Streamflow Responses to Runoff and Shallow Groundwater Fluctuations within Two Nested Watersheds in Costa Rica

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Introduction

In the last decade, there has been increased awareness of climate variability over tropical regions based on the premise that changes in regional and global circulation trends may have an adverse effect on the hydrological cycle in these regions. Watersheds within the tropical montane rainforests of Costa Rica are generally understudied. Hydrologic processes along the mountainous hillslope terrain impact the storage and movement of water that supplies downstream agriculture and human consumption. In this study, we focus on characterizing streamflow responses to precipitation and groundwater fluctuations across two watershed scales (first-order and second-order). To this end, we observed lag times and baseflow contributions to streamflow along this pristine watershed.

Study Site

- Texas A&M Soltis Center, San Isidro de Peñas Blancas, Alajuela, Costa Rica
- Receives moisture inputs from Caribbean Sea and Pacific Ocean
- Tropical pre-montane transitional forest ecosystem
- 460 masl
- Total rainfall = 4200 mm/year
- Subsurface soil composed of clay with saprolitic tuff at depth, andesitic basaltic bedrock
- Groundwater seeps common

Watershed:

- Howler Monkey Stream (HM): First-order mountain stream (2.2-2.6 ha)
  - HM Upstream (HMU) is 75 m upstream of HM Downstream (HMD)
- Rio Chachagua: Second-order stream downstream of HM

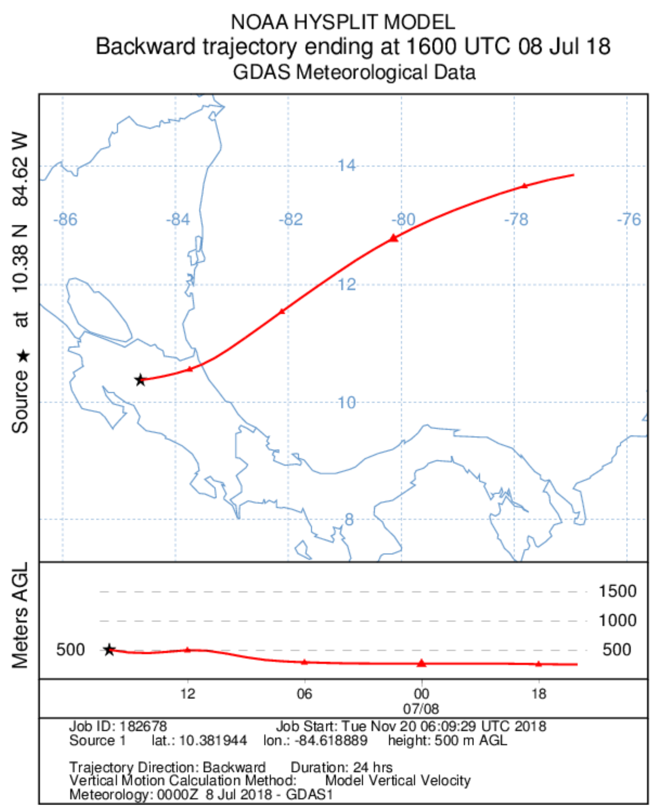


Figure 2. Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) depicting trajectory of storm event backcasted to the Caribbean Ocean. The location of the watershed is denoted by the star.

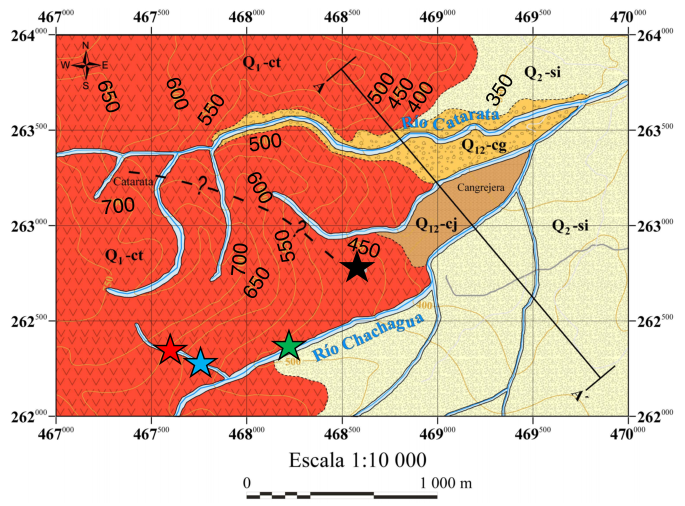


Figure 3. Topography map of Soltis Center and study sites denoted by colored stars: rain gauge (black), Chachagua (green), HMU (red), and HMD (blue). Adapted from Gonzalez, 2013. Red depicts andesitic basalt flows and light tan depicts Quaternary deposits.

