Luquillo Experimental Forest: catchment science in the montane tropics

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Abstract

Catchments in the Luquillo Mountains of Puerto Rico are warm, wet, and tropical with steep elevational relief creating gradients in temperature and rainfall. Long-term objectives of research at the site are to understand how changing climate and disturbance regimes alter hydrological and biogeochemical processes in the montane tropics and to provide information critical for managing and conserving tropical forest ecosystems globally. Measurements of hydrology and meteorology span decades, and currently include temperature, humidity, precipitation, cloud base, throughfall, groundwater table elevation, and stream discharge. The chemistry of rain, throughfall, and streams is measured weekly, and lysimeters and wells are sampled monthly to quarterly. Multiple data sets document the effects of major hurricanes including Hugo (1989), Georges (1998), and Maria (2017) on vegetation, biota, and catchment biogeochemistry and provide some of the longest available records of biogeochemical fluxes in tropical forests. Here we present an overview of the findings and the data sets that have been generated from the Luquillo Mountains, highlighting their importance for understanding montane tropical watersheds in the context of disturbance and global environmental change

1.0 Site Description and Methods

The Luquillo Mountains (LM) have a long history of research on their flora and fauna, with the earliest work published shortly after the US acquired Puerto Rico from Spain in 1898. The pace of research increased with establishment of the Luquillo National Forest by the US Forest Service in 1907 (Lugo et al. 2012), and publications increased in the 1920s with seminal papers on vegetative composition and succession (Gleason and Cook 1926). In the 1930-40s, the US Forest Service International Institute of Tropical Forestry (IITF) conducted silvicultural studies that served as the basis for managing tropical forest production, and led to the designation of the entire National Forest as the Luquillo Experimental Forest in 1956. An emphasis on ecosystem science at the site began in 1963 with initiation of the Rain Forest Project (Odum and Pigeon 1970). Long-term watershed-scale hydrology and biogeochemistry began in 1983 (McDowell et al. 1990; McDowell and Asbury 1994) and continued with U.S. National Science Foundation funding of the Luquillo Long-Term Ecological Research (LUQ-LTER) site in 1988. LUQ-LTER is a multi-faceted research program focused on long-term ecosystem response to disturbance and is jointly led by the University of Puerto Rico and IITF. The University of New Hampshire, the US Geological Survey (USGS) and IITF have led efforts to understand catchment-scale biogeochemical cycles (e.g. Scatena 1989, 1990; McDowell 1998; Schaeffer et al. 2000; Crook et al. 2007; Heartsill-Scalley et al. 2007; Murphy and Stallard 2012; McDowell et al. 2013; Clark et al. 2017; Wymore et al. 2017). This long history of catchment research has resulted in one of the best understood tropical forest systems in the world, including forest plots that span almost 100 years of measurement (Harris et al. 2012) and the longest continuous record of tropical stream chemistry on Earth (McDowell 2017b). These observations provide an important basis for understanding tropical montane forests in a global context (Lugo et al. 2012).

Geologic setting

The island of Puerto Rico is the smallest and easternmost of the Greater Antilles (Fig. 1) and the current land mass was formed during submarine and subaerial volcanism that ended approximately 30 million years ago (MYA). Uplift at approximately 5 MYA resulted in the current configuration of the island (Brocard et al. 2016). Puerto Rico has never been connected to a continental land mass and sits on the edge of the Caribbean Plate adjacent to the Puerto Rico trench, second only to the Marianas trench in depth. Lithology in the Luquillo Mountains is primarily volcaniclastic, but a granitoid pluton underlies some of the Mountain massif (Figure 2), providing a second major lithology in the Luquillo Mountains as well as contacts where the pluton metamorphosed volcaniclastic materials into more erosion-resistant hornfels that is found on many of the mountain peaks and high elevation ridges (Seiders 1971). The two lithologies result in very different weathering regimes and stark contrasts in stream channel grain size and morphology (Fig. 2).

