

## **Performance of Two Hydrological Models in Predicting Daily Flow under a Climate Change Scenario for Mountainous Catchments in Northwestern Costa Rica**

Author(s): César D. Jiménez-Rodríguez, Julio C. Calvo-Alvarado, and John K. Jackson

Source: Mountain Research and Development, 35(3):240-253.

Published By: International Mountain Society

DOI: <http://dx.doi.org/10.1659/MRD-JOURNAL-D-14-00109.1>

URL: <http://www.bioone.org/doi/full/10.1659/MRD-JOURNAL-D-14-00109.1>

---

BioOne ([www.bioone.org](http://www.bioone.org)) is a nonprofit, online aggregation of core research in the biological, ecological, and environmental sciences. BioOne provides a sustainable online platform for over 170 journals and books published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Web site, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at [www.bioone.org/page/terms\\_of\\_use](http://www.bioone.org/page/terms_of_use).

Usage of BioOne content is strictly limited to personal, educational, and non-commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

# Performance of Two Hydrological Models in Predicting Daily Flow under a Climate Change Scenario for Mountainous Catchments in Northwestern Costa Rica

César D. Jiménez-Rodríguez<sup>1\*</sup>, Julio C. Calvo-Alvarado<sup>1</sup>, and John K. Jackson<sup>2</sup>

\* Corresponding author: cdjimenezcr@gmail.com

<sup>1</sup> Escuela de Ingeniería Forestal, Instituto Tecnológico de Costa Rica, Barrio Los Ángeles, P.O. Box 159-7050, Cartago, Costa Rica

<sup>2</sup> Stroud Water Research Center, 970 Spencer Road, Avondale, PA 19311, USA

Open access article: please credit the authors and the full source.



Tropical mountain regions contain the main headwaters of important rivers in Central America. We selected 2 contrasting catchments located in a mountainous region to evaluate the precision of daily flow estimates based on the

Hydrological Land Use Change (HYLUC) and Nedbør-Afstrømnings Model (NAM) hydrological models. A second objective was to simulate the impact of expected climate change for the year 2050 on stream flows and seasonal distribution of rainfall. We studied the catchments of the Tempisque and Cucaracho streams, located in the

Guanacaste volcanic mountain range of Costa Rica, from April 2008 to October 2010. Modeling of discharge using the NAM and HYLUC models suggested difficulties in their calibration due to intrinsic catchment characteristics because of their volcanic origin. The climate change scenario applied in both catchments depicted a strong reduction in discharge. However, the Cucaracho catchment, on the Caribbean slope, is predicted to experience a smaller reduction in discharge than the Tempisque catchment, located on the Pacific slope.

**Keywords:** HYLUC; NAM; Guanacaste Conservation Area; Central America; climate change.

**Peer-reviewed:** March 2015 **Accepted:** April 2015

## Introduction

Central America is in the northern Neotropics (Morrone 2006) and has a bimodal rainfall regime due to the influence of the Intertropical Convergence Zone (Wang 1994). The isthmus is located close to the subduction zone where the Cocos tectonic plate slides beneath the Caribbean plate, which creates a longitudinal topographical divide that forms the border between different rainfall regimes on the Caribbean and Pacific slopes (Hastenrath 1968; Coates and Obando 1996; Xu et al 2005).

Geological, topographical, and climatic patterns in the Central American isthmus create a large number of life zones (Khatun et al 2013) with high species richness and species endemism (Olson et al 2001), as well as vulnerability to climate change (Khatun et al 2013). However, human pressure damages the hydrological processes in poor uplands, increases the transport of sediments downhill, and threatens biodiversity (Krishnaswamy et al 2001; Nelson and Chomitz 2007).

The continental water divide in Costa Rica is defined by the Guanacaste Volcanic, Central Volcanic, and Talamanca mountain ranges (Calvo 1990; Haber et al 2000; Marshall et al 2003; Guzmán and Calvo-Alvarado

2013). The first two ranges are located in the north and middle of the country, respectively, and are dominated by active and dormant volcanoes, while the Talamanca mountain range is a tectonic geological formation (Coates and Obando 1996).

The El Niño–Southern Oscillation (ENSO) affects the spatial distribution of tropical storms as well as their frequency and intensity (McPhaden et al 2006). These phenomena modulate the temporal and spatial distribution of rainfall in Costa Rica (Manso et al 2005), which is considered the most important element of climatic variability. El Niño events create drier conditions (Philander et al 1989; Waylen et al 1994; Giannini et al 2000; Haber et al 2000) and contribute to tree mortality in secondary tropical rain forests (Chazdon et al 2005), while La Niña events increase precipitation (Philander et al 1989; Meza Ocampo 2004).

The combination of topographical and climatological conditions in northwestern Costa Rica makes this region an important ecological zone, which is characterized by high species richness in response to diverse geomorphological formations and climate conditions (Holdridge 1967; Hartshorn 1983; Denyer and Kussmaul 2000; Kalacska et al 2004; Hajibabaei et al 2006).

A prominent scientific resource in northwestern Costa Rica is the Área de Conservación Guanacaste, which offers the opportunity to investigate the hydrology of catchments covered with natural vegetation under different weather patterns.

Several streams flowing from the Orosi, Cacao, and Rincón del la Vieja volcanoes are important water sources for the ecosystems and human settlements downstream in the lower catchment of the Río Tempisque (Guzmán Arias and Calvo-Alvarado 2012). The Río Cucaracho has its headwaters on the northern slopes of the Rincón de la Vieja. However, its hydrology is unstudied, as are all the streams of the Guanacaste Range. The Río Tempisque has its headwaters on the slopes between Orosi and Cacao and is one of the most important tributaries of the Río Tempisque (Collado et al 2000; Calvo-Alvarado et al 2008; Guzmán Arias and Calvo-Alvarado 2012). Little information on hydrology and climate is available, although Newbold et al (1995) presented a brief hydrological and meteorological description of 6 Tempisque headwater tributaries.

This study undertook a hydrological analysis of 2 forested catchments never analyzed before—the catchments of the streams Tempisque and Cucaracho—representing 2 different climatic regimes in the mountainous section of the Área de Conservación Guanacaste in Costa Rica. The first objective was to evaluate the performance of 2 hydrological models—the Hydrological Land Use Change (HYLUC) and Nedbør-Afstrømnings-Model (NAM) hydrological models. A second objective of this study was to simulate the impact of expected climate change for 2050 on stream flows and seasonal distribution of rainfall.

## Methodology

### Study sites

The Área de Conservación Guanacaste is a 163,000 ha conservation area in northwestern Costa Rica that protects 4 important tropical ecosystems: coastal-marine, dry forest, wet forest, and cloud forest (ACG 2013). Elevation ranges from sea level to the tops of Volcán Orosi, Cerro Cacao, and Volcán Rincón de la Vieja at 1487, 1659, and 1851 masl (meters above sea level), respectively. The combination of coastal and mountain topography results in the presence of wet, moist, and dry forests facing the Pacific slope, and predominately moist and wet forests on the Caribbean slope. The 3 mountaintops have rain forests with a strong influence of fog and drizzle.

Two catchments located within the Área de Conservación Guanacaste were selected, one on the headwaters of the Cucaracho River and another on the headwaters of the Tempisque River. Water forming the Río Cucaracho flows from the northwest face of Rincón de la Vieja volcano to the San Juan River along the Costa Rica–Nicaragua border, and finally into the Caribbean

Sea (Figure 1). The gauging station at Cucaracho stream is located at the bottom of a 348.5 ha (3.4 km<sup>2</sup>) catchment (10°52'16"N, 85°23'30"W), at 663.7 masl, and only 1 climate station near the gauging station provides meteorological data for the catchment. This catchment contains 2 life zones according to the Holdridge classification system (Holdridge 1967; Bolaños and Watson 1993): transitional tropical wet forest and montane rain forest, at the bottom and top of the catchment, respectively. Significant rainfall occurs during most months of the year; the catchment has almost no dry season, with a slight water deficit only during April.

In contrast, water forming the Tempisque stream flows from the eastern slope of Volcan Orosi to the Río Tempisque, and finally to the Pacific Ocean (Gulf of Nicoya). The gauging station for the Tempisque stream is located at the bottom of a 304.1 ha (3.04 km<sup>2</sup>) catchment (10°57'28"N, 85°29'40"W), at 585 masl, and there are 3 climate stations—Maritza (579.7 masl), Cumbre (796.4 masl), and Cacao (1122.9 masl)—that provide meteorological data for the catchment. This catchment is characterized by 2 Holdridge life zones (Holdridge 1967; Bolaños and Watson 1993): premontane wet forest and premontane pluvial forest. Rainfall is more seasonal on the Tempisque, with a dry season from February to April. The dry season for the Tempisque stream is thus longer than for the Cucaracho stream.

