The Role of Unpaved Roads as Active Source Areas of Precipitation Excess in Small Watersheds Drained by Ephemeral Streams In the Northeastern Caribbean

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ABSTRACT

Quantitative understanding of the impacts of land development on runoff generation is vital for managing aquatic habitats. Although unpaved roads are broadly recognized as significant sources of sediment within managed forested landscapes, their role in altering runoff response is characteristically dependent on rainstorm and watershed size. Here we evaluate the role of unpaved roads in the development of Horton overland flow and their potential to influence the delivery of runoff from small watersheds (~ 1s km^2) drained by ephemeral streams flowing towards coral reef bearing waters of the Northeastern Caribbean.

Infiltration capacity curves for undisturbed forest soils and unpaved roads were developed based on hydrologic characterization performed with a Guelph permeameter. Results demonstrate that infiltration capacities from unpaved roads are roughly a quarter of those for forest soils. Consequently, localized precipitation excess is about four times greater on unpaved roads than on forest soils. Analyses indicate that unpaved roads generate precipitation excess roughly ten times more frequently than

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watershed-scale storm flow generated by the combined effects of precipitation excess and saturation overland flow. Comparison of unpaved road precipitation excess with observed watershed discharge suggests that road networks may produce localized surface runoff equal to 62% of total watershed discharge for rainstorms up to 3.0 cm, and this holds even for watersheds with low and moderate road densities (0.8 to 2.3 km km^{-2}). For watersheds with high road densities (~7.6 km km^{-2}), roads may contribute about one-quarter of storm flow for rain events up to 10 cm.

Our results stress the high sensitivity of runoff response in dry tropical watersheds to land disturbance, even when this disturbance occurs on only about 1% of the land surface. In this particular case study, unpaved roads prove capable of altering the time distribution of runoff and, by extension, sediment delivery, from one that is naturally infrequent and sporadic to one that is potentially chronic.

1. INTRODUCTION

1.1 BACKGROUND

Roads induce some of the most pervasive anthropogenic alterations to the hydrologic regimes of managed forested landscapes (Gucinski et al., 2000; Jones et al., 2000; Luce and Wemple, 2001; Luce, 2002). Roads are *active source areas* (Ambroise, 2004), with lower rainfall thresholds for runoff initiation than those of undisturbed soils or intermittent headwater streams (Ziegler and Giambelluca, 1997). In addition, roads may increase hillslope-stream connectivity by intercepting subsurface flows at cutslopes (Wemple and Jones, 2003; Negishi et al., 2008) and by concentrating large quantities of runoff and sediment to distinct drainage locations (Montgomery, 1994; Wemple et al., 1996; Croke and Mockler, 2001; Takken et al., 2008; Thomaz et al., 2014). Thus, roads have the potential to represent runoff *contributing areas* (Ambroise, 2004), which directly affect storm flow frequency and magnitude, particularly in small catchments (~ 100 ha) and during frequent rainstorms (< 1 yr recurrence interval)

(Harr et al., 1975; Beschta et al., 2000; Jones, 2000; Thomas and Megahan, 1998). The higher frequency and magnitude of runoff generation, in addition to the high erodibility of unpaved road surfaces, make roads of utmost importance to the sediment budgets of many tropical forested and rural landscapes (e.g., MacDonald et al., 2001; Douglas, 2003; Ziegler et al., 2004).

Even though unpaved roads have been shown to alter watershed-scale sediment yields and peak flows (e.g., Beschta, 1978; Jones, 2000), their potential to increase the frequency of ephemeral stream runoff generation has received relatively little attention. Here, we evaluate the potential of precipitation excess runoff (i.e., Horton overland flow or HOF) from unpaved roads to increase the frequency of runoff yields from small coastal watersheds (0.1s to 1s of km^2) within a tropical-dry setting in the Northeastern Caribbean. Dry tropical areas are those where annual precipitation ranges from 250 to 2,000 mm and where the overall ratio of potential evapotranspiration to precipitation exceeds unity (Holdridge, 1967). Highly seasonal rainfall conditions in which rainfall exceeds evapotranspiration during only two months of the year are typical of dry tropical regions. Although tropical dry forests represent about 42% of the earth’s tropical and subtropical landmass, they have been underrepresented in the scientific literature (Murphy and Lugo, 1986).

Alterations to the spatial and temporal generation of runoff and sediments are of particular concern where watersheds drain towards coral reef-bearing coastal waters (McClanahan and Obura, 1997; Edinger et al., 1998; Hodgson and Dixon, 2000; Dutra et al., 2006; Bartley et al., 2014). Coral polyps represent the elemental constituents of coral colonies, and they thrive in low nutrient and low turbidity oligotrophic conditions (Sorokin, 1993). Increases in the quantity and/or frequency of runoff and sediment delivery to these waters may adversely affect coral communities in part by enhancing nutrient content and increasing water turbidity (Rogers, 1990; Richmond et al., 2007). These altered conditions tend to favor the proliferation of fast-growing macroalgae on surfaces that otherwise could be occupied by coral colonies (Fabricius, 2005; Erftemeijer et al., 2012).

Land disturbance and its associated increases in sediment delivery rates are recognized as key sources of stress to coral reef ecosystems of the Caribbean (Loya, 1976; Lugo, 1978; Rogers, 1979, 1983; Jackson et al., 2014), and the U.S. Virgin Islands (USVI) are no exception (MacDonald et al., 1997; Brooks et al., 2008). In addition to anomalously warm surface seawater temperatures, heightened levels of terrestrial sediment loads rank among the most detrimental abiotic stressors of coral reef systems within the USVI (Rothenberger et al., 2008; Rogers et al., 2008). On the island of St. John (USVI), the threat posed by the development of land draining towards coral reef ecosystems within the Virgin Islands Biosphere Reserve and National Park has been recognized since the mid-1980s (Hubbard, 1987; Rogers and Teytaud, 1988). Subsequent research identified the island's unpaved road network as the main source of terrestrial sediment, responsible for 80-85% of the total delivered to coastal waters and for increasing sediment yields between 3 and 9 times above background levels (Anderson and MacDonald, 1998; Ramos-Scharrón and MacDonald, 2007a, 2007b). Although previous research on St. John has addressed the effects of land development on onsite runoff (MacDonald et al., 2001; Ramos-Scharrón and MacDonald, 2007c) and sediment production rates (Ramos-Scharrón and MacDonald, 2005), no attention has been given to the potential role of roads in altering the frequency and magnitude of runoff yields to coastal waters. This is particularly relevant given the island's dry tropical climate and intermittent streamflow pattern (Cosner, 1972), and the potential for road development to change sediment delivery from a mostly pulse-type, sporadic scenario under undisturbed conditions to one that is potentially chronic.

1.2 <u>Objectives</u>

Addressing some of the watershed-centered coral reef management recommendations for the USVI (Territory of the USVI and NOAA, 2010), this study examines how land development on St. John, in the form of unpaved road construction, may be altering runoff generation at the local and watershed scales. To this end, we formulated the following research objectives:

1. To compare in-situ saturated hydraulic conductivity (K_{sat}) of unpaved roads with that from adjacent undisturbed soils;
2. To assess the potential for localized unpaved road HOF-generation in relation to that for undisturbed soils;
3. To evaluate the potential for HOF generated from unpaved roads to alter the frequency of watershed-scale storm flows, and to assess the road densities and storm sizes at which roads may be most influential in watershed-scale runoff response.