Climate/Hydrometeorology

The Luquillo Mountains have steep slopes and rise abruptly from the coast to peaks nearly 1100 m asl over the course of 10 km (González et al. 2013). Average annual temperatures range from 20 to 25° C (Harris et al. 2012). Average annual rainfall ranges from approximately 2500 to 5000 mm varying primarily with elevation, but patterns of rainfall shadowing depending on wind direction also have a strong influence on annual rainfall (Murphy et al. 2017). Hurricanes occur frequently at the site, with direct hits to the Luquillo Mountains by Category 3 or higher storms thought to occur about every 60 years, based on historic records of several hundred years duration (Scatena and Larsen 1991, López-Marrero et al. 2019). Interception rates decline following hurricane defoliation and canopy damage; rates return to background levels once canopy cover has been re-established (Heartsill-Scalley et al. 2007). Interception loss is high at the site, and has been attributed to the rainfall pattern, with many small storms that wet the canopy but generate relatively little throughfall (Scatena 1990).

Atmospheric inputs to LM catchments include large amounts of marine aerosols (Gioda et al. 2013, Medina et al. 2013, McDowell et al. 1990). Transport of dust from North African deserts occurs frequently and affects both rain and throughfall chemistry (Heartsill-Scalley et al. 2007; McClintock et al. 2019). Clouds and fog inputs are large relative to many sites (Eugster et al. 2006) but represent a small proportion of total precipitation input on the highest peaks. Although previous studies reported cloud base level starts at 600 m, Van Beusekom et al. (2017) showed that the lowest cloud base most frequently occurs at 702 to 915 m. Weekly measurements of throughfall volume and chemistry have been made since 1988, providing the only published record of long-term variation in throughfall volume and chemistry in a tropical forest (McDowell 2017a). Throughfall in the Luquillo Mountains is particularly enriched in potassium (K^+) relative to rainfall, as is observed globally (McDowell et al. 2020). Annual fluxes of K^+ in throughfall are twice as high as litterfall K^+ fluxes, and proportionally much higher than those of any other element (McDowell 1998). Hydrologic infrastructure includes 4 meteorological stations, an NADP station (PR 20), 3 bulk precipitation collectors, a network of throughfall collectors, 12 stream gages, 3 walk-up canopy towers, 3 deep observation wells, several dozen riparian wells, and 3 lysimeter nests.

Soil biogeochemistry

Soils are deep, highly weathered, and generally Inceptisols or Ultisols (Boccheciamp 1977; Soil Survey Staff 1995). Soils are high in clay content and regolith extends to 10s of meters below the soil surface (Buss et al. 2017). Organic matter, nutrients, and exchangeable cations vary with lithology (volcaniclastic vs granitoid; McDowell et al. 2012), geomorphic position (ridge vs valley; McDowell et al. 2012), and position in the drainage network (higher soil cations below knickpoints in the granitoid terrain; Porder et al. 2015). Soils on middle to high elevations are very strongly acidic with low base saturation ($<20\%$) due to a strong leaching environment (Ping et al. 2013). Weathering rates are very rapid, and the well-studied Icacos watershed is the fastest weathering granitic terrain on Earth (White et al. 1995). Soils show strong temporal and spatial variability in redox regime (Liptzin et al. 2010, Liptzin and Silver 2015), with drought causing large increases in average oxygen concentration at all topographic positions except riparian valleys (O'Connell et al. 2018). Landscape movement on uplands through landslides, slumps and fluvial/alluvial processes has a significant effect on variation of C stores (Ping et al. 2013). Earthworms play a major role in soil nutrient cycling as well as in maintaining soil infiltration (Larsen et al. 2012).

Catchment vegetation dynamics

Vegetation in the Luquillo Mountains shows strong variation along a complex elevation gradient (Gould et al. 2006, Barone et al. 2008) with forest types typically described as those occurring either above or below the cloud condensation level. Lower elevation riparian wetlands and tabonuco forest (dominated by *Dacryodes excelsa*) occur below the cloud levels. At higher elevations, forest community structure includes an increase in epiphytes, bromeliads on the forest floor, and a higher density of shorter and smaller trees. The upper cloud forests comprise palo colorado communities (*Cyrilla racemiflora*) and sierra palm (*Prestoea montana*) in both floodplain and palm break forests. At the highest elevations, elfin forests are the dominant vegetative community (*Tabebuia rigida)* , and include herbaceous and *Sphagnum* bogs (Harris et al. 2012). Palms are found throughout all elevations in the Luquillo Mountains. Hurricanes disturbances cause significant stem breakage, leading to changes in forest structure and shifts in species composition during succession (Heartsill-Scalley 2017, Uriarte et al. 2019). *Cecropia schreberiana* is an early successional species that contributes to re-establish canopy cover following hurricanes (Thompson et al. 2002). Export of stream coarse particulate organic matter (CPOM) has been measured biweekly since 1993, and response to hurricanes indicates that total CPOM export is strongly associated with the level of maturity of watershed vegetation (Heartsill-Scalley et al. 2012). Litterfall is measured biweekly at multiple sites and is altered by both hurricanes and experiments that simulate a portion of hurricane effects (Silver et al. 2014; Silver 2018). Seasonal patterns in leaf fall are correlated mainly with solar radiation, photosynthetic photon flux density (PPFD), day length, and temperature; and secondarily with rainfall (Zalamea and González 2008). Vegetation is not limited to any significant extent by nitrogen availability. A long-term N fertilization experiment resulted in no change in biomass increment or litterfall, and only modest impacts on litter chemistry (Cusack et al. 2011). Soil organisms and hurricanes have significant effects on litter decay and associated nutrient release (González et al. 2014).