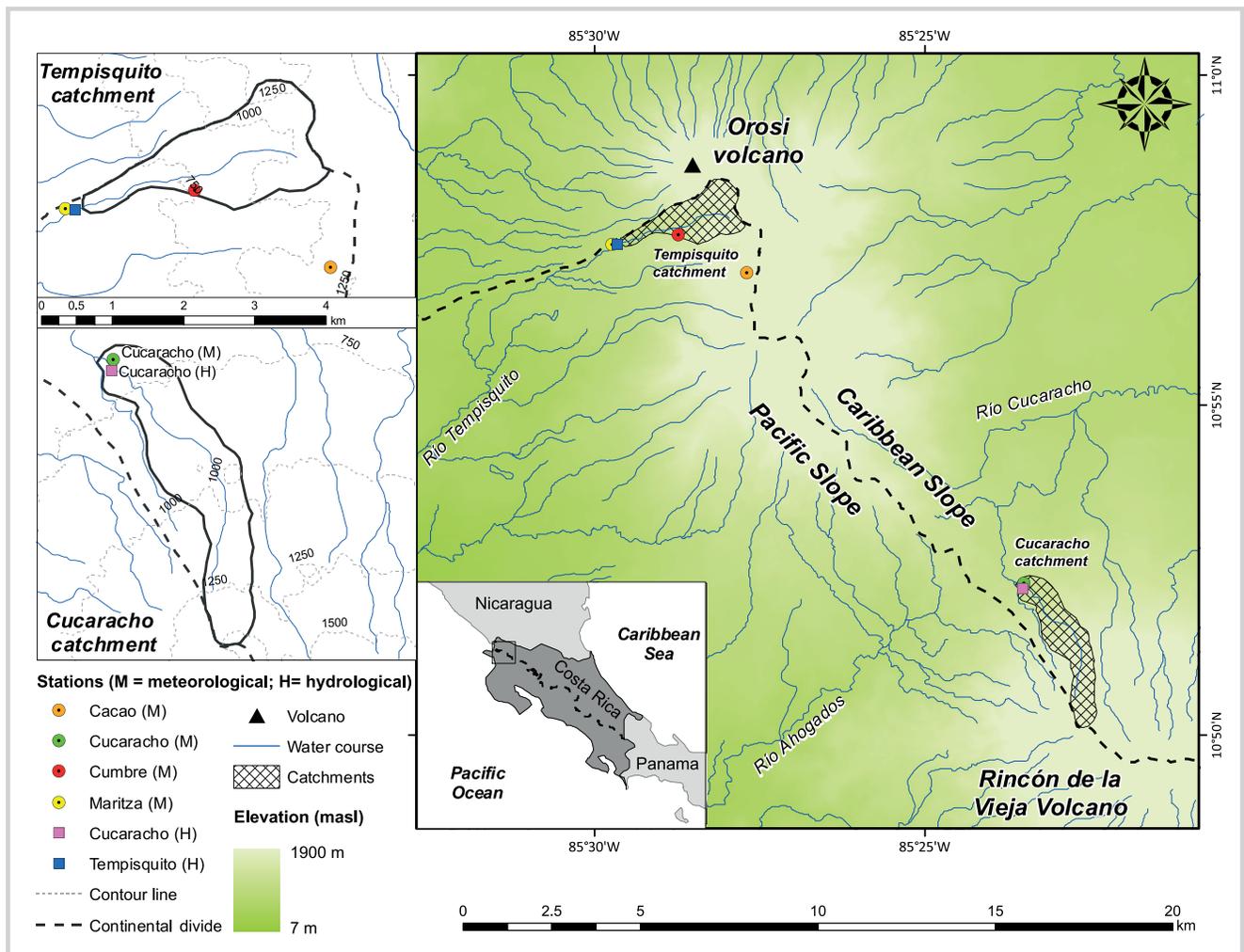
The soils in both catchments are classified according to the Food and Agriculture Organization (FAO) soil taxonomy system as Andisols with a low base saturation; these soils have strong differentiation within the catchment due to the steep slope present in the upper catchment (CCT 1989; Ortiz Malavassi 2004; FAO 2006). Both catchments are covered by pristine forests upstream of the gauging stations, with little evidence of anthropogenic alteration, except for some evidence of limited selective logging in the Tempisque catchment (Newbold et al 1995), as well as in the Cucaracho catchment.

### Catchment instrumentation

Stream flow gauging stations were installed at the lowest point of each catchment. A staff gauge was attached to a 10-cm-diameter polyvinyl chloride (PVC) pipe installed near the stream bank to measure water levels. Inside the PVC pipe, a stage recorder (Solinst Levelogger Gold Model 3001) was deployed to record the stream level every 5 minutes. Atmospheric pressure was measured and recorded (Solinst Barologger Gold Model 3001) close to each gauging station to apply a barometric compensation procedure to correct the water levels. Instantaneous stream discharge measurements (m<sup>3</sup> s<sup>-1</sup>) were collected monthly at each site to develop a rating curve, translating the water levels into stream discharge.

The meteorological stations in both catchments recorded precipitation with a tipping-bucket rain gauge

FIGURE 1 Location of Tempisquito and Cucaracho catchments. (Map by César Jiménez)



(HOBO Onset Data Logging Rain Gauge model RG3-M), as well as air temperature and relative humidity (HOBO Onset U23 Pro v2-U23-001). Temperature and relative humidity sensors collected data every 30 minutes; they were covered by a radiation shield at all the meteorological stations. Rainfall measurements were gathered at 1.5 m above the ground, with the exception of the Cumbre station, where there was no suitable open area for placement at ground level. The rainfall at this station was collected in a 16.5-cm-diameter funnel installed above the forest canopy and conveyed to the rain gauge at ground level through a plastic pipe.

#### Data collection and processing

The study period began when stream gauging stations were installed in April 2008 and continued for 30 months, until a flood destroyed the station in Cucaracho in October 2010. Total rainfall for the Cucaracho catchment

was collected at only 1 site; no extrapolation was performed for this catchment due to the absence of more stations in the area. Establishing total rainfall for Tempisquito involved data interpolation based on the Thiessen polygons method (Maritza, Cumbre, and Cacao at 7.0%, 39.8%, and 53.2%, respectively). Potential evapotranspiration was estimated using the Romanenko method (Xu and Singh 2001), as shown in Equation 1.

$$ET_o = 0.0018(25 + T)^2(100 - RH), \quad (1)$$

where  $ET_o$  is potential evapotranspiration,  $T$  is mean daily temperature ( $^{\circ}\text{C}$ ), and  $RH$  is relative humidity (%).

Water levels (cm) recorded every 5 minutes were converted to stream discharge ( $\text{m}^3 \text{s}^{-1}$ ) using a rating curve developed for each gauging station. A complete statistical analysis was conducted to select the best

regression. Exponential equations describe the best rating curves for both Cucaracho (Equation 2) and Tempisquito (Equation 3) streams.

$$Q = 0.002e^{0.075 * L}, \text{ with } n = 26 \text{ and } R^2 = 0.56, \quad (2)$$

$$Q = 0.036e^{0.065 * L}, \text{ with } n = 49 \text{ and } R^2 = 0.73, \quad (3)$$

where  $Q$  is the stream discharge ( $\text{m}^3 \text{s}^{-1}$ ),  $L$  is the stream water level (cm),  $n$  is the number of stream flow measurements, and  $R^2$  is the coefficient of determination.

Climate and stream seasonality were defined based on the monthly water deficit. Months with more precipitation than potential evapotranspiration were classified within the wet season, while those with less precipitation than potential evapotranspiration were classified as dry season months. Due to the limited data available, it was not possible to use the extreme event definition given by Carvalho et al (2002). Instead, we used the Beniston et al (2007) definition of extreme events as those occurring with relatively low frequency. We used 2 event categories—peak events, defined as those with an accumulated frequency greater than 95%, and extreme events, defined as those with an accumulated frequency greater than 99%—to classify precipitation and stream discharge for the climate description and model evaluation.

### Hydrological models

The HYLUC model is based on the underlying biophysical processes that drive evaporation. The structure is based on a lumped model working on a cascade methodology to estimate the final daily discharge. The HYLUC model is transformed by the Land Use Change model written for Microsoft Excel software into a semidistributed hydrological model through the segmentation of cover units within the influence area of a rain gauge. The HYLUC model determines the seasonal evapotranspiration from different land covers, based on the Penman-Monteith equation (Allen et al 1998), which takes into account vegetation roughness; it includes 2 parameters that allow the calculation of soil water content and soil drainage (Calder 2003). This model has been applied to different land-use covers from the United Kingdom, including Scots pine, lowlands, and tree plantations; to a Mediterranean catchment in Spain; to a semiarid region of South Africa; and to tropical forests in Panama (Haria and Price 2000; Calder 2002; Calder 2003; Calder et al 2003; Jewitt et al 2004; Calder et al 2009; Delgado et al 2010).

