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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

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Luquillo Experimental Forest: Catchment science in the montane tropics

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Abstract

Catchments in the Luquillo Experimental Forest (LEF) 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 level, 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 LEF, highlighting their importance for understanding montane tropical watersheds in the context of disturbance and global environmental change.

KEYWORDS

Caribbean, disturbance, hurricane, nitrate, potassium, precipitation chemistry, stream chemistry, throughfall chemistry, tropics, vegetation dynamics, weathering

1 | DATA SET NAME

Luquillo Experimental Forest Long-term Catchment Study.

2 | SITE DESCRIPTION AND METHODS

The Luquillo Experimental Forest (LEF; 18.298 N, 65.791 W) encompasses most of the Luquillo Mountains in Northeastern Puerto Rico (Figure 1). The Luquillo Mountains have a long history of research on their flora and fauna, with the earliest work published over a centruy ago (Bruner, 1919). The pace of research increased with establishment of the Luquillo National Forest by the U.S. Forest Service in 1907 (Lugo et al., 2012), and publications increased in the 1920s with seminal papers on vegetative composition and succession (Gleason & Cook, 1927). In the 1930–40s, the U.S. 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 & Pigeon, 1970). Long-term watershed-scale hydrology and biogeochemistry began in 1983 (McDowell et al., 1990; McDowell & Asbury, 1994) and continued with National Science Foundation funding of the Luquillo

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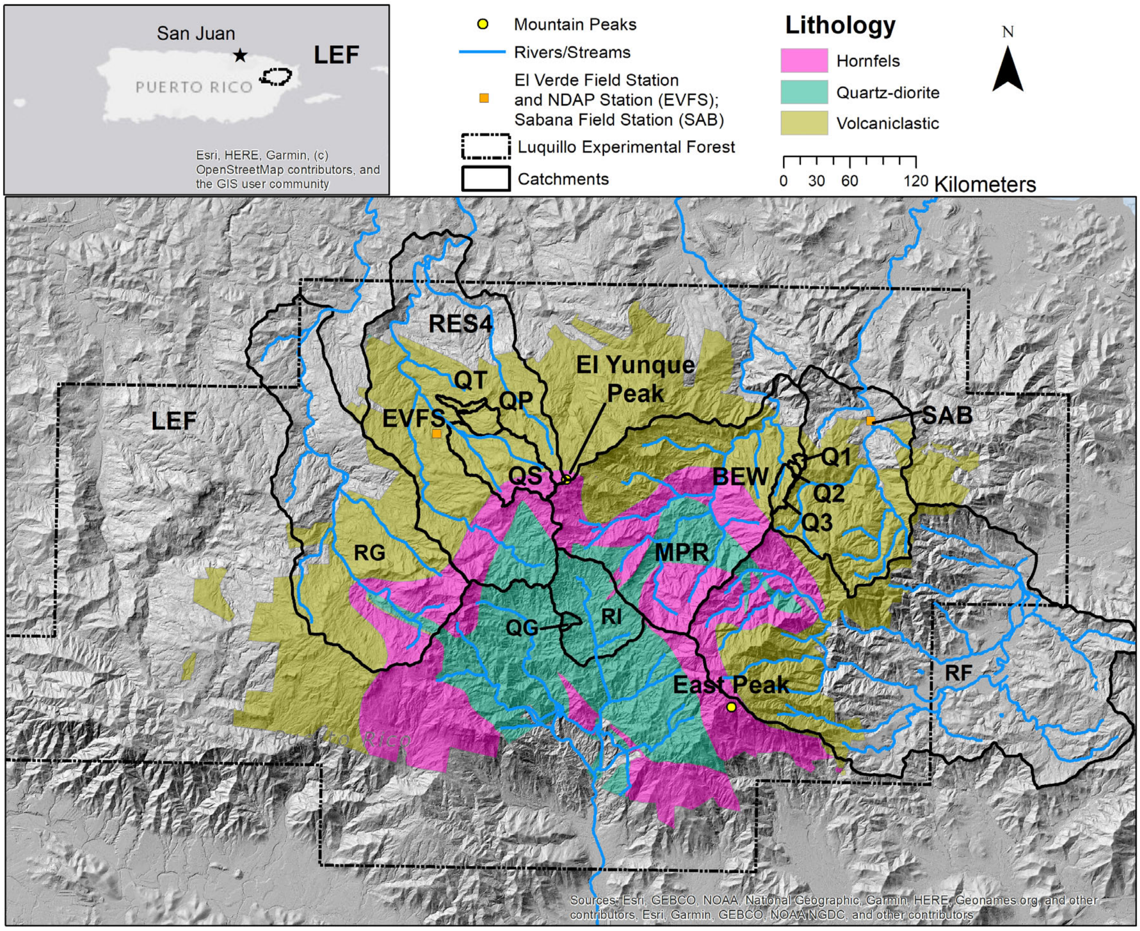