2. Study Area

At 50 km^2, St. John is the third largest island composing the USVI Territory (Figure 1). The USVI lie within the Puerto Rico-Virgin Islands microplate, at the contact zone between the Caribbean and the North American plates (Jansma et al., 2000). Tectonic activity along this highly active margin has produced a very rugged topography with more than 60% of St. John having slopes greater than 30% (16 degrees) (Anderson, 1994). Volcanic rocks exposed to deformation, magmatic intrusions, and hydrothermal alterations dominate the island's lithology (Rankin, 2002). Soils are predominantly shallow, moderately permeable, and well-drained, gravelly clay loams (USDA, 1995).

St. John's climate is dry tropical with several distinct precipitation zones ranging from 90 – 100 cm yr^{-1} in the dry eastern end of the island to a high of 130 – 140 cm yr^{-1} near the island's highest peak, Bordeaux Mountain (387 m) (Figure 1) (Bowden et al., 1970). Two relatively dry seasons, together responsible for only about 27% of annual average rainfall, extend from January through March and from June through July (Calversbert, 1970). About 16% of annual rainfall occurs during the relatively wetter months of April and May, but the majority of annual rainfall (57%) normally occurs between the months of August and December (NOAA, 2001) when easterly waves and tropical storms are common to the region. Average daily temperatures range from 25 to 26.5° C. Dry-evergreen forests and shrubs cover almost two-thirds of St. John, while moist forest assemblages dominate most of the remaining landmass (Woodbury and Weaver, 1987). Monthly potential evapotranspiration exceeds monthly precipitation for most of the year (Bowden et al., 1970). Surface drainage is ephemeral and 'flashy', and is limited to periods of high-intensity precipitation (Jordan and Cosner, 1973; MacDonald et al., 2001). In addition to many portions of the Insular Caribbean, dry tropical climate conditions similar to those existing in St. John prevail in parts of Mexico, southeastern Africa, Indochina, Madagascar, along the coasts of Ecuador and Peru, and central India, amongst other areas (WWF, 2015).

All saturated hydraulic conductivity measurements described here were collected within the Coral Bay Watershed (CBW) (Figure 1). Analyses of the potential role of roads in watershed-scale storm flow were based on simulations using observed rainfall intensity data and streamflow measurements from the area located upstream of a stream gauging station in the main tributary of the Fish Bay Watershed (FBW) (Ramos-Scharrón, 2004). Both CBW and FBW drain towards well-enclosed bays on the southern shores of St. John. These areas represent two of the four coral reef mitigation priority sites chosen by both federal and territorial agencies for the USVI Territory (Territory of the USVI and NOAA, 2010), thus making a better understanding of surface hydrology here critical to the management of coral reefs throughout the region. The 3.5 km^2 source area of FBW is very steep with over half of the slope gradients exceeding 30%. Average annual rainfall rates within FBW range from 100 – 140 cm with average monthly temperatures from 24 to 27° C (Bowden et al., 1970). Ephemeral streams drain FBW with runoff lasting from only a few hours to as much as several weeks (Ramos-Scharrón, 2004). The Annaberg-Maho and Fredriskdal-Susannaberg gravelly loam and gravelly clayey loam series are the dominant soil types (NRCS, 1998). Dry forest complexes cover about 65% of the watershed, with some areas at the upper elevations mantled by moist forest and both shrublands and mangrove forests covering most of the lower elevations. Of the 18.5 km of roads in the watershed, 44% remain unpaved. Overall unpaved road density is 2.31 km km^{-2}. This road density is considered to be moderate within the context of small islands in the Northeastern Caribbean where unpaved road densities may approach 20 km km^{-2}, particularly in small watersheds (~10-15 ha) (Ramos-Scharrón et al., 2012a, b). At an average width of 4.7 m, the 8.1 km of unpaved roads in FBW have a roadbed surface area of 38,120 m^2, which covers 1.1% of the total watershed. Roads are typically insloped or are bordered by an outside berm created during road grading activities. Therefore, runoff generated by the road network flows either along an inside ditch or on the road surface concentrating within wheel ruts or rills (Figure 2a). Road runoff is drained at specific locations that are either unplanned yet defined by the local topographic layout of the landscape or are designed in the form of culverts, swales, and water bars.

3. Methods

3.1 Saturated Hydraulic Conductivity

In August 2014, saturated hydraulic conductivity (K_{sat}) measurements were made at twenty unpaved road locations and twenty adjacent undisturbed soil locations (hereafter referred to as 'soil' sites) within CBW. Measurement sites were located along the watershed ridgeline (7 sites), on sideslopes (7 locations), and on the main valley bottom (6 locations) assuming that topographic position was a main determinant controlling soil conditions in such a small area with a homogeneous lithological substrate (Table 1). Sites were chosen within road segments where a hand-held auger could dig a well-formed borehole into the roadway. Soil locations were positioned as near to the road sites as possible on undisturbed forest surfaces. Measurement locations were recorded with a handheld GPS unit and mapped over a digital soils map (NRCS, 1998, 2014).

A Guelph permeameter was employed to estimate K_{sat} and soil sorptivity, or the capacity of the soil to absorb water by capillarity (Philip, 1957), on both the undisturbed soils and road sites (Elrick et al., 1989) (Figure 2b). Boreholes of up to 30 cm deep (average ranging from 7 to 18 cm) were made with an auger and shaped as consistently as possible, leaving the interior smooth and receptive to infiltration.

For greater accuracy, the 'two-head' procedure was employed. Borehole water column depth began at 5 cm and ranged up to 20 cm. These water column depths were chosen as optimal for establishing the saturation bulb and achieving the steady state of the hydraulic head within a 30-minute period. K_{sat} values were determined from the last 9 – 24 min of steady flow rates out of the boreholes following the procedure described by Reynolds and Elrick (1986).

Guelph permeameter experiments were performed within three distinct soil types according to soil maps. Two of the soil types were identified as loams (i.e., Cinnamon Bay and Victory-Southgate series), and one as a gravelly-sandy loam (i.e., Lameshur series) (Table 1). A fourth set of measurements lay within what was characterized as a rock outcrop (Southgate rock outcrop) although a very fine layer of soil, presumably belonging to the Victory-Southgate soil type, covered these sites. The two site types (i.e., soils and roads) and soil types resulted in eight different location-substrate groupings.

Differences in average hydraulic conductivity values between soils and roads were evaluated by a two-sample t-test (Zar, 1984). Statistical differences in K_{sat} values for unique site groupings based on substrate type (unpaved roads versus soils) and soil series were evaluated using the Least Significant Difference (LSD) method (Zar, 1984) using both untransformed and square-root transformed values.

A single, 80-550 g (average: 170 g) substrate sample was collected with the soil auger as the borehole was being dug. These samples were taken to the lab for texture analyses based on a combination of dry sieving (Gee and Bauder, 1986) and a laser diffraction analyses for all material finer than 125 μm (Fritsch Analysette 22 Compact).