The NAM model, developed at the Institute of Hydrodynamics and Hydraulic Engineering at the Technical University of Denmark (Nielsen and Hansen 1973), is a deterministic, conceptual, lumped model that simulates rainfall-discharge processes in rural catchments. It works on a cascade methodology with

9 parameters that need to be calibrated for the calculations (Madsen 2000). The NAM model used in this study is an adaptation written on a Microsoft Excel spreadsheet. The NAM model has been evaluated in a variety of locations, including the Nile River in Egypt, tropical forests of Vietnam and Zimbabwe, arid areas of California and Africa, and agricultural and forested catchments in Denmark (Yew Gan et al 1997; Jeppesen et al 2009; Taye et al 2011; Ngoc et al 2013).

### Model performance

Our analysis of model performance was based on a daily assessment of 4 error parameters: mean error (*BIAS*, Equation 4), mass balance error (*MBE*, Equation 5), coefficient of determination ( $R^2$ , Equation 6), and the Nash-Sutcliffe model efficiency coefficient ( $E_{NS}$ , Equation 7).

$$BIAS = \frac{1}{N} \sum_{i=1}^N (Q_{sim} - Q_{obs}), \quad (4)$$

$$MBE = \frac{\sum_{i=1}^N Q_{sim} - \sum_{i=1}^N Q_{obs}}{\sum_{i=1}^N Q_{obs}} \times 100, \quad (5)$$

$$R^2 = \frac{\left[ \sum_{i=1}^N (Q_{obs} - \bar{Q}_{obs}) (Q_{sim} - \bar{Q}_{sim}) \right]}{\left[ \sum_{i=1}^N (Q_{obs} - \bar{Q}_{obs})^2 \right] \left[ \sum_{i=1}^N (Q_{sim} - \bar{Q}_{sim})^2 \right]}, \quad (6)$$

$$E_{NS} = 1 - \frac{\sum_{i=1}^N (Q_{obs}^i - Q_{sim}^i)^2}{\sum_{i=1}^N (Q_{obs}^i - \bar{Q}_{obs})^2}, \quad (7)$$

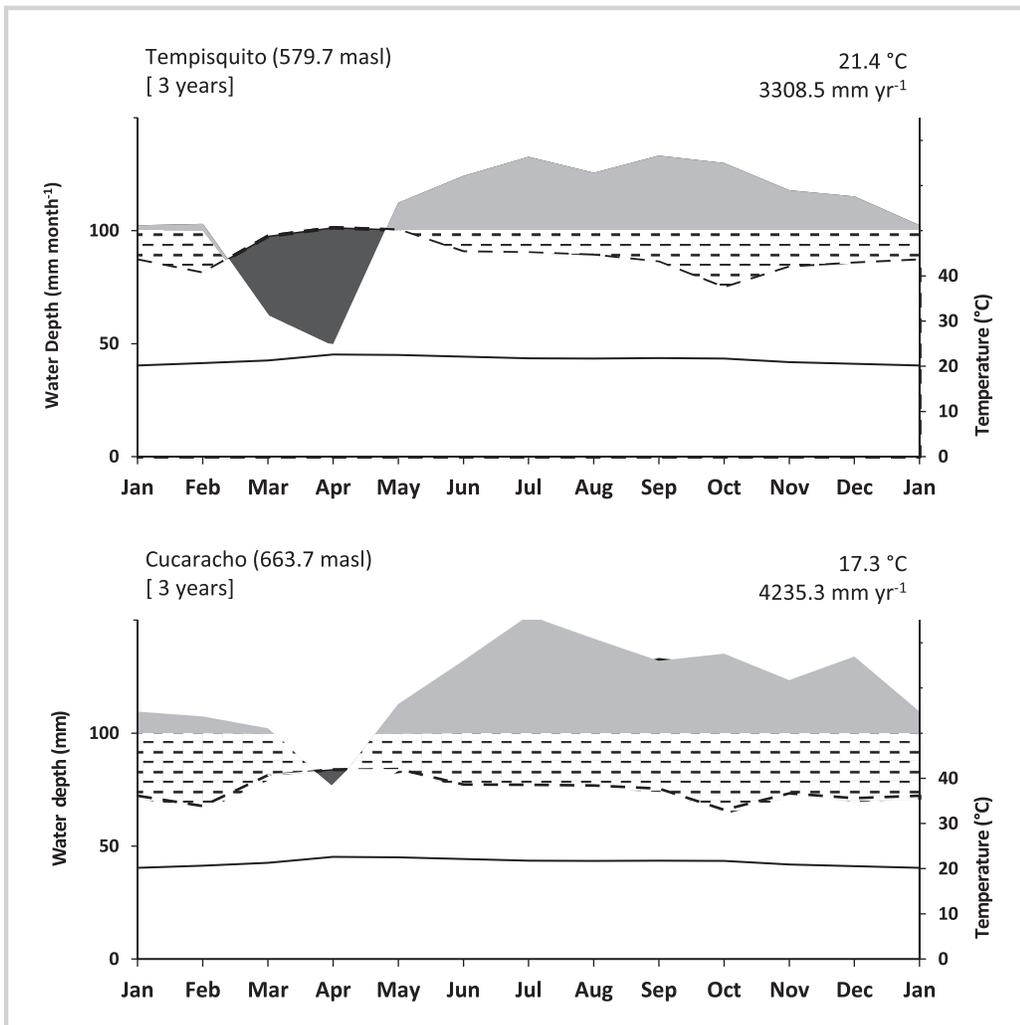
where  $Q_{sim}$  is the simulated river discharge ( $\text{mm d}^{-1}$ ),  $Q_{obs}$  is the observed stream discharge ( $\text{mm d}^{-1}$ ),  $i$  is the daily event,  $N$  is the total number of monitored days, and  $\bar{Q}_{obs}$  is the mean observed stream discharge ( $\text{mm d}^{-1}$ ).

### Climate change scenario

Magrin et al (2007) described projected scenarios of climate change for Latin America. The scenario for 2050 involves a temperature increase of 1.0–3.0°C in the dry season and 1.0–4.0°C in the wet season. The precipitation regime is expected to be highly variable and quite unpredictable, ranging from –12 to +5% during the dry season and –15 to +3% during the wet season. These projections agree with recent findings for Central America by Hidalgo et al (2013), who predicted a temperature increase of up to 4°C and a precipitation reduction of 10%.

Based on these 2 studies, a 2.0°C temperature increase and 10% rainfall reduction in 2050 were used as the climate change scenario for this study. These conditions were applied to the recorded data sets of the Cucaracho and Tempisquito catchments, which were used to evaluate both models (HYLUC and NAM). The modeled output from the recorded climatological conditions was the starting point

**FIGURE 2** Climate diagram showing the wettest months (black solid area), water excess (area with dots), water deficit (area with vertical lines), and temperature (solid line) for the Cucaracho and Tempisquito catchments.



for all later comparisons. The impact of the climate change scenario was evaluated by comparing the results to the total modeled discharge under the recorded climatological conditions. This analysis considered the total stream discharge, total dry season discharge, frequency of peak events, and total discharge from peak events.

## Results

### Catchment seasonality

Hydrological monitoring performed in Cucaracho and Tempisquito catchments gathered data from 3 La Niña events (April 2008 to June 2008, October 2008 to April 2009, and June 2010 to October 2010) and 1 El Niño event (July 2009 to April 2010) (Climate Prediction Center Internet Team 2013). El Niño–Southern Oscillation–neutral conditions were observed among the La Niña and El Niño events.

The catchments differed in the seasonal distribution of precipitation. The dry season at Cucaracho occurs only during April and is relatively weak, while the dry season at Tempisquito lasts from February to April. Temperature at Cucaracho showed seasonal oscillations within each year (Figure 2). Relative humidity at Cucaracho ranged from 75% in the dry season to 100% in the wet season. Mean relative humidity was 86.1% in the dry season and 92% in the wet season. The high relative humidity across seasons and years indicates the high content of atmospheric water vapor at this site. Mean annual precipitation at Cucaracho was 4235.3 mm, with a mean annual stream discharge of 3690.7 mm and a mean annual potential evapotranspiration of 927.5 mm (Table 1).

Cucaracho catchment experienced a 1 month dry season during April each year, during which potential evapotranspiration (81.4 mm) was higher than precipitation (78.4 mm) (Table 1). Because of the dry

**TABLE 1** Mean annual and seasonal values for hydrological and meteorological variables at Cucaracho and Tempisquito catchments from April 2008 to October 2010.

Hydrological and meteorological parameters	Cucaracho			Tempisquito		
	Dry season	Wet season	Annual	Dry season	Wet season	Annual
Mean temperature (°C)	18.2	17.3	17.4	21.9	21.4	21.5
Mean relative humidity (%)	86.1	92.0	91.5	80.7	88.5	87.2
Annual potential evapotranspiration (mm)	81.4	846.2	927.5	204.2	885.9	1090.1
Annual precipitation (mm)	78.4	4156.9	4235.3	111.5	3196.9	3308.5
Annual river discharge (mm)	241.4	3449.3	3690.7	251.6	2103.8	2355.5

season's brevity, its precipitation and stream discharge represent only 1.9% and 6.5% of annual values, respectively. The remaining 11 months are categorized as wet season with a high incidence of large storms (>50 mm/event). For example, 2008 recorded a storm of 196.6 mm d<sup>-1</sup> (Figure 3). This large storm exceeded the extreme event threshold (99th percentile) for precipitation in this catchment of 94.8 mm d<sup>-1</sup> (Table 2). The catchment response to precipitation observed as daily stream discharge exceeded the extreme event threshold of 28.8 mm d<sup>-1</sup> on 4 days.

