Assessing the impact of land-use change on surface runoff generation

within the Panama Canal Watershed

by

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B.S., University of Virginia, 2015

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirement for the degree of

Master of Arts

Department of Geography

2017

This thesis entitled:
Assessing the impact of land-use change on surface runoff generation
within the Panama Canal Watershed
written by Sidney Anne Bush
has been approved for the Department of Geography

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Bush, Sidney Anne (M.A., Geography)
Assessing the impact of land-use change on surface runoff generation within the Panama Canal Watershed
Thesis directed by Associate Professor Holly R. Barnard

Abstract

Land-use in the tropics has changed dramatically with increased conversion of forests to subsistence farms and cattle pastures. Land-use change alters soil properties that drive the hydrological processes of infiltration and surface runoff generation. We compared surface runoff generation between two steep, humid, tropical lowland catchments in Panama: a mature forest and an actively grazed cattle pasture. Soil hydrologic properties, soil moisture and surface runoff were measured along hillslopes of each land-use type. We parameterized the numerical model HYDRUS-1D with soil characteristics and rain event data to simulate surface runoff, which was then compared to that observed at the forest and pasture. Runoff ratios were generally higher at the pasture site, though we did not observe any overall trends between rainfall characteristics and runoff ratios across different land-uses. We did observe significant differences in saturated hydraulic conductivity (K_s), bulk density and porosity between the forest and pasture ($p < 0.05$). Surface runoff simulated in HYDRUS-1D produced outputs similar to observed surface runoff at the pasture, but little to no surface runoff was predicted at the forest. Results from our study suggest the combination of a leaf-litter layer and the activation of shallow preferential flow paths are the main drivers for surface-runoff generation at the forest site, while Hortonion overland flow is the main driver for surface runoff at the pasture site. Results from this study contribute to the broader understanding of the delivery of stormwater to streams, both in terms of timing and quantity, which will become increasingly important in the tropics in light of freshwater resource scarcity.

Acknowledgements

I would like to thank my patient and supportive advisor Dr. Holly Barnard for her unending guidance and mentoring throughout this project. I would also like to thank my committee members Dr. Brian Ebel and Dr. John Pitlick for lending me their academic expertise. I would like to specifically thank Brian for his immense help in both designing field equipment and for his continued assistance in working through results. Thank you to Dr. Robert Stallard for introducing me to the Panamanian tropics and for continually sharing his expertise and passion for all things tropical. I would like to thank the primary investigators associated with the Agua Salud Project – Jefferson Hall, Robert Stallard and Fred Ogden (NSF EAR Award Number: 1360305), the Autoridad Canal de Panamá, and the Smithsonian Tropical Research Institute for making this research possible. Thank you to the Ecohydrology lab group for editing this work, and a special thank you to Andrew Birch for his assistance both in the field and navigating Panama in general. Thank you to Smithsonian interns Laura Lyon and Joan Hermann, field technicians Jorge Batista and Eric Diaz and postdoctoral researcher Mario Bretfeld, who assisted greatly with field work in Panama. Thank you to Carson Farmer for assistance with statistical analyses and to Germán Schmeda for his work on in-lab equipment calibration. I would like to extend a special thank you to my fiancé Austin for both his emotional support and for his help writing efficient scripts in MATLAB, without which I would probably still be sorting through this dataset. Finally, I would like to thank the University of Colorado Boulder Geography Department and the Institute of Arctic and Alpine Research for the supportive community and opportunity to complete this level of graduate research. Both programs have afforded me an immense amount of personal and academic growth.

Contents

List of Tables

List of Figures

1. Introduction

Since the onset of development in the tropics, land-use has changed dramatically with conversion of forests to subsistence farms and cattle pastures [*ACP*, 2006, 2010; *Bonell*, 1993; *Achard et al*., 2002; *Wohl et al.*, 2012; *Albrecht et al.*, 2017]. Land-use change alters soil properties that drive the hydrological processes of infiltration and surface runoff (i.e. overland flow) [*Zimmermann et al.*, 2006; *Biggs et al.*, 2006; *Chaves et al*., 2008; *Costa*, 2005; *de Moraes et al*., 2006]. Surface runoff (SR) is an important hydrological pathway in many landscapes, as it affects several ecosystem processes including nutrient and carbon fluxes [*Stallard and Murphy*, 2012; *Chaves et al., 2008*; *Eddy et al*., 1999; *Johnson et al*., 2006; *Williams et al*., 1997], sediment transport [*Jansson and Strombert*, 2004; *Sidle et al*., 2006; *Zimmermann et al*., 2012], soil moisture [*Grayson et al*., 1997] and flow path connectivity across hillslopes [*Zimmermann et al., 2014*]. While the occurrence and relevance of SR in the humid tropics has been well documented [*Bonell and Gilmour*, 1978; *Bruijnzeel et al.*, 2004; *Germer et al*., 2010; *Godsey et al.*, 2004; *Zimmermann et al*., 2006; *Elsenbeer and Lack*, 1996; *Zimmermann and Elsenbeer*, 2008], our current understanding of the major factors controlling the magnitude and spatial organization of SR limits our ability to accurately model and predict SR generation, particularly in tropical forests.

Surface runoff is generated by two main processes: infiltration-excess, or Hortonian overland flow (HOF) [*Horton*, 1933], occurs when intense rainfall rates exceed the infiltration capacity of the soil surface, whereas saturation-excess overland flow (SOF) occurs when soil becomes saturated or the water table intersects the soil surface. It is generally accepted that HOF occurs rarely on vegetated surfaces in humid regions because the infiltration capacity of soils is higher than observed rainfall intensities in most cases [*Chow et al.*, 1988; *Dingman*, 2002]. In contrast, SOF in tropical forests is more common [*Bonell and Gilmour*, 1978; *Elsenbeer and Lack*, 1996; *Elsenbeer*, 2001; *Godsey et al*., 2004; *Johnson et al.*, 2006]. In a tropical rainforest catchment in Queensland, *Bonell and Gilmour* [1978] found that intense storms combined with the shallow depth of an impeding soil layer led to the formation of a perched water table, causing SOF. The formation of perched water tables resulting in SOF has also been observed in Panamanian forests [*Godsey et al*., 2004, *Hassler et al*., 2011] and in both forests and pastures in Amazonia *[de Moraes et al*., 2006; *Germer et al*. 2009]. On the other hand, some studies of tropical forest catchments observed no or only negligible amounts of SR, or only observed SOF near stream channels where soil water content is high and/or groundwater level is shallow [*Lesack*, 1993; *Litt*, 2016; *Ogden et al*., 2013; *Roose et al*., 1977; *Wierda et al*., 1989].

Compared to tropical forest catchments, the factors governing the occurrence of SR in pastures are less complex. While reported magnitude of change in soil physical and hydraulic properties varies, studies consistently demonstrate that soil compaction caused by forest-to-pasture conversion generally increases soil bulk density thus reducing macroporosity, infiltration capacity and hydraulic conductivities [*de Moraes et al*., 1996; *de Moraes et al*., 2006; *Hassler et al*., 2011; *Lal*, 1996; *Martinez and Zinck*, 2004; *McDowell et al*., 2003; *Zimmermann et al.,* 2006]. These changes in soil properties imply that HOF is the dominant driver of SR generation in pasture landscapes, though SOF has also been reported [*de Moraes et al*., 2006; *Germer et al*., 2009].

Prior research on SR in the humid tropics has been conducted across a range of scales. Studies in Panama [*Godsey et al.*, 2004; *Zimmermann et al.*, 2014; *Hassler*, 2013] and in the Amazon [*Germer et al.*, 2009] have measured SR at the point scale (<1 m^2) using overland flow detectors (OFDs) [*Kirkby et al*., 1976]. Although OFDs provide a binary measure of SR, OFDs do not characterize the timing and amount of SR generated following a specific rain event. Studies of SR in the tropics have also been conducted at the hillslope scale (10 - 100 m^2) [*de Moraes et al*., 2006; *Ogden et al*., 2013; *Zimmermann et al*., 2013; *Larsen et al*., 2012]. *de Moraes et al.* [2006] used 2 m troughs to measure SR draining from a 12 m long hillslope in the Amazon, for example. Measurements of SR at the plot scale (>1 m^2) combined with point to plot scale measurements of soil-hydraulic properties and soil-moisture conditions provide insight into how SR generation processes change with increasing scale of observation [*Moody and Ebel*, 2012].

While numerous studies have reported SR in the tropics, the spatial variability of its occurrence has resulted in differing reports in SR frequency, amounts and interpretations of SR generation processes, particularly in tropical forests [*Elsenbeer and Vertessy*, 2000; *Germer et al*., 2010; *Godsey et al*., 2004]. Further complicating the prediction of SR, certain interactions of rainfall intensity, duration or amount and soil characteristics are more conducive than others to SR generation [*Dunne and Leopold*, 1978; *Elsenbeer and Vertessy*, 2000] suggesting complex feedbacks among land-use, soil structure, infiltration, storage and SR. Yet, few studies have documented the impact of land-use on the frequency, timing and amount of SR in the tropics, and many of these studies are based on saturated soil conditions. We studied the impact of land-use on SR generation between two hillslopes within the headwaters of the Panama Canal Watershed (PCW): a mature, tropical forest and an actively-grazed cattle pasture. We instrumented each hillslope with difference infiltrometers [*Moody and Ebel*, 2012] and soil moisture sensors, and measured saturated hydraulic conductivity (K_s) to quantify SR and characterize soil properties at the plot scale. Our plot scale measurements of SR and soil-hydraulic properties shed light on SR generation in the tropics and differences in observations of

SR at different scales. The goal of our research was to quantify the impact of land-use practices on SR generation processes. Specifically, we investigated:

1. What is the impact of rainfall intensity, duration and amount on SR generation processes and how does this differ with land-use?
2. How do the interactions between different rainfall regimes and soil physical and hydraulic characteristics determine SR generation across different land-uses?
3. Can we recreate observed plot-scale SR dependencies on rainfall characteristics and soil-hydraulic properties using physically-based hydrologic modeling incorporating field measurements and observations from different land-uses?

2. Methods

2.1. Study area

We instrumented hillslopes in two catchments with contrasting land use and vegetation: a mature forest and an actively-grazed cattle pasture. The two catchments are located in the Panama Canal Watershed within the headwaters of the Agua Salud River (Figure 1a). Land-uses within the Agua Salud headwaters are typical of the greater Panama Canal Watershed and include mature and young secondary forests, native-species forests, teak plantations and pastures [*Ogden et al*., 2013, *Stallard et al*., 2010, *Weber and Hall*, 2009]. The area is characterized by a strongly dissected pre-tertiary basalt plateau with narrow interfluves, steep linear slopes averaging 42% and narrow or absent valley floors [*Hassler et al*., 2011, *Ogden et al*., 2013].

The climate is seasonal-tropical with strong wet and dry seasons [*Callaghan and Bonell*, 2005]. During the wet season, convective thunderstorms that produce high intensity, short duration rain events dominate [*Bonell*, 1993; *Ogden et al*., 2013]. The wet season extends from early to mid-May through mid-December. Total annual rainfall at our field site averages 2300 mm [*Neumann-Cosel et al*., 2010]. Mean daily temperature on nearby Barro Colorado Island is 27°C and only varies slightly throughout the year [*Windsor*, 1990].

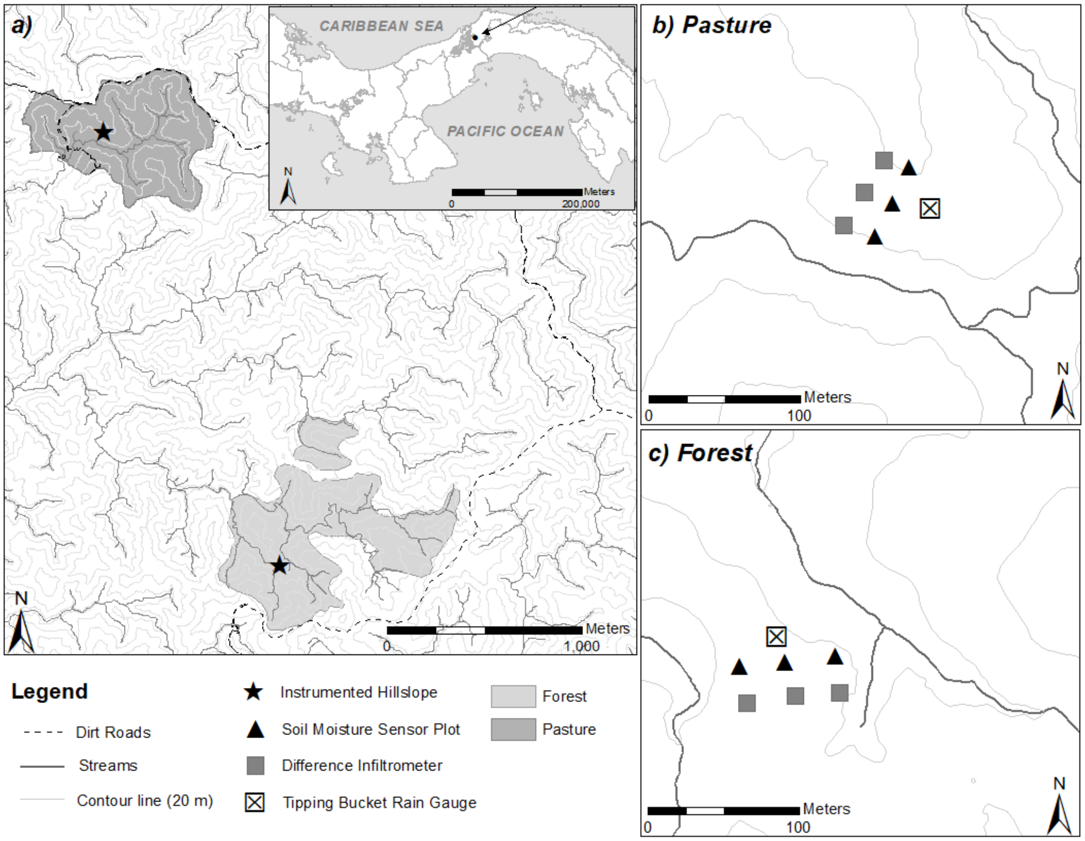

Figure 1. Map of the Agua Salud Watershed within the Panama Canal Watershed *(a)* and instrumented pasture *(b)* and forest *(c)* hillslopes [GIS data obtained from Robert F. Stallard (unpublished)].