4. Theory and Calculations

4.1 Infiltration Capacity Curves & Local Scale Precipitation Excess Calculations

Infiltration capacity curves were developed for both soils and unpaved roads, and followed the approximation developed by Loague and Freeze (1985):

$$I_t = \frac{1}{2} * \left[S * t^{-\frac{1}{2}} + K_{sat}\right] \quad \text{(Eq. 1)}$$

where, 'I_t' is infiltration capacity at time 't' (in cm hr^{-1} and hours, respectively), and 'S' is sorptivity (in cm $hr^{-1/2}$). Sorptivity was determined by plotting the cumulative amount of water infiltrated during the initial 1-8 minutes of the permeameter experiments (in cm) versus the squared root of elapsed time (in hours) and determining the regression slope of the line (Cook and Broeren, 1994). One-minute resolution infiltration capacity curves were developed based on the average sorptivity value and the variance (mean $\pm$ standard error) of K_{sat} values for soils and unpaved roads.

Comparisons between observed rainfall intensities and infiltration capacity curves were used to identify the rainfall thresholds for localized HOF development on soils and unpaved roads for individual rainstorms. This analysis relied on 15-min rainfall intensity data collected at CBW from Sep-2009 to Nov-2011 (Ramos-Scharrón, unpublished data). The temporal resolution of the 15-min resolution rainfall database was matched to the 1-min time-steps of the infiltration capacity curves by applying the average 15-min rainfall rates to every 1-min interval. Precipitation excess total was determined as the difference between rainfall rate and infiltration capacity for individual one-minute periods when rainfall rates exceeded infiltration capacity. The precipitation excess calculation used here is an oversimplification of the actual processes leading to runoff development as, for example, it neglects the role of interception by vegetation and is not based on a soil moisture sensitive, process-based infiltration model (e.g., Green-Ampt equation; Scott, 2000). Nevertheless, it still serves to evaluate the relative potential for HOF development on unpaved roads versus on adjacent undisturbed soils.

4.2 Potential role of roads in Watershed-scale Storm flow

The total drainage area upstream of the FBW gauging station was determined through ArcGIS 10.1 tools based on a 6 m resolution DEM. The DEM was also used to generate a 3.9 km km^{-2} stream network based on a 0.1 ha source area threshold, that although not formally field-verified, mimics well the extent of the network based on our knowledge of the watershed. Road network layouts were defined by a combination of onscreen digitizing, field mapping with a GPS unit, and field observations on road width and surfacing (i.e., paved versus unpaved) representing the network in 1998-99 (Ramos-Scharrón, 2004). Detailed mapping of road drainage patterns allowed us to match all road segments to their respective road drainage points (i.e., culverts, swales, ditches, etc.). Identification of the portion of the road network that is most certainly delivering runoff to the stream network was conducted through GIS analyses. We assumed that any road drainage point would be capable of delivering most of its runoff to the stream network if it was located no farther than 75 m from streams. Our use of the 75 m value is not based on local observations as no formal mapping of runoff pathways has been conducted on St. John, but it is considered quite conservative when compared to other locations where the average extension of rilled and diffuse pathways below road drainage points have been noted to extend up to 90 m and 120 m, respectively (Croke et al., 2005).

Our approach follows that used by Ziegler et al. (2001a) in that it directly compares the amount of unpaved road HOF presumed to be delivered to the stream network during individual storm events to the total amount of discharge observed at the watershed outlet. The approach allows us to contrast the rainfall threshold differences between runoff at the watershed scale and HOF development on unpaved roads at the local scale. This comparison also allows us to estimate the proportion of watershed-scale discharge attributable to unpaved road HOF for storms of varying sizes.

Watershed-scale unpaved road generated HOF was calculated as:

$$Q = A_{<75} * \sum \frac{(R_t - I_t)}{100} \qquad \text{For } R_t > I_t \qquad \text{(Eq. 2a)}$$

$Q = 0$ For $R_t < I_t$ (Eq. 2b)

where Q refers to the total unpaved road HOF during individual rainstorms (in m^3), $A_{<75}$ refers to the total unpaved road surface area draining towards drainage points located within 75 m of the stream network (in m^2), R_t refers to 1-minute rainfall intensities, and I_t refers to infiltration capacities for unpaved roads (in cm min^{-1}).

HOF values estimated by these equations represent the maximum potential contribution of the connected portion of the unpaved road network to watershed discharge since these assume no transmission losses. No runoff contribution is assumed for portions of the unpaved road network draining farther than 75 m from the stream network. Rainfall intensity data used for these analyses were collected by a 0.01 cm resolution tipping bucket rain gauge intermittently operating within FBW from Oct-1998 to Oct-2001. Watershed-scale discharge was available for a similar period. Discharge calculations relied on stage measurements (15-min resolution) collected by a submersible pressure transducer and a combination of the slope-area method (Smith et al., 2010) with field-based discharge measurements (Ramos-Scharrón, 2004).

5. Results

5.1 Saturated Hydraulic Conductivity

The overall average saturated hydraulic conductivity value for the forty undisturbed soil and unpaved road locations was 1.50 cm hr^{-1}. The overall average K_{sat} value for all soil sites was 2.42 cm hr^{-1} (standard error $\pm$ 0.46 cm hr^{-1}) while that for roads was only 0.59 cm hr^{-1} (s.e. $\pm$ 0.13 cm hr^{-1}) or 24% of the soil average (Figure 3a). The difference between these two values proved to be statistically significant (p-value < 0.001). Average sorptivity at all sites was 0.70 cm $hr^{-½}$, and average values for soils and roads were 1.11 and 0.28 cm $hr^{-½}$, respectively (Figure 3b).

Among all soil types sampled, those within the Victory-Southgate and the Southgate Rock outcrop series had the smallest and largest K_{sat} values, respectively (Table 2). The lowest and largest K_{sat} values for road sites were for the Cinnamon Bay loam and Lameshur gravelly sandy loam sites, respectively. Multiple comparisons of means based on the Least Significant Difference test (LSD) highlighted some statistical differences among the means of the eight different location-substrate combinations (Table 2). Results of the LSD groupings were identical regardless of whether the K_{sat} data was untransformed or square root-transformed. No significant differences were detected for groupings belonging to the same location types (soils or roads), but some differences were identified across location groupings. Given the small number of sites measured and the lack of a very distinct differentiation among the different soil types, here we only honor the overall difference between soils and roads in the development of the infiltration capacity curves.

5.2 Infiltration capacity curves and local scale HOF response predictions

Average K_{sat} and sorptivity values for soils and roads resulted in the following infiltration capacity curves (standard errors shown in parentheses):

$$I = \frac{1}{2} * \left[1.11 * t^{-\frac{1}{2}} + 2.42(\pm 0.46)\right] \quad \text{For soils} \qquad \text{(Eq. 3a)}$$

$$I = \frac{1}{2} * \left[0.28 * t^{-\frac{1}{2}} + 0.59(\pm 0.13)\right] \quad \text{For unpaved roads} \qquad \text{(Eq. 3b)}$$

The infiltration capacity curve for soils resulted in maximum values of 5.28 to 5.74 cm hr^{-1} at the onset of precipitation and a steady state infiltration rate of 1.77 to 2.22 cm hr^{-1} thirty minutes later (Figure 4). The road infiltration curve resulted in infiltration capacities ranging from 1.31 to 1.44 cm hr^{-1} at the beginning of rainstorms to 0.43 to 0.56 cm hr^{-1} thirty minutes into the event, or approximately 25% of soil infiltration capacity.