Tempisquito experienced drier conditions than Cucaracho; it had a mean annual precipitation of 3308.5 mm and a mean annual stream discharge of 2355.5 mm (Table 1). Annual discharge represented 71.2% of the mean annual precipitation. The dry season was strongest from February to April and contributed only 3.4% of mean annual precipitation and 10.7% of annual stream discharge. Warmer air temperatures in both seasons and extremely variable relative humidity resulted in a higher annual potential evapotranspiration (1090.1 mm) at Cucaracho (Table 1). The Tempisquito hydrograph showed a rapid catchment response to precipitation events (Figure 3). The extreme event thresholds for precipitation and discharge were 116.8 mm d<sup>-1</sup> and 50.2 mm d<sup>-1</sup>, respectively, while the peak event thresholds were 64.9 mm d<sup>-1</sup> and 14.1 mm d<sup>-1</sup> for precipitation and discharge, respectively (Table 2).

#### Hydrological model performance

The HYLUC and NAM models underestimated stream discharge in both Cucaracho and Tempisquito: NAM by about 13% and HYLUC by much as 25%. The catchments showed a mean error ranging from -0.9 to -2.7 in daily calculations.  $R^2$  and Nash-Sutcliffe coefficients indicate there was a relatively good fit of the model to the data, slightly better for HYLUC at Tempisquito and NAM at Cucaracho (Table 3).

Daily stream discharge (Figure 4) was better described in Tempisquito by the HYLUC model ( $R^2 = 0.88$ ,  $E_{NS} = 0.59$ ), which successfully described the

events with a probability lower than 0.01 (Figure 4). The HYLUC model underestimated the discharge with an exceedance probability higher than 0.1 (representing 75% of all the records). The NAM model fit better for the Cucaracho stream ( $R^2 = 0.80$ ,  $E_{NS} = 0.45$ ). The NAM model described with high fidelity the discharge events with exceedance probabilities lower than 0.1, but it underestimated base flows similar to the HYLUC model.

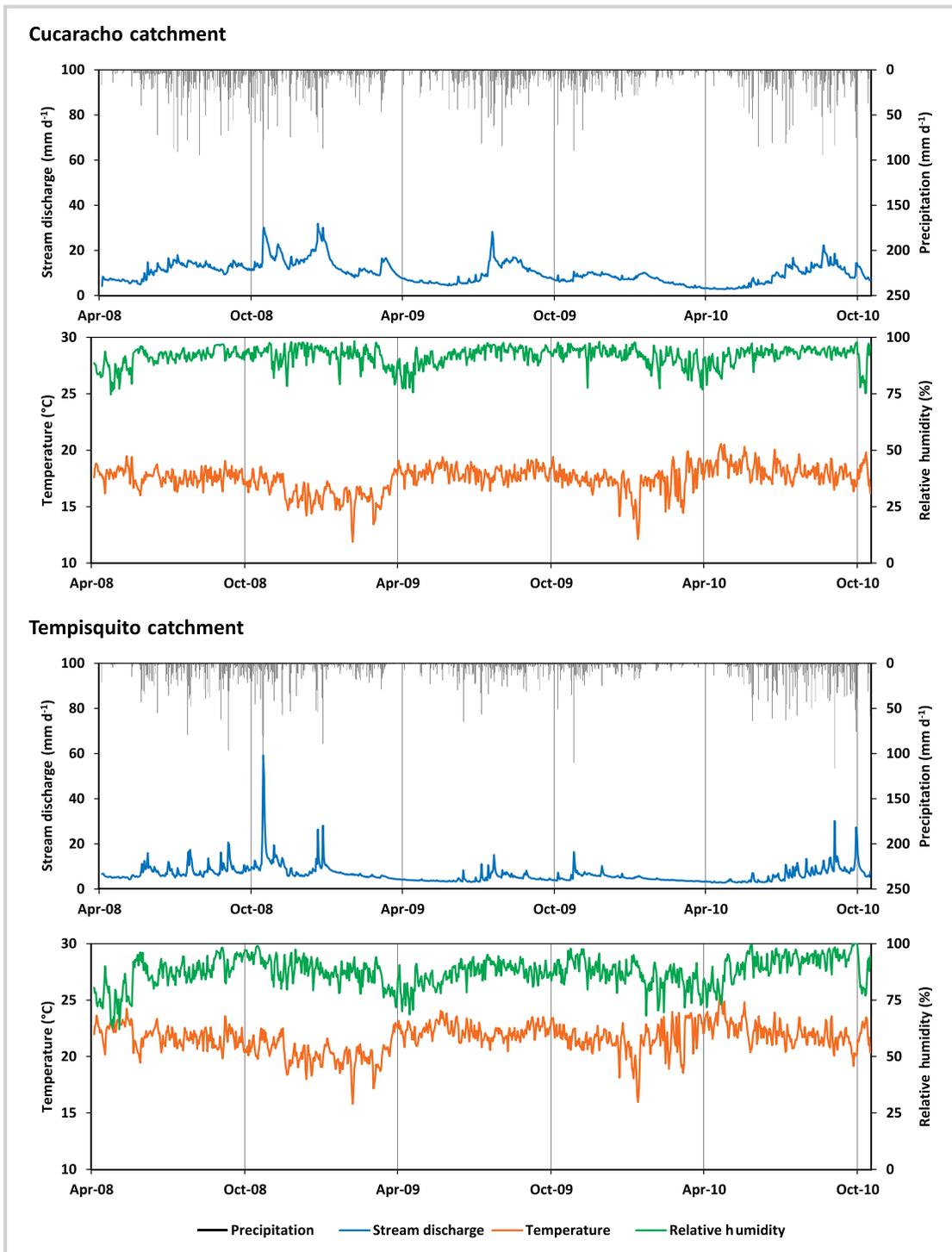
#### Modelling climate change

Based on a climate change scenario of a 10% reduction in rainfall and a 2°C increase in temperature, outputs were generated using both models and compared to the recorded conditions for both catchments. The climate change scenario resulted in a significant decrease in stream discharge for both streams. The 2 models differed in the modeled total discharge, but they were consistent in the yearly percentage decrease in stream flows.

Both models predicted that annual stream discharge would decrease, by 15.7–16.6% at Cucaracho and 20.0–21.0% at Tempisquito (Table 4). However, they differed distinctly in their predictions of seasonal reductions in stream discharge. The NAM model for Cucaracho stream showed seasonal reduction of stream flows, with a strong reduction in stream discharge in the transitional period between the dry and wet seasons. A reduction of 26% to 30.7% was observed at the beginning of the wet season each year; however, the decrease in stream discharge was not as great during the dry season, reaching a maximum of 5.8%. HYLUC modeled discharge was more constant through the year. Both the HYLUC and NAM models were able to accurately model the discharge peaks during the transitional months (Figure 5).

Tempisquito and Cucaracho exhibited similar model results, with strong seasonal differences in the NAM model that were not apparent in the HYLUC model. The HYLUC model exhibited a more constant

**FIGURE 3** Daily precipitation, stream discharge, relative humidity, and temperature measured at Cucaracho and Tempisquito catchments from April 2008 to October 2010.



reduction throughout the year, with peaks reaching the 37.3% difference during the transitional months (from dry to wet season). Important seasonal differences in discharge were shown by the NAM model in these

catchments, with random peaks throughout the wet season. There was no reduction in dry-season flows in the models' predicted response to the climate change scenario (Figure 5).

**TABLE 2** Thresholds values ( $\text{mm d}^{-1}$ ) for precipitation and stream discharge in Cucaracho and Tempisquito catchments.

Thresholds		Cucaracho ( $\text{mm d}^{-1}$ )	Tempisquito ( $\text{mm d}^{-1}$ )
Precipitation	Peak event threshold	81.4	64.9
	Extreme event threshold	94.8	116.8
Stream discharge	Peak event threshold	19.4	14.1
	Extreme event threshold	28.8	50.2

## Discussion

### Catchment hydrology

Throughout the year, the passage of the Intertropical Convergence Zone and southwest trade winds bring rain to the northwest-southeast ridges of the Caribbean slope. The Caribbean atmospheric moisture is transported by the Caribbean Low-Level Jet (Durán-Quesada et al 2010) and obstructed by the mountain ranges that constitute a physical barrier to the trade winds, allowing the development of a more humid climate on the Caribbean slope (Haber et al 2000; Leclerc et al 2000; Xu et al 2005; Nair et al 2010).

