Modeled forest conversion influences humid tropical watershed hydrology more than projected climate change

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December 5, 2021

Abstract

In the humid tropics, forest conversion and climate change threaten the hydrological function and stationarity of watersheds, particularly in steep terrain. As climate change intensifies, shifting precipitation patterns and expanding agricultural and pastoral land use may effectively reduce the resilience of headwater catchments. Compounding this problem is the limited long-term monitoring in developing countries for planning in an uncertain future. In this paper, we asked which change, climate or land use, more greatly affects stream discharge in humid tropical mountain watersheds? To answer this question, we used the process-based, spatially distributed Soil Moisture Routing model. After first evaluating model performance ($N_s = 0.73$), we conducted a global sensitivity analysis to identify the model parameters that most strongly influence simulated watershed discharge. In particular, peak flows are most influenced by input model parameters that represent baseflow and shallow subsurface soil pathways while low flows are most sensitive to antecedent moisture, macropore hydraulic conductivity, soil depth and porosity parameters. We then simulated a range of land use and climate scenarios in three mountain watersheds of central Costa Rica. Our results show that deforestation influences streamflow more than altered precipitation and temperature patterns through changes in first-order hydrologic hillslope processes. However, forest conversion coupled with intensifying precipitation events amplifies hydrological extremes, reducing the hydrological resilience to predicted climate shifts in mountain watersheds of the humid tropics. This finding suggests that reforestation can help mitigate the effects of climate change on streamflow dynamics in the tropics including impacts to water availability, flood pulses, channel geomorphology and aquatic habitat associated with altered flow regimes.

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Table 1. Watershed Characteristics

Watershed	Drainage Area	Elevation Range	Max Slope	Median Slope	Altered Land Cover
Gato	3,340 ha	755-2,355 m	58°	31°	<0.1%
Atirro	3,249 ha	780-1,980 m	60°	26°	2.5%
Platanillo	2,595 ha	700-1,940 m	56°	24°	41.0%

Table 2. Input Parameters for Soil Moisture Routing Model

SMR Input Parameter	Source	Value
Precipitation (not in GSA)	Meteorological station data (ICE), Climate models (Solomon (2007), Stocker (2014))	See Figure 4
PET (not in GSA)	Hamon PET equation	Calculated ET: 0.16-0.24 cm/day
Crop Coefficient	General value for humid tropical vegetation (Allen et al. 1998)	0.8
Soil Depth	Field sampled and corrected for slope; depth of hydrologic soil layers A & B adopted from Hanson et al. (2004) and Toohey et al. (2018)	Forest: A: 35 cm, B: 65 cm Coffee: A: 50 cm, B: 50 cm Sugar Cane: A: 50 cm, B: 50 cm Pasture: A: 10 cm, B: 90 cm Road†: A: 50 cm, B: 50 cm
Slope (not in GSA)	DEM	Range: 0-62°
K_{sat} Matrix	Spaans et al. (1989), Hanson et al. (2004), Toohey et al. (2018)	Forest: A: 13.4, B: 8.9 cm/day Coffee: A: 7.7, B: 8.9 cm/day Sugar Cane: A: 3.1, B: 1.7 cm/day Pasture: A: 2.9, B: 5.5 cm/day Road†: A: 0.05, B: 0.05 cm/day
K_{sat} Macropore	Spaans et al. (1989), Hanson et al. (2004), Toohey (2012)	Forest: A: 134.4, B: 88.8 cm/day Coffee: A: 76.8, B: 88.8 cm/day Sugar Cane: A: 31.2, B: 16.8 cm/day Pasture: A: 28.8, B: 55.2 cm/day Road†: A: 1.0, B: 1.0 cm/day
K_{sub}	Toohey (2012), Estimated	Forest: 84.0 cm/day Coffee: 84.0 cm/day Sugar Cane: 1.4 cm/day Pasture: 4.8 cm/day Road†: 1.4 cm/day
Field Capacity Moisture Content	Toohey (2012)	Forest: 28% Coffee: 28% Sugar Cane: 28% Pasture: 18% Road†: 8%
Porosity (Saturated Moisture Content)	Field sampled; Spaans et al. (1989)	Forest: A: 38%, B: 28% Coffee: A: 38%, B: 28% Sugar Cane: A: 38%, B: 28% Pasture: A: 28%, B: 18% Road†: A: 3.8%, B: 2.8%
Residual Moisture Content	Spaans et al. (1989), Toohey (2012)	All land cover types: 2%
Wilting Point Moisture Content	Toohey (2012)	All land cover types: A: 1.94%, B: 1.21%
Max Canopy Storage Amount (not in GSA)	Welsh et al. (2018); Estimated	Forest: 0.2 cm Coffee: 0.1 cm Sugar Cane: 0.05 cm Pasture: 0.05 cm Road: 0.0 cm
Rock Content	Field sampled	All land cover types: 10%
Road Area (not in GSA)	Peréz (2009), Aerial imagery	Atirro: 7.66ha; 0.24% cover Gato: 0ha; 0% cover Platanillo: 22.98 ha; 0.89% cover
Recession Constants	Estimated based on gauge data	a=75; b=0.2 (See equation in text)
Antecedent Moisture Content	Estimated (model equilibrates)	72 cm