FIGURE 1 Map of the Luquillo Mountains of Puerto Rico and the Luquillo experimental Forest. Colours represent major lithology types and the primary study catchments are outlined. RI: Río Icacos; QG: Quebrada Guaba; MPR: Mameyes at Puente Roto; Q1-3: Bisley experimental watershed (BEW) 1, 2 and 3; RS: Río Sabana; RES4: Río Espíritu Santo; QS: Quebrada Sonadora; QP: Quebrada Prieta; RG: Río Grande; RF: Río Fajardo. Stream chemistry is sampled in all the outlined catchments. Throughfall is measured in catchments Q1 and Q2

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 U.S. Geological Survey (USGS) and IITF have led efforts to understand catchment-scale biogeochemical cycles (e.g. Clark et al., 2017; Crook et al., 2007; Heartsill-Scalley et al., 2007; McDowell, 1998; McDowell et al., 2013; Murphy & Stallard, 2012; Scatena, 1989, 1990; Schaefer et al., 2000; 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 (e.g., McDowell et al., 2013). These observations provide an important basis for understanding tropical montane forests in a global context (Lugo et al., 2012).

2.1 | Geologic setting

The island of Puerto Rico is the smallest and easternmost of the Greater Antilles (Figure 1) and the current land mass was formed during submarine and subaerial volcanism that ended approximately 30 million years ago. Uplift at approximately 5 million years ago resulted in the current configuration of the island (Brocard et al., 2016), which has never been connected to a continental land mass. Lithology in the Luquillo Mountains is primarily volcaniclastic (Figure 1), although a granitoid pluton underlies some of the Mountain massif and provides a second major lithology in the LEF as well as contacts where the pluton metamorphosed volcaniclastic materials into more erosion-resistant hornfels (Seiders, 1971). Hornfels is found on many of the mountain peaks and high elevation ridges (Figure 1). The two major lithologies result in different weathering regimes and stark contrasts in stream channel grain size and morphology, with large boulders in streams draining the volcaniclastic terrain such as the Sonadora catchment, and sand-filled channels in the granitoid terrain such as the Icacos catchment (Pike et al., 2010; Figure 2). Both lithologies have deep regolith with soils grading to saprolite (Buss et al., 2017) and in the granitic terrain, spherically weathering core stones within sets of vertical fractures, as determined by Ground Penetrating Radar and seismic techniques (Comas et al., 2020; data set 1). Landslides are common throughout the LEF and accelerate delivery of sediment from the land surface to streams and rivers (Larsen, 2012).