On the other hand, the Pacific slope experiences a dry season from December to April because the atmospheric moisture carried by the Choco Jet during these months is lost over the Pacific Ocean (Durán-Quesada et al 2010). As a result, the streams of the Caribbean slope have a plentiful flow throughout the year, while the streams of the Pacific slope experience low flows during the dry season (Calvo 1990; Guzmán and Calvo-Alvarado 2013; Calvo-Alvarado et al 2014). The Cucaracho and Tempisquito catchments are only 15 km apart, but there are distinct differences in their hydrological regimes due their topographical location on opposite slopes, reflecting the effect of the mountains that separate the two catchments (Cavender-Bares et al 2011; Kirby 2011).

The remaining water content that comes from the east forms clouds at the upper reaches of the Tempisquito catchment on the Pacific slope. This overtopping of atmospheric moisture contributes to an increase in rainfall at the summits, facilitating the growth of montane forests on the upper slopes and the permanence of dry-season discharges (Haber et al 2000; Kirby 2011). This phenomenon has been recorded in the Monteverde Cloud Forest in Costa Rica (Guswa et al 2007; Tobon et al 2010), contributing to maintaining the typical dry-season discharge of the Tempisquito catchment streams.

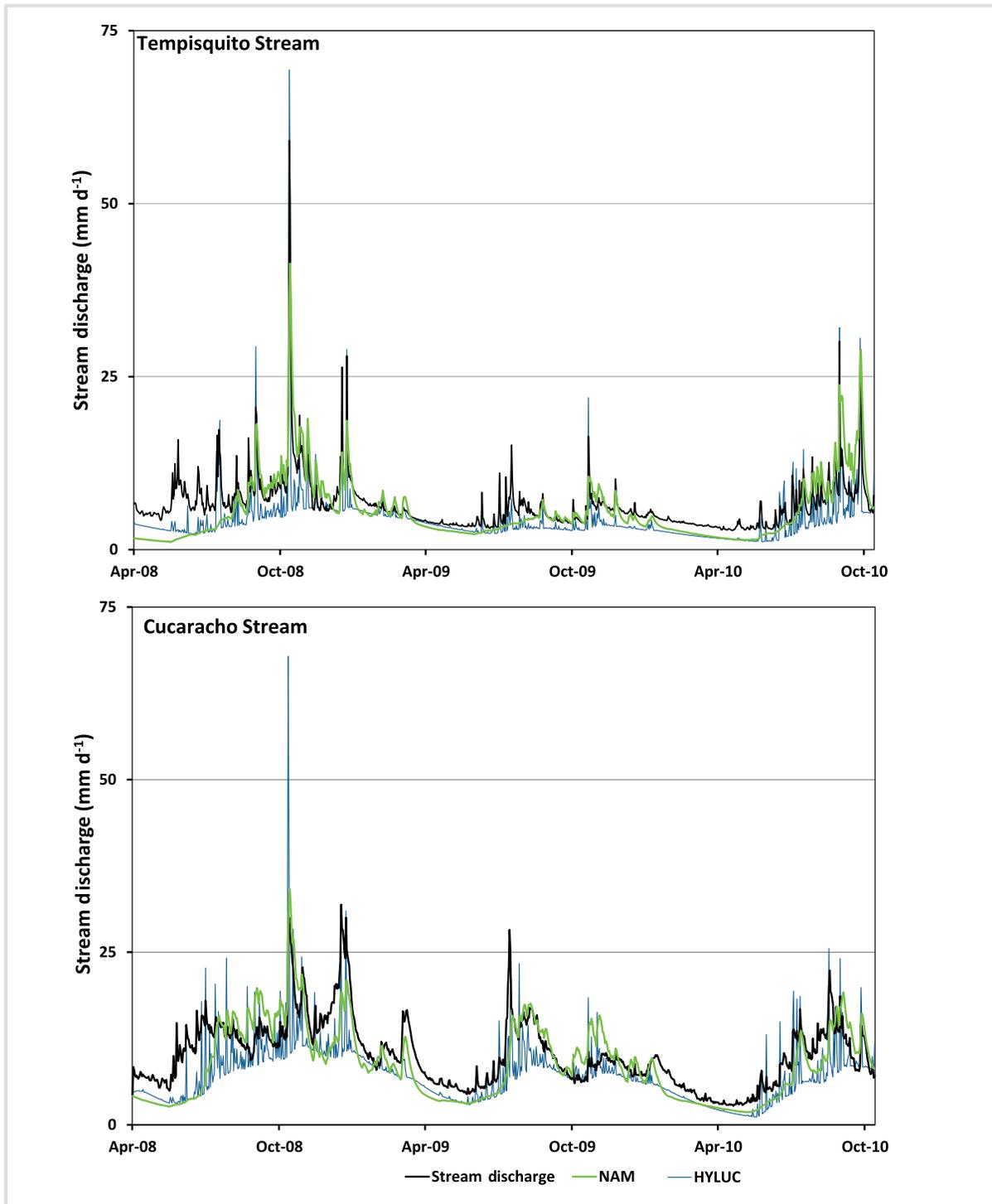
The difference in potential evapotranspiration between the 2 catchments reflects differences in the intensity and length of the dry season, during which Tempisquito can lose 204.2 mm (in 2 months), while Cucaracho loses only 84.1 mm (in 1 month). On the other hand, total potential evapotranspiration losses for both catchments during the wet season differ by only 39.7 mm. This difference illustrates the drier conditions, even during the rainy season, on the Pacific slope.

The high humidity throughout the year on the Caribbean side reduces potential evapotranspiration losses at the catchment level. Even if the water loss by potential evapotranspiration accounts for at most 21.9% of the total rainfall, the real evapotranspiration is much lower. This is consistent with the high discharge observed,

**TABLE 3** Performance parameters used to evaluate the NAM and HYLUC models in Cucaracho and Tempisquito catchments. The discharge values represent the total amounts throughout the study period (4 April 2008 to 16 October 2010, a total of 926 days).

		Cucaracho		Tempisquito	
		NAM	HYLUC	NAM	HYLUC
Total discharge (mm)	Measured	9363.2		5975.8	
	Modeled	8094.3	6845.7	5184.3	4433.4
Mean error (mm)		-1.4	-2.7	-0.9	-1.7
Mass balance error (%)		-13.6	-26.9	-13.2	-25.8
$R^2$		0.80	0.72	0.79	0.88
Nash-Sutcliffe coefficient		0.45	0.15	0.44	0.59

**FIGURE 4** Daily stream discharge, observed and modeled with NAM (green lines) and HYLUC (blue line) models for Cucaracho and Tempisquito streams, April 2008 to October 2010.



which represented 87.1% of the rainfall within the catchment. Tempisquito discharge represented 71.2% of the rainfall, whereas 28.8% of rainfall could be lost to potential evapotranspiration. The hydrological response

in both catchments is similar to conditions in southwestern mountainous catchments in Costa Rica, where the discharge accounts for 70 to 75% of the total rainfall (Krishnaswamy et al 2001).

**TABLE 4** Reduction in monthly discharge (%), estimated with both the NAM and HYLUC models for Cucaracho and Tempisquito catchments according to climate change scenarios.

Month	Cucaracho		Tempisquito	
	NAM	HYLUC	NAM	HYLUC
January	12.9	15.4	12.2	19.7
February	8.7	16.8	13.9	20.4
March	8.7	17.6	8.7	20.6
April	3.7	12.1	0.9	18.1
May	6.9	15.8	4.7	18.3
June	14.7	24.1	13.0	27.9
July	28.8	19.5	23.3	27.6
August	19.0	17.2	31.9	23.9
September	14.1	16.0	23.6	22.0
October	14.6	16.4	23.1	20.5
November	14.2	15.0	20.7	19.9
December	15.2	16.1	20.0	20.4
Annual	<b>15.7</b>	<b>16.6</b>	<b>20.1</b>	<b>21.1</b>

### Hydrological models

The inconsistencies among estimates for modeled potential evapotranspiration, stream discharge, and precipitation could reflect the strong effect of a complex groundwater system in both catchments. Additionally, difficulty modeling precipitation patterns due to the complexity of the regional system in Central America could result in underestimation of rainfall at higher elevations, because of the importance of the contribution of fog to net precipitation (Bruijnzeel 2005). The HYLUC model shows high infiltration rates reaching 500 mm d<sup>-1</sup> and 750 mm d<sup>-1</sup> for Tempisquito and Cucaracho, respectively. Additionally, the NAM model depicts high storage in both catchments—447.8 mm y<sup>-1</sup> and 415.2 mm y<sup>-1</sup> in Cucaracho and Tempisquito, respectively. This water storage capacity has to be related to the volcanic conditions in the area. The geology of these volcanic strata is characterized by porous rocks such as basaltic-andesite and andesite lavas, pyroclastic flows, and lahars (Molina Zuñiga 2000). The presence of superficial soil layers with high porosity and volcanic tuff underneath affects hydrological analysis in these catchments.