By comparing rainfall intensities recorded during 446 storms at Coral Bay between Sept-2009 and Nov-2011 with infiltration capacities based on Equations 3a and 3b, we estimated HOF response for both undisturbed soils and unpaved roads. The 446 rainstorms produced 305.5 cm of total rainfall, with individual events producing between 0.025 and 13.1 cm and averaging 0.68 cm. Eighty percent of the storms totaled less than 1.0 cm of rain and were responsible for 32% of the total rainfall. The maximum 15-min intensity recorded was 9.96 cm hr^{-1} and this was exceeded only during 0.5% of the periods with recorded rainfall at the only long-term rainfall intensity station on island (Caneel Bay; 1979 to 1995).

Application of the average infiltration capacities implied by Equation 3a to every individual storm event suggests that soils should have produced HOF during 18% of the rainstorms for an overall runoff coefficient of 18% (Figure 5). Runoff coefficients for individual storms ranged up to 68% but averaged only 4%. When considering the range of soil infiltration capacities suggested by the standard errors of K_{sat} values, between 15% and 23% of total rainfall is estimated to have been generated as HOF during 65 to 99 of the 446 storms. In contrast, average infiltration rates implied by Equation 3b suggest that unpaved roads produced HOF during 61% of the rainstorms. Total HOF estimated from unpaved roads corresponds to 53% of the total rainfall or almost three times as soils. Runoff coefficients for unpaved roads during individual events averaged 23%, ranged up to 90%, and were positively related to storm rainfall. Based on the entire range of infiltration capacities, unpaved roads were estimated to have produced 48% to 58% of the total rainfall during 248 – 304 of the storms.

The smallest rainstorm totals required for HOF generation on soils ranged from 0.58 to 0.84 cm, while the largest was 2.31 cm. These differences can be explained by the time distribution of rainfall intensities relative to the infiltration capacity curve. Based on the average infiltration capacity curve (Equation 3a), more than 1.40 cm of rainfall was required for more than half of the rainstorms to generate HOF on soils (1.0 to 1.8 cm when the entire variability of Equation 3a is considered). In comparison, HOF was expected on unpaved roads during rain events as small as 0.15 cm, while the largest storm without any estimated HOF had 0.36 cm of rainfall. More than 50% of the rainstorms with more than 0.18 cm of rainfall generated runoff from unpaved roads based on the average infiltration capacities estimated by Equation 3b (Figure 6). Therefore, we chose 0.18 cm as the rainfall threshold for HOF generation on unpaved roads. The apparent rainfall threshold range for soils (~ 1.4 cm) is almost a full order of magnitude larger than that for unpaved roads.

5.3 Physical Characteristics of Soil and Unpaved Road Substrate Material

Unpaved road substrates were generally coarser than undisturbed soils with a median particle size (D_{50}) mean of 0.35 mm in comparison with a 0.17 mm for undisturbed soils. The mean particle size distribution for the unpaved road substrates was 23% gravel, 38% sand, and 39% silt and clay. In contrast, mean values for undisturbed soils were 12% gravel, 35% sand, and 53% silt and clay (Table 1).

5.4 Watershed-scale Storm flow and Road Network HOF Development

Storm flow response to individual rainstorms at FBW was analyzed for 273 events recorded between Oct-1998 and Dec-2001 for which both rainfall and runoff data were available. Precipitation totaled 125 cm while individual storms generated from 0.03 to 12.9 cm with an overall mean of 0.46 cm. The frequency distribution of these storms was very similar to that for local long-term rainfall data (Caneel Bay, 1979 – 1995) (Ramos-Scharrón and MacDonald, 2005) in that 90% of the events generated less than 1.0 cm of rainfall and were responsible for roughly 36% of the total rainfall. Fifteen-minute precipitation intensities ranged from 0.10 to 7.0 cm hr^{-1}, with an overall mean of 0.4 cm hr^{-1}.

FBW produced direct runoff during 25% of the 273 rainstorms (Figure 7). Watershed-scale area-normalized storm flow amounted to 10.5% of net rainfall. Storm flow totals during individual events ranged from 0.0 to 6.4 cm with an overall average of 0.048 cm. Runoff coefficients from individual events ranged from 0 to 55% with an average of just 1.7%. Only 6% of storms smaller than 1.0 cm of rainfall generated any runoff. In contrast, 79% of the storms with more than 1.0 cm of rainfall generated runoff. Therefore, we chose 1.0 cm as the rainfall threshold for runoff development at FBW.

A total of 7.1 km or 88% of the 8.1 km of unpaved roads in FBW delivered runoff at discrete drainage locations within 75 m from streams. The estimated total length of unpaved roads effectively draining to streams was only 25% less and 11% greater than 7.1 km when relying on 50 m and 100 m stream buffer widths, respectively. Therefore, calculations based on the 7.1 km long unpaved road network were considered as a reasonable approximation of the portion of the road network with a high potential to effectively deliver HOF to the FBW stream network. Based on the average infiltration capacity curve (Equation 3b), the 7.1 km of unpaved roads were estimated to generate HOF during 34% of the 273 rainstorms. Overall watershed-scale unpaved road HOF equaled only 0.42% of the total rainfall for the entire watershed. The per-storm unpaved road HOF ranged from 6.3×10^{-6} to 0.06 cm, with an overall average of 0.006 cm. As with the CBW rainfall dataset, the rainfall threshold for HOF development on unpaved roads was approximately 0.18 cm.

6. DISCUSSION

Determining K_{sat} values is crucial for quantifying HOF development from soils and unpaved road surfaces through the application of infiltration models. Model application allows for the integration of road networks in the hydrologic response of watersheds – a spatial scale at which road effects may be more adequately evaluated (Harden, 1992) and at which management decisions are typically made (e.g., Swift, 1988). Changes to the hydrologic response of unpaved roads associated to their relatively low K_{sat} values may potentially produce changes in the amount and timing of watershed-scale runoff response and, correspondingly, to sediment yields. These effects are particularly relevant to land management in areas drained by ephemeral stream networks, where surface runoff is sporadic and restricted to only a fraction of the land surface. Of special importance are those unpaved roads that deliver runoff directly to or near the coastlines and therefore are not dependent on watershed-scale runoff generation to earn access to coastal waters.

Our results imply that HOF on undisturbed soils is lower in total runoff and frequency than on unpaved roads. The overall average runoff coefficient from roads was 43%, or about three times higher than that from soils. However, soil runoff coefficients estimated here for individual rainstorms are slightly higher than those observed from hillslope runoff plots on St. John (1.5 – 3.0%; MacDonald et al., 2001), and this implies an even more pronounced effect of unpaved roads on HOF development potential. Runoff data generated by previous studies from undisturbed hillslope plots in similar locations to those where K_{sat} and sorptivity values were measured produced runoff only during events exceeding 2.1 cm (Ramos-Scharrón and MacDonald, 2007b). According to long-term rainfall data, rainfall events exceeding 2.1 cm occur on average only about seven times per year. In contrast, assuming an average rainfall threshold of about 1.4 cm based on Equation 3a, the long-term rainfall data suggest that HOF would be generated from soils on average about twelve times every year. The faintly higher HOF rates and frequencies based on our calculations can be attributed in part to the simplicity of our approach, since it does not incorporate potentially important losses associated with canopy and litter interception. In addition, the use of the Guelph permeameter precludes documenting K_{sat} values at the soil surface, where infiltration rates are typically at their highest values. Although the rainfall thresholds for HOF development on soils based on Equation 3a and watershed-scale thresholds are similar (~ 1.4 and 1.0 cm, respectively), watershed storm flow is still presumed to be controlled by saturation overland flow and not HOF (MacDonald et al., 2001).