River runoff and chemistry

River drainage networks occur in a radial fashion around the central peaks of the Luquillo Mountains, El Yunque and East Peak (Fig. 1) and drain into both the Caribbean Sea and the North Atlantic. Streams and rivers are very flashy in the Luquillo Mountains (Jones et al. 2012). Instantaneous discharge is collected by the USGS at multiple sites, with the longest record (since 1945) at Río Icacos (50075000); other past or current USGS gauges include Quebrada Guaba (50074950) in the Icacos/Blanco drainage; Río Mameyes at Puente Roto (50065500), Río Espiritu Santo at El Verde (50063800), Quebrada Sonadora (50063440) and Quebrada Toronja at El Verde (50063500), and Río Sabana at Luquillo (50067000). The University of Puerto Rico and the US Forest Service International Institute of Tropical Forestry also maintain discharge records for Quebrada Prieta (El Verde) and the Bisley Experimental Watersheds (Sabana), respectively. Smaller headwater tributaries are nested within mainstem rivers (Figure 1; Wymore et al. 2017). Critical zone structure drives flow duration, with long periods of sustained baseflow in the granitoid Icacos basin when compared to the Sonadora and Toronja basins, which are on largely volcaniclastic parent material (McDowell and Asbury 1994).

Multiple streams are sampled weekly in the Luquillo Mountains, with periodic storm sampling (e.g. Clark et al. 2017, Wymore et al. 2017). Analysis of major cations and anions, nutrients and dissolved organic matter has occurred since 1983 (Figure 3), with a focus on understanding the response of forested catchments to the frequent hurricane disturbances in the LEF (McDowell et al. 2013) and describing the role of watershed (McDowell and Liptzin 2014) versus in-channel controls on stream N dynamics (Merriam et al. 2002; Rodriguez-Cardona et al. in press). Recent deployment of high-frequency water quality sensors that measure NO_3^-, conductivity, temperature, dissolved oxygen, fluorescent dissolved organic matter and turbidity provides new insights into controls on stream chemistry (e.g. Wymore et al. 2019).

Stream chemistry in the Luquillo Mountains is typically circumneutral, has relatively high concentrations of sea salts due to large inputs of marine aerosols, and high concentrations of various weathering products (e.g. SiO_2 and bicarbonate) due to the warm and wet environment that promotes rapid weathering in both volcaniclastic and granitoid lithologies (McDowell and Asbury 1994; Shanley et al. 2011; Murphy and Stallard 2012). Nitrogen concentrations are relatively high, with inorganic N dominated by nitrate, as is typical of many tropical forests (Lewis et al. 1999). Phosphorus concentrations are moderate, and dissolved organic matter concentrations (dissolved organic carbon and nitrogen) are low to moderate as found in many well-drained forested catchments (McDowell and Asbury 1994). Concentrations of many solutes are highly responsive to flow, with strong dilution observed for weathering products and strong flushing of dissolved organic carbon (McDowell and Asbury 1994; Shanley et al. 2011). Hurricanes result in increased concentrations and fluxes of NO_3^- and K^+, but little change in other solutes (McDowell et al. 2013; Schaefer et al. 2000; Fig. 3). Differences in structure of the critical zone drive differences among watersheds in concentration-discharge relationships, which are particularly evident for dissolved phosphorus (Wymore et al. 2017). Weathering at the bedrock-regolith interface almost 10 m below the soil surface is a significant source of Mg^{2+} at low flows (Chapela Lara et al. 2017), showing that weathering products may be transported to streams along deep flow paths with little opportunity for uptake by upland vegetation (McDowell 1998). Biota can affect stream chemistry, as the assemblage of shrimp species has been shown experimentally to affect both nitrate and dissolved organic carbon concentrations (Crowl et al. 2000).