The NAM model depicts groundwater contributions of 57.6% and 68.4% of annual stream discharge in Cucaracho and Tempisquito, respectively. The NAM model is difficult to calibrate (Madsen 2000); simplifications in the model structure, use of nonoptimal parameters, or errors in data can reduce its accuracy. A study conducted in Monteverde, Costa Rica, proved that under windy conditions on mountaintops, an

underestimation of water input by more than 20% is possible, regardless of the density of rain gauges (Frumau et al 2010, 2011).

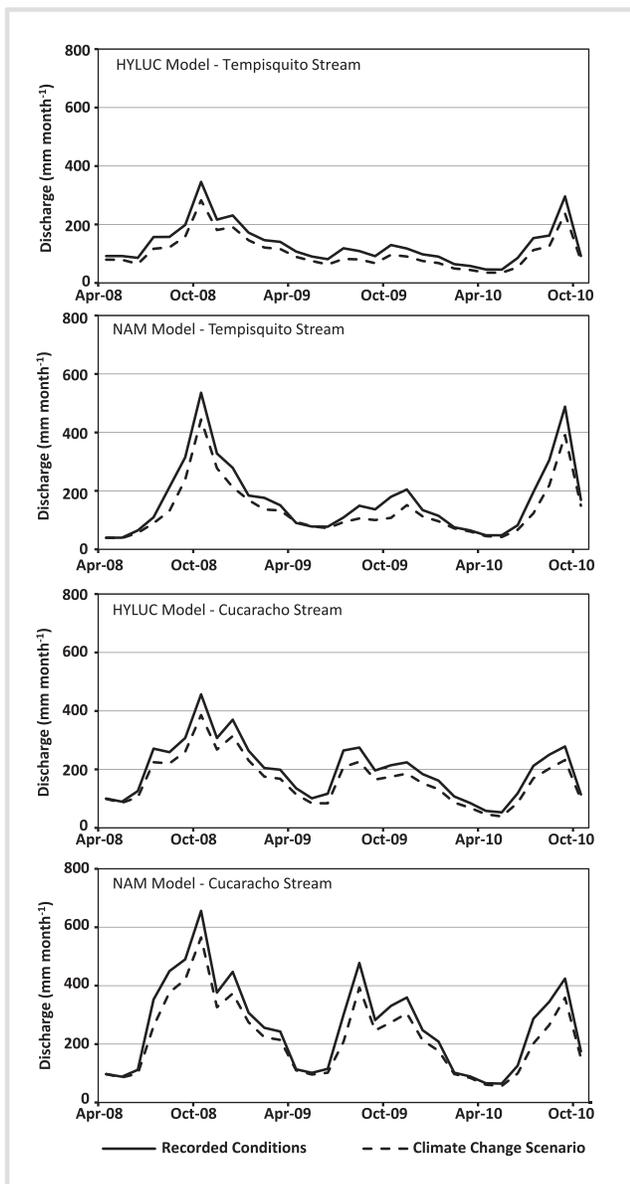
The mass balance error for both models shows a trend toward a reduction in discharge in both streams. The low capacity to model the discharge in Cucaracho could be because rainfall was underestimated due to the absence of rain gauges in the upper part of the catchment. The same problem exists at the top of Tempisquito catchment, where cloudy conditions are constant all year, which suggests that an underestimation of precipitation due to the horizontal precipitation effect in both catchments is likely. Even with the potential estimation errors, however, both models produce estimates of real evapotranspiration that are similar to the annual potential evapotranspiration rate of 1355 mm reported by Komatsu et al (2012) for tropical environments located between 20°S and 20°N.

Hydrological modeling within the mountainous regions of Central America is hampered by lack of information. Major efforts to model hydrological conditions have focused on medium-to large-scale catchments like Terraba basin in Costa Rica (Krishnaswamy et al 2001; Hendrickx et al 2005; Westerberg et al 2010, 2011).

### Effects of climate change

In Central America, climate change effects are reflected strongly in temperature and rainfall readings. A warming trend has been recorded in the last 4 decades, while the intensity of rainfall events has increased (Aguilar et al

**FIGURE 5** Effect of climate change scenario on monthly water flows in Cucaracho and Tempisquito streams under NAM and HYLUC models: modeled discharge under recorded conditions, modeled discharge under climate change scenario, and discharge reduction.



2005). Several recent alterations in the climatic pattern have been reported in Costa Rica. The change in magnitude and duration of rainfall, as well as an increase in droughts appear to be indicators of an important climatic change in the country (Leclerc et al 2000). Due to Costa Rica's geographical location, the climatological conditions are linked directly to the regional climate (Xu et al 2005). The high variability in precipitation in both seasons increases the difficulty of applying climate change scenarios in Central America (Karmalkar et al 2011).

The climate change scenario selected for this study, a 2°C increase in temperature and a 10% reduction in rainfall, is consistent with the expected effect of a global

increase in temperature of 1–3.5°C (Matondo and Msibi 2001) and local variation in precipitation rates (Karmalkar et al 2011). Both Tempisquito and Cucaracho catchments are expected to experience a strong reduction in stream discharge. Discharge in Cucaracho and Tempisquito decreased more than 20% in both models from current recorded conditions between June and July. A drastic alteration is predicted for Cucaracho, which may lose up to 30% of the monthly discharge during the transition between dry and wet seasons. However, stream base flows during the dry season will not be altered strongly by climatic change, according to the NAM model. Both models predict annual reduction in discharge for each catchment, although the predicted reduction is smaller in Cucaracho than in Tempisquito (Table 4).

The climate change scenario used in this analysis would not change the life zones within the Tempisquito catchment. However, the Cucaracho catchment is expected to experience a shift to a drier life zone near the catchment bottom, from transitional tropical wet forest toward tropical wet forest. Khatun et al (2013) registered similar trends throughout Central America, where different climate change scenarios involved the shift of the wettest life zones toward drier conditions. This shift may lead to species migrations in the medium to long term, depending on the species' adaptive capacity (Parmesan 2006; Dawson et al 2011).

#### Applicability to mountain regions

The mountain regions of Central America have an urgent need of effective planning for water resources. However, the lack of hydrological and meteorological field data (Westerberg et al 2010) does not allow a reliable evaluation of water resources. In this context, the use of remote-sensing data, such as the CRN073 data set (Magaña et al 1999, 2003) or the Tropical Rainfall Measuring Mission (TRMM) data set (Huffman et al 2010), has to be considered to make up for the lack of field stations.

Lowland farming and livestock activities in northwestern Costa Rica depend directly on the water drained from the mountaintops, and the replenishment of groundwater downstream. Models for estimating water resources have to be able to work with limited data and take advantage of available remote-sensing data. Both models analyzed in this paper, NAM and HYLUC, utilize simple data sets based on precipitation and potential evapotranspiration, where aerial losses can be computed from temperature and relative humidity data. This makes them promising tools for evaluating the hydrology of catchments based on limited data.

#### Conclusions

Different hydrological models are appropriate for different climate patterns and catchment

characteristics. The NAM and HYLUC models were able to model the Cucaracho and Tempisque hydrology with acceptable accuracy. However, discharge was underestimated in both models for both catchments; this was influenced by the poor capacity to estimate rainfall, especially the horizontal rainfall that occurs at higher elevations. Important differences existed in the models' performance when applied to the Cucaracho and Tempisque catchments. The HYLUC model predicted a reduction of stream discharge in both catchments homogeneously, with a strong reduction during the transitional months between dry and rainy seasons. Conversely, the NAM model showed a more dynamic pattern in both catchments. Given its precision in re-creating the

recorded conditions in both catchments, the use of the NAM model is more appropriate than the HYLUC model for mountainous regions that have uniform land cover and no strong seasonality. The models' proficiency also varied between catchments based on rainfall regime and rainfall intensity. Overall, the climate change scenario examined here showed a reduction in available water to the ecosystems that appears to be ecologically significant. This reduction will affect both catchments during the rainy season, while the impacts during the dry season will not be easily quantifiable. The dry season flows will last for 2 reasons: the short duration of the dry period (<3 months) in both catchments, and the contribution of horizontal rain at the summits.

## ACKNOWLEDGMENTS

This work was done as part of a research project funded by the US National Science Foundation (NSF DEB 05-16516) for support of Long Term Research in Environmental Biology (LTREB): Dynamics of Stream Ecosystem Responses across Gradients of Reforestation and Changing Climate in a Tropical Dry Forest, conducted by the Stroud Water Research Center. Additional support was provided by the TROPIDRY Research Network with the aid of a grant from the Inter-American Institute for Global Change Research (IAI CRN3025), which was supported by the US National Science Foundation (grant GEO-1128040).