GSA – Global Sensitivity Analysis; †all road parameters estimated

Table 3. Simulation Scenario Matrix

	Land Use	Rainfall Intensity	Temperature (based on 2002 record)	Rainfall Amount (% of 2002 precipitation)
Atirro	· All pasture · Existing	· High rate · Existing rate	· Existing Temperature · +1 °C (daily time step only) · +4 °C	· 70% · 100% · 110%
Gato	· All pasture · Existing	· High rate · Existing rate		
Platanillo	· All pasture · Existing · All forested	· High rate · Existing rate		

Table 4. Gini Importance Values in SMR Sensitivity Analysis

	LowFlow	LowDuration	PeakFlow	PeakDuration	WetStandDev
Field Capacity Moisture Content	2.5%	4.0%	3.8%	3.4%	2.9%
Ksub	1.9%	1.8%	14.7%	2.4%	7.0%
Macropore Ksat	30.8%	11.6%	12.3%	21.1%	20.8%
Matrix Ksat	1.9%	1.7%	2.3%	2.3%	1.6%
Max Canopy Storage	1.9%	1.7%	2.3%	2.4%	1.6%
Porosity	9.7%	5.7%	9.8%	11.6%	4.8%
Recession Constant	2.0%	4.3%	26.0%	2.5%	23.6%
Residual Moisture Content	3.9%	3.7%	3.1%	4.9%	2.3%
Rock Content	5.0%	4.4%	4.1%	6.4%	2.7%
Soil Depth	8.4%	8.6%	7.3%	19.8%	4.2%
Antecedent Storage	30.3%	50.8%	12.1%	20.7%	26.9%
Wilting Point Moisture Content	1.9%	1.6%	2.2%	2.5%	1.6%

Table 5. Atirro Mass Balance (Daily Time Step Simulations)

Atirro Existing			Atirro Pasture Conversion			Atirro Pasture with Restrictive Layer		
MASS BALANCE		DEFICIT	MASS BALANCE		DEFICIT	MASS BALANCE		DEFICIT
ppt input (cm/basin)	output (cm/basin)	ppt – output	ppt input (cm/basin)	output (cm/basin)	ppt – output	ppt input (cm/basin)	output (cm/basin)	ppt – output
503.5	480.8	22.7	503.5	496.3	7.2	503.5	496.3	7.2
Water Balance Term	%	cm	Water Balance Term	%	cm	Water Balance Term	%	cm
Precipitation	100.0%	503.5	Precipitation	100.0%	503.5	Precipitation	100.0%	503.5
Evapotranspiration	11.6%	58.4	Evapotranspiration	12.3%	61.8	Evapotranspiration	12.3%	61.8
Baseflow	76.5%	385.3	Baseflow	74.4%	374.8	Baseflow	40.8%	205.6
Saturation Excess Runoff	7.4%	37.1	Saturation Excess Runoff	11.9%	59.8	Saturation Excess Runoff	45.5%	229.0
Storage	4.5%	22.7	Storage	1.4%	7.2	Storage	1.4%	7.2