3.0 Data availability statement

Data are freely available at the LTER network EDI data portal, https://portal.edirepository.org, and the NWIS for stream gauging by USGS, https://waterdata.usgs.gov/pr/nwis/rt.

4.0 Acknowledgements

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Figure 1. Map of the Luquillo Mountains of Puerto Rico and the Luquillo Experimental Forest. Colors represent major lithology types and the primary study catchments are outlined. RI: Río Icacos; QG: Quebrada Guaba; MPR: Mameyes at Puente Roto; Q1-3: Bisley 1,2, and 3; RS: Río Sabana; RES4: Rio Espiritu Santo; QS: Quebrada Sonadora; QP: Quebrada Prieta; RG: Río Grande.

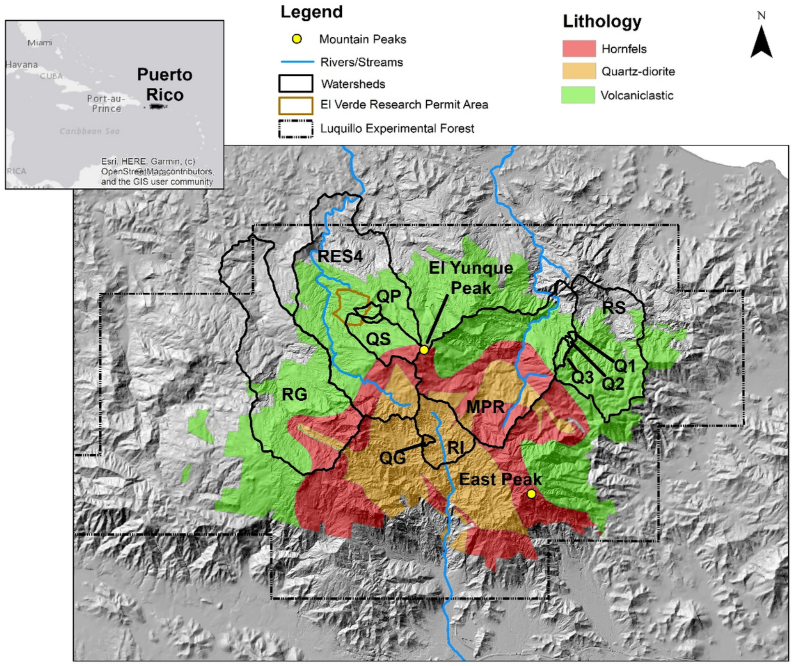
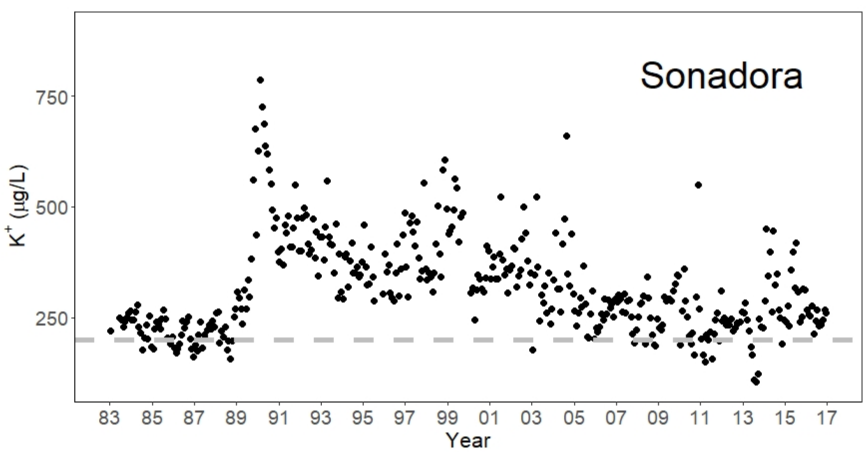