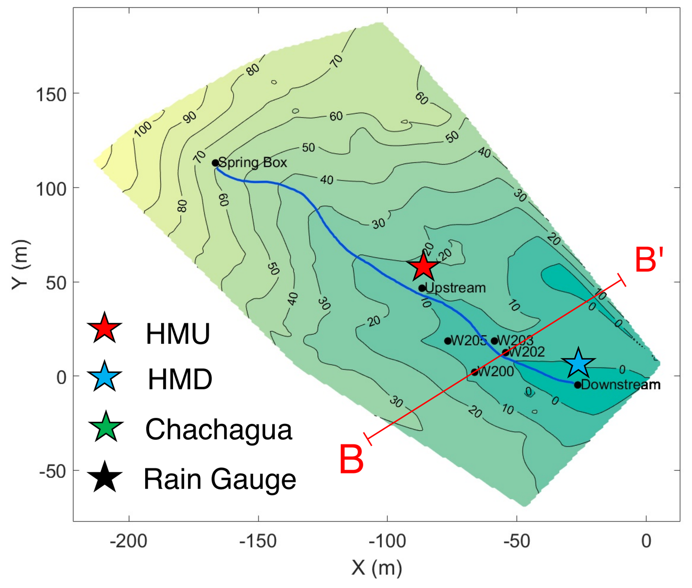


Figure 1. Topographic map of HM watershed denoting well locations, spring, and stream gauge locations (HMU and HMD). Red line denotes path of cross-section on Figure 4.

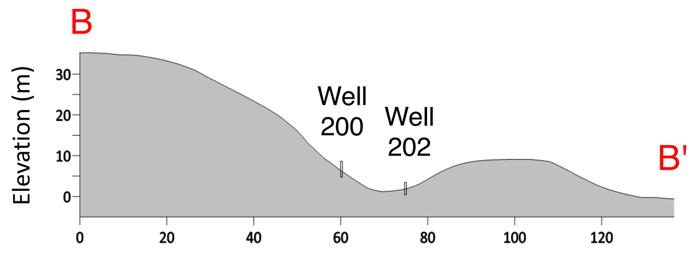


Figure 4. Cross-section of B-B' depicting locations of Well 200 and Well 202.

Methods

Sample Collection

Sampling Period: 6/19/2018 – 7/13/2018 (Wet season)

Water Table

- 4 shallow piezometers installed along banks of HM (Well 200, Well 202, Well 203, & Well 205)
- Recording raw pressure and temperature every 10 minutes

Stream Gauges

- Temporary V-notch weir installed 75 m upstream of permanent on-site V-notch weir along HM
- HMU recording raw pressure and conductivity every 10 minutes
- HMD recording water height above V-notch every 5 minutes and conductivity every 10 minutes
- Chachagua recording absolute pressure every 5 minutes and calibrated using rating curve

Precipitation

- Recorded every 5 minutes from on-site meteorological station

Stable Water Isotopes

- High frequency water samples were collected for 4 rain events along HW: stream, spring, and precipitation
- Water samples taken every 2 hours for a 48-hour period ("48-hour intensive sampling event")
- 17 daily samples
- Analyzed for $\delta^{18}O$ and δD
- External precision was ±0.12‰ for $\delta^{18}O$ and ±0.3‰ for δD

Analytical

Lag Time

- Stream: time between peak discharge and peak rainfall
- Groundwater: time between peak water level height and peak rainfall

Baseflow Separation Methods:

A. Mass balance

- One tracer, two component method
- Tracers: $\delta^{18}O, \delta D$, specific conductance
- C_p is the concentration of event water, C_{GW} is the concentration of the older groundwater, C_s is the concentration of the stream, Q_s is the total streamflow, and Q_b is the resultant baseflow

$$Q_b = Q_s\left(\frac{C_s - C_p}{C_{GW} - C_p}\right) \qquad \text{(Eq. 1)}$$

- Dumont, 2014 derived an empirical relationship between specific conductance and baseflow % for HMD using Equation 1 on $\delta^{18}O$ and δD:

