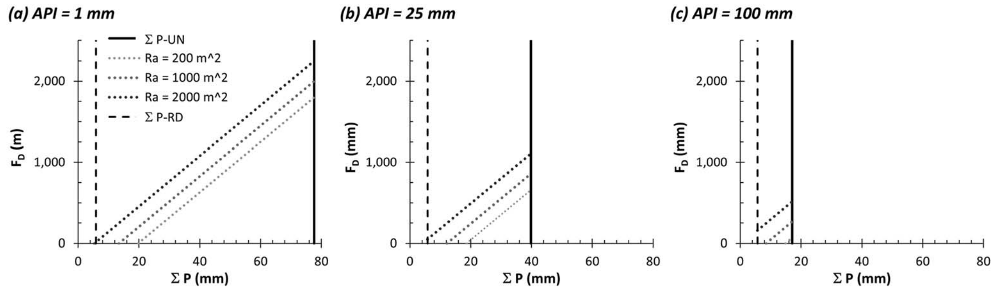

Figure 6. Model ΣP-RI-1 predicted F_Ds for varying ΣP and R_a values at API values of 1, 25, and 100 mm (Figures 6a, 6b, and 6c, respectively). The figure also displays the ΣP thresholds for a road segment based on model ΣP-RD and unroaded ephemeral streams based on model ΣP-UN for the same three API values. API = antecedent precipitation index.

P_{int} also confirmed the significance of API in defining runoff generation thresholds. These two approaches represent improvements from previous local attempts that had exclusively relied on total rainfall as a controlling factor (Cosner, 1972; Jordan & Cosner, 1973; Larson et al., 2015; Ramos-Scharrón & LaFevor, 2016).

ΣP thresholds for runoff initiation for undisturbed sites in Coral Bay ranged from 78 mm for dry conditions to 10 mm for wet conditions (API = 1 mm and 200 mm, respectively). Results are consistent with previous observations in St. John that established ~20–30 mm of ΣP as the amount needed to establish some soil profile saturation during a slightly wetter than normal period (Ramos-Scharrón & MacDonald, 2007b). Results also reflect local edaphic controls as the amount of rainfall expected to generate runoff during dry conditions is sufficient to saturate a significant portion of St. John's soil mantle (either an 18-cm-deep gravelly loam with a 43% porosity or up to 29 cm of a gravelly clayey loam with a porosity of 27%).

Application of model ΣP-UN to 3 years' worth of ΣP and API observations (November 2013 to November 2016) resulted in predicting runoff generation from undisturbed watersheds only during 12 out of 880 rainstorms (1.4%). This yields an annual frequency of only 4 times per year. Three out of the 12 storms with expected runoff had a ΣP value exceeding 70 mm, but four of them had ΣP values within a 25- to 35-mm range. Given the dependency of these events on antecedent conditions, many runoff-triggering storms occur within days of each other and with long periods in between triggering periods. On average, the predicted average time between runoff triggering storms for the November 2013 to November 2016 period was 100 days. Our findings suggest that roughly a fourth of runoff triggering storms at UN sites were infrequent, large events exceeding 70 mm; these storms triggered runoff regardless of antecedent rain conditions. About a third of the runoff-triggering storms were moderately sized (25 to 35 mm) and occurred during wetter conditions.

Rain-related runoff thresholds for the road segment (RD) were very distinct from those for UN sites—in part because API was not a significant regression parameter. Therefore, RD does not have the wide range of threshold ΣP and P_{int} values for dry and wet conditions found for the UN sites. In contrast with the UN sites, the P_{int}-based road segment model (P_{int}-RD) proved more accurate in defining runoff versus nonrunoff observations than the ΣP-based model (ΣP-RD). These findings are in agreement with the expectations that the SOF- and SSSF-driven runoff at UN sites are storage dependent and, in addition, that precipitation intensity is the key factor controlling the generation of road runoff by precipitation excess (McGrath et al., 2007).

Application of the P_{int}-RD model to the November 2013 to November 2016 rain data set predicts road runoff for 119 out of 880 storms (13%). The estimated average number of road runoff-generating storms per year is a full order of magnitude greater than that for UN sites (40 versus 4 events per year, respectively). The smallest event expected to have triggered runoff from roads based on this model had a ΣP of 2.0 mm. Due to the lower rainfall threshold requirements and the irrelevance of API, about 88% of the storms expected to have triggered road runoff during this period had ΣP values ranging from 2.5 to 25 mm. This contrasts with the UN sites where the majority of runoff-triggering events range either from 25 to 35 mm or are greater than 70 mm. Average time between road runoff-triggering storms was only 9 to 10 days, and this is a full order of magnitude shorter than that for UN sites.