2.2. Paired hillslopes

We used a paired hillslope approach to evaluate the magnitude of hydrologic changes resulting from shifts in land-use from forest to pasture *[Brown et al*., 2005]. We selected one hillslope in each land-use type (forest and pasture) with relatively similar characteristics including slope, geology, soil composition and catchment morphology and area. We instrumented portions of forest and pasture hillslopes with slopes of approximately 30%. Both catchments are underlain by deeply weathered basaltic and andesitic parent rocks, resulting in largely homogenous Oxisol soils ranging in texture from silty clay to clay [*Ogden et al*., 2013; *PMCC*, 1999; *Turner and Engelbrecht*, 2010].

The forest catchment area covers approximately 50 ha. and forest at this site is at least 80 years old. The pasture catchment covers 40 ha and has been maintained as a pasture with a one-month-on, one-month-off rotation for at least 20 years. Cattle grazing occurs at a relatively low intensity, with a grazing density of about 1.3 head of cattle per ha [*Ogden et al*., 2013]. Active grazing is ongoing at the pasture, and successional tree and shrub growth are manually cleared.

2.3. Soil moisture

To characterize soil moisture response to rain events, we installed soil-moisture sensors (GS1 Ruggedized Soil Moisture Sensor, Decagon Devices, Pullman, WA) along a depth profile of 10 cm, 30 cm, 50 cm and 100 cm. Soil moisture sensor clusters were installed at three locations, approximately 10 m apart in the downslope direction along the planar hillslopes. We avoided ridge crest and riparian zones by installing sensor clusters approximately 15 m below the crest of the hillslope ridge and 15 m above the stream channel at the pasture, and approximately 10 m below the crest of the hillslope and 15 m above the stream channel at the forest. (Figure 1b and 1c). An installation trench was excavated, sensors were emplaced in the trench headwall at the selected depths, and then the trench was backfilled with soil. Soil moisture sensors recorded volumetric water content (VWC_{sensor}) every 15 minutes. Sensors were not calibrated for site-specific soil and therefore have accuracy of approximately ± 3% VWC (*Decagon Devices*, 2015). Data for time periods when soil-moisture sensors malfunctioned were not included in our analysis.

2.4. Soil hydrologic properties

To characterize differences in soil hydrologic properties between the forest and the pasture hillslopes, we collected soil samples weekly near the soil moisture sensor clusters at each field site. We collected four soil samples and alternated sampling between a surface spatial profile (generally upslope, downslope, left and right relative to each soil moisture sensor cluster) and along a depth profile (0 cm, 10 cm, 30 cm and 50 cm depths) every other week. Samples were collected from different areas near each soil moisture sensor cluster each week to prevent oversampling. We collected samples using 6 cm long soil cores (4.7 cm diameter, 104.1 cm^3), and pushed soil from the core into double-bagged ziplock bags before transporting them to the lab to prevent evaporation. Soils were weighed before and after drying at 105°C for 24 hours. Wet and dry weights were then used to calculate dry bulk density (g cm^{-3}) and VWC_{manual}. Porosity (Φ) was calculated from dry bulk density using the equation:

$$\Phi = [1 - \left(\frac{\rho b}{\rho d}\right) \times 100] \qquad \text{Eq. 1}$$

where ρ_b is dry bulk density and ρ_d is solid particle density, using a solid particle density of 2.65 g cm^{-3}.

We evaluated K_s along the hillslopes of each field site using two different methods: single-ring, ponded falling head infiltration tests (referred to as falling head tests) were used to measure matrix and macropore K_s while minidisk infiltrometers (Decagon Minidisk Portable Tension, Decagon Devices, Pullman, WA) were used to measure matrix K_s. Because we applied a suction of 2 cm, our minidisk measurements are closer to a field-saturated hydraulic conductivity measurement [*Decagon Devices*, 2012]; however, these are referred to throughout this manuscript as K_s for simplicity. We conducted falling head tests adjacent to each soil moisture sensor plot at each field site following the protocol detailed in *Nimmo et al*. [2009]. Using a 22.9 cm diameter ring, we recorded time in seconds for 1 L of water to infiltrate into the soil completely. We used these values to calculate a geometric mean K_s for each hillslope *[Nimmo et al*., 2009; *Eq. 12*). Minidisk infiltrometer measurements were conducted on soil cores (6 cm length, 4.7 cm diameter) alternating weekly between spatial and depth profile cores. Collection of these samples coincided spatially and temporally with soil samples collected for evaluating volumetric water content, dry bulk density and porosity. Minidisk soil core samples were capped and sealed with electrical tape to prevent evaporation. Samples were taken back to the laboratory and placed in a stand where the minidisk infiltrometer could be applied to the soil surface. Coupling between the minidisk and the core edges was accomplished by using a waterproof, flexible plastic sleeve. Contact sand was placed between the soil surface and the minidisk base to ensure hydraulic connection. The volume of water in the minidisk reservoir was recorded every 30 seconds for 15 minutes or until the reservoir was emptied. Hydraulic conductivity was estimated using the cumulative infiltration method described in *Vandervaere et al*. [2000] for each soil core collected from each field site.

2.5. Rainfall and throughfall measurements

One tipping bucket rain gage (TR-525M, Texas Electronics, Dallas, TX) was installed in a central location along the hillslope of each field site to measure rainfall. The rain gage installed at the forest site was equipped with troughs to increase the spatial extent of sampling similar to *Keim et al.* [2005]. The troughs consisted of two PVC pipes with a slot cut in each measuring 2.54 cm wide and 93 cm long to equal the catch area of the tipping bucket rain gage. To characterize the spatial variability of rainfall at the forest site, we installed 12 throughfall collectors during the following field season in Summer 2017. Although these throughfall data were not collected concurrently with our 2016 rainfall data, they allow us to characterize the spatial variability of rainfall at our forest site. Throughfall collectors were installed in two rows of six on either side of the soil moisture sensor and difference infiltrometer plots along the forest hillslope. Each row was separated by 8 m and each collector within a row was 5 m apart. Each throughfall collector consisted of a 10 cm diameter funnel installed on top of a 1-L bottle. Volumes of stored rainfall from the throughfall collectors were recorded, and tipping bucket rain gage data were downloaded twice per week.

2.6. Surface runoff measurements

To evaluate the impact of land-use on the generation of SR, we designed and installed difference infiltrometers [*Moody and Ebel*, 2012] on the pasture and forested hillslopes. Difference infiltrometers were installed at both the forest and pasture site adjacent to soil moisture sensor clusters (10 m apart) (Figure 1b, c). The system consists of one tipping bucket rain gage to measure rainfall (described in the previous section) and both a tipping bucket rain gage and a water level logger to measure SR from an enclosed plot of known area. At the plot scale, surface runoff routing can be neglected because surface travel times across such small plots are negligible [*Moody and Ebel*, 2012]. Differencing rainfall and plot-area-corrected runoff allows direct measurement of temporally variable infiltration.

To account for potentially large differences in SR between the forest and pasture sites, we designed the difference infiltrometer so that SR generated during lower intensity rain events could be captured by the tipping bucket runoff gage while higher intensity events could be captured by the level loggers. The runoff plot was sized so that lower intensity rainfall events with a peak rainfall intensity of 20 mm hr^{-1} and a runoff coefficient of 0.3 could be accurately measured with the tipping bucket runoff gage. Surface runoff from the difference infiltrometer (~0.44 m diameter and an area of 0.15 m^2) was directed downhill through a PVC pipe into the tipping bucket runoff gage, the orifice of which was equipped with a plastic cap to prevent rainfall from entering the tipping bucket runoff gage. A nylon mesh screen was secured to both ends of the pipe to prevent debris from clogging the tipping bucket runoff gage. Each rain gage was checked and cleaned twice per week, ensuring the delivery pipe was free of debris. The tipping bucket rain gage used to measure SR (TR525I - metric, Texas Electronics, Dallas, TX) was housed within an 18.9 L (i.e. 5-gallon) bucket equipped with a level logger (Odyssey Capacitance Water Level Logger, Dataflow Systems Limited, Christchurch, NZ) with a customized 35 cm probe length.

2.7. Rainfall - runoff events

Runoff ratios for each rain event were calculated as the ratio of SR values recorded either by the tipping bucket runoff gages or the level loggers. Raw values reported by tipping bucket runoff gages were adjusted for the measurement area of the SR plot. Odyssey Water Level Capacitance level loggers record changes in height of water in millimeters. To convert height changes to a volume of SR, we determined a calibration curve using data from in-lab calibration tests. These tests consisted of sequentially adding increments of 0.5 L of water into an 18.9 L (i.e. 5-gallon) bucket and correlating these known volumes of water to the water level heights recorded by the level loggers. Through this calibration, we discovered the level loggers inaccurately reported water level when the bucket had less than approximately 5.1 cm of water height (values varied slightly for each individual level logger). Surface runoff that occurred when the water table in the bucket was below 5.1 cm was not included in our analysis of rainfall-runoff relationships. We used a linear regression model for the calibration curves above approximately 5.1 cm of water height (mean $R^2 = 0.99$ for all calibrations). We converted raw SR values to calibrated volumes of SR using our linear regression model, and then to calibrated millimeters of SR adjusted to the area of our runoff plot. Only water level height changes greater than 0.5 mm were considered to represent a change in SR volume due to the resolution of the level logger sensors.

Because we recorded SR using two methods (i.e. tipping bucket gage and level logger), there were several events that had both tipping bucket runoff gage and level logger data. In order to simplify SR analysis, either the tipping bucket runoff gage or the level logger values were used for SR data for each rainfall event. Three criteria guided our selection of either tipping bucket runoff gage or level-logger SR data: 1- if tipping bucket runoff gages were overwhelmed by the rate of SR (i.e. during larger intensity events with rainfall intensities greater than 20 mm hr^{-1}), only level logger values were used; 2- if level-logger SR values overestimated SR, (i.e- level loggers recorded SR values much higher than those recorded by the tipping bucket runoff gages and produced greater runoff ratios than typical of events of a similar magnitude), only tipping bucket SR values were used. This scenario is explained by movement of the water surface (greater than the 0.5 mm height change tolerance) within the bucket during SR events, causing noisy time series that posed issues when examining the cumulative SR record; 3- if the level-logger and the tipping bucket runoff gages produced widely different SR values, the rain event was not used in our analysis. This occurrence was rare but was observed when either the tipping bucket runoff gage recorded SR but the level logger did not record any SR or vice versa. The first scenario occurred when the buckets housing the level loggers were completely full of water, but the tipping bucket runoff gage was not. The second scenario occurred when there was not enough water in the bucket at the start of a rain event for the level logger to record SR accurately. Surface runoff values given when there was not enough water in the bucket were set to zero in our data analysis, resulting in no SR recorded for the level logger.

For a subset of rain events, both tipping bucket and level logger SR data passed the criteria detailed above. For these cases, we defaulted to using the level logger SR data, because the tipping bucket runoff gage accuracy could be variable with increasing runoff ratio. For example, because we designed the runoff plot to accommodate a rain event of 20 mm hr^{-1} with a runoff coefficient of 0.3, the accuracy of our measurements could decrease if the runoff ratio for a rain event was 0.4. On the other hand, the level loggers measured height changes within the bucket, and runoff ratios and rainfall intensities did not directly impact measurement accuracy.

Individual rain events were defined by a two-hour dry period between rain events [*Zimmermann et al*., 2014]. Rain events with greater than 3 mm of total rainfall were considered hydrologically significant [*Ogden et al.*, 2013], resulting in 169 rain events: 67 from the forest and 102 from the pasture. After removing events based on SR measurement issues described previously, 58 rain events remained: 23 from the forest and 35 from the pasture (Table 1). Rainfall events starting within one hour between the forest and pasture sites were evaluated separately as paired events (16 of total paired rainfall events) (Table 2).

Table 1. Rainfall duration, peak intensity, mean intensity and total with rainfall-runoff ratios for all events occurring at the forest and pasture.

Measure	Duration (min)	Peak Intensity (mm hr^{-1})	Mean Intensity (mm hr^{-1})	Rainfall Total (mm)	Runoff Ratio
Forest					
Minimum	40	5	1	3	0.01
1st Quartile	100	11	2	4	0.07
Mean	166	24	5	14	0.14
Median	160	19	4	7	0.12
3rd Quartile	183	23	5	11	0.15
Maximum	310	73	12	47	0.38
Pasture					
Minimum	30	2	1	3	0.04
1st Quartile	55	13	2	5	0.12
Mean	176	33	6	16	0.23
Median	200	25	5	9	0.19
3rd Quartile	210	32	6	12	0.22
Maximum	410	95	24	83	0.60

Table 2. Rainfall duration, peak intensity, mean intensity and total with rainfall-runoff ratios for events occurring simultaneously (paired events) at the forest and pasture.

Measure	Duration (min)	Peak Intensity (mm hr^{-1})	Mean Intensity (mm hr^{-1})	Rainfall Total (mm)	Runoff Ratio
Forest					
Minimum	50	9	1	3	0.04
1st Quartile	91	12	2	5	0.06
Mean	173	27	6	15	0.13
Median	155	23	4	9	0.11
3rd Quartile	212	26	5	14	0.13
Maximum	310	73	12	47	0.38
Pasture					
Minimum	50	10	1	4	0.05
1st Quartile	94	17	3	7	0.10
Mean	208	46	8	25	0.20
Median	205	35	5	17	0.15
3rd Quartile	250	60	6	23	0.19
Maximum	370	95	24	83	0.47

2.8. Modeling surface runoff with HYDRUS-1D

To address our final research question, we used the HYDRUS-1D modeling software [*Šimùnek et al*., 2008] to simulate surface runoff for the 16 paired events from the forest and pasture. This numerical model solves the one-dimensional (i.e. vertical) form of Richards equation and accounts for multiple soil layers and complex rainfall time series more easily than the Green-Ampt or Smith Parlange infiltration approaches [*Šimùnek et al*., 2008]. We used a two-layer soil system within the HYDRUS-1D model. This was based off of the soil layers defined by *Hassler et al*. [2011] who evaluated soils at a pasture and a 100-year-old secondary forest near our study sites. *Hassler et al*. [2011] defined an upper layer from 0- 6 cm and a lower layer from 6-12 cm. We used 0- 6 cm for our upper layer, which was also the length of the soil cores we used for manual soil sampling and calculations of volumetric water content, dry bulk density and porosity. We used a depth of 6 – 100 cm for our lower layer to coincide with Hassler's lower layer as well as our soil moisture sensor data.