FIGURE 2 Photographs of (a) Quebrada Sonadora, which drains volcaniclastic lithology and (b) Río Icacos, which drains a granitoid pluton (photographs by William McDowell)

2.2 | Climate

The Luquillo Mountains rise abruptly from the coast to peaks nearly 1100 m above sea level (a.s.l.) over the course of 10 km (González et al., 2013), and average stream channel slopes range from 1.4% to 24% in various study catchments of the LEF (McDowell & Asbury, 1994). Average annual temperatures range from 20°C to 25°C (Harris et al., 2012, Ramírez, 2017; data set 2). Average annual rainfall ranges from approximately 2500–5000 mm varying primarily with elevation, but patterns of rainfall shadowing depending on wind direction also have a strong influence on spatial variability of annual rainfall (Murphy et al., 2017, Ramírez, 2021a; data set 3). On-going records of temperature, rainfall and wind speed are available at the Sabana Field Station and East Peak (González, 2017; data set 4) and at El Verde Field Station (Ramírez, 2021b; data set 5). On-going rainfall is also recorded by the National Atmospheric Deposition Program (NADP) at El Verde Field station (data set 6) and by the USGS at Rio Icacos (data set 7). Major hurricanes (>Category 3) have traversed the Luquillo Mountains about every 60 years with records dating back to 1700 (López-Marrero et al., 2019; Scatena & Larsen, 1991).

2.3 | Hydrometeorology

Interception rates decline following hurricane defoliation and canopy damage; rates return to background levels once canopy cover has been re-established after 2–3 years of regrowth (Heartsill-Scalley et al., 2007) and records of interception are on-going (Heartsill-Scalley, 2017a; data set 8). Interception loss is high at the site due to the rainfall pattern, with many small storms that wet the canopy but generate relatively little throughfall (Scatena, 1990).

Atmospheric inputs to LEF catchments include large amounts of marine aerosols (Gioda et al., 2013; McDowell et al., 1990; Medina et al., 2013). Transport of dust from North African deserts occurs periodically and affects both rain and throughfall chemistry (Heartsill-Scalley et al., 2007; McClintock et al., 2019) and can suppress precipitation (Mote et al., 2017). Clouds and fog inputs at high elevations are large relative to many sites (Eugster et al., 2006) although they represent only a small fraction of total precipitation input even on the highest peaks. The cloud base most frequently occurs at 700–900 m (Van Beusekom et al., 2017; data set 9), but rises during periods of drought and after hurricane defoliation (Scholl, Bassiouni, et al., 2021; Scholl, Torres-Sánchez, et al., 2021; data set 10).

2.4 | Atmospheric deposition chemistry

Weekly measurements of bulk rainfall chemistry, and throughfall volume and chemistry have been made since 1988 at the Bisley Experimental Watersheds (BEW; Figure 1) and are on-going (Heartsill-Scalley 2017a; McDowell, 2017a; data set 11), providing the only published record of long-term variation in throughfall volume and chemistry in a tropical forest (Heartsill-Scalley et al., 2007). Throughfall in the LEF 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; for other elements litterfall fluxes greatly exceed those of throughfall (McDowell, 1998). Rainfall in the LEF has higher levels of marine aerosols and non-sea salt calcium in the upwind Bisley site than in El Verde (Gioda et al., 2013), where weekly bulk rain chemistry has been collected since 1983 and is on-going (McDowell, 2017a; data set 11). Along an elevational gradient (0–1045 m a.s.l.) of 21 bulk deposition stations collected monthly, Torres-Delgado et al. (2021) found that annual inputs of crustal aerosols from Africa and marine aerosols generally increased with elevation up to cloud formation level but decreased at the highest elevations. Wet deposition is lower in all solutes than bulk deposition (McDowell et al., 1990) and weekly measurements of wet deposition are on-going as part of the NADP (data set 12).