$$Q_{b\%} = 1.09(SC) - 2.38 \qquad \text{(Eq. 2)}$$

- $Q_{b\%}$ is the percent baseflow, SC is specific conductivity

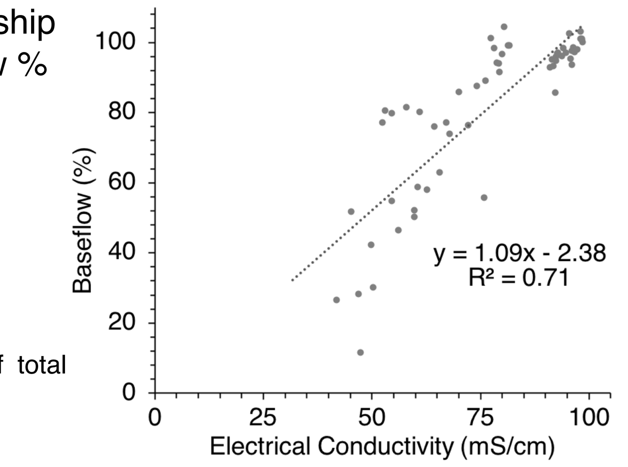


Figure 5 (right). Electrical conductivity and % baseflow of total streamflow relationship derived for HMD from Dumont, 2014.

B. Recursive Digital Filter

- R Package EcoHydRology (Based on Lyne and Hollick, 1979)
- Filtering high frequency signal as quickflow, low frequency signal as baseflow
- f_k is the filtered quick response at kth sampling instant, y_k is streamflow, and α is the filter parameter
- $y_k - f_k$ = filtered baseflow
- Per Nathan and McMahon, 1990, α is set to 0.925 and filter is passed over 3 times

$$f_k = \alpha f_{k-1} + \frac{(1+\alpha)}{2}(y_k - y_{k-1}) \qquad \text{(Eq. 3)}$$

Results

Hydrograph

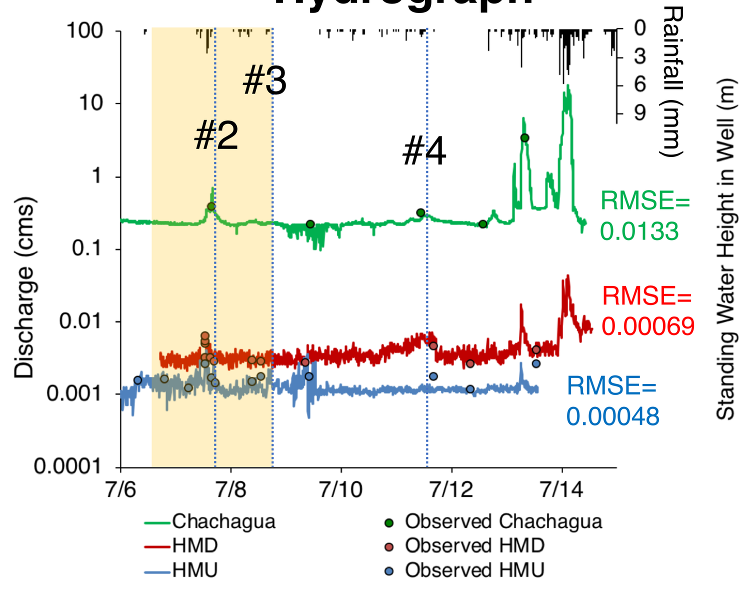


Figure 6. Streamflow hydrographs at the three gaging sites. Yellow region denotes 48-hour intensive sampling event. The numbers 2, 3 and 4 indicate high frequency, paired rainfall and stream sampling events. Root mean square error (RMSE) is the difference between the values predicted and the values observed.

Water Table

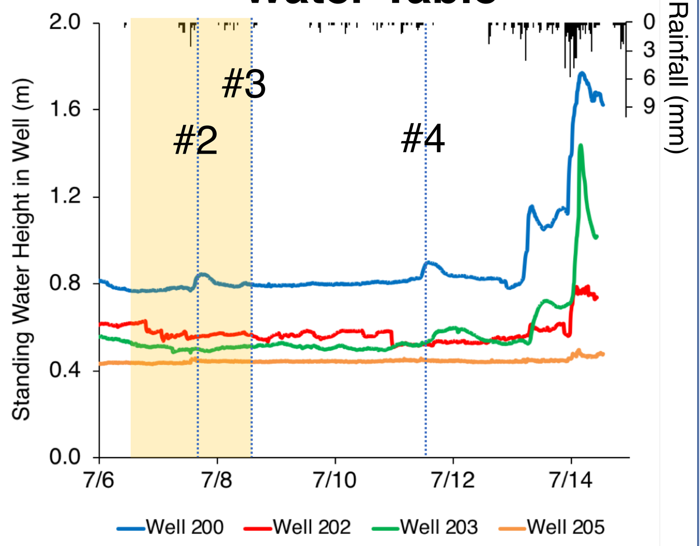


Figure 7. Hydraulic heads in 4 shallow, near-stream monitoring wells. Yellow region denotes 48-hour intensive sampling event. The numbers 2, 3 and 4 indicate high frequency, paired rainfall and stream sampling events.