We used the van Genuchten-Mualem analytical single porosity model [*van Genuchten*, 1980] option within HYDRUS-1D, which requires five independent parameters for each soil layer: the residual soil water content (SWC), θ_r; the saturated SWC, θ_s; two van Genuchten fitting parameters (α, related to the inverse of the air entry pressure and n, related to the pore size distribution; *Cherrey et al*., 2003] and the pore connectivity parameter I. Parameters θ_r, θ_s, α and n were estimated using the program RETC [van Genuchten et al., 1991] fit to sand, silt and clay soil composition and dry bulk density data (Table 3). Sand, silt and clay soil composition data for the upper and lower soil layers were taken from values reported from 0 to 6 cm and 6 to 12 cm, respectively, in *Hassler et al*. [2011] (Table 4). For both the upper and lower soil layers, we used mean dry bulk density values obtained from our manual soil samples (Table 5, 6). I was set to

0.5 for both soil layers [Mualem, 1976]. The remaining soil parameter used by HYDRUS-1D to simulate surface runoff is K_s. While the majority of the other modeling parameters remain relatively static, K_s varied both spatially and temporally in both catchments. Therefore, to recreate observed field observations within the HYDRUS-1D modeling environment, we performed a calibration to determine a suitable value of K_s. Results from previous studies indicate that the land-use influence on K_s is limited to only the uppermost soil layer; in the Amazon, land-use was considered irrelevant for K_s values below 20 cm [*Godsey and Elsenbeer*, 2002; *Zimmermann et al*., 2006]. Because of this, we only calibrated K_s values for our upper soil layer and used K_s values similar to those reported from 6-12 cm in forest and pasture catchment from *Hassler et al*. [2011] for our lower soil layer for all rain events (Table 3).

Table 3. The *Van-Genuchten-Mualem* [1980] parameters for HYDRUS 1-D for forest and pasture. Surface values of K_s were obtained from mean calibration K_s values.

Site	Depth (cm)	Q_r	Q_s	α (mm^{-1})	*N*	K_s (mm hr^{-1})	I	Bulk Density (g cm^{-3})
Forest	0-6	0.129	0.752	0.005	1.231	256	0.5	0.60
	6-100	0.119	0.674	0.003	1.257	120	0.5	0.82
Pasture	0-6	0.118	0.683	0.003	1.267	30	0.5	0.78
	6-100	0.117	0.669	0.003	1.272	60	0.5	0.82

Table 4. Sand, silt, clay content (SSC) input for the forest and pasture sites in HYDRUS-1D taken from *Hassler et al*. (2011).

SSC (%)	Forest	Pasture
Sand	9.6	12.3
Silt	33.4	34.0
Clay	57.0	53.6

To determine K_s values for our simulated upper soil layer for each of the 16 paired rain events, we calibrated K_s to a subset of rain events. Calibration rain events were selected to cover a range of peak rainfall intensities from each field site; 5 events were chosen for the forest and 5 for the pasture. Calibration K_s values were limited to the range of values measured from our minidisk and falling head tests and those reported in *Hassler et al*. [2011] for forest and pasture. For each rain event, the K_s value that was ultimately selected optimized the fit (i.e. percent difference between observed and simulated data was < 20%) between observed surface runoff (runoff) and that simulated in HYDRUS-1D when considering peak runoff timing, peak runoff rate and/or runoff total. For one pasture event, the fit for these variables could not be optimized below 20% with a reasonable K_s value, and surface K_s was optimized for SR start time instead. For the mature forest none of the variables could be optimized below 20%, so SR total was optimized to the lowest possible percent difference at 51%. Similarly to the pasture, one event could not be optimized to the standard variables so it was optimized for SR start time instead. When SR could not be simulated in HYDRUS-1D, our geometric mean for surface K_s from in-field K_s measurements taken at the forest was input for the upper layer. This occurred for 3 of the 5 calibration rain events at the forest site. K_s values were averaged for the 5 calibration rainfall events from each site and applied to the remaining 16 paired rainfall events for the forest and pasture.

Initial soil-water content values were input into the HYDRUS soil profile by zoning each soil-moisture observation point: 0 to 6 cm for surface soil moisture values collected with soil cores (VWC_{manual}), 6 to 20 cm for 10 cm soil-moisture sensor values, 20 to 40 cm for the 30 cm sensor, 40 to 75 cm for the 50 cm sensor and 75 to 100 cm for the 100 cm sensor. Volumetric water content values obtained manually were only used when we collected soil samples on the same day, prior to a rainfall event (this occurred for 6 events from each site). We used 10 cm VWC_{sensor} when manual measurements were not available. Rainfall data from each event was applied using the “atmospheric boundary condition” in HYDRUS-1D (i.e. a specified flux at the soil surface) and SR outputs were simulated for each site assuming zero depression storage.

2.9. Statistical Analyses

Due to the non-normality of our runoff ratio data that could not be alleviated with common transformations, we used nonparametric statistical tests to determine significance of difference between forest and pasture sites. To keep statistics consistent across all analyses, the two-sample Kolmogorov- Smirnov (KS) Test [*Kolmogorov*, 1933; *Smirnov*, 1948] was used for all statistical inference. Due to the small sample size in a number of our analyses, differences were taken to be significant with $\alpha < 0.1$. In order to objectively bin the rainfall events for forest and pasture sites in Figures 2 and 3, we analyzed historical rainfall data from within the Agua Salud Watershed. We grouped the historical data into quantiles and applied the resulting bin edges to our rainfall-runoff event analysis. All data processing and statistical analyses were performed using the computer programming language and numerical computing environment MATLAB (Version 9.2, The MathWorks Inc., Natick, MA).

3. Results

3.1. Soil moisture

Soil moisture responded to rainfall similarly between the forest and the pasture. We observed the largest soil moisture responses at 10 cm (mean response time of 12 minutes at the forest, 43 minutes at the pasture) and 30 cm depths (mean response time of 36 minutes at the forest and 50 minutes at the pasture), while the deeper sensors at 50 and 100 cm showed little to no immediate response to rain events.

One notable difference between the two sites was the soil moisture response at a depth of 30 cm. We observed a greater response from this layer at the pasture site than the forest site, and occasionally this layer became more saturated than the 10-cm layer. The 30-cm layer was consistently the most saturated of all the soil moisture layers at the forest site, whereas VWC_{sensor} increased with depth at the pasture site (Figure 2). The minimum rainfall intensity required to initiate soil moisture response was slightly lower at the forest at 9 mm hr^{-1}, compared to 15 mm hr^{-1} at the pasture. The difference between measurements of VWC obtained manually using soil cores (from depth 0-6 cm) and the VWC reported by soil moisture sensors were also slightly different between the forest and the pasture, with manual measurements consistently approximately 3% drier at the forest, but approximately 3% wetter at the pasture.

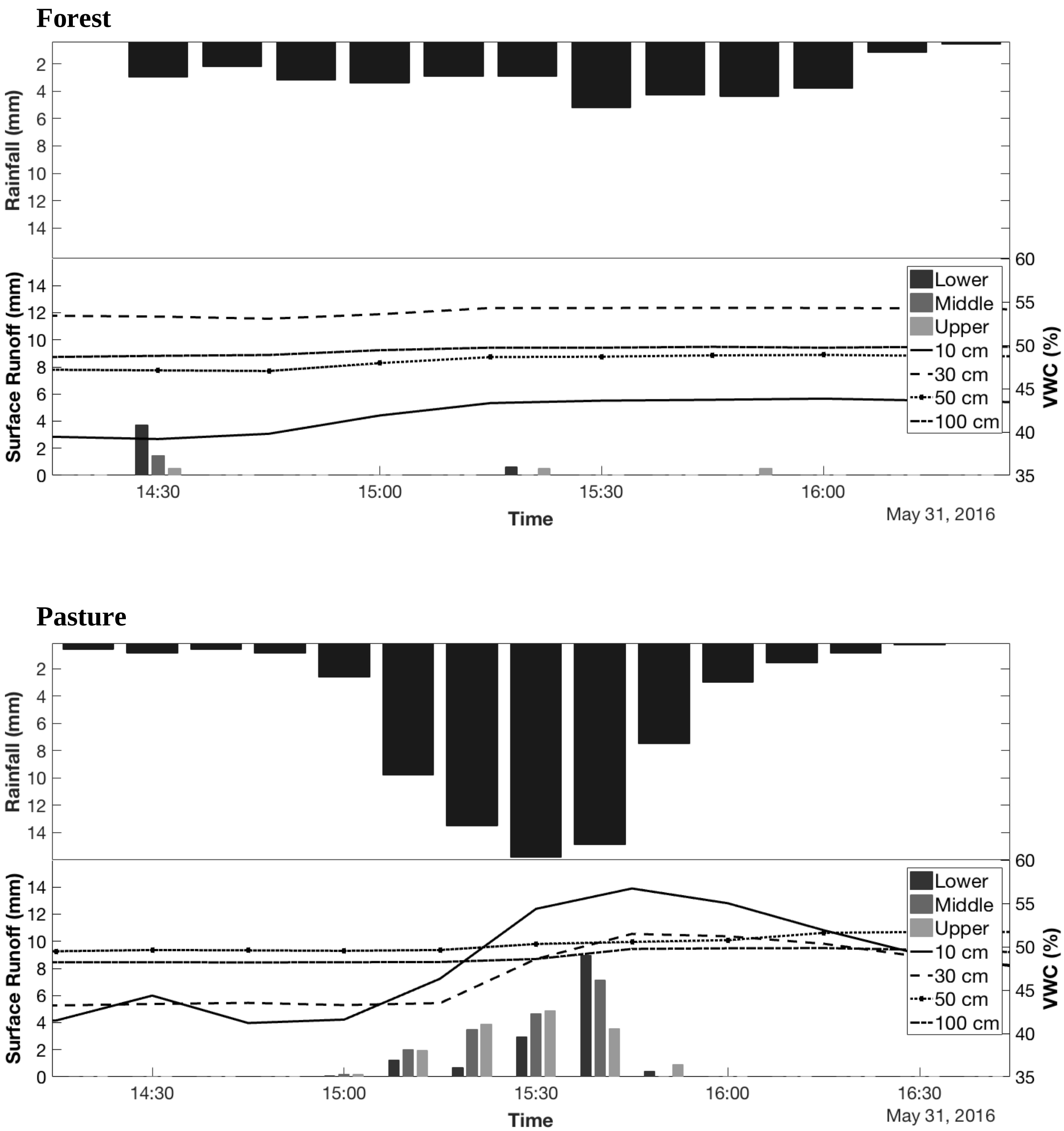

Figure 2. Rainfall, surface runoff and soil moisture response to an event occurring on May 31, 2016 at the forest and pasture. Each surface runoff bar represents response by instrumentation installed nearest to the stream channel (*lower*), nearest the hillslope ridge (*upper*) and between the two (*middle*). Mean porosity (which is approximately equal to saturated soil water content) measured at the surface was 77% at the forest and 71% at the pasture (Table 5), and 69% at both sites between 10 cm and 50 cm depths (Table 6). Thus, soil does not become saturated during this rain event at either site.

3.2. Soil hydrologic properties

Soil hydrologic properties of dry bulk density, porosity, and saturated hydraulic conductivity were significantly different between forest and pasture at the surface, though were only slightly different between 10 cm and 50 cm. Surface dry bulk density calculated from our 0-6 cm soil cores ranged from 0.31 to 0.82 g cm^{-3} (mean = 0.60 g cm^{-3}) at the forest site. Surface dry bulk density was higher at the pasture site, with values ranging from 0.60 g cm^{-3} to 0.97 g cm^{-3} (mean = 0.78 g cm^{-3}). Porosity was higher at the forest site with values ranging from 69% to 88% and a mean of 77%. Porosity at the pasture site ranged from 64% to 78% with a mean of 71% (Table 5). Surface dry bulk density and porosity values were significantly different between forest and pasture sites ($p < 0.05$ for all comparisons). Bulk density and, correspondingly, porosity were also evaluated along a depth profile of 10 cm, 30 cm, and 50 cm. Given the small sample size for these data (n = 6 and 7 for forest and pasture, respectively) we did not evaluate significance among these data, and instead analyzed summary statistics for all depth measurements obtained from 10-50 cm (Table 6). However, we observed a general increase in bulk density with depth (ranging from 0.62 g cm^{-3} at the surface to 0.88 g cm^{-3} at a depth of 50 cm) and a coinciding decrease in porosity (77% at the surface to 67% at 50 cm depth) at the forest site. Conversely, a general decrease in bulk density (0.86 g cm^{-3} at the surface to 0.79 g cm^{-3} at 50 cm depth) and a coinciding increase in porosity (67% at the surface to 70% at 50 cm depth) was observed at the pasture site. The large differences in bulk density and porosity observed between the two sites above 30 cm depth did not extend below this depth. Porosity was only slightly higher at the pasture site at depths of 30 and 50 cm (both at 70%) than at the forest (68% and 67%) and bulk density was only slightly higher at the forest site at depths of 30 and 50 cm (0.85 g cm^{-3} and 0.88 g cm^{-3}) compared to the pasture (0.82 g cm^{-3} and 0.79 g cm^{-3}).

Surface K_s measured using the minidisk tension infiltrometers ranged from 27 mm hr^{-1} to 15,615 mm hr^{-1} at the forest site and from 1 mm hr^{-1} to 1,666 mm hr^{-1} at the pasture with a geometric mean of 390 mm hr^{-1} at the forest and 99 mm hr^{-1} at the pasture. Minidisk hydraulic conductivity was also evaluated at depths of 10 cm, 30 cm and 50 cm. We observed a decrease in hydraulic conductivity with depth at both the forest and the pasture, although sample size was too small to test for significance (n<3 for all depths from both sites) (**Table 7)**. Mean K_s values ranged from 40 mm hr^{-1} at the surface to 162 mm hr^{-1} at a depth of 50 cm at the pasture, whereas mean forest K_s values ranged from 287 mm hr^{-1} at the surface to 140 mm hr^{-1} at 50 cm depth.

Surface hydraulic conductivity measured using falling head infiltration tests ranged from 16 mm hr^{-1} to 2,746 mm hr^{-1} at the forest site with a geometric mean of 650 mm/hr. Within the pasture values ranged from 7 mm hr^{-1} to 526 mm hr^{-1} with a geometric mean of 82 mm hr^{-1} (Table 5).

Table 5. Soil physical characteristics measured spatially at the surface with 6 cm soil cores for forest and pasture.