Previous research has documented K_{sat} values for unpaved road substrates in a variety of settings including rural and logging road networks, volcanic and plutonic lithologies, and both continental and oceanic climatic settings (e.g., Ziegler et al., 2001b; Ramos-Scharrón and MacDonald, 2007c; Foltz et al., 2011). Reported K_{sat} values have ranged widely from 5×10^{-6} cm hr^{-1} to 2.1 cm hr^{-1}, with most values fluctuating between 0.1 and 1.0 cm hr^{-1} (Table 3). Steady-state infiltration rates reported in the literature (0.3 – 0.5 cm hr^{-1}) have been in general agreement with these K_{sat} values, and the resulting runoff coefficients of actively used unpaved roads have shown values up to 100%, depending on rainfall totals (Ramos-Scharrón and MacDonald, 2007c) and management history (Foltz et al., 2009), among other factors. The K_{sat} and hydrologic response values reported by this study are well within the range of those found in the literature and those previously estimated for St. John (Table 3).

Our results demonstrate that the amount of rainfall needed to generate HOF from unpaved roads (~0.18 cm) is about a fifth of that needed to generate runoff at the watershed scale (~1 cm). The proportion of watershed storm flow that potentially can be generated as HOF on unpaved roads was inversely related to the size of the storm event, as noted elsewhere (e.g., Jones and Grant, 1996; Thomas and Megahan, 1998).

The location of road drainage points plays a crucial role in defining the likelihood of road runoff and sediment delivery to downslope aquatic resources (Croke et al., 2005). HOF from the 7.1 km unpaved road network draining within 75 m of the FBW stream network was estimated to contribute on average only 7.6% of the watershed runoff response for six out of seven storms that exceeded 3 cm of rainfall. Storms exceeding 3.0 cm of rainfall occur on average only about 3-4 times per year. In contrast, about 62% of the watershed storm flow generated from the 114 storms with rainfall totals between 0.18 and 3.0 cm could be potentially attributed to unpaved road HOF. Storms exceeding the unpaved road HOF threshold of 0.18 cm but remaining below 3.0 cm generate more than half (55%) of the annual unpaved road HOF and occur about 45 times per year on St. John (Ramos-Scharrón, 2004).

Our results demonstrate that unpaved roads on St. John have a more frequent 'active *period*' (Ambroise, 2004) than other runoff development processes such as HOF on soils and watershed-scale storm flow. Therefore, unpaved roads in FBW have the potential to increase the frequency of runoff development and delivery to coastal waters during relatively small but frequent rain events when watershed storm flow through soil HOF or saturation overland flow is non-existent or negligible. Under these conditions, a type of chronic sediment yield scenario could occur, where undiluted runoff may be delivered to receiving waters more than 40 times every year, or roughly ten times more frequently than under undisturbed conditions (approximately 3-4 times per year).

The relevance of road HOF to watershed-scale storm flow has been previously shown to depend on storm size, road network density, and watershed size (e.g., Jones and Grant, 1996). When compared with the range of unpaved road densities found on St. John and those reported for the Northeastern Caribbean, FBW has a moderate density of 2.31 km km^{-2}. Therefore, to evaluate the maximum potential effects of varying road densities on storm flow, we relied on the same set of precipitation and runoff data used for the FBW analyses and simulated unpaved road HOF response for two other cases representing both low and high road density scenarios. For the purposes of this analysis, we assumed that 100% of these road networks were efficiently connected to the stream network. For each storm event, we determined the ratio of unpaved road HOF to observed storm flow. We assumed a 100% unpaved road contribution for those events in which HOF was estimated but no storm flow was observed, and maintained this assumption for storms during which estimated HOF exceeded storm flow.

The low unpaved road density scenario corresponds with the Lameshur Bay watershed in St. John (3.4 km of unpaved roads, 4.3 km^2 drainage area, unpaved road density 0.8 km km^{-2}; Figure 1). Lameshur Bay mostly lies within the VI National Park, a relatively undisturbed area used as a reference site for watershed-marine linkage studies (e.g., Anderson and MacDonald, 1998; Gray et al., 2008). The high-unpaved road density scenario (0.61 km of unpaved roads, 0.08 km^2, 7.6 km km^{-2}) has been documented for sub-catchments roughly 0.10 km^2 in size throughout the northeastern Caribbean (Ramos-Scharrón et al., 2012a, b), some of which drain directly into coastal waters.

Results demonstrate that on average, unpaved road HOF has the potential to account for over 25% of watershed storm flow for rain events ranging between 0.2 and 3.0 cm and that this holds for all unpaved road densities considered (Figure 8). Unpaved road HOF accounted for less than 25% of storm flow for all storms exceeding 3.0 cm of rainfall in the case of low road density areas. By contrast, HOF may account for more than a quarter of storm flow for precipitation events of up to 10 cm for the high road density scenario. Therefore, for high road density scenarios, unpaved road HOF is likely to constitute a significant portion of storm flow for a wide variety of storm sizes. Consequently, HOF from areas with high unpaved road densities may significantly influence the frequency of runoff delivery to coastal waters or any other aquatic habitat. This is of particular importance for the relatively small storm sizes that rarely trigger any storm flow from ephemeral channels. Moreover, during small storms this unpaved road runoff can be delivered undiluted to receiving waters and this can induce significant changes in turbidity and suspended sediment concentration levels. Erosion mitigation management strategies enforced throughout the Northeastern Caribbean have focused on the identification of 'erosion hotspots' by weighing sediment sources by their estimated annual contribution to sediment yields (PR-DNER & NOAA, 2012; Carriger et al., 2013). Our findings imply the need to incorporate the effects of land development in increasing the frequency of runoff delivery to coastal waters when prioritizing efforts to reduce land-based sources of stress to nearshore marine environments.

7. CONCLUSIONS

The potential impact of unpaved roads on hydro-geomorphological processes is unquestionable, even though roads typically represent a fraction of most forested and rural landscapes. Although roads have consistently proven relevant in the sediment budgets of diverse landscapes, their role in altering runoff response appears limited to small watersheds and rainstorms. In this study, we evaluated the role of unpaved roads in increasing the magnitude and frequency of precipitation excess runoff (Horton overland flow) at the local scale, while also assessing the potential contribution of unpaved roads to watershed-scale storm flow. Field measurements of saturated hydraulic conductivity and soil sorptivity performed with a Guelph permeameter led to the development of infiltration capacity curves for both undisturbed soils and unpaved roads on the island of St. John, U.S. Virgin Islands. Localized excess runoff for soils and unpaved roads were calculated by comparing infiltration capacity curves with precipitation intensities for a series of observed rainstorms. In addition, estimated runoff totals from an unpaved road network were compared against observed discharges from a 3.5 km^2 watershed drained by ephemeral streams.

Unpaved road infiltration rates were about a quarter of those estimated for undisturbed soils. Consequently, the total rainfall threshold for runoff development for unpaved roads was about a tenth of that for soils and their runoff coefficients were about three times higher than those for soils. Unpaved roads had an estimated rainfall threshold for precipitation excess development of about a fifth of that required for watershed-scale discharge, and roads appear capable of generating a substantial portion of the storm flow for events ranging between 0.18 and 3.0 cm, regardless of road densities. Projection of our results to various unpaved road density scenarios observed throughout the region suggest that unpaved roads can contribute a significant amount of storm flow for storm events with up to 10 cm in rainfall in watersheds with dense road networks (~7.6 km km^{-2}).