Our results confirm that rainfall-related thresholds for runoff development at RI sites represent an intermediate condition between those for UN and RD sites (Figures 4f, 5f, and 6). One consequence of this intermediate condition is that threshold values are not as clearly defined as for UN or RD sites. Neither of the two rainfall- and API-based regression models for the RI data set (ΣP-RI-1 and ΣP-RI-2) accomplished the same level of certainty as the UN and RD models in discerning between runoff and nonrunoff observations (pseudo R^2 of 0.64 for both). However, all regression parameters in models accounting for rainfall as well as road surface area and flow distance were statistically significant and agreed with the expected patterns. Model ΣP-RI-2 suggests that less rainfall is needed to initiate runoff along a stream with increasing R_a and API, but that larger storms are required with increasing F_D.

According to ΣP-RI-2, an additional 0.8 mm of rainfall is required to initiate runoff at any given F_D per every 100-m^2 reduction in R_a (~20 m of road length). Similarly, an additional 0.5 mm of rainfall is needed to trigger runoff per every 10-mm reduction in API. Since runoff generation along UN sites is strongly dependent on API, the range of Σ*P* values over which contributing road runoff can be the cause of runoff within a stream becomes more restricted with decreasing R_a and increasing API (Figures 6a–6c). This is because the Σ*P* threshold values are higher for low R_a values and because the required Σ*P* for runoff to begin regardless of roads is less with increasing API. The finding that the importance of roads in establishing runoff downslope from drains diminishes the wetter the antecedent conditions is consistent to that previously established for zero-order basins in Japan (Woldie et al., 2009).

The Σ*P*-based model ΣP-RI-1 predicts a 100-m increase in F_D for every 3.2-mm increase in rainfall beyond the threshold, and this is consistent for any combination of Σ*P*, API, and R_a. It also implies a 100-m increase in F_D for every 400-m^2 increase in R_a (~80 m in road length) (Figures 6a–6c). Translating these findings into the volume of runoff required to advance a given flow distance (i.e., volume to breakthrough) requires a consideration of road runoff coefficient, which we will presume to range from 30% to 70% (Ramos-Scharrón & MacDonald, 2007a). For storm sizes ranging from 25 to 60 mm, ΣP-RI-1 predicts that from 0.03 to 0.07 m^3 of road runoff is required for every single meter advance along a flow path (150–350 L for a 5-m-long flow path). This estimate can be directly compared to the volume to breakthrough results for roads in harvested eucalyptus forests in southeastern Australia (Croke et al., 1999). In that study, the volume to breakthrough was determined during controlled, 30-min long, 22.5- to 55-mm rain experiments on flow paths consisting of <1-m-deep sandy loams and gravelly clay loam soils similar to those in St. John. The average road runoff volume required to advance along a road flow path in Australia was 0.067 m^3/m (336 L for a 5-m-long flow path). The similarity between the two estimates is surprising given that the Australian case represents unchanneled soil surface flow paths while the St. John estimate is for flows along low-order ephemeral streams.

Application of ΣP-RI-1 to November 2013 to November 2016 rain data demonstrates how the probability that any random event can generate stream runoff varies according to R_a and F_D. For example, for a crest gauge like JH-5 with a low R_a/F_D ratio (2.1 m^2/m), the probability of any storm triggering runoff equals only 0.5%. At JH-5, the frequency that roads are expected to be the runoff-triggering factor is only 1.3 times per year. In contrast, for site SWS3 with a R_a/F_D ratio of 61.2 m^2/m, the probability and frequency of runoff are 6.1% and 18 times per year, respectively. Therefore, the road contributing to SWS3 is expected to induce 4.5 times more frequent runoff than if the stream had no contributing road. Regardless of F_D, roads with R_a values exceeding 1,250 m^2 (~250-m long) are capable of inducing runoff generation an excess of 10 times every year. Roads with R_a values of 2,500 m^2 (~500-m long) appear capable of inducing runoff at F_D up to 150 m about 30 times every year or during 75% of the storms for which road runoff is generated.