Measure (surface)	Dry Bulk Density (g cm^{-3})	Volumetric Water Content (cm^3 cm^{-3})	Porosity (%)
Forest			
Minimum	0.31	18	69
1st Quartile	0.52	32	74
Mean	0.60	37	77
Median	0.62	37	77
3rd Quartile	0.64	38	78
Maximum	0.82	47	88
Pasture			
Minimum	0.60	30	64
1st Quartile	0.70	37	68
Mean	0.78	41	71
Median	0.78	41	71
3rd Quartile	0.80	43	71
Maximum	0.97	53	78

Table 6. Soil physical characteristics measured at depths 10-50 cm at the forest and pasture.

Measure (depth)	Dry Bulk Density ($g\ cm^{-3}$)	Volumetric Water Content ($cm^3\ cm^{-3}$)	Porosity (%)
Forest			
Minimum	0.53	30	60
1st Quartile	0.73	32	66
Mean	0.82	36	69
Median	0.81	35	69
3rd Quartile	0.83	37	70
Maximum	1.06	46	80
Pasture			
Minimum	0.62	27	63
1st Quartile	0.73	32	65
Mean	0.82	37	69
Median	0.82	38	69
3rd Quartile	0.84	39	71
Maximum	0.97	45	77

Table 7. Hydraulic conductivity (K_s) measured using ponded falling head tests and minidisk infiltrometers at the surface, and minidisk infiltrometers measured at depth from 10 - 50 cm at the forest and pasture.

Measure ($mm\ hr^{-1}$)	Falling Head K_s (surface)	Minidisk K_s (surface)	Mini- Disk K_s (depth)
Forest			
Minimum	16	27	81
1st Quartile	359	127	90
Mean	992	892	136
Geometric Mean	650	390	131
Median	797	485	157
3rd Quartile	1,061	607	158
Maximum	2,746	15,616	162
Pasture			
Minimum	7	1	1
1st Quartile	30	33	21
Mean	132	269	82
Geometric Mean	82	99	30
Median	108	108	83
3rd Quartile	138	128	95
Maximum	526	1,666	162

3.3. Rainfall and throughfall

We recorded a total of 58 rainfall events: 23 from the forest and 35 from the pasture. Although rainfall was recorded at the pasture site and throughfall was measured at the forest site, both are referred to as rainfall throughout in the following text for simplicity of comparison between field sites. Rainfall duration was similar between the forest and the pasture for all rainfall events, ranging from 40 to 310 minutes with a mean of 166 minutes at the forest and from 30 to 410 minutes with a mean of 176 minutes at the pasture. Peak rainfall intensity was greater at the pasture site ranging from 2 to 95 mm hr^{-1} with a mean of 33 mm hr^{-1} compared to the forest peak rainfall intensity ranging from 5 to 73 mm hr^{-1} with a mean of 24 mm hr^{-1}. Mean rainfall intensity was slightly higher at the pasture with values ranging from 1 to 24 mm hr^{-1} with a mean of 6 mm hr^{-1} compared to a range of 1 to 12 mm hr^{-1} with a mean of 5 mm hr^{-1} at the forest. Rainfall totals were slightly greater at the pasture ranging from 3 to 83 mm and a mean of 16 mm compared to a range of 3 to 47 mm and a mean of 14 mm at the forest (Table 1); presumably, this reflects canopy interception at the forest site. Data collected during Summer 2017 indicate that throughfall at the forest site is highly variable. For example, during a rain event with a rainfall total of 18 mm, throughfall ranged from 21% to 74% of total incident rainfall at the collectors nearest the difference infiltrometers. This is consistent with results of other throughfall studies conducted near our field site [*Niedzialek and Ogden*, 2012; *Zimmermann et al.*, 2009]. Throughfall values have also been observed to range from 0 – 200% of incident rainfall in tropical rainforests in Amazonia [*Lloyd and Marques*, 1988] and in Puerto Rico [*Holwerda et al.*, 2006].

Rainfall duration, peak intensity, mean intensity and rainfall totals for paired events were each slightly greater than those for all events at both the forest and the pasture. Rainfall durations for paired events were slightly longer on average than that of all events between the forest and the pasture, ranging from 50 to 310 minutes with a mean of 173 minutes at the forest site and from 50 to 370 minutes with a mean of 208 minutes at the pasture site. Peak rainfall intensity was greater for paired events ranging from 10 to 95 mm hr^{-1} with a mean of 46 mm hr^{-1} at the pasture and 9 to 73 mm hr^{-1} with a mean of 27 mm hr^{-1} at the forest. Mean rainfall intensity was similar for paired events with pasture values ranging from 1 to 24 mm hr^{-1} with a mean of 8 mm hr^{-1} compared to a range of 1 to 12 mm hr^{-1} with a mean of 6 mm hr^{-1} at the forest. Rainfall totals were greater for paired events with pasture site totals ranging from 4 to 83 mm and a mean of 25 mm and forest rainfall totals ranging from 3 to 47 mm with a mean of 15 mm (Table 2).

3.4. Surface runoff

Runoff ratios for all events ranged from 0.01 to 0.38 at the forest and from 0.04 to 0.60 at the pasture. The mean and standard error of the runoff ratios for the forest and pasture sites were 0.14 ± 0.02 and 0.23 ± 0.03, respectively ($p = 0.04$) (Table 1). This is consistent with our qualitative observations. On several occasions, the buckets housing the level loggers at the pasture site were half full. After two large rain events, both the buckets and the tipping bucket runoff gages overflowed with SR for two of the three difference infiltrometers installed on the pasture hillslope. The buckets were covered, indicating the water present in the buckets could not be from rainfall. In contrast, the five-gallon bucket installed at the forest site was rarely more than a quarter of the way filled with SR.

Runoff ratio as a function of rainfall event duration, rainfall total, peak rainfall intensity and average rainfall intensity were compared between the forest and pasture hillslopes (Figure

3). We observed a general decrease in runoff ratios for longer duration events, and events with greater rainfall totals. Runoff ratios for pasture events increased with mean rainfall intensity up to 11 mm hr^{-1}, with relatively lower runoff ratios recorded for events with mean rainfall intensities between 11 and 25 mm hr^{-1}. Forest runoff ratios increased with mean rainfall intensity up to 7 mm hr^{-1}, and decreased for events with mean rainfall intensities between 7 and 25 mm hr^{-1}. A general trend was not observed between runoff ratio and peak rainfall intensity for either the forest or the pasture, though runoff ratios increased with increasing peak intensities up to 30 mm hr^{-1} for both the forest and pasture. Runoff ratios were generally greater at the pasture site with comparisons of each rainfall characteristic quantile. Runoff ratios differed between the pasture and forest when rain event duration was between 60 and 110 minutes ($p = 0.04$) and between 180 and 140 minutes ($p = 0.08$). Additionally, runoff ratios differed when rainfall totals ranged from 0 to 4 mm ($p = 0.08$) and from 10 to 84 mm ($p = 0.02$), when mean rainfall intensities were between 11 mm hr^{-1} and 25 mm hr^{-1} ($p = 0.04$) and when peak rainfall intensities ranged between 30 mm hr^{-1} and 42 mm hr^{-1} ($p = 0.05$) (Figure 3).

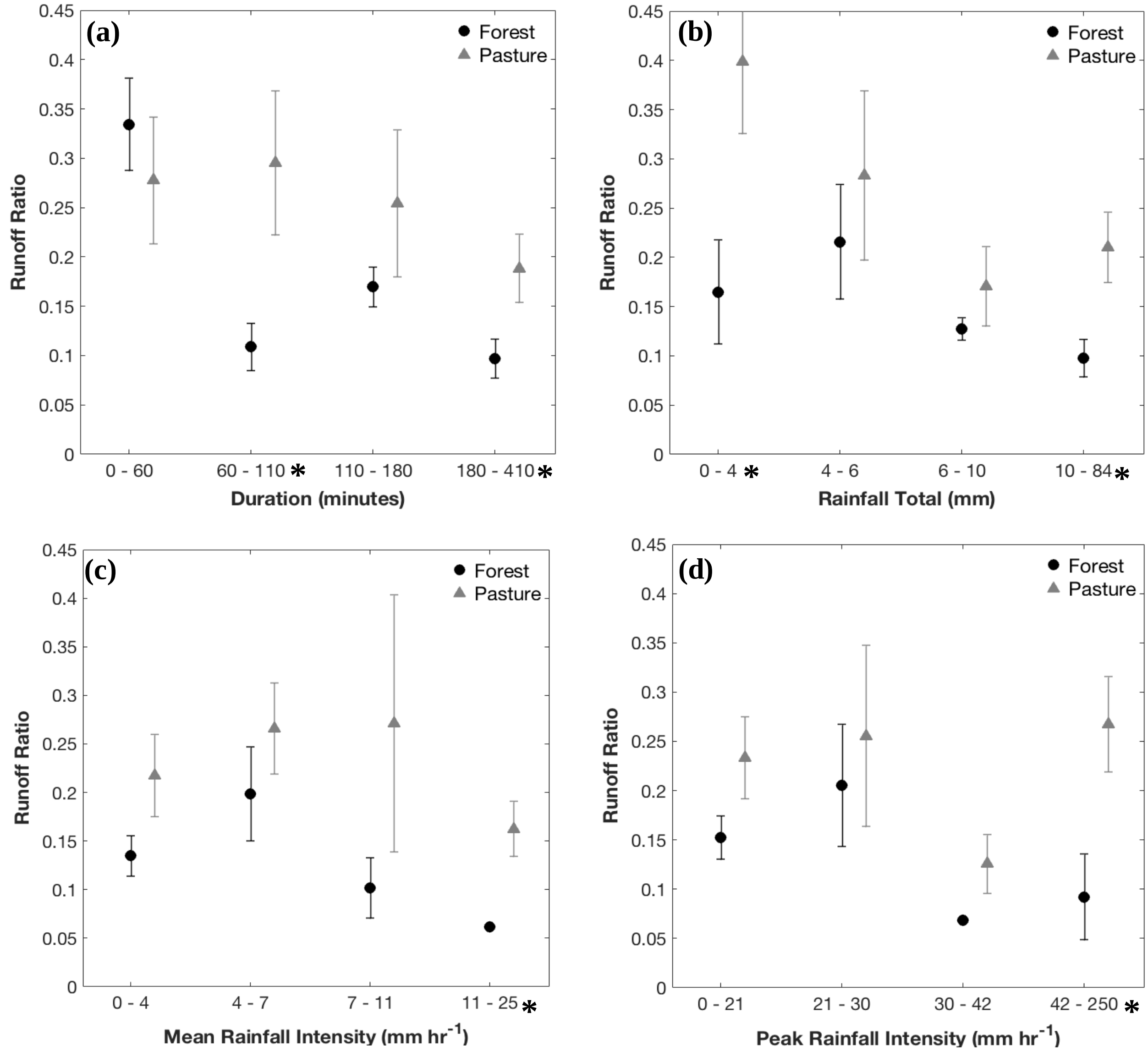

Figure 3. Runoff ratio as a function of rainfall duration *(a)*, rainfall total *(b)*, mean rainfall intensity *(c)* and peak rainfall intensity *(d)* for all rain events. Bin edges were determined using historical Agua Salud rainfall data. Points represent mean runoff ratio values and bars represent the standard error of the mean. Large standard error bars are attributed to natural variability and the small sample size within each bin. Asterisks indicate significant differences between forest and pasture.

Of the 58 rainfall events, 16 occurred simultaneously at the forest and pasture and were analyzed separately as paired events. Runoff ratios for paired events ranged from 0.04 to 0.38 at the forest and from 0.05 to 0.47 at the pasture. The mean and standard error of the runoff ratios for paired events were 0.13 ± 0.02 and 0.20 ± 0.03 for forest and pasture, respectively (Table 2). Mean runoff ratios were 50% higher at the pasture site than the forest site, though we did not observe statistically significant differences between paired events ($p = 0.3$). The comparison of SR between the forest and pasture in Figure 2 exemplifies the typically lower SR response observed during a paired event at the forest (Figure 2a), compared to the pasture (Figure 2b). Runoff ratio as a function of rainfall event duration, rainfall total, mean rainfall intensity and peak rainfall intensity were also compared between the forest and pasture catchments for the 16 paired events. Trends in each of these variables were similar to those seen when analyzing all events. Significant differences were observed for runoff ratios of rain events with durations between 180 and 410 minutes ($p = 0.06$), rainfall totals between 10 and 84 mm ($p = 0.03$), mean rainfall intensities between 11 mm hr^{-1} and 25 mm hr^{-1} ($p = 0.04$) and peak rainfall intensities between 30 mm hr^{-1} and 42 mm hr^{-1} ($p = 0.03$) (Figure 4). Rain events with durations greater than 180 minutes, rainfall totals between 10 and 84 mm, mean rainfall intensities between 11 and 25 mm hr^{-1} and peak rainfall intensities between 30 mm hr^{-1} and 42 mm hr^{-1} resulted in significantly higher runoff ratios in the pasture than the forest (Figure 3, 4) in both the analyses of all the events and the paired events.