We also acknowledge the financial and logistical support of the Vicerectoría de Investigación y Extensión, Instituto Tecnológico de Costa Rica, and the research endowments of the Stroud Water Research Center. Additionally, we are grateful for the logistical support provided by the staff of the Área de Conservación Guanacaste and the field staff of Stroud Water Research Center (Rafael Morales and Cristian Collado), and we thank Dorian Carvajal-Vanegas, Branko Hilje-Rodríguez, and Ana Calvo-Obando for their support during the field campaigns.

## REFERENCES

- ACG [Área de Conservación Guanacaste].** 2013. *Área de Conservación Guanacaste*. <http://www.acguanacaste.ac.cr/>; accessed on 12 June
- Aguiar E, Peterson TC, Obando PR, Frutos R, Retana JA, Solera M, Soley J, García IG, Araujo RM, Santos AR, Valle VE, Brunet LA, Aguiar L, Álvarez L, Bautista M, et al.** 2005. Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. *Journal of Geophysical Research: Atmospheres* 110:1–15.
- Allen RG, Pereira LS, Raes D, Smith M.** 1998. Crop evapotranspiration—Guidelines for computing crop water requirements—FAO Irrigation and drainage paper 56 [Internet]. 2004th ed. Rome: Food and Agriculture Organization of the United Nations. <http://www.fao.org/docrep/x0490e/x0490e070.htm>; accessed 30 July 2015.
- Beniston M, Stephenson D, Christensen O, Ferro CT, Frei C, Goyette S, Halsnaes K, Holt T, Jylhä K, Koffi B, Palutikof J, Schöll R, Semmler T, Woth K.** 2007. Future extreme events in European climate: An exploration of regional climate model projections. *Climatic Change* 81:71–95.
- Bolaños R, Watson V.** 1993. *Mapa Ecológico de Costa Rica, Según el Sistema de Zonas de Vida de Holdridge*. Escala 1:200,000. San José, Costa Rica: Centro Científico Tropical.
- Brujinzeel LA.** 2005. Tropical montane cloud forest: A unique hydrological case. In: Bonell M, Brujinzeel LA, editors. *Forests, Water and People in the Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management*. Cambridge, UK: Cambridge University Press, pp 462–483.
- Calder IR.** 2002. Forests and hydrological services: Reconciling public and science perceptions. *Land Use and Water Resources Research* 2:2.1–2.12.
- Calder IR.** 2003. Assessing the water use of short vegetation and forests: Development of the Hydrological Land Use Change (HYLUC) model. *Water Resources Research* 39:1318.
- Calder IR, Nisbet T, Harrison JA.** 2009. An evaluation of the impacts of energy tree plantations on water resources in the United Kingdom under present and future UKCIP02 climate scenarios. *Water Resources Research* 45: W00A17.
- Calder IR, Reid I, Nisbet TR, Green JC.** 2003. Impact of lowland forests in England on water resources: Application of the Hydrological Land Use Change (HYLUC) model. *Water Resources Research* 39:1319.
- Calvo JC.** 1990. Water resources development in Costa Rica 1970–2000. *Hydrological Sciences Journal* 35:185–196.
- Calvo-Alvarado JC, Jiménez JA, González E, Pizarro F, Jiménez A.** 2008. Estimación preliminar del caudal ambiental en el río Tempisque, Costa Rica: El enfoque hidrológico con pocos datos. *Kurú: Revista Forestal (Costa Rica)* 5:1–18.
- Calvo-Alvarado JC, Jiménez-Rodríguez CD, Jiménez-Salazar V.** 2014. Determining rainfall erosivity in Costa Rica: A practical approach. *Mountain Research and Development* 34:48–55.
- Carvalho LMV, Jones C, Liebmann B.** 2002. Extreme precipitation events in southeastern South America and large-scale convective patterns in the South Atlantic Convergence Zone. *Journal of Climate* 15:2377–2394.
- Cavender-Bares J, Gonzalez-Rodriguez A, Pahlich A, Koehler K, Deacon N.** 2011. Phylogeography and climatic niche evolution in live oaks (*Quercus series Virentes*) from the tropics to the temperate zone. *Journal of Biogeography* 38:962–981.
- CCT [Centro Científico Tropical].** 1989. *Tipo de Suelos de Costa Rica*. San José, Costa Rica: CCT.
- Chazdon RL, Redondo Brenes A, Vilchez Alvarado B.** 2005. Effects of climate and stand age on annual tree dynamics in tropical second-growth rain forests. *Ecology* 86:1808–1815.
- Climate Prediction Center Internet Team.** 2013. *Cold and Warm Episodes by Season*. [http://www.cpc.ncep.noaa.gov/products/analysis\\_monitoring/ensostuff/ensoyears.shtml](http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml); accessed on 17 April 2013.
- Coates AG, Obando JA.** 1996. The geologic evolution of the Central American Isthmus. In: Jackson JBC, Budd AF, Coates AG, editors. *Evolution and Environment in Tropical America*. Chicago, IL: University of Chicago Press, pp 21–56.
- Collado J, Villalobos A, Villalobos R, Retana J, Magrin GO, Travasso MI, Rodríguez GR, Boullón DR, Isabella M, Meira S, Guevara E, Jones JW, Royce F.** 2000. *Comparative Assessment of Agricultural Uses of ENSO-Based Climate Forecasts in Argentina, Costa Rica and Mexico*. An IAI Initial Science Program (ISP)-III Project. Final Report. GainesvilleFL: University of Florida.
- Dawson TP, Jackson ST, House JJ, Prentice IC, Mace GM.** 2011. Beyond predictions: Biodiversity conservation in a changing climate. *Science* 332:53–58.
- Delgado J, Llorens P, Nord G, Calder IR, Gallart F.** 2010. Modelling the hydrological response of a Mediterranean medium-sized headwater basin subject to land cover change: The Cardener River basin (NE Spain). *Journal of Hydrology* 383:125–134.
- Denyer P, Kussmaul S.** 2000. *Geología de Costa Rica*. Cartago, Costa Rica: Editorial Tecnológica de Costa Rica.