The impacts of unpaved roads are not limited to their sediment budget effects as downstream aquatic habitats also may be sensitive to changes in runoff frequency. This is particularly important in tropical dry forested ecoregions drained by ephemeral streams. In several islands of the Caribbean, unpaved roads are of particular importance on land areas draining towards coral reef bearing waters previously accustomed to infrequent delivery of land-based runoff, sediments, and nutrients. Our results highlight the sensitivity of land development practices, in that a type of land disturbance like unpaved roads that typically covers only about 1% of the landscape may induce up to a tenfold increase in the frequency of watershed-to-marine hydrologic connectivity. These findings suggest that management strategies attempting to reduce stress levels to downstream aquatic resources from land-based sources of pollution should not only attempt to reduce the net magnitude of pollutant loads, but also should curtail the frequency of runoff delivery.

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FIGURE CAPTIONS

Figure 1. Map of St. John displaying the location of the Coral Bay (CBW), Fish Bay, and Lameshur Bay (LBW) Watersheds. The area drained by the Main Fish Bay tributary (FBW) is shown separately and also display the location of road drainage points located within 75 m of the stream network. Individual watershed maps show the extent of the unpaved and paved road networks, 20 m contours, and locations where Guelph permeameter tests were conducted within the Coral Bay Watershed.

Figure 2. (a) A typical unpaved road drainage pattern on St. John with an insloped tilt and an inside ditch that funnels runoff onto easily discernible drainage locations. (b) Guelph permeameter used to determine saturated hydraulic conductivity and soil sorptivity of undisturbed soils and unpaved roads on St. John.

Figure 3. Average saturated hydraulic conductivity (3a) and sorptivity (3b) values determined from Guelph permeameter measurements. Error bars represent standard errors (n=20 for each group).

Figure 4. Average infiltration curves for undisturbed soils (Equation 3a) and unpaved roads (Equation 3b) based on average sorptivity and the variance of saturated hydraulic conductivity (K_{sat}) determined through Guelph permeameter experiments. Solid lines represent infiltration capacities based on the average K_{sat} value, while the dotted lines represent capacities based on plus or minus the standard error.

Figure 5. Relationship between total storm rainfall and HOF totals calculated as the difference between rainfall intensities recorded at Coral Bay (Sep-2009 to Nov-2011) and average infiltration capacities based on Equations 3a and 3b. Each point represents the net balance between rainfall intensities and infiltration capacities for all of the 446 storms for which precipitation excess was estimated.

Figure 6. Relationship between total storm rainfall and the proportion of storms generating HOF based on the difference between rainfall intensities recorded at Coral Bay (Sep-2009 to Nov-2011) and average infiltration capacities based on Equations 3a and 3b.

Figure 7. Comparison of the relationship between total storm rainfall and observed storm flow at the Fish Bay Watershed with the relationship between storm rainfall and the Horton overland flow estimated for the entire 7.1 km long unpaved road network that drains to discrete points within 75 m from streams.

Figure 8. Relationship between storm rainfall and the average ratio of estimated unpaved road precipitation excess (HOF) to storm flow for three unpaved road densities typical of small watersheds throughout the Northeastern Caribbean.

Table 1. Basic characterization of Guelph permeameter site location, representative depths of K_{sat} values, substrate texture and organic content, and hydraulic parameters.