4.2. Management Implications

Practical implications of the regression analyses presented here were explored for two small catchments. These catchments have been the target of watershed management actions that rely on the the ephemeral stream network as a buffer to prevent the frequent delivery of road runoff into Coral Bay. The 18.7-ha Shipwreck Catchment (SW) is a second-order catchment with 4,660 m^2 of roads and individual drains with F_D values ranging from 260 to 1,480 m from drain to coast. The Johnny Horn Catchment (JH) covers 27.6 ha and is drained by a first-order stream receiving runoff from a 10,510-m^2 road surface area with drains having F_D values ranging from 110 to 950 m to the coastline. Individual R_a values for road drains in the SW and JH are 880 and 600 m^2, respectively. The relative percent of roaded area is 2.5% in SW and 3.9% in JH (Figure 7; Table 3).

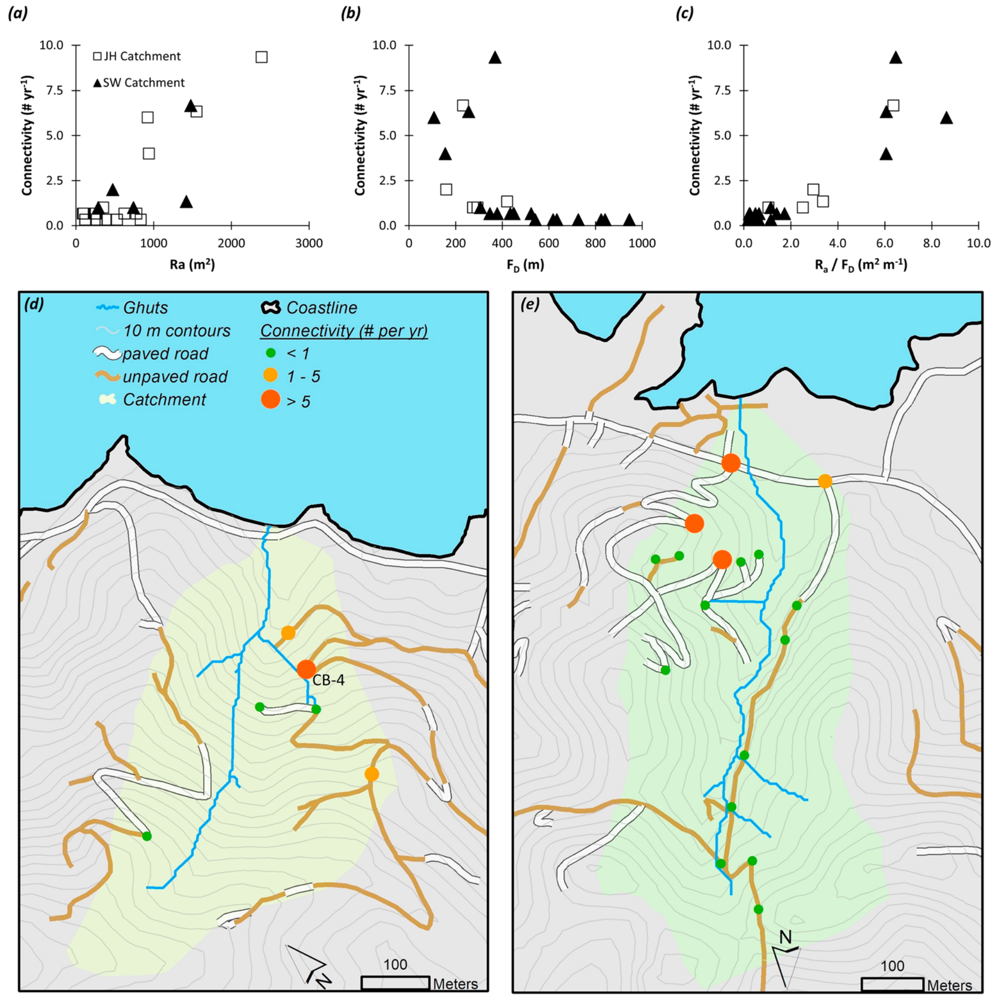

Figure 7. Results of the application of logistic regression model ΣP-RI-2 to the shipwreck (SW) and Johnny Horn (JH) catchments based on the November 2013 to November 2016 rain database. Figures 7a, 7b, and 7c display the predicted relationships between R_a, F_D, and R_a/F_D with the average number of storms per year for which individual road drains are expected to deliver runoff to the coastline while no natural runoff was generated. Figures 7d and 7e represent maps displaying the spatial distribution of the predicted connectivity frequency for the SW and JH catchments, respectively.