- Durán-Quesada AM, Gimeno L, Amador JA, Nieto R.** 2010. Moisture sources for Central America: Identification of moisture sources using a Lagrangian analysis technique. *Journal of Geophysical Research: Atmospheres* 115:D05103.
- FAO [Food and Agriculture Organization].** 2006. *Guidelines for Soil Description*. Rome, Italy: Food and Agriculture Organization of the United Nations.
- Frumau KFA, Burkard R, Schmid S, Bruijnzeel LA (Sampurno), Tobón C, Calvo-Alvarado JC.** 2010. Fog gauge performance under conditions of fog and wind-driven rain. In: Bruijnzeel LA, Scatena FN, Hamilton LS, editors. *Tropical Montane Cloud Forests: Science for Conservation and Management*. Cambridge, UK: Cambridge University Press, pp 293–301.
- Frumau KFA, Burkard R, Schmid S, Bruijnzeel LA (Sampurno), Tobón C, Calvo-Alvarado JC.** 2011. A comparison of the performance of three types of passive fog gauges under conditions of wind-driven fog and precipitation. *Hydrological Processes* 25:374–383.
- Giannini A, Kushnir Y, Cane MA.** 2000. Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *Journal of Climate* 13:297–311.
- Guswa AJ, Rhodes AL, Newell SE.** 2007. Importance of orographic precipitation to the water resources of Monteverde, Costa Rica. *Advances in Water Resources* 30:2098–2112.
- Guzmán I, Calvo-Alvarado J.** 2013. Planning and development of Costa Rica water resources: Current status and perspectives. *Tecnología en Marcha* 26:52–63.
- Guzmán Arias I, Calvo-Alvarado JC.** 2012. Water resources of the Upper Tempisque River watershed, Costa Rica (Technical note). *Tecnología en Marcha* 25:63–70.
- Haber WA, Zuchowski W, Bello E.** 2000. *An Introduction to Cloud Forest Trees: Monteverde, Costa Rica*. Monteverde de Puntarenas, Costa Rica: Mountain Gem Publications.
- Hajibabaei M, Janzen DH, Burns JM, Hallwachs W, Hebert PDN.** 2006. DNA barcodes distinguish species of tropical Lepidoptera. *Proceedings of the National Academy of Sciences of the United States of America* 103:968–971.
- Haria AH, Price DJ.** 2000. Evaporation from Scots pine (*Pinus sylvestris*) following natural re-colonisation of the Cairngorm mountains, Scotland. *Hydrology and Earth System Sciences* 4:451–461.
- Hartshorn GS.** 1983. 7 Plants. Introduction. In: Janzen DH, editor. *Costa Rican Natural History*. Chicago, IL: The University of Chicago Press, pp 118–157.
- Hastenrath S.** 1968. Fourier analysis of Central American rainfall. *Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie B* 16:81–94.
- Hendrickx JH, Vega D, Harrison JB, Calvo Gobbetti L, Rojas P, Miller T.** 2005. Hydrology of hillslope soils in the Upper Río Chagres watershed, Panama. In: Harmon R, editor. *The Río Chagres, Panama*. Dordrecht, Netherlands: Springer, pp 113–138.
- Hidalgo HG, Amador JA, Alfaro EJ, Quesada B.** 2013. Hydrological climate change projections for Central America. *Journal of Hydrology* 495:94–112.
- Holdridge LR.** 1967. *Life Zone Ecology*. San José, Costa Rica: Tropical Science Center.
- Huffman G, Adler R, Bolvin D, Nelkin E.** 2010. The TRMM Multi-Satellite Precipitation Analysis (TMPA). In: Gebremichael M, Hossain F, editors. *Satellite Rainfall Applications for Surface Hydrology*. Dordrecht, Netherlands: Springer, pp 3–22.
- Jeppesen E, Kronvang B, Meerhoff M, Sondergaard M, Hansen KM, Andersen HE, Lauridsen TL, Liboriussen L, Beklioglu M, Ozen A, Olesen JE.** 2009. Climate change effects on runoff, catchment phosphorus loading and lake ecological state, and potential adaptations. *Journal of Environmental Quality* 38:1930–1941.
- Jewitt GPW, Garratt JA, Calder IR, Fuller L.** 2004. Water resources planning and modelling tools for the assessment of land use change in the Luvuvhu catchment, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C* 29:1233–1241.
- Kalacska M, Sanchez-Azofeifa GA, Calvo-Alvarado JC, Quesada M, Rivard B, Janzen DH.** 2004. Species composition, similarity and diversity in three successional stages of a seasonally dry tropical forest. *Forest Ecology and Management* 200:227–247.
- Karmalkar A, Bradley R, Diaz H.** 2011. Climate change in Central America and Mexico: Regional climate model validation and climate change projections. *Climate Dynamics* 37:605–629.
- Khatun K, Imbach P, Zamora J.** 2013. An assessment of climate change impacts on the tropical forests of Central America using the Holdridge life zone (HLZ) land classification system. *iForest—Biogeosciences and Forestry* 6:183–189.
- Kirby SH.** 2011. Active mountain building and the distribution of “core” Maxillariinae species in tropical Mexico and Central America. *LANKESTERIANA* 11:275–291.
- Komatsu H, Cho J, Matsumoto K, Otsuki K.** 2012. Simple modeling of the global variation in annual forest evapotranspiration. *Journal of Hydrology* 420–421:380–390.
- Krishnaswamy J, Halpin PN, Richter DD.** 2001. Dynamics of sediment discharge in relation to land-use and hydro-climatology in a humid tropical watershed in Costa Rica. *Journal of Hydrology* 253:91–109.
- Leclerc G, Reyes C, Hall CAS.** 2000. Chapter 9: Synthesis of Costa Rican meteorological information in a geographical context. In: Hall CAS, Perez CL, Leclerc G, editors. *Quantifying Sustainable Development*. San Diego, CA: Academic Press, pp 223–264.
- Madsen H.** 2000. Automatic calibration of a conceptual rainfall–runoff model using multiple objectives. *Journal of Hydrology* 235:276–288.
- Magaña V, Amador JA, Medina S.** 1999. The midsummer drought over Mexico and Central America. *Journal of Climate* 12:1577–1588.
- Magaña V, Vázquez JL, Pérez J, Pérez J.** 2003. Impact of El Niño on precipitation in Mexico. *Geofísica Internacional* 42:313–330.
- Magrin G, Gay Garcia C, Cruz Choque D, Giménez JC, Moreno AR, Nagy GJ, Nobre C, Villamizar A.** 2007. Chapter 13: Latin America. Climate Change 2007. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, editors. *Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, pp 581–615.
- Manso P, Stolz W, Fallas JC.** 2005 Sep. El régimen de la precipitación en Costa Rica. *Ambientico* 144:7–8.
- Marshall JS, Idleman BD, Gardner TW, Fisher DM.** 2003. Landscape evolution within a retreating volcanic arc, Costa Rica, Central America. *Geology* 31:419–422.
- Matondo J, Msibi KM.** 2001. Estimation of the impact of climate change on hydrology and water resources in Swaziland. *Water International* 26:425–434.
- McPhaden MJ, Zebiak SE, Glantz MH.** 2006. ENSO as an integrating concept in earth science. *Science* 314:1740–1745.
- Meza Ocampo TA.** 2004. *Geografía de Costa Rica. Geología, Naturaleza y Políticas Ambientales*. Primera Edición 2001. Cartago, Costa Rica: Editorial Tecnológica.
- Molina Zuñiga F.** 2000. Las Pailas geothermal area, Rincón de la Vieja Volcano, Costa Rica. *United Nations University Geothermal Training Programme Reports* 2000(13):267–284. <http://raffliadan.is/bitstream/handle/10802/7258/UNU-GTP-2000-13.pdf?sequence=1>; accessed on 30 June 2015.
- Morrone JJ.** 2006. Biogeographic areas and transition zones of Latin America and the Caribbean islands based on panbiogeographic and cladistic analyses of the entomofauna. *Annual Review of Entomology* 51:467–494.
- Nair U, Ray D, Lawton R, Welch R, Pielke P, Calvo-Alvarado J.** 2010. The impact of deforestation on orographic cloud formation in a complex tropical environment. In: Bruijnzeel LA, Scatena FN, Hamilton LS, editors. *Tropical Montane Cloud Forests: Science for Conservation and Management*. Cambridge, UK: Cambridge University Press, pp 238–348.
- Nelson A, Chomitz K.** 2007. The forest–hydrology–poverty nexus in Central America: An heuristic analysis. *Environment, Development and Sustainability* 9:369–385.
- Newbold JD, Sweeney BW, Jackson JK, Kaplan L.** 1995. Concentrations and export of solutes from six mountain streams in northwestern Costa Rica. *Journal of the North American Benthological Society* 14:21–37.
- Ngoc TA, Hiramatsu K, Harada M.** 2013. Optimizing parameters for two conceptual hydrological models using a genetic algorithm: A case study in the Dau Tieng River watershed, Vietnam. *Japan Agricultural Research Quarterly* 47:85–96.
- Nielsen SA, Hansen E.** 1973. Numerical simulation of the rainfall runoff process on a daily basis. *Nordic Hydrology* 4:171–190.
- Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, Underwood EC, D’Amico JA, Itoua I, Strand HE, Morrison JC, Loucks CJ, Allnutt TF, Ricketts TH, Kura Y, Lamoreux JF, et al.** 2001. Terrestrial ecoregions of the world: A new map of life on earth: A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *BioScience* 51:933–938.
- Ortiz Malavassi E.** 2004. *Atlas Digital de Costa Rica*. Cartago, Costa Rica: Instituto Tecnológico de Costa Rica.
- Parmesan C.** 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics* 37:637–669.
- Philander SG, Holton JR, Dmowska R.** 1989. *El Niño, La Niña, and the Southern Oscillation*. International Geophysics Volume 46. San Diego, CA: Academic Press.
- Taye MT, Ntegeka V, Ogramoi NP, Willems P.** 2011. Assessment of climate change impact on hydrological extremes in two source regions of the Nile River Basin. *Hydrology and Earth System Sciences* 15:209–222.
- Tobon C, Bruijnzeel LA, Frumau F, Calvo-Alvarado J.** 2010. Changes in soil hydraulic properties and soil water status after conversion of tropical montane cloud forest to pasture in northern Costa Rica. In: Bruijnzeel LA, Scatena FN, Hamilton LS, editors. *Tropical Montane Cloud Forests: Science for Conservation and Management*. Cambridge, UK: Cambridge University Press, pp 502–515.

- Wang B.** 1994. Climatic regimes of tropical convection and rainfall. *Journal of Climate* 7:1109–1118.
- Waylen PR, Quesada ME, Caviedes CN.** 1994. The effects of El Niño–Southern Oscillation on precipitation in San José, Costa Rica. *International Journal of Climatology* 14:559–568.
- Westerberg IK, Guerrero J-L, Younger PM, Beven KJ, Seibert J, Halldin S, Freer JE, Xu C-Y.** 2011. Calibration of hydrological models using flow-duration curves. *Hydrology and Earth System Sciences* 15:2205–2227.
- Westerberg I, Walther A, Guerrero J-L, Coello Z, Halldin S, Xu C-Y, Chen D, Lundin L-C.** 2010. Precipitation data in a mountainous catchment in Honduras: Quality assessment and spatiotemporal characteristics. *Theoretical and Applied Climatology* 101:381–396.
- Xu C-Y, Singh VP.** 2001. Evaluation and generalization of temperature-based methods for calculating evaporation. *Hydrological Processes* 15:305–319.
- Xu H, Xie S-P, Wang Y, Small RJ.** 2005. Effects of Central American mountains on the eastern Pacific winter ITCZ and moisture transport. *Journal of Climate* 18:3856–3873.
- Yew Gan T, Dlamini EM, Biftu GF.** 1997. Effects of model complexity and structure, data quality, and objective functions on hydrologic modeling. *Journal of Hydrology* 192:81–103.