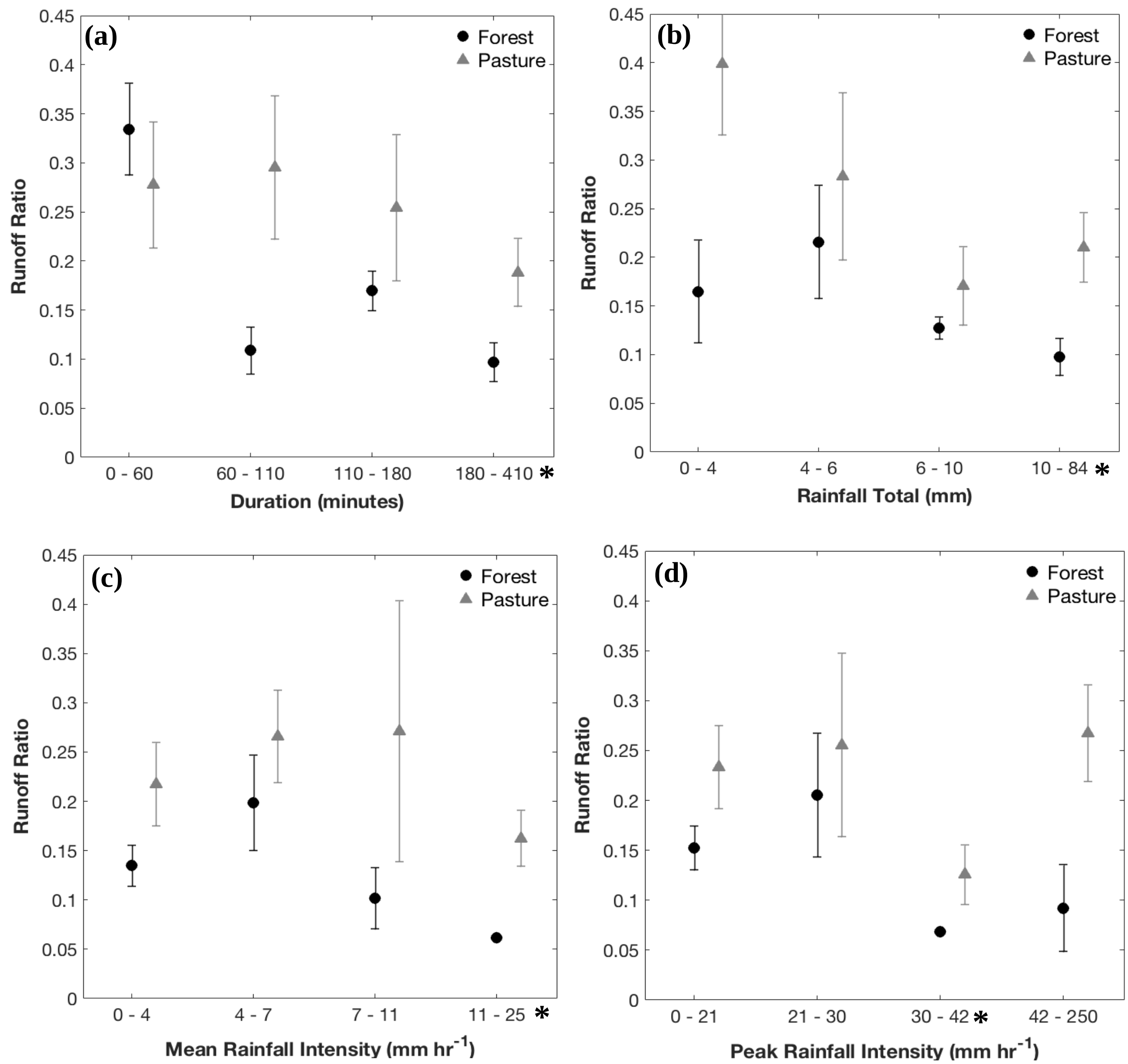

Figure 4. Runoff ratio as a function of rainfall duration *(a)*, rainfall total *(b)*, mean rainfall intensity *(c)* and peak rainfall intensity *(d)* for paired rain events. Bin edges were determined using historical Guabo Camp rainfall data. Points represent mean runoff ratio values and bars represent the standard error of the mean. Large standard error bars are attributed to natural variability and the small sample size within each bin. Asterisks indicate significant differences between forest and pasture.

3.5. HYDRUS-1D

Surface K_s values obtained while calibrating HYDRUS-1D simulated SR to observed SR varied widely between the forest and pasture sites. Calibrated surface K_s values for the forest (256 mm hr^{-1}) and pasture (30 mm hr^{-1}) sites were both lower than the geometric mean we calculated using falling head tests for each site: 390 mm hr^{-1} and 82 mm hr^{-1} for the forest and pasture, respectively (Table 7). Calibrated K_s values for forest were more similar to our geometric mean K_s values because surface runoff could not be accurately simulated for 3 of the 5 calibration events (i.e. simulated surface runoff was ~ 0 for these rain events), and the geometric mean value of 390 mm hr^{-1} was substituted as K_s for these events. Calibration K_s values for both sites fell between and the mean and median K_s values reported for depths 0-6 cm by *Hassler et al.* [2011].

Peak runoff rate, peak runoff time, runoff ratio and total runoff amounts simulated in HYDRUS-1D were compared to that of observed SR data for each of the 16 paired events (Figure 5). The visual and numerical analyses suggest different conclusions about the effectiveness of HYDRUS-1D in modeling SR in the forest and the pasture. Peak SR rates were better simulated in forest relative to pature (Root Mean Square Error (RMSE) = 11 mm hr^{-1} and 18 mm hr^{-1}, respectively)**.** However, visual comparison suggests that the pasture produced a better fit between observed and modeled data (i.e. has more points with non-zero simulated peak SR) than the forest (Figure 5a). The low RMSE for the forest may be attributed to the lower observed peak SR values, which results in small contributions to the RMSE even when no simulated SR is produced. Simulated peak SR timing in the forest also produced a lower RMSE (47 minutes) than the pasture (92 minutes). However, the pasture site had two large outliers with errors over 100 minutes (Figure 5b); when these two outliers are removed, we report a RMSE of 38 minutes at the pasture site, which better agrees with our visual comparison. Runoff ratio between observed and simulated data was similar for both forest and pasture (RMSE= 0.15 and 0.19, respectively) (Figure 5c). Both sites had large outliers (error > 0.3) which when removed produced a RMSE of 0.12 at the forest and 0.15 at the pasture. Surface runoff total also produced a better fit for the forest than the pasture (RMSE = 3 and 6 mm, respectively) (Figure 5d). However, removal of large outliers (error > 100 mm) resulted in a RMSE of 2 mm at the pasture. For each SR characteristic, the fit between observed and simulated data was better (i.e. lower RMSE) at the forest site than the pasture, but removal of large outliers resulted in lower RMSE at the pasture with the exception of runoff ratio. This agrees with the visual comparison, which typically shows that more pasture events are present near the 1:1 line in each scenario.

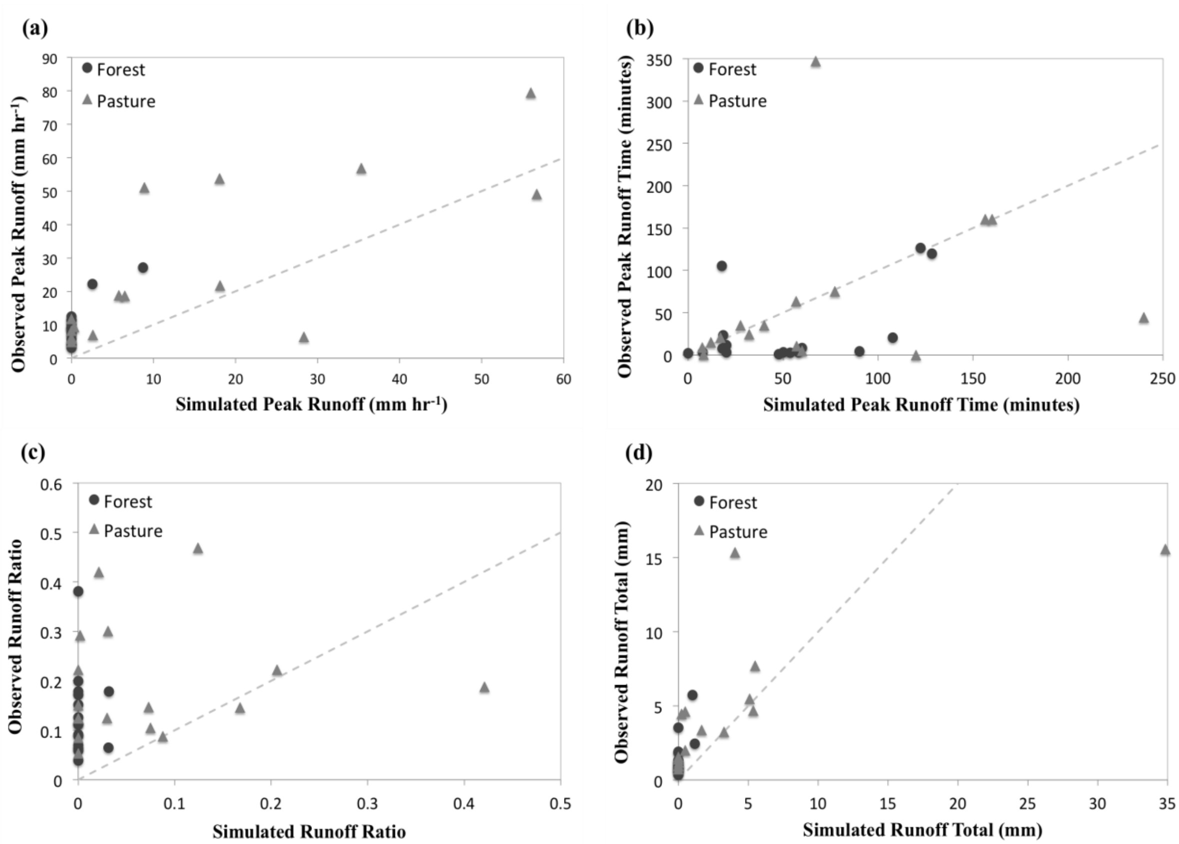

Figure 5. Simulated versus observed peak runoff *(a)*, peak runoff time *(b)*, runoff ratio *(c)* and runoff total *(d)*. Dashed lines represent a 1:1 relationship between observed and simulated data

HYDRUS-1D tended to underestimate peak runoff rate and total runoff values at both the forest and the pasture. Simulated total runoff was only greater than observed total runoff in 3 pasture events and 0 forest events. Similarly, simulated peak runoff rate only exceeded observed peak SR rate in 2 pasture events and 0 forest events. Little to no runoff could be simulated for the majority of rain events at the forest site. Additionally, when simulated peak runoff timing was not close to that of observed (within 20%), simulated peak runoff tended to occur later than that of observed peak SR. This was particularly true at the forest site: all forest events that produced surface runoff recorded a peak in runoff at the start of the rain event, which could not be simulated in HYDRUS-1D (Figure 6).

In addition to comparing observed and simulated SR characteristics, we used HYDRUS-1D outputs of soil water content to characterize soil saturation at each site during a rain event (Figure 7). These plots characterize soil saturation during rainfall events with high rainfall totals (24 mm at the forest and 23 mm at the pasture). Each plot contains saturation for five different times: one at the beginning of the event (initial conditions), two output times before and two output times after simulated peak SR. During the high rainfall total event at the forest, we observe that soil does not become saturated, indicating no simulated surface runoff during this rain event (Figure 7a). However, for the corresponding pasture site, we observe soil saturation moving from the surface to depth, indicating HOF is driving simulated surface runoff generation during this rain event, rather than SOF (Figure 7b). However, we observed SR for each rain event in Figure 7, and were able to simulate SR for the pasture event.

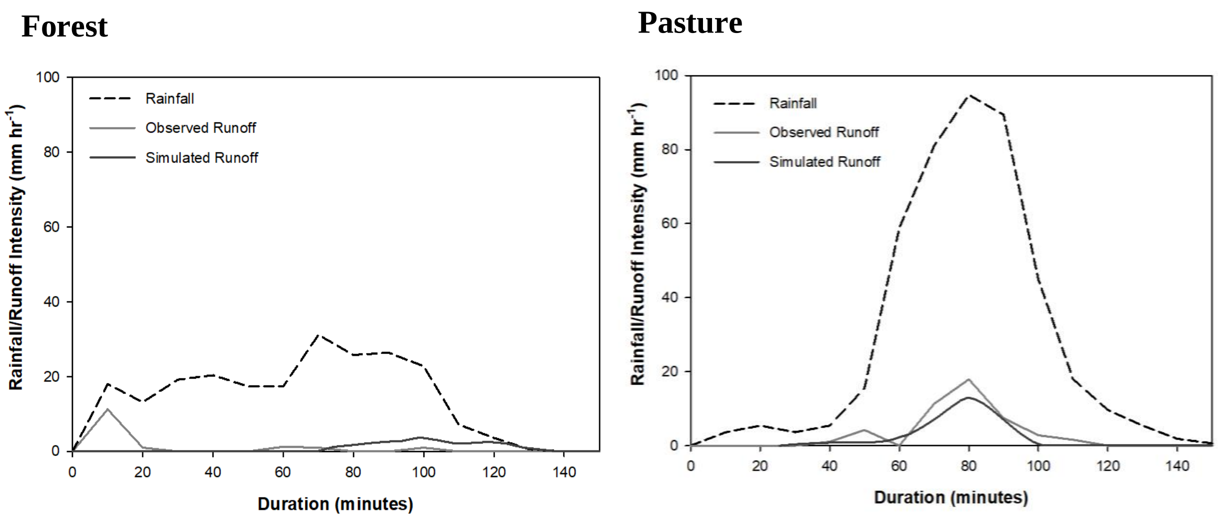

Figure 6. Observed and HYDRUS-1D simulated surface runoff for a paired rain event occurring on May 31, 2016 at approximately 2:30pm for the forest and pasture. The immediate surface runoff response observed at the forest could not be simulated in HYDRUS-1D as parameterized, while the peak surface runoff rate, peak surface runoff timing, runoff ratio and surface runoff totals matched well between observed and simulated runoff at the pasture.

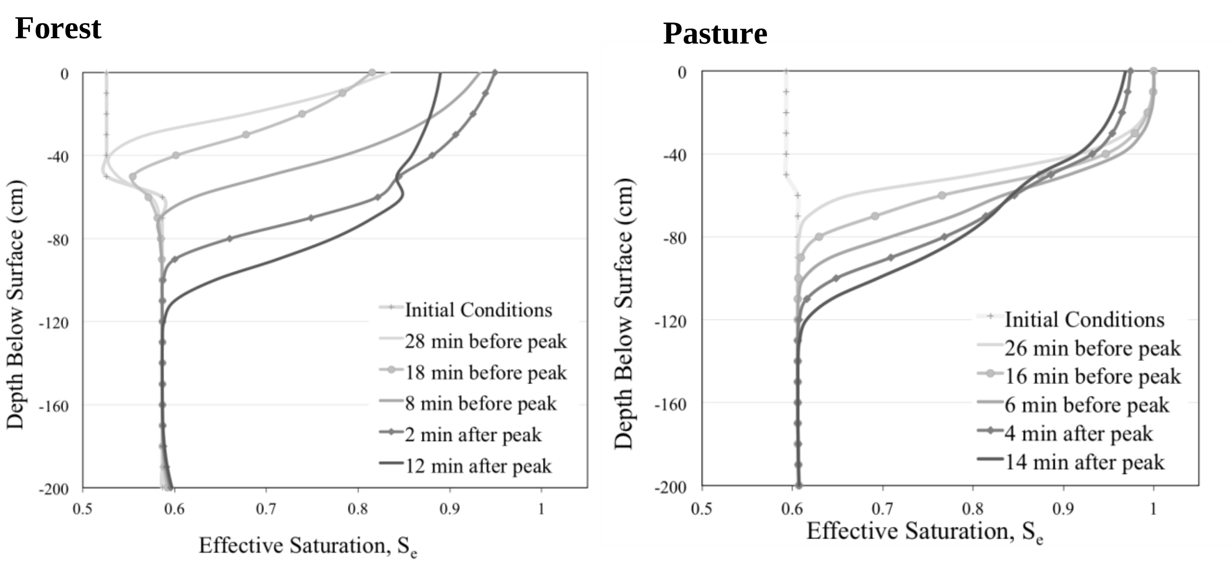

Figure 7. Simulated soil saturation plotted against depth below the soil surface for a high rainfall total event at the forest (24 mm total) and pasture (23 mm total). Time stamps are taken from before and after simulated peak surface runoff. The event from the forest occurred on June 16, 2016 at 12:45pm while the event from the pasture occurred on July 19, 2016 at 2pm. Peak rainfall intensity occurred 8 minutes before simulated peak runoff for the forest rain event (30 minutes after the start of the rain event), and 76 minutes before simulated peak runoff at the pasture (10 minutes after the start of the rain event).