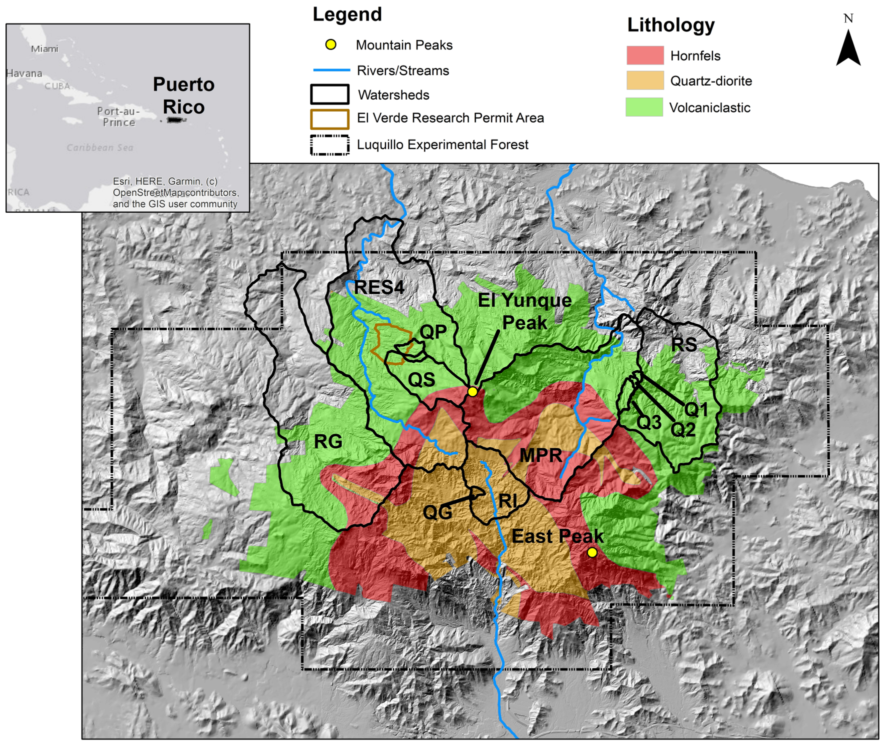
Figure 2. Photos of (A) Quebrada Sonadora which drains volcaniclastic lithology and (B) Río Icacos which drains a granitoid pluton. (photos by William McDowell)

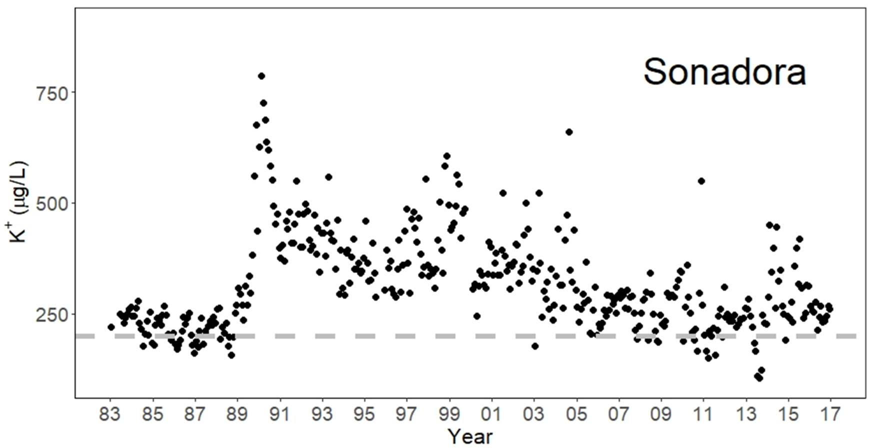
A

B

Figure 3. Exemplar stream chemistry data set showing average monthly concentrations of potassium (K^+) from weekly samples taken 1983-2017 in Quebrada Sonadora. Major hurricanes occurred in 1989 (Hugo) and 1998 (Georges). Dashed horizontal line is average concentration prior to Hurricane Hugo in 1989. Data from McDowell 2017b.




Legend
Mountain Peaks
Rivers/Streams
Watersheds
El Verde Research Permit Area
Luquillo Experimental Forest
Lithology
Hornfels
Quartz-diorite
Volcaniclastic
N
Miami
Havana
CUBA
Puerto Rico
Port-au-Prince
Caribbean Sea
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community
RES4
El Yunque Peak
QP
QS
RS
Q1
Q3
Q2
RG
MPR
QG
RI
East Peak


Sonadora
750
500
250
K+ (µg/L)
83
85
87
89
91
93
95
97
99
01
03
05
07
09
11
13
15
17
Year