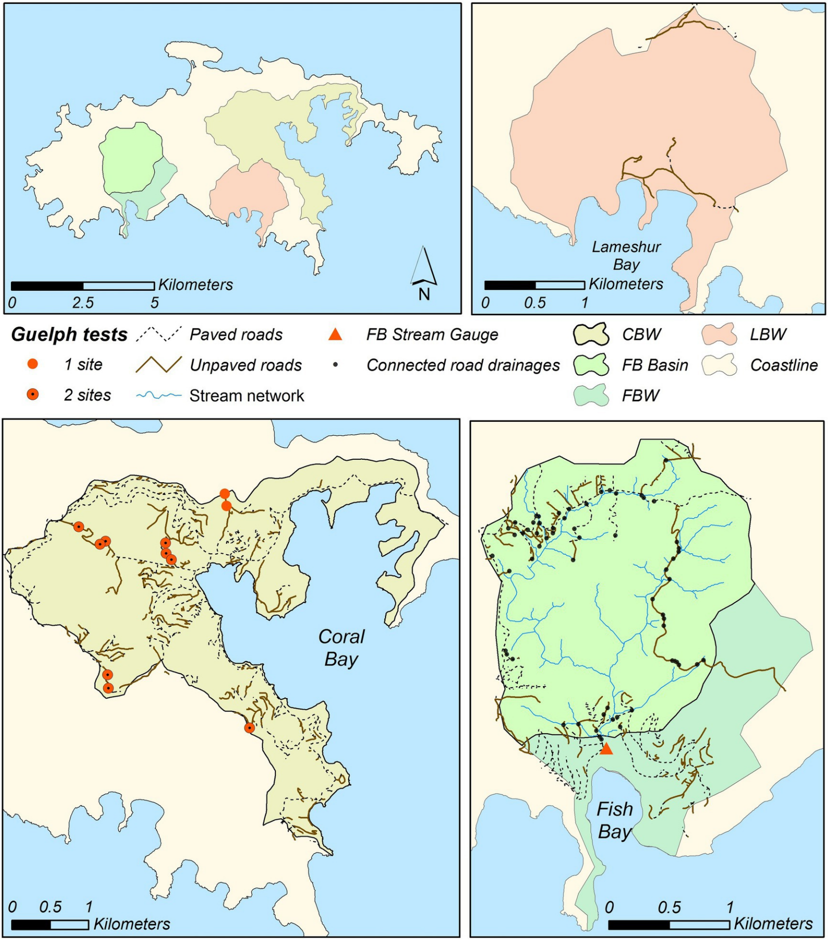
				Range of depths (cm)			Road substrate and soil characteristics					Permeameter Results	
Site Code	***Site type***	***Location***	***Soil Type***	***From***	***-***	***To***	***% gravel***	***% sand***	***% silt***	***% clay***	***D50 (mm)***	***K_{sat} (cm hr^{-1})***	***Sorptivity (cm hr$^{-1/2}$)***
MV1a	Road	Valley	Cin	10.9	-	15.9	13	58	27	2.5	0.18	0.52	0.19
MV2	"	Valley	Cin	5.5	-	10.5	8.1	49	39	3.2	0.08	0.68	0.56
MV3	"	Valley	Cin	7.8	-	17.8	--	--	--	--	--	0.39	0.18
MV4	"	Valley	Cin	8.4	-	18.4	17	53	27	3.0	0.20	0.23	0.24
KH1	"	Sideslope	Lam	6.5	-	16.5	55	26	17	1.6	1.80	1.71	0.73
KH2	"	Sideslope	Lam	9.1	-	19.1	41	44	14	1.2	0.60	0.52	0.29
JH1	"	Sideslope	Sou	8.4	-	18.4	41	34	23	1.4	0.40	0.09	0.04
JH2	"	Ridge	Sou	7.1	-	17.1	52	28	18	1.3	1.05	1.21	0.58
MV5	"	Valley	Vic	4.0	-	14.0	54	30	14	1.6	1.10	0.26	0.14
MV6	"	Valley	Vic	3.7	-	13.7	3.3	37	55	5.4	0.03	0.32	0.21
KH3	"	Sideslope	Vic	7.1	-	17.1	39	32	27	2.3	0.30	0.27	0.19
KH4	"	Sideslope	Vic	7.8	-	17.8	2.9	39	53	5.6	0.03	2.00	0.20
KH5	"	Sideslope	Vic	5.2	-	15.2	23	34	41	2.9	0.14	0.03	0.02
KH6	"	Sideslope	Vic	6.8	-	16.8	2.9	34	59	4.5	0.025	0.19	0.04
Bdx1	"	Ridge	Vic	8.3	-	13.3	31	45	21	2.9	0.30	0.02	0.04
Bdx2	"	Ridge	Vic	8.4	-	18.4	11	48	36	5.0	0.14	0.58	0.36
Bdx3	"	Ridge	Vic	10.3	-	20.3	0.0	17	72	11	0.006	0.27	0.22
Bdx4	"	Ridge	Vic	5.9	-	15.9	1.6	37	56	5.9	0.025	0.58	0.40
Ca1	"	Ridge	Vic	6.5	-	16.5	0.7	48	47	3.9	0.048	1.58	0.73
Ca2	"	Ridge	Vic	6.7	-	11.7	42.3	26.6	27.7	3.3	0.30	0.30	0.25
			Mean	7.2	-	16.2	23	38	35	3.6	0.35	0.59	0.28
			S.D.	1.8	-	2.5	20	10	17	2.2	0.46	0.56	0.21
MV1a	Soil	Valley	Cin	7.5	-	17.5	1.2	31	61	6.4	0.023	0.10	0.13
MV2	"	Valley	Cin	8.7	-	18.7	14	52	31	2.5	0.15	2.58	1.51
MV3	"	Valley	Cin	9.1	-	19.1	13	48	35	3.8	0.14	6.89	2.60
MV4	"	Valley	Cin	0.0	-	19.1	21	29	45	4.8	0.05	1.93	0.55
KH1	"	Sideslope	Lam	1.0	-	21.0	13	30	52	4.9	0.35	0.95	0.62
KH2	"	Sideslope	Lam	5.5	-	30.5	7.9	46	42	4.2	0.071	0.70	0.28
JH1	"	Sideslope	Sou	5.6	-	15.6	37	13	47	3.1	0.050	2.91	1.47
JH2	"	Ridge	Sou	5.2	-	15.2	9.3	28	56	7.6	0.022	4.82	2.26
MV5	"	Valley	Vic	4.7	-	19.7	3.3	38	54	4.9	0.030	0.54	0.22
MV6	"	Valley	Vic	11.6	-	21.6	15	28	52	5.3	0.030	4.19	1.90
KH3	"	Sideslope	Vic	9.1	-	19.1	0.22	39	58	2.8	0.018	0.68	0.14
KH4	"	Sideslope	Vic	8.7	-	18.7	9.8	27	58	5.4	0.025	1.16	0.50
KH5	"	Sideslope	Vic	11.0	-	21.0	23	35	38	3.6	1.7	1.53	0.61
KH6	"	Sideslope	Vic	9.7	-	19.7	26	29	42	3.8	0.2	0.81	0.36
Bdx1	"	Ridge	Vic	12.2	-	22.2	12	46	37	4.7	0.18	2.25	1.19
Bdx2	"	Ridge	Vic	9.1	-	19.1	21	40	36	3.0	0.1	2.94	1.46
Bdx3	"	Ridge	Vic	8.4	-	18.4	1.8	42	52	4.5	0.028	1.21	0.79
Bdx4	"	Ridge	Vic	2.9	-	22.9	4.4	41	50	4.7	0.040	0.71	0.42
Ca1	"	Ridge	Vic	3.3	-	13.3	1.4	45	48	5.1	0.041	7.38	3.08
Ca2	"	Ridge	Vic	3.3	-	13.3	10	16	67	6.8	0.2	4.14	2.19
			Mean	*6.8*	-	*19.3*	12	35	48	4.6	0.17	*2.42*	*1.11*
			S.D.	3.419	-	3.63	9.4	10	9.4	1.3	0.36	2.04	0.88

Table 2. Summary of Least Significant Difference (LSD) analyses of saturated hydraulic conductivity (K_{sat}) values determined for undisturbed soils and unpaved roads in the Coral Bay watershed of St. John. Rows with the same letters in the two 'LSD groupings' columns refer to soil types for which mean saturated hydraulic conductivity values were undistinguishable according LSD analyses.

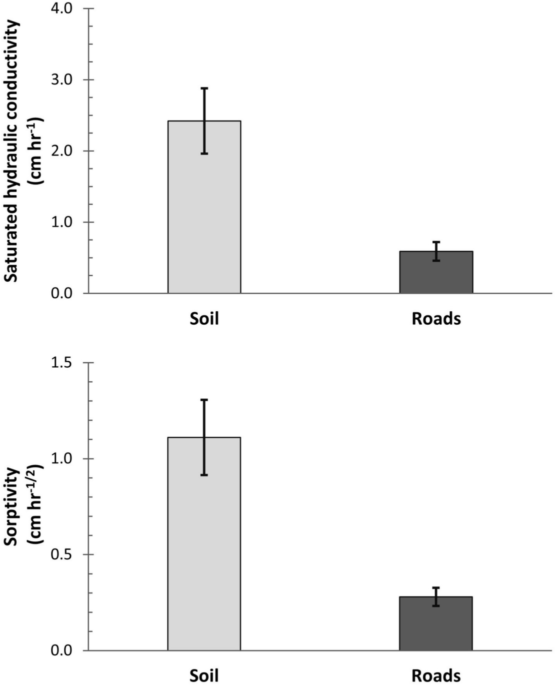
	Soils K_{sat} *(cm hr⁻¹)*				***Roads*** K_{sat} *(cm hr⁻¹)*			
Soil Type Name	***n***	***Mean***	***Std. Error***	***LSD grouping***	***n***	***Mean***	***Std. Error***	***LSD grouping***
Cinnamon Bay loam	4	2.87	0.83	C D E	4	0.45	0.06	A B E
Lameshur Gravelly sandy loam	2	0.82	0.13	A B C D E	2	1.12	0.59	A B C D E
Southgate-Rock Outcrop	2	3.87	0.95	C D E	2	0.65	0.56	A B C D E
Victory Southgate	12	2.30	0.18	A C D E	12	0.53	0.05	A B

Table 3. Summary of saturated hydraulic conductivity, steady state infiltration rates and runoff coefficients reported in the literature.