4. Discussion

Land-use change has important consequences to surface runoff generation. We observed greater mean runoff ratios at the pasture site compared to the forest site. This is in line with previous studies on the impact of land-use change on the occurrence of SR in the tropics, where SR occurs twice as frequently at a pasture site compared to a forest [*Germer et al*., 2009; *de Moraes et al*., 2006]. Although we did not observe consistent differences in SR response to different rainfall characteristics, differences in runoff ratios can be explained in part by observed differences in soil physical and hydraulic properties between forest and pasture. Simulated outputs of SR and soil saturation using HYDRUS-1D can be used to augment our conceptual model of SR generation between the forest and pasture sites.

4.1. Impact of rainfall intensity, duration and amount on surface runoff

While it is generally known that different rainfall characteristics impact SR generation processes [*Dunne et al*., 1970; *Hassler et al.*, 2013; *Elsenbeer and Vertessy*, 2000; *Ziegler et al*., 2004; *Bonell and Gilmour*, 1978], we analyzed observed SR data as a function of rainfall characteristics at our field sites to determine whether different land-use types result in differing SR responses to a given rainfall characteristic. *Elsenbeer and Vertessy* [2000] present a conceptual model for hydrological flowpaths in tropical hillslopes wherein combinations of soil and rainfall characteristics can be used to determine exactly which flowpaths (i.e. vertical or lateral) are activated in response to a given rain event. For example, compacted soil surfaces have the propensity to generate HOF during high intensity rain events even with low rainfall totals [*Ziegler et al*., 2004], resulting in generally higher runoff ratios. On the other hand, longer duration events with higher rainfall totals may allow a relatively undisturbed soil surface to become saturated, resulting in SOF or return flow [*Elsenbeer and Vertessy*, 2000; *Ziegler et al*., 2004] and in some cases lower runoff ratios. Therefore, we could expect to see a surface runoff response to rainfall intensity for the majority of events in the pasture but a response at the forest during long-duration events and events with high rainfall totals.

However, our comparison of runoff ratio to rainfall duration, rainfall total, mean rainfall intensity and peak rainfall intensity did not yield any overall trends that differentiate forest versus pasture land-uses. In general, mean runoff ratio was higher at the pasture than in the forest for every comparison with the exception of short duration rainfall events. Two potential concerns for this lack of trends could be equipment failures in measuring SR as previously discussed, and the higher number of observed events in the pasture. We address these concerns by performing the same analysis on paired events, which only use valid SR data and the same number of events for forest and pasture. This analysis of paired events produces similar trends in runoff ratio to rainfall characteristics for both land covers, thereby negating these concerns. Furthermore, events in this paired data set should have exposure to similar rainfall characteristics, meaning that differences in surface runoff response are primarily a function of land-use.

4.2. Impact of soil physical and hydraulic characteristics on surface runoff

We hypothesized that patterns in SR were driven either by rainfall characteristics or by changes in soil properties related to land-use change. While rainfall characteristics did not inform differences in SR generation, measurements of physical soil properties suggest that the observed disparity in SR is driven mainly by altered soil structure. Conversion of undisturbed tropical forest to pasture has been known to alter soil properties, among them bulk density and K_s, that strongly influence the generation of surface runoff [*Alegre and Cassel*, 1996; *Hassler et al.*, 2011; *Martinez and Zinck, 2004; McDowell et al., 2003*; *de Moraes et al.*, 2006; *Ziegler et al.*, 2004; *Zimmermann et al.*, 2006; *Zimmermann and Elsenbeer*, 2008]. Land-use change alters both K_s and bulk density [*Ahuja et al*., 1984], which is inversely related to macroporosity. We observed a significantly higher bulk density and lower K_s at the pasture site, consistent with previous studies on the impact of soil compaction by trampling in pasture landscapes [*Alegre and Cassel*, 1996; *Giertz and Diekkrueger*, 2003; *Martinez and Zinck*, 2004; *McDowell et al*., 2003; *Hassler et al*., 2011]. Our measured values of K_s were within the range of values reported for 100 year old secondary forest (0 to 1,229 mm hr^{-1} at 0-6 cm, 0 to 1,033 mm hr^{-1} from 6-12 cm) and pasture (0 to 588 mm hr^{-1} at 0-6 cm, 0 to 535 mm hr^{-1} from 6-12 cm) landscapes [*Hassler et al*., 2011].

We also observed a distinct difference in K_s with depth at both sites, a trend that has important implications for the generation of SR [*Bonnell et al*., 1978; *Elsenbeer et al.*, 1992; *Malmer*, 1996; *Godsey et al*., 2004; *Ziegler et al*., 2004]. In landscapes where K_s decreases sharply with soil depth, lateral surface and near surface flowpaths will likely dominate, while a less marked decrease in K_s with depth results in vertical flowpaths to be more prevalent [*de Moraes et al*., 2006; *Godsey et al.*, 2004; *Germer et al*., 2009]. In some cases, this strong vertical decline in K_s has resulted in the formation of a perched water table, causing widespread SOF in both forested and pasture landscapes. *Hassler et al*. [2011] has observed SR at their old forest catchments with mean 0-6 cm K_s values of 349 mm hr^{-1} and 6-12 cm K_s values of 127 mm hr^{-1}, which they speculate causes the formation of a perched table during high intensity rainfall. This difference in surface and shallow surface K_S values is similar to our observed values from 390 mm hr^{-1} from 0-6 cm and 135 mm hr^{-1} taken at 10 cm depth using minidisk infiltrometers. However, VWC_{sensor} at our sites do not indicate the presence of a perched water table deeper than 10 cm depth because soil moisture sensor data did not report VWC at (or near) saturation during rain events producing surface runoff at either the forest or the pasture. Therefore, the only way there could have been a perched water table leading to SOF is if it occurred between the surface and our 10 cm soil moisture sensor. Another study conducted within the Upper Rio Chagres basin in the PCW found reduced permeability of the B horizon between 0 and 10 cm [*Hendrickx et al.*, 2005], and speculated that the formation of a shallow perched water table at this depth causes SOF throughout the wet season. However, *Litt* [2016] performed a study within the Agua Salud Watershed wherein 480 mm of simulated rainfall was applied to a 30 year old forest over the course of 3 hours, and simulated rainfall infiltrated to a depth of 1.5- 2 m with no detected surface ponding, surface runoff or lateral preferential flow path (PFP) flow. Because these two studies within similar regions of our study yielded different results in terms of the existence of an impeding soil layer, we cannot speculate as to whether or not a perched water table formed at our catchment between 0 and 10 cm.

4.3. Comparisons of observed and simulated surface runoff

We rely on the simulation of SR in HYDRUS-1D to augment our conceptual model of the impact of land-use on surface runoff generation processes. Although we were able to simulate peak SR, peak SR timing, SR ratio and SR totals in the pasture, we could not do this for the majority of forest rain events. Despite the forest having lower RMSE values than the pasture in our comparison of observed versus simulated SR characteristics, simulated SR in the forest substantially underestimated our observed forest SR. On the other hand, the pasture often produced a better qualitative comparison between simulated and observed data. We speculate that this could be a result of our inability to parameterize the upper layer of the forest within HYDRUS-1D. The upper layer is critical to the occurrence of surface runoff; land-use impacts on soil-hydraulic properties, such as K_s, are commonly confined to the uppermost soil layer (tens of cm in thickness). In the Amazon, land-use was considered irrelevant to SR generation for K_s

values below 20 cm [*Godsey and Elsenbeer*, 2002; *Zimmermann et al*., 2006] and K_s differences between forest, secondary forest and pasture were insignificant below 50 cm depths in Ecuador *[Zimmermann and Elsenbeer*, 2008].

We identify two characteristics within the upper layer that may both be inadequately represented within HYDRUS-1D. First, the assumption in HYDRUS-1D of minimal understory or litter interception is valid for our pasture site but not for our forest site. Vegetation at the pasture consisted of discontinuous grasses, while the forest had a persistent layer of leaf litter and other organic material in various stages of decay. In the field, we did not clear our forest plots of large leaves in order to most accurately capture natural infiltration-runoff processes. These large, waxy leaves might provide a hydrophobic layer at the soil surface at the start of a rain event, causing a small, brief amount of SR to form atop this leaf litter layer in the forest. The leaf litter layer could not be characterized in HYDRUS-1D and without this layer, observed SR in the forest site could not be adequately simulated. Second, the presence of shallow (i.e. within the upper layer) preferential flowpaths have been known to play a considerable role in soil infiltration characteristics in tropical forests [*Chappell*, 2010; *Litt*, 2016; *Putty and Prasad*, 2000] including within the Agua Salud Watershed [*Cheng et al*., 2017]. Studies conducted within old forests within Soberania and Chagres National Parks in Panama by *Niedzialek* [2007] and *Hendrickx et al*. [2005] respectively, observed well-developed PFPs in the form of soil pipes. These soil pipes were formed from live and decayed tree roots and animal burrows and exhibited high infiltration rates [*Bonell, 1993*; *Noguchi et al*., 1999; *Niedzialek*, 2007]. In those studies, surface runoff was observed as return flow from large diameter soil pipes [*Niedzialek*, 2007; *Hendrickx et al*., 2005]. Return flow from soil pipes has been documented as a source of SR in Amazonia and Panama [*Elsenbeer and Lack*, 1996; *Ogden et al.*, 2014, respectively]. A study in

French Guiana also observed SR generation at mid- and upper- slope locations and reported evidence of pipe flow. In Puerto Rico, *Larsen et al*. [2012] found that the exclusion of the PFPs created by earthworms nearly doubled surface runoff observations. Stallard and Murphy (2014) noted that shallow soil flowpaths helped explain the biogeochemical response of rivers on similar geology in Puerto Rico. Finally, *Gardner et al*. [2017] observed geochemical evidence of the rapid activation of shallow (< 15 cm) flow paths during rain events within an old forest and a "mosaic" catchment (i.e. possessing a combination of different land-use types) in Agua Salud. Surface runoff in the form of return or pipe flow as a result of these PFPs cannot be simulated in HYDRUS-1D as parameterized in this work. This may contribute to the inability of HYDRUS-1D to accurately model SR in the forest. The fact that we observe surface runoff in the forest during small rainfall amounts and relatively low rainfall intensities gives credibility to the idea that SR occurring atop the leaf litter layer and the activation of shallow PFPs are the main drivers of SR generation at the forest.

Another consideration for the discrepancy in simulated and observed SR is throughfall variability observed at the forest site. We know from our throughfall data and results from other studies that throughfall amounts and intensities vary spatially in tropical rainforests [*Niedzialek and Ogden*, 2012; *Park et al*., 2008; *Dykes*, 1997; *Zimmermann et al*., 2008]. Only throughfall data collected from the centrally located rain gage equipped with troughs was input into the HYDRUS-1D model. While our throughfall troughs were approximately 2 m long, we found from our throughfall collection during the following field season that the rainfall measured at our rain gage could have varied widely from throughfall falling directly on our runoff plots. Despite this observation in throughfall variability, surface runoff among the three plots at the forest site was relatively similar both in magnitude and frequency of response. For the majority of rain events, either two or three of the level loggers recorded similar runoff response, and no single hillslope position consistently recorded more or less surface runoff compared to other hillslope positions. Thus, throughfall variability is not likely a large contributer to the mismatch between our simulated data to our observed data for the forest site.

4.4. Simulated soil moisture

Analyzing simulated soil moisture saturation with depth helps inform our interpretation of which SR generation processes may occur at forest and pasture sites. Figure 7b indicates HOF occurs at the pasture site, similar to previous studies [*de Moraes et al*., 2006; *Germer et al.*, 2009]. This is consistent with our observation of reduced K_s values near the surface resulting from cattle trampling. Soil saturation with depth at the forest, however, does not definitively suggest HOF or SOF (Figure 7a). A possible explanation for the observed SR at the forest could be the formation of an impeding soil layer, resulting in shallow subsurface flow. The slope of the plot could result in the "pinching out" of subsurface flow lower along the hillslope. HYDRUS-1D solves the vertical form of Richard's equation, so if convergence in lateral subsurface flow is driving a perched water table to the near surface, acting as the main driver for SOF generation in this landscape, then the HYDRUS-1D simulations in this work will not provide insight into that process. Despite this limitation, the simulated soil moisture data agrees with our observed VWC_{sensor} data in that deeper soil layers do not become saturated during a rain event. This suggests that SOF is not occurring at our forest site. Another line of evidence suggesting that SOF is not occurring at our forest site as a result of the presence of an impeding layer is the timing of SR: we observe a peak of SR occurring promptly at the start of the rain event with little to none recorded thereafter. We speculate that a portion of our observed forest SR may result from the leaf litter layer present on the forest floor. Shallow PFPs (i.e. from 0-10 cm) could also be activated at the immediate start of rainfall [*Gardner et al*., 2017], becoming connected in saturated flow lines similar to that observed in *Zimmermann et al*. [2014]. It is known that water flow through PFPs in tropical soils cannot be modeled using soil texture properties alone [*Hendrickx and Flury*, 2001] and neither the leaf litter layer nor the shallow PFPs are characterized in HYDRUS-1D as parameterized. In a modeling study on the impact of PFPs on SR generation in Agua Salud, *Cheng et al*. [2017] found that of four differing model structures, the one that explicitly simulated PFPs performed best in matching simulated and observed hydrograph outputs. Therefore, HYDRUS-1D as used in this study is useful for exploring SR generation processes at the pasture, but results for the forest have limitations

4.5. Comparison of observed SR with observations based on stream discharge

In Agua Salud, runoff response to rainfall at the watershed scale, described by *Ogden et al*. [2013], differs from what we see at the plot scale described here. A key parameter to compare with 'runoff ratio' of the present paper is 'runoff efficiency' in Figure 7 and Table 9 of *Ogden et al*. [2013]. Runoff efficiency is defined as the ratio of direct runoff for a rain event to the rainfall of that event. Direct runoff is calculated by integrating the runoff associated with the rapid rise and fall of the hydrograph following a storm, and is assumed to be water that rapidly gets into the channel. This would include macropore and pipe flow as well as SR. Accordingly, runoff efficiency should be greater than the runoff ratio. For smaller events in *Ogden et al*. [2013], runoff efficiency is considerably less than runoff ratio. For the largest rain events in *Ogden et al*. [2013] (rainfall totals from 100-316 mm) runoff efficiency is similar to the runoff ratio in forests or exceeds runoff ratio in pasture. This suggests that water associated with SR in smaller events (< 100 mm), and perhaps most events, does not travel down entire hillslopes into the flowing stream network where it would affect the hydrograph. Moreover, this smaller-event SR water must not enter macropore or pipeflow to be fed into the stream network, otherwise the runoff efficiencies would be greater.