Groundwater Response

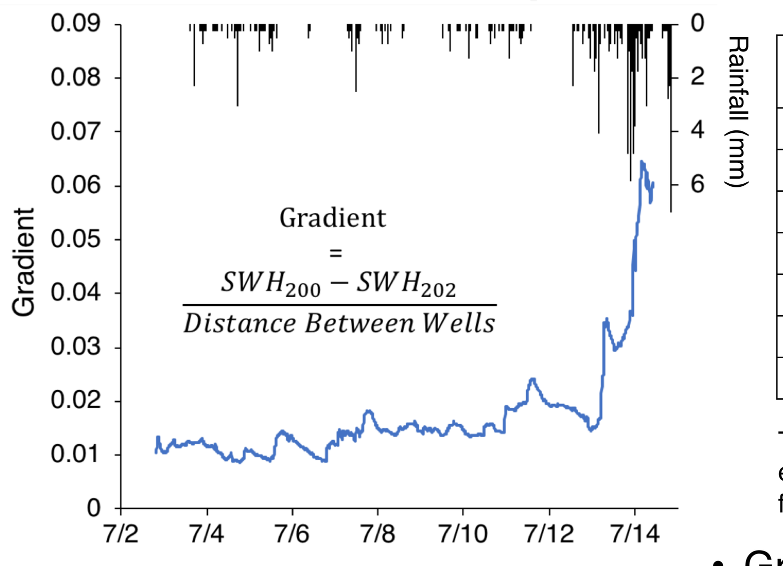


Figure 8 (left). Gradient response between Well 200 and Well 202

Lag Time Response

7/7 storm: Peak: 2.54 mm

Site	Lag time (min)
HMU	<10
HMD	<5
Chachagua	145
Well 200	255
Well 202	Negligible
Well 203	Negligible
Well 205	Negligible

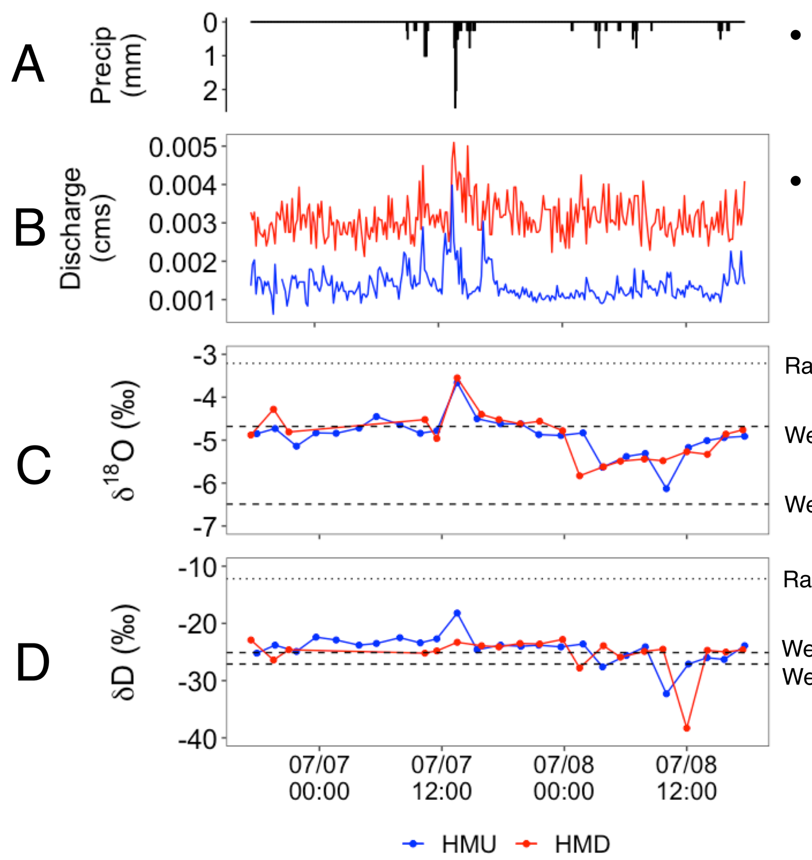
7/14 storm: Peak: 5.84 mm

Site	Lag time (min)
HMU	-
HMD	150
Chachagua	145
Well 200	230
Well 202	370
Well 203	100
Well 205	170

Table 1 (up). Lag time responses to two storm events in streamflow and SWH. Streams respond faster than groundwater in most cases.