According to model ΣP-RI-1, the drain-specific precipitation thresholds for achieving connectivity to the coastline for SW and JH ranged from 9.3 to 50 mm, depending on API (1–100 mm), R_a, and drain-to-coast F_D from drain to the coastline. Application of ΣP-RI-1 to all road drains within these two catchments based on the November 2013 to November 2016 rainfall database indicates that the probability of any random storm achieving road to coast connectivity averages 2% for these two catchments with a range of 1.5% to 4.5% (Table 3). For individual road drains, the calculated average frequency of connectivity to the coastline during events when no natural runoff is generated varied from less than once per year to 9.3 times per year (Figures 7a–7c). The spatial distribution of the drain-specific connectivity frequencies displayed for the JH and SW catchments is complex due to varying R_a and F_D values. This implies that catchment-scale lumped characterizations (e.g., the proportion of a catchment occupied by roads) alone are not appropriate for determining the impacts of road networks on catchment-scale connectivity.

Although higher total sediment loads are recognized to adversely affect coral reefs, little is known about the effects of increased frequency of delivery. Of particular relevance for the reef systems of Coral Bay is whether frequently connected road drains convey sediment-laden runoff from unpaved roads. For instance, all the road drains in JH that are predicted to connect to the bay when no natural runoff is generated at least 6 times per year are paved, but since they are paved they will contribute minimal sediment to Coral Bay (Figure 7d). All unpaved roads in JH have an estimated connectivity of less than once per year, which makes them

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Table 3
Drain-by-Drain Site Description and Results Summary of the Application of the P_{int}-RI-2 Model for Each Drain Based on Rainfall Data Spanning From November 2013 to November 2016

Drain id	Watershed	Road area (m^2)	Flow dist (m)	R_a/F_D (m^2/m)	Σ P threshold for API = 1 mm (mm)	Σ P threshold for API = 100 mm (mm)	Prob. any storm triggering runoff	Connectivity (events/year)
cb_16	SW	1421	421	3.37	23.6	18.7	1.8%	1.3
cb_15	SW	740	294	2.52	24.9	20.1	1.7%	1.0
cb_19	SW	287	275	1.04	27.9	23.1	1.7%	1.0
cb_4	SW	1477	232	6.37	17.1	12.2	3.6%	6.7
cb_3	SW	474	160	2.96	22.8	17.9	2.0%	2.0
jb_8	SW	257	524	0.49	36.2	31.3	1.6%	0.7
jho_8	JH	269	945	0.28	49.6	44.7	1.5%	0.3
jho_6	JH	266	824	0.32	45.7	40.9	1.5%	0.3
jho_5	JH	833	726	1.15	38.1	33.2	1.5%	0.3
jho_9	JH	528	841	0.63	44.2	39.3	1.5%	0.3
jho_12	JH	381	634	0.60	38.7	33.9	1.5%	0.3
jho_4	JH	779	450	1.73	29.6	24.8	1.6%	0.7
jho_3	JH	245	378	0.65	31.6	26.7	1.6%	0.7
jho_1	JH	939	155	6.06	18.9	14.0	2.7%	4.0
sg_8a	JH	119	618	0.19	40.3	35.4	1.5%	0.3
sg_9a	JH	2388	369	6.47	14.2	9.3	4.5%	9.3
sg_10a	JH	624	447	1.40	30.8	25.9	1.6%	0.7
sg_11a	JH	90	347	0.26	31.8	27.0	1.6%	0.7
sg_12a	JH	351	306	1.15	28.4	23.6	1.7%	1.0
sg_6a	JH	121	541	0.22	37.8	32.9	1.5%	0.3
sg_7a	JH	101	434	0.23	34.5	29.7	1.6%	0.7
sg_4a	JH	1553	256	6.07	17.2	12.3	3.5%	6.3
sg_1a	JH	923	107	8.63	17.5	12.6	3.4%	6.0

minimally capable of enhancing catchment-scale runoff response. Therefore, roads within JH do not appear to enhance the frequency of unpaved road sediment delivery to Coral Bay.

