Journal of Hydrology 533 (2016) 168–179

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

The role of unpaved roads as active source areas of precipitation excess in small watersheds drained by ephemeral streams in the Northeastern Caribbean

Carlos E. Ramos-Scharrón [a,*], Matthew C. LaFevor [b]

[a] Department of Geography & the Environment and Lozano Long Institute of Latin American Studies, The University of Texas at Austin, A3100, Austin, TX 78748, United States
[b] National Socio-Environmental Synthesis Center, University of Maryland, 1 Park Place, Suite 300, Annapolis, MD 21401, United States

ARTICLE INFO

Article history:
Received 17 April 2015
Received in revised form 5 October 2015
Accepted 28 November 2015
Available online 12 December 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Jennifer Guohong Duan, Associate Editor

Keywords:
Coral reefs
Dry tropics
Forest roads
Horton overland flow
Runoff

SUMMARY

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 ($\sim$1s km^2) drained by ephemeral streams flowing toward 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 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 (0.8–2.3 km km^{-2}). For watersheds with high road densities ($\sim$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 ($\sim$100 ha) and during frequent rainstorms (<1 yr recurrence interval) (Harr et al., 1975; Beschta et al., 2000; Jones, 2000; Thomas and Megahan, 1998).

* Corresponding author at: Department of Geography & the Environment, The University of Texas at Austin, A3100, Austin, TX 78712, United States. Tel.: +1 512 232 5067.

E-mail address: cramos@austin.utexas.edu (C.E. Ramos-Scharrón).

http://dx.doi.org/10.1016/j.jhydrol.2015.11.051

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 2000 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 toward 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 toward 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. Objectives

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 (Fig. 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 deg) (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) (Fig. 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) (Fig. 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 toward 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