- Gradient changes during rain events
- Intense gradient difference on 7/14

48-Hour Intensive Sampling Event: $\delta^{18}O, \delta D$



- Enrichment of heavier isotopes in highest intensity rain event (7/7)
- Enrichment of lighter isotopes during another minor storm event (7/8)
  - Quickly attenuates to baseflow conditions
- Heavier isotopes in HMD
- Dashed lines represent range in isotope values indicating groundwater endmember. Greater range in $\delta^{18}O$ than δD
- Dotted lines represent rainfall endmember

Figure 9. Time series of discharge, $\delta^{18}O$, and δD ratios over a 48-hour intensity period for HMU (red) and HMD (blue) where samples were taken every 2 hours. Figure 9A shows the hyetograph for the sampling period. Figure 9B displays the streamflow hydrographs at the HMU and HMD. Figures 9C-D present the time series of $\delta^{18}O$ and δD in the stream with horizontal lines indicating the signature rainfall isotope ratios and the absolute ranges of isotope values found in the shallow wells.

Results and Conclusion

$\delta^{18}O$ and δD during high frequency, paired rainfall, and stream sampling events

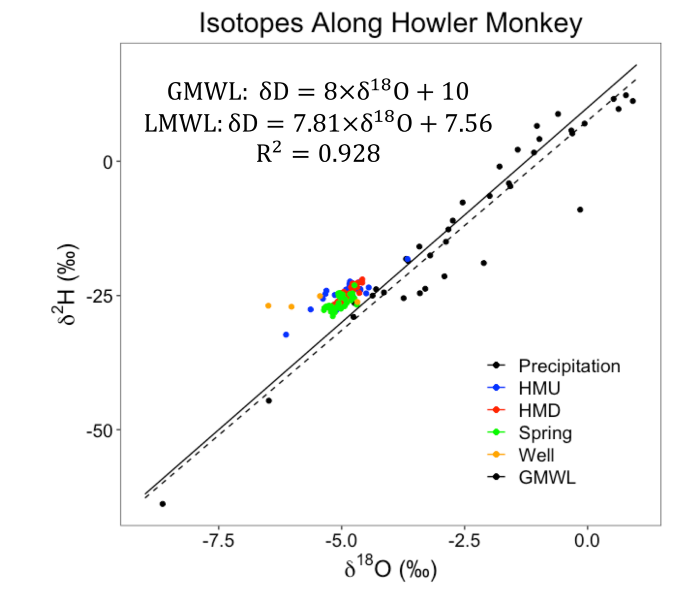


Figure 10. Distribution of deuterium and oxygen ratios occurring along the Howler Monkey Stream.

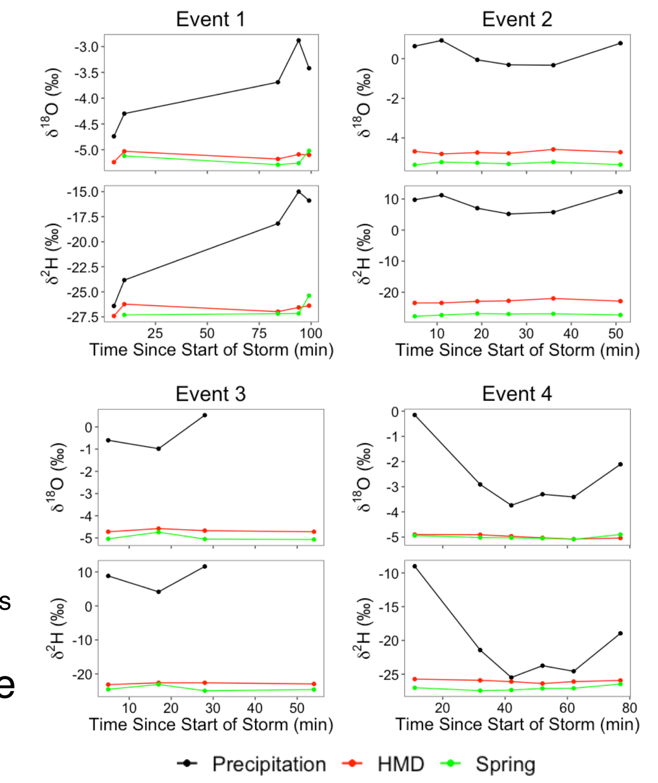


Figure 11. Time series of $\delta^{18}O$ and δD ratios over 4 storm events. Some events are susceptible to rainout/amount effect.