5. Conclusions

Our study illustrates fundamental differences in the timing, frequency and amount of surface runoff generation between a Panamanian forest and cattle pasture at scale on the order of a meter. The mean ratio of surface runoff to rainfall (runoff ratios) were significantly higher at the pasture than the forest for all rain events occurring during our field season in Summer 2016. Although we did not observe distinct trends in surface runoff response to rainfall characteristics, soil physical and hydraulic properties were significantly different between forest and pasture. Forest landscapes are generally more complex, characterized by the presence of a leaf-litter layer, a shallow bioturbation layer, and macropores of variable size, all of which influence infiltration capacity. Compared to pasture, forest soils are associated with higher rates of infiltration and greater hydraulic conductivities [*de Moraes et al., 2006; Zimmermann et al*., 2006; *Martinez and Zincke*, 2004]. Consequently, an increase in the frequency and volume of SR is observed at pasture catchments while lower rates of SR are observed at forested catchments [*Germer et al*., 2009; *de Moraes et al*., 2006; *Ziegler et al*., 2004; *Zimmermann et al.*, 2006].

Differences in observed and simulated SR help inform differences in SR generation processes between our forest and pasture sites. Surface runoff varies with land-use [*Germer et al*., 2009; *Zimmermann et al*., 2006] and is typically characterized as SOF in forested landscapes, while a combination of SOF and/or HOF have been observed in pasture landscapes [*de Moraes et al.*, 2006; *Germer et al*., 2009; *Zimmermann et al*., 2006]. Observed and simulated SR suggest HOF is the dominant driver of SR generation at the pasture. However, the process of SR generation at our forest site remains unclear. While it is possible that the sharp decline in K_s

values could cause the formation of a shallow perched water table, we observe an immediate SR response to rainfall at the forest site, indicating SOF is not the driver of SR at the forest. Rather, this suggests that the combination of a leaf litter layer that allows for rapid SR response, combined with the activation of shallow PFPs is the cause of SR generation at our forest site.

Although our results indicate greater SR at the pasture over the forest, these measurements were collected at 3 plots along two hillslopes. Hillslope SR generation in both tropical and temperate climates is highly spatially and temporally variable [*Wood et al*., 1986; *Sidle et al*., 2000; *Godsey et al*., 2004]. Controls on surface runoff like surface topography [*McDonnell et al*., 1998], throughfall amounts and intensities [*Dykes*, 1997; *Zimmermann et al*., 2008], surface roughness [*Martin et al*., 2008] and return flow from pipe openings [*Elsenbeer and Lack*, 1996; *Chappell and Sherlock*, 2005] are all highly spatially variable, particularly in tropical rainforests. The occurrence and transfer of SR is spatially variable and the order of magnitude of infiltration and SR in small plots is not always the same as in hillslopes or catchments [*Gomi et al*., 2008; *Sivapalan and Wood*, 1986; *Parsons et al*., 2004]. Therefore, plot-scale measurements of SR and soil hydraulic properties may result in shortcomings when scaling up to hillslope and catchment processes, and vice versa, because of plot-scale infiltration rate variability across a hillslope [*Brooks et al*., 2004]. An example of the complexity involved in generalizing these measurements lies within our own dataset: K_s is highly spatially variable, and K_s measured with small diameter minidisks does not accurately capture this variability when averaged across the area of the difference infiltrometer plot. This is particularly important when accurately characterizing HOF at the pasture site. With reduced K_s, one might expect that increased rainfall intensity would correspond to increased HOF surface runoff response. However, this is not the trend we observe at our pasture site: runoff ratios did not increase with increased rainfall intensity, indicating that increasing rainfall rates do not generate much additionall runoff. This can be explained by possible run-on phenomena wherein patches of soil with high K_s infiltrate excess rainfall, effectively cancelling out runoff produced by patches of soil with low K_s, preventing large amounts of HOF even during high rainfall intensities. Thus, it is questionable as to how these plot-scale measurements of SR translate to catchment scale differences between these different land-use types, particularly in terms of impacts to streamflow. However, our results support a growing body of evidence that suggests that land-use is a significant driver of SR generation, and thus has the potential to have catchment-scale implications for freshwater provisioning.

The observation that high runoff ratios at the plot scale, described here, are not reflected by high runoff efficiencies at the watershed scale by *Ogden et al*. [2013] suggests that much SR fails to make it to the stream channel. *McDonnell* [2013] suggests a number of mechanisms by which this would happen. It is likely that surface runoff measured at the plot scale is infiltrating in areas of greater permeability, whether it be due to higher K_s or denser areas of macropores and pipe flow, and not becoming connected at the hillslope or watershed scale.

Understanding the delivery of freshwater to streams, both in terms of timing and quantity, requires precise modeling to fully capture the effects of land-use change on SR generation. As this work demonstrates, these models must account for a variety of SR generation mechanisms including ground cover or vegetation characteristics (i.e. leaf litter variability in forests), the activation of PFPs and subsurface flow to accurately capture these complex processes. The ability to model freshwater delivery is of growing importance. The Panama Canal lock system requires an average of 52 million gallons of freshwater per transit, all of which is sourced from within the PCW [*Knight*, 2008; *Salin*, 2010]. In the PCW and the tropics in general, growing water scarcity will exacerbate demands on freshwater resources. Enhancing our understanding of SR in the tropics will be of vital importance in mitigating these challenges.

Bibliography

Achard, F., Eva, H., Mayaux, P., 2002. Tropical forest mapping from coarse spatial resolution satellite data: Production and accuracy assessment issues. Int. J. Remote Sens. 22, 2741–2762. https://doi.org/10.1080/01431160120548

Ahuja, L.R., Naney, J.W., Green, R.E., Nielsen, D.R., 1984. Macroporosity to Characterize Spatial Variability of Hydraulic Conductivity and Effects of Land Management1. Soil Sci. Soc. Am. J. 48, 699. https://doi.org/10.2136/sssaj1984.03615995004800040001x

Albrecht L, Stallard RF, Kalko EKV., 2017. Land use history and population dynamics of free-standing figs in a maturing forest. PLoS ONE 12(5): e0177060. https://doi.org/10.1371/journal.pone.0177060

Alegre, J.C., Cassel, D.K., 1996. Dynamics of soil physical properties under alternative systems to slash-and-burn. Agric. Ecosyst. Environ. 58, 39–48. https://doi.org/10.1016/0167-8809(95)00654-0

Autoridad del Canal de Panama (ACP)., 2006. Manual de Reforestacion, Division de Administracion Ambiental Seccion de Manejo de Cuenca. [Available at https://micanaldepanama.com/wp-content/uploads/2012/ 06/manual-de-reforestacion.pdf.]

Autoridad del Canal de Panama (ACP)., 2010. Annual Report of the Panama Canal Authority. [Available at http://www.pancanal.com/eng/gen eral/reporte-anual/2010/flash.html#/1/.] Autoridad

Biggs, T.W., Dunne, T., Muraoka, T., 2006. Transport of water, solutes and nutrients from a pasture hillslope, southwestern Brazilian Amazon. Hydrol. Process. 20, 2527–2547. https://doi.org/10.1002/hyp.6214

Bonell, M., 1993. Progress in the understanding of runoff generation dynamics in forests. J. Hydrol. 150, 217–275. https://doi.org/10.1016/0022-1694(93)90112-M

Bonell, M., Eds, L.A.B., 2005. Tropical Forest Management to Sustain Water and Civilization Forests , Water & People in the Humid Tropics : Past , Present and Future Hydrological Research for Integrated Land and Water Management Reviewer :, Water Management. Cambridge University Press. https://doi.org/10.1002/hyp.5882

Bonell, M., Gilmour, D.A., 1978. The development of overland flow in a tropical rainforest catchment. J. Hydrol. 39, 365–382. https://doi.org/10.1016/0022-1694(78)90012-4

Brooks, E.S., Boll, J., Martin, J.W., Mcdaniel, P.A., 2004. A hillslope-scale experiment to measure lateral saturated hydraulic conductivity. Water Resour. Res 40. https://doi.org/10.1029/2003WR002858

Brown, A.E., Zhang, L., Mcmahon, T.A., Western, A.W., Vertessy, R.A., 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. J. Hydrol. 310, 28–61. https://doi.org/10.1016/j.jhydrol.2004.12.010

Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? Agric. Ecosyst. Environ. 104, 185–228. https://doi.org/10.1016/J.AGEE.2004.01.015

Chappell, N.A., 2010. Soil pipe distribution and hydrological functioning within the humid tropics: a synthesis. Hydrol. Process. 24, 1567–1581. https://doi.org/10.1002/hyp.7579

Chappell, N.A., Sherlock, M.D., 2005. Contrasting flow pathways within tropical forest slopes of Ultisol soils. Earth Surf. Process. Landforms 30, 735–753. https://doi.org/10.1002/esp.1173

Chaves, J., Neill, C., Germer, S., Neto, S.G., Krusche, A., Elsenbeer, H., 2008. Land management impacts on runoff sources in small Amazon watersheds. Hydrol. Process. 22, 1766–1775. https://doi.org/10.1002/hyp.6803

Cheng, Y., Ogden, F.L., Zhu, J., 2017. Earthworms and tree roots: A model study of the effect of preferential flow paths on runoff generation and groundwater recharge in steep, saprolitic, tropical lowland catchments. Water Resour. Res. 53, 5400–5419. https://doi.org/10.1002/2016WR020258

Cherrey, K.D., Flury, M., Harsh, J.B., Flury, M., Harsh, J.B., 2003. Nitrate and colloid transport through coarse Hanford sediments under steady state, variably saturated flow. Water Resour. Res 39. https://doi.org/10.1029/2002WR001944

Chow, V.T., Maidment, D.R., Mays, L.W., 1968. Applied hydrology, Journal of Hydrology. McGraw Hill. https://doi.org/10.1016/0022-1694(68)90169-8

Costa, M. H. (2005), Large-scale hydrological impacts of tropical forest conversion, in Forest, Water and People in the Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management, edited by M. Bonell and L. Bruijnzeel, pp. 590–597, UNESCO, Cambridge Univ. Press, Cambridge. https://doi.org/10.1017/CBO9780511535666

Devices, Decagon., 2015. GS1 Soil Moisture Sensor Operator's Manual. Decagon Devices. Pullman, WA

Devices, Decagon. 2012. Minidisk Infiltrometer User's Manual Version 10. Decagon Devices. Pullman, WA.

de Moraes, J.M., Schuler, A.E., Dunne, T., Figueiredo, R. de O., Victoria, R.L., 2006. Water storage and runoff processes in plinthic soils under forest and pasture in eastern Amazonia. Hydrol. Process. 20, 2509–2526. https://doi.org/10.1002/hyp.6213

Dingman, SL, 2002, Physical Hydrology, Prentice-Hall, Inc., Upper Saddle River, NJ.

Dunne, T., Black, R.D., 1970. Partial Area Contributions to Storm Runoff in a Small New England Watershed. Water Resour. Res. 6, 1296–1311. https://doi.org/10.1029/WR006i005p01296

Dykes, A.P., 1997. Rainfall interception from a lowland tropical rainforest in Brunei. J. Hydrol. 200, 260–279. https://doi.org/10.1016/S0022-1694(97)00023-1

Eddy, J., Humphreys, G.., Hart, D.., Mitchell, P.., Fanning, P.., 1999. Vegetation arcs and litter dams: similarities and differences. CATENA 37, 57–73. https://doi.org/10.1016/S0341-8162(98)00055-1

Elsenbeer, H., 2001. Hydrologic flowpaths in tropical rainforest soilscapes-A review. Hydrol. Process. 15, 1751–1759. https://doi.org/10.1002/hyp.237

Elsenbeer, H., Cassel, K., Castro, J., 1992. Spatial analysis of soil hydraulic conductivity in a tropical rain forest catchment. Water Resour. Res. 28, 3201–3214. https://doi.org/10.1029/92WR01762

Elsenbeer, H., Lack, A., 1996. Hydrometric and hydrochemical evidence for fast flowpaths at La Cuenca, Western Amazonia. J. Hydrol. 180, 237–250.

Elsenbeer, H., Vertessy, R.A., 2000. Stormflow generation and flowpath characteristics in an Amazonian rainforest catchment. Hydrol. Process. 14, 2367–2381. https://doi.org/10.1002/1099-1085(20001015)14:14<2367::AID-HYP107>3.0.CO;2-H

Gardner, C.B., Litt, G.F., Lyons, W.B., Ogden, F.L., 2017. Evidence for the Activation of Shallow Preferential Flow Paths in a Tropical Panama Watershed Using Germanium and Silicon. Water Resour. Res. 53, 8533–8553. https://doi.org/10.1002/2017WR020429

Germer, S., Neill, C., Krusche, A. V., Elsenbeer, H., 2010. Influence of land-use change on near-surface hydrological processes: Undisturbed forest to pasture. J. Hydrol. 380, 473–480. https://doi.org/10.1016/j.jhydrol.2009.11.022

Giertz, S., Diekk, B., Steup, G., 2006. Physically-based modelling of hydrological processes in a tropical headwater catchment (West Africa) – process representation and multi-criteria validation. Hydrol. Earth Syst. Sci 10, 829–847.