In contrast, only one of the six road drains in SW is predicted to deliver sediment six times per year in addition to the four storms generating runoff naturally (Figure 7e). However, this drain handles runoff from a 300-m-long (R_a = 1,500 m^2), steep and frequently graded road segment estimated to produce nearly 4 Mg of sediment per 10 mm of rainfall according to a locally derived road erosion model (Ramos-Scharrón & MacDonald, 2005). Therefore, any road runoff delivered during these events will be undiluted and could contain high suspended sediment concentrations (5,000–80,000 mg/L range) (MacDonald et al., 2001; Ramos-Scharrón & MacDonald, 2007a). The sediment delivery potential for this stream is high due to its steepness (4–45%), general lack of landscape features promoting deposition, and because about 64% of the sediment generated is expected to be sand-sized and finer, and thus easily transportable (Ramos-Scharrón & MacDonald, 2007c). The average rainfall associated with the six storms leading to road-driven connectivity for drain CB-4 is about 140 mm. Therefore, CB-4 could potentially deliver a maximum of 55 Mg/year of sediment in addition to the four storms when runoff is expected to be generated regardless of roads. This is 4–16% of the total estimated annual sediment yield for the entire 10.7 km^2 Coral Bay watershed under undisturbed conditions (Ramos-Scharrón, Reale-Munroe, et al., 2012) and about 300 times higher than the expected contribution from an unroaded SW catchment (Ramos-Scharrón & MacDonald, 2007b). These findings highlight the importance of individual road drains in dictating a significant portion of the sediment delivery regime in settings similar to Coral Bay.

Ranking sediment sources based on frequency of connectivity represents a departure from the widely used approach of calculating annual sediment budgets (e.g., Anderson & MacDonald, 1998; Bartley et al., 2014; Ramos-Scharrón & MacDonald, 2007c). With only few exceptions (e.g., Hodgson, 1989; Messina, 2016), marine-based research attempting to understand terrestrial runoff inputs to coral reef ecosystems has lacked an explicit runoff monitoring component. Previous work on St. John has compensated for this limitation by relying on existing rainfall data (e.g., Edmunds & Gray, 2014; Gray et al., 2008; Larson et al., 2015). Therefore, the rainfall-driven methods described here can serve as a framework for better distinguishing, which specific portions of the contributing watersheds are actively delivering runoff and sediment to marine monitoring sites. In addition, the parsimonious nature of this framework could also allow it to become integrated into land management plans. This is particularly true in St. John, where precipitation data are accessible and the required road network characteristics can be readily documented and manipulated through management practices.

5. Conclusions

In the U.S. Virgin Islands, coral reefs are threatened by anthropogenic sediment inputs. Previous work has shown that unpaved roads are a primary source of this sediment for St. John and other Caribbean islands. Under natural conditions, runoff generation in dry tropical settings is ephemeral, sporadic, and dependent on a combination of water storage-dependent and storm-specific rainfall conditions. In contrast, unpaved roads generate runoff even during smaller storms once precipitation intensities exceed their low infiltration capacities. This study shows that the ephemeral streams have flow and connect to the coastline about 4 times per year only when storm total rainfall exceeds 78 mm under dry antecedent conditions or 10 mm under wet antecedent conditions. The presence of roads alters this pattern but the level of impact on rain-controlled runoff thresholds is dependent on the road surface area and the flow path distance of individual road drains. For two road influenced watersheds in St. John, storm total rainfall thresholds for runoff generation range from 9.3 to 50 mm for wet and dry conditions, respectively. In contrast to unroaded catchments, road-influenced streams can potentially deliver runoff 10 to 13 times every year to coastal waters.

These results highlight the sensitivity of individual road drain characteristics in enhancing the frequency of runoff delivery to coastal waters. The runoff threshold modeling approach developed here helps to assess connectivity potential from individual road drains and represents an alternative means of assessing environmental threats, establishing mitigation goals, and prioritizing efforts to lessen the effects of runoff and sediment. Similar approaches could be adopted where policy and management needs require site-specific estimates of road-related hydrologic connectivity.

Acknowledgments
This project was supported by a Fisheries Habitat Conservation Program Office of the National Oceanic and Atmospheric Administration grant (NOAA Non-Competitive award: NA13NMF4630189) managed by the University of San Diego (Sarah Gray). Additional funds were obtained from the National Fish and Wildlife Foundation (grant 0302.13.039345). Many thanks to Julia Royster, Lisa Vandiver, and Daphne Booth from NOAA who partnered with us on this grant, to Jeremiah Roy for help in putting together some of the databases, and to Eugenio Arima (Geography, UT-Austin) for his help with the statistical analyses. Our deepest gratitude goes to Lee MacDonald and three anonymous reviewers for their insightful review of earlier versions of this paper. Our gratitude goes to the incomparable staff of Concordia EcoResort for hosting our stay in St. John. Data collection was only possible through the dedicated work of Bruce Swanson and Matt Rasmussen. Data is available at https://doi.org/10.5281/zenodo.1287267.

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