- Stream values indicate large influence from groundwater
- Evidence of evaporation even during wet season because slope of LMWL is less than GMWL

Baseflow Separation Comparison

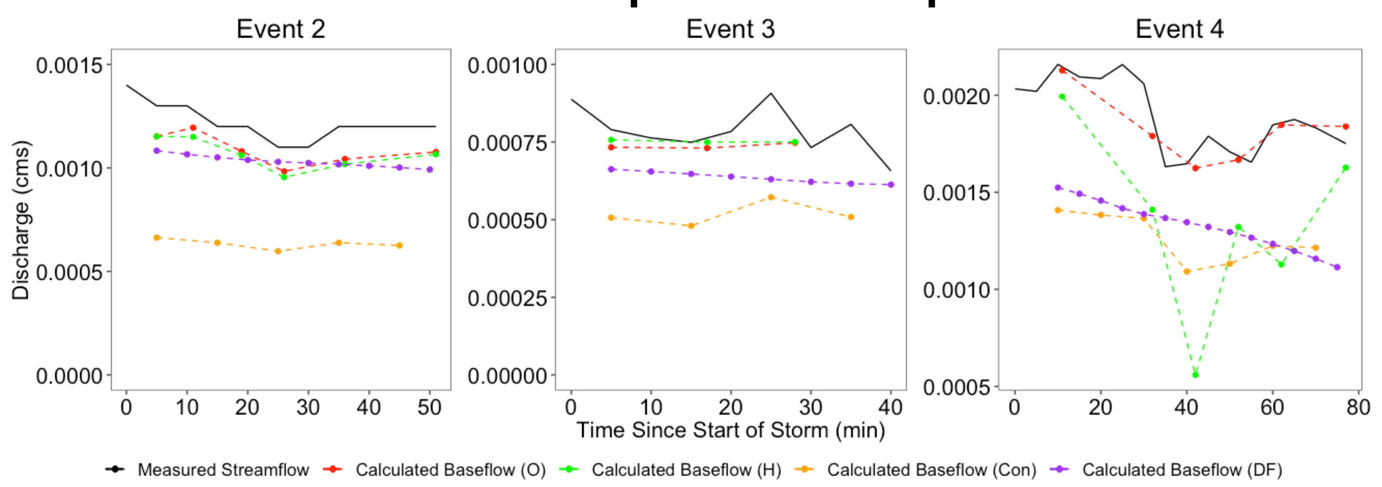


Figure 12. Separating baseflow from hydrograph using Eq.1-3 for each storm. Colored lines represent calculated baseflow by method: $\delta^{18}O$ (red), δD (green), specific conductance (orange), and digital filter.

1. Baseflow dominates streamflow (%) during storms, minimal overland flow component
2. On average, mass balance method using $\delta^{18}O$ estimates highest baseflow index while the empirical model using specific conductance estimates the lowest baseflow index
3. Rapid responses to rainfall in discharge and wells
4. Evaporation is occurring to precipitation sources before or after it reaches the watershed

Baseflow % of Howler Monkey

Method	Event 2	Event 3	Event 4	Average
$\delta^{18}O$	89.9	92.5	97.4	93.3
δD	87.9	94.5	71.4	84.6
SC	52.7	64.9	66.6	61.4
DF	86.3	84.0	72.0	80.8
Average	79.2	84.0	76.9	80.0
Rain (mm)	2.032	1.524	0.254	

Table 2. Displays baseflow percent of streamflow based on the four methods analyzed in the study.

5. Differences between baseflow separation methods could be attributed to different groundwater fluxes
6. Digital filter method seems like promising tool in runoff analyses of Chachagua

References & Acknowledgements

Dumont, A. (2014). *Hillslope Hydrological Processes in a Costa Rican Rainforest: Water Supply Partitioning Using Isotope Tracers.* (Unpublished master's thesis). Texas A&M University.

González, A. (2013). *Geología del Soltis Center for Research and Education y alrededores.* (Unpublished undergraduate thesis). Universidad de Costa Rica & Texas A&M University.

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