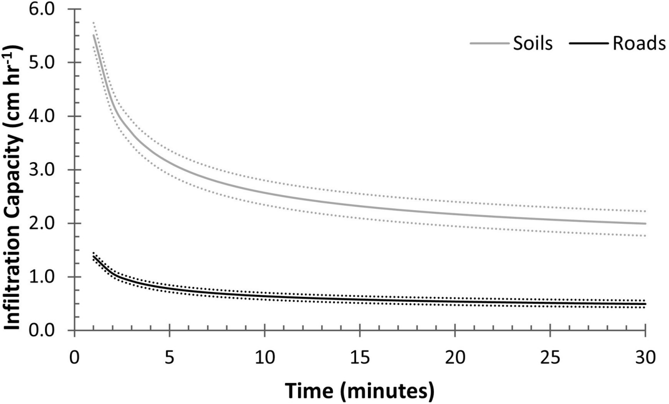
Reference	*Description*	*Saturated hydraulic conductivity (cm hr^{-1})*	*Steady state infiltration rate (cm hr^{-1})*	*Runoff coefficient (%)*
Arnáez et al. (2004)	Sedimentary rocks, Iberian Range-Spain	-	-	32 - 60%
Bren and Leitch (1985)	Australia	-	-	4 - 80%
Coker et al. (1993)	New Zealand	-	-	42 - 66%
Fahey and Coker (1992)	Metamorphic rocks, New Zealand	-	0.3	-
Foltz et al. (2009)	Reopened roads; Idaho-USA	1.3 - 2.1	-	64 - 78%
Foltz et al. (2011)	Granitic rocks; northern CA-USA	0.93	-	64%
	Volcanic rocks; northern CA-USA	0.75	-	70%
Forsyth et al. (2006)	Gravelled; Queensland-AUS	-	-	57%
	Ungravelled; Queensland-AUS	-	-	38%
Harden (1992)	East Tennessee-USA & Ecuador		0.4 - 3.6	0 - 100%
Luce and Cundy (1992)	Western USA	0.17 - 0.60	-	-
Luce and Cundy (1994)	Various western USA	5 x 10^{-6} - 0.88	-	-
Luce (1997)	Metamorphic rocks, Idaho-USA	0 - 1.2	-	-
MacDonald et al. (2001)	Volcanic rocks, St. John-USVI		-	2 - 13%
Ramos-Scharrón and MacDonald (2007c)	Volcanic rocks, St. John-USVI	0.2	-	3 - 72%
Reid (1984), Reid & Dunne (1984)	Sedimentary rocks; WA-USA	-	0.5	44 - 58%
Rijsdijk et al. (2007)	Volcanic rocks; East Java-Indonesia	-	-	65%
Thomaz and Ramos-Scharrón (2015)	Volcanic rocks; Parana State, Brazil	-	-	17 - 78%
Ziegler and Giambelluca (1997)	Various lithologies, Thailand	0.02 - 0.5	-	-
Ziegler et al. (2001)	Thailand	0.7 - 2.3	-	-
This study	Volcanic rocks, St. John-USVI	0.59	0.49	0 - 90%



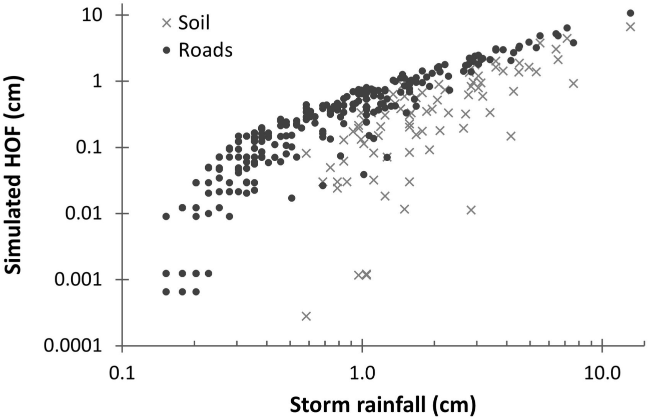
Kilometers
0
2.5
5
N
Lameshur Bay
Kilometers
0
0.5
1
Guelph tests
1 site
2 sites
Paved roads
Unpaved roads
Stream network
FB Stream Gauge
Connected road drainages
CBW
FB Basin
FBW
LBW
Coastline
Coral Bay
0
0.5
1
Kilometers
Fish Bay
0
0.5
1
Kilometers

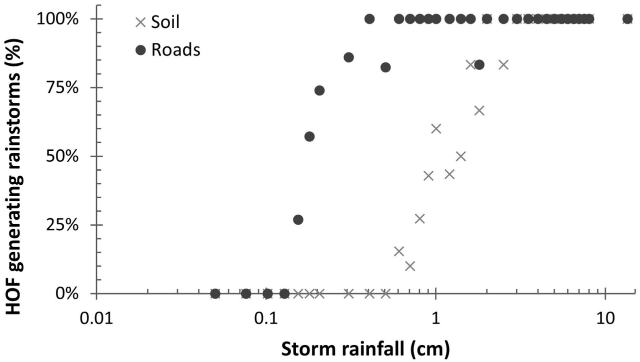


4.0
3.0
2.0
1.0
0.0
Saturated hydraulic conductivity (cm hr-1)
Soil
Roads
1.5
1.0
0.5
0.0
Sorptivity (cm hr-1/2)
Soil
Roads

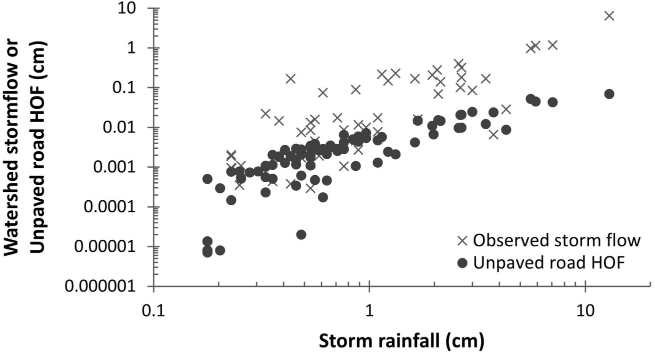


Soils
Roads
Infiltration Capacity (cm hr-1)
Time (minutes)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
5
10
15
20
25
30

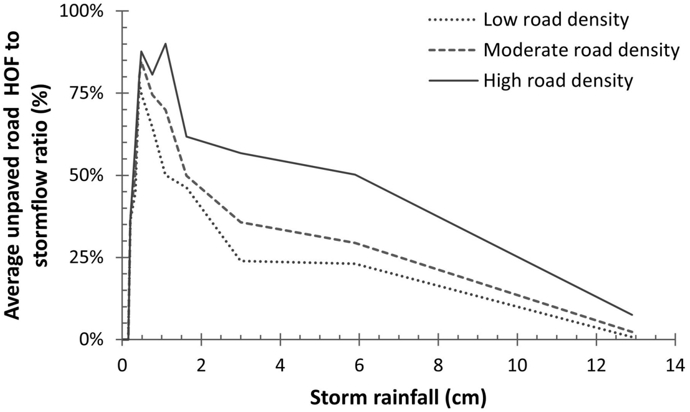

Soil
Roads
Simulated HOF (cm)
Storm rainfall (cm)
10
1
0.1
0.01
0.001
0.0001
0.1
1.0
10.0



Soil
Roads
HOF generating rainstorms (%)
100%
75%
50%
25%
0%
0.01
0.1
1
10
Storm rainfall (cm)



Watershed stormflow or Unpaved road HOF (cm)
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.1
1
10
Storm rainfall (cm)
Observed storm flow
Unpaved road HOF



100%
75%
50%
25%
0%
Average unpaved road HOF to stormflow ratio (%)
0
2
4
6
8
10
12
14
Storm rainfall (cm)
Low road density
Moderate road density
High road density