Godsey, S., Elsenbeer, H., 2002. The soil hydrologic response to forest regrowth: a case study from southwestern Amazonia. Hydrol. Process. 16, 1519–1522. https://doi.org/10.1002/hyp.605

Godsey, S., Elsenbeer, H., Stallard, R., 2004. Overland flow generation in two lithologically distinct rainforest catchments. J. Hydrol. 295, 276–290. https://doi.org/10.1016/j.jhydrol.2004.03.014

Gomi, T., Sidle, R.C., Ueno, M., Miyata, S., Kosugi, K., 2008. Characteristics of overland flow generation on steep forested hillslopes of central Japan. J. Hydrol. 361, 275–290. https://doi.org/10.1016/J.JHYDROL.2008.07.045

Haßler, S.K., 2013. Saturated hydraulic conductivity in the humid tropics : Sources of variability, implications for monitoring and effects on near-surface hydrological flow paths. University of Potsdam PhD Dissertation.

Hassler, S.K., Zimmermann, B., van Breugel, M., Hall, J.S., Elsenbeer, H., 2011. Recovery of saturated hydraulic conductivity under secondary succession on former pasture in the humid tropics. For. Ecol. Manage. 261, 1634–1642. https://doi.org/10.1016/j.foreco.2010.06.031

Hendrickx, J. M. H., and Flury, M., 2001. Uniform and preferential flow mechanisms in the vadose zone, in Conceptual Models of Flow and Transport in the Fractured Vadose Zone. Edited by P. A. Hsieh. 149–187, National Academy Press, Washington, D. C., https://doi.org/10.17226/10102

Hendrickx, J. M. H., D. Vega, J. B. J. Harrison, L. E. Calvo-Gobbetti, P. Rojas, and T. W. Miller, 2005. Hydrology of hillslope soils in the Upper Rio Chagres watershed, Panama: A Multidisciplinary Profile of a Tropical Watershed. Edited by R. S. Harmon. 113–138, Springer, Dordrecht, Netherlands.

Holwerda, F., Scatena, F.N., and Bruijnzeel, L.A., 2006. Puerto Rican lower montane rain forest: A comparison of sampling strategies. J. Hydrol. 327, 592-602.

Jansson, M., Stromberg, K., 2004. Surface runoff and soil loss in tropical rainforest and pasture, Costa Rica, and indices explaining their variation. Zeitschrift für Geomorphologie. 48, 25–51.

Johnson, M.S., Lehmann, A.J., Couto, E.G., Filho, J.P.N., Riha, S.J., Johnson, M.S., Lehmann, J., Guimarã, E., Joã, C., Novã, P., Ae, F., Riha, S.J., 2006. DOC and DIC in flowpaths of Amazonian headwater catchments with hydrologically contrasting soils. Biogeochemistry 81, 45–57. https://doi.org/10.1007/s10533-006-9029-3

Keim, R.F., Skaugset, A.E., Weiler, M., 2005. Temporal persistence of spatial patterns in throughfall. J. Hydrol. 314, 263–274. https://doi.org/10.1016/J.JHYDROL.2005.03.021

Kirkby, M., Callan, J., Weyman, D., Wood, J., 1976. Measurement and modelling of dynamic contributing areas in very small catchments. Working Paper No. 167, School of Geography University of Leeds, Leeds, 39 pp þ 18 fig

Kolmogorov, A. 1933. “Sulla Determinazione Empirica di una Legge di Distributione”. *Giornale dell'Istituto Italiano degli Attuari*. 4, 1–11.

Lal, R., 1996. Deforestation and land-use effects on soil degradation and rehabilitation in western Nigeria. I. Soil physical and hydrological properties. L. Degrad. Dev. 7, 19–45. https://doi.org/10.1002/(SICI)1099-145X(199603)7:1<19::AID-LDR212>3.0.CO;2-M

Larsen MC, Liu Z, Zou X., 2012. Effects of earthworms on slope wash, surface runoff, and fine-litter transport on a humid tropical forested hillslope, Luquillo experimental forest, Puerto Rico. In: Murphy SF, Stallard RF (eds) Water quality and landscape processes of four watersheds in eastern Puerto Rico: US Geol Surv Prof Pap. 1789- G:179–197.

Lesack, L.F.W., 1993. Water balance and hydrologic characteristics of a rain forest catchment in the Central Amazon Basin. Water Resour. Res. 29, 759–773. https://doi.org/10.1029/92WR02371

Litt, G. F., 2016. Hydrometric, hydrochemical, and hydrogeophysical runoff characterization across multiple land covers in the Agua Salud Project, Panama. University of Wyoming PhD Dissertation.

Lloyd, C.R. & Marques, A.O., 1988. Spatial variability of throughfall and stemflow measurements in Amazonian rainforest. Agric. For. Meteorol. 42, 63-73.

Malmer, A., 1996. Observations on slope processes in a tropical rain forest environment before and after forest plantation establishment. In: Anderson, M.G., Brooks, S.M. (Eds.), Advances in Hillslope Processes. Wiley, Chichester, pp. 961–974.

Martin, Y., Valeo, C., Tait, M., 2008. Centimetre-scale digital representations of terrain and impacts on depression storage and runoff. Catena 75, 223–233. https://doi.org/10.1016/j.catena.2008.07.005

Martinez, L. J. & Zinck, J. A., 2004. Temporal variation of soil compaction and deterioration of soil quality in pasture areas of Colombian Amazonia, Soil & Tillage Research. 75, 3– 1.

McDowell, R.W., Drewry, J.J., Muirhead, R.W., Paton, R.J., 2003. Cattle treading and phosphorus and sediment loss in overland flow from grazed cropland. Aust. J. Soil Res. 41, 1521. https://doi.org/10.1071/SR03042

McDonnell, J.J, 2013, Are all runoff processes the same? Hydrol. Process. 27, 4103–4111. http://doi.org/10.1002/hyp.10076

McDonnell, J., Brammer, D., Kendall, C., Hjerdt, N., Rowe, L., Stewart, M., Woods, R., 1998. Flow pathways on steep forested hillslopes: the tracer, tensiometer and trough approach. Environ. Forest Sci. 54, 463–474.

Moody, J.A., Ebel, B.A., 2012. Difference infiltrometer: a method to measure temporally variable infiltration rates during rainstorms. Hydrol. Process. 26, 3312–3318. https://doi.org/10.1002/hyp.9424

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12, 513–522. https://doi.org/10.1029/WR012i003p00513

Neumann-Cosel, L., Zimmermann, B., Hall, J.S., van Breugel, M., Elsenbeer, H., 2011. Soil carbon dynamics under young tropical secondary forests on former pastures-A case study from Panama. For. Ecol. Manage. 261, 1625–1633. https://doi.org/10.1016/j.foreco.2010.07.023

Niedzialek, J.M., 2007. Unusual hydrograph characteristics, upper Rio Chagres, Panama. PhD dissertation, Dep. of Civ. and Environ. Eng., Univ. of Conn., Storrs.

Niedzialek, J.M., Ogden, F.L., 2012. First-order catchment mass balance during the wet season in the Panama Canal Watershed. J. Hydrol. 462–463, 77–86. https://doi.org/10.1016/j.jhydrol.2010.07.044

Nimmo, J.R., Schmidt, K.M., Perkins, K.S., Stock, J.D., 2009. Rapid Measurement of Field-Saturated Hydraulic Conductivity for Areal Characterization. Vadose Zo. J. 8, 142. https://doi.org/10.2136/vzj2007.0159

Noguchi, S., Tsuboyama, Y., Sidle, R.C., Hosoda, I., 1999. Morphological Characteristics of Macropores and the Distribution of Preferential Flow Pathways in a Forested Slope Segment. Soil Sci. Soc. Am. J. 63, 1413. https://doi.org/10.2136/sssaj1999.6351413x

Ogden, F.L., Crouch, T.D., Stallard, R.F., Hall, J.S., 2013. Effect of land cover and use on dry season river runoff, runoff efficiency, and peak storm runoff in the seasonal tropics of Central Panama. Water Resour. Res. 49, 8443–8462. https://doi.org/10.1002/2013WR013956

Ogden, F.L., Mojica, A., Kempema, E.W., Briceno, J.C., Regina, J.A., 2014. Diagnosing Hydrologic Flow Paths in Forest and Pasture Land Uses within the Panama Canal Watershed Using Simulated Rainfall and Electrical Resistivity Tomography. Am. Geophys. Union, Fall Meet. 2014, Abstr. #H21F-0795.

Parsons, A.J., Wainwright, J., Mark Powell, D., Kaduk, J., Brazier, R.E., 2004. A conceptual model for determining soil erosion by water. Earth Surf. Process. Landforms 29, 1293–1302. https://doi.org/10.1002/esp.1096

Proyecto de Monitoreo de la Cuenca del Canal de Panama (PMCC), 1999. Cuenca experimental del rio Agua Salud,.Chapter II.3. Informe Final del Proyecto de Monitoreo de la Cuenca del Canal de Panama. 671, 33. Smithsonian Tropical Research Institute. Balboa, Panama (available from Smithsonian Institution Library).

Putty, M.R.Y., Prasad, R., 2000. Runoff processes in headwater catchments—an experimental study in Western Ghats, South India. J. Hydrol. 235, 63–71.

Roose, E.J., 1979. Dynamique actuelle d'un sol ferrallitique très désaturé sur sédiments argilo-sableux sous culture et sous forêt dense humide subéquatoriale du sud de la Côte d'Ivoire Adiopodoumé: 1964 à 1976.

Sidle, R.C., Tsuboyama, Y., Noguchi, S., Hosoda, I., Fujieda, M., Shimizu, T., 2000. Stormflow generation in steep forested headwaters: a linked hydrogeomorphic paradigm. Hydrol. Process. 369–385.

Šimůnek, J., van Genuchten, M.T., Šejna, M., 2008. Development and Applications of the HYDRUS and STANMOD Software Packages and Related Codes. Vadose Zo. J. 7, 587. https://doi.org/10.2136/vzj2007.0077

Sivapalan, M., and E. F. Wood., 1986. Spatial heterogeneity and scale in the infiltration response of catchments. Scale Problems in Hydrology. Water Sci. Technol. Libr. Vol. 6. Edited by K. V. Gupita, I. Rodriguez- Iturbe, and E. F. Wood, pp. 81–106. D. Reidel, Dordrecht, Netherlands

Smirnov, N. 1948. "Table for Estimating the Goodness of Fit of Empirical Distributions". *Annals of Mathematical Statistics*. 19, 279–281

Stallard, R.F., and Murphy, S.F., 2014. A unified assessment of hydrologic and biogeochemical responses in research watersheds in eastern Puerto Rico using runoff–concentration relations. Aquatic Geochemistry. 20, 115-139. https://doi.org/10.1007/s10498-013-9216-5

Stallard, R. F., F. L. Ogden, H. Elsenbeer, and J. S. Hall. 2010. Panama Canal Watershed Experiment: Agua Salud Project. Water Resour. Impact. 12, 17–20.

Turner, B.L., Engelbrecht, B.M.J., 2011. Soil organic phosphorus in lowland tropical rain forests. Biogeochemistry. 103, 297–315. https://doi.org/10.1007/s10533-010-9466-x

van Genuchten, M., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soil. Soil Sci. Soc. Am. 44, 892–898.

van Genuchten MT, Leij FJ, Yates SR. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils, EPA/600/2091/ 065, Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Ada, Oklahoma.

Vandervaere, J.-P., Vauclin, M., Elrick, D.E., 2000. Transient Flow from Tension Infiltrometers: I. The Two-Parameter Equation. Soil Sci. Soc. Am. 64, 1272–1284.

Weber, D., and J. S. Hall. 2009. Resumen del Proyecto Agua Salud: Enero 2008-Julio del 2009.

Wierda, A., Veen, A.W.L., Hutjes, R.W.A., 1989. Infiltration at the Tai rain forest (Ivory Coast): Measurements and modelling. Hydrol. Process. 3, 371–382. https://doi.org/10.1002/hyp.3360030408

Williams, M.R., Fisher, T.R., Melack, J.M., 1997. Solute dynamics in soil water and groundwater in a central Amazon catchment undergoing deforestation. Biogeochemistry 38, 303–335. https://doi.org/10.1023/A:1005801303639

Windsor, D.M., 1990. Climate and moisture variability in a tropical forest : long-term records from Barro Colorado Island, PanamÃ¡. Smithson. Contrib. to Earth Sci. 29, 1–145. https://doi.org/10.5479/si.00810274.29.1

Wohl, E., Barros, a., Brunsell, N., Chappell, N. a., Coe, M., Giambelluca, T., Goldsmith, S., Harmon, R., Hendrickx, J., Juvik, J., McDonnell, J.J., Ogden, F., 2012. The hydrology of the humid tropics. Nat. Publ. Gr. 2, 655–662. https://doi.org/10.1038/nclimate1556

Wood, E., Sivapalan, M., Beven, K.J., 1986. Scale effects in infiltration and runoff production. IAHS Publ. 156, 375-387.

Ziegler, A. D., Giambelluca, T. W., Tran, L. T., Vana, T. T., Nullet, M. A., Fox, J., Vien, T. D., Pinthong, J., Maxwell, J. F. & Evett, S. 2004. Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: evidence of accelerated overland flow generation. Journal Of Hydrology. 287, 124–146.

Zimmermann, A., B. Zimmermann, and H. Elsenbeer., 2009. Rainfall redistribution in a tropical forest: Spatial and temporal patterns. Water Resour. Res. 45, W11413. https://doi.org/10.1029/2008WR007470

Zimmermann, Beate, Zimmermann, Alexander, Turner, Benjamin L., Francke, Till, Elsenbeer, H., 2014. Connectivity of overland flow by drainage network expansion in a rain forest catchment. Water Resour. Res. 2108–2123. https://doi.org/10.1002/2012WR013085

Zimmermann, A., Francke, T., Elsenbeer, H., 2012. Forests and erosion: Insights from a study of suspended-sediment dynamics in an overland flow-prone rainforest catchment. J. Hydrol. 428–429, 170–181. https://doi.org/10.1016/j.jhydrol.2012.01.039

Zimmermann, A., Schinn, D.S., Francke, T., Elsenbeer, H., Zimmermann, B., 2013. Uncovering patterns of near-surface saturated hydraulic conductivity in an overland flow-controlled landscape. Geoderma 195–196, 1–11. https://doi.org/10.1016/j.geoderma.2012.11.002

Zimmermann, B., Elsenbeer, H., 2008. Spatial and temporal variability of soil saturated hydraulic conductivity in gradients of disturbance. J. Hydrol. 361, 78–95. https://doi.org/10.1016/j.jhydrol.2008.07.027

Zimmermann, B., Elsenbeer, H., De Moraes, J.M., 2006. The influence of land-use changes on soil hydraulic properties: Implications for runoff generation. For. Ecol. Manage. 222, 29–38. https://doi.org/10.1016/j.foreco.2005.10.070