2.5 | Soil biogeochemistry

Soils are deep, highly weathered, high in clay content, and generally Inceptisols or Ultisols (Boccheciamp, 1977; Soil Survey Staff, 1995). Organic matter, nutrients and exchangeable cations vary with lithology (volcaniclastic vs. granitoid; McDowell et al., 2012; data set 13), geomorphic position (ridge vs. valley; McDowell et al., 2012; Johnson & Xing, 2020), 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%; Ping et al., 2013). Weathering rates are rapid, and the well-studied Icacos watershed is thought to be one of the fastest weathering granitic terrains on Earth (White & Blum, 1995). Soils show strong temporal and spatial variability in redox regime (Liptzin et al., 2010; Liptzin & Silver, 2015), with drought causing large increases in average oxygen concentration at all topographic positions except riparian valleys (O'Connell et al., 2018). Landscape movements on uplands such as landslides, slumps and fluvial/alluvial processes have a significant effect on variation in carbon 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).

2.6 | Catchment vegetation dynamics

Vegetation in the LEF shows striking variation with elevation (Barone et al., 2008; Gould et al., 2006). Lower elevation riparian wetlands and tabonuco forest (dominated by *Dacryodes excelsa*) occur at 200–600 m a.s.l. At higher elevations, where cloud condensation can be significant, forest communities have a higher density of shorter and smaller trees, and epiphytes and ground-dwelling bromeliads are more numerous. Cloud forest (largely 600–900 m a.s.l.) is characterized by palo colorado communities (*Cyrilla racemiflora*) and sierra palm (*Prestoea montana*) in both floodplain palm forests and palm brakes on steep slopes. At the highest elevations (900–1000 m a.s.l), elfin forests are the dominant vegetative community (*Tabebuia rigida*) and include *Sphagnum* bogs (Harris et al., 2012). Palms are found at all elevations. Hurricane winds can cause significant stem breakage at all elevations, leading to changes in forest structure and shifts in species composition during succession (Heartsill-Scalley, 2017b; Uriarte et al., 2019). *Cecropia schreberiana* is an early successional species that contributes to re-establishment of 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; data set 14). Seasonal patterns in leaf fall are correlated mainly with solar radiation, day length, and temperature (Zalamea & 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 increases in N content of leaf litter (Cusack et al., 2011). Litter decay rates on the forest floor are rapid and driven by microbes as well as earthworms and springtails (González et al., 2014).

2.7 | River runoff and subsurface hydrology

River drainage networks occur in a radial fashion around the central peaks of the Luquillo Mountains, El Yunque and East Peak (Figure 1) and drain into both the Caribbean Sea and the North Atlantic. Streams and rivers are flashy in the LEF (Jones et al., 2012). Instantaneous discharge is collected by the USGS at multiple sites (Table 1). Río Icacos (50075000; data set 15), which with its small tributary Quebrada Guaba (50074950; data set 16) drains south to the Caribbean, has the longest record (since 1945). The other current or discontinued USGS gauges drain north to the Atlantic and include Río Mameyes at Puente Roto (50065500; data set 17), Río Espíritu Santo at El Verde (50063800; data set 18), Río Grande near El Verde (50064200; data set 19), Quebrada Sonadora (50063440; data set 20) and Quebrada Toronja at El Verde (50063500; data set 21), Río Sabana at Luquillo (50067000; data set 22) and Río Fajardo (50070900; data set 23). The University of Puerto Rico also maintains discharge records for Quebrada Prieta at El Verde; data set 24). Accuracy of the USGS gauging is typically rated as fair, with 95% of daily values accurate to within 15%. 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 volcaniclastic parent material (McDowell & Asbury, 1994). Stream hydrologic interpretation is supported by continuous groundwater level monitoring (Luquillo, 2020; data set 25) and continuous soil moisture at several depths (González et al., 2019; data set 26).

2.8 | Stream and subsurface chemistry

Multiple streams are sampled weekly in the LEF, with periodic storm sampling (Clark et al., 2017; Scholl et al., 2015; Wymore et al., 2017). To our knowledge this is the longest such record of tropical stream chemistry on Earth. 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; data set 27) and describing the role of watershed (McDowell & Liptzin, 2014) versus in-channel controls on stream nitrogen (N) dynamics (Merriam et al., 2002; Rodríguez-Cardona et al., 2021). The solutes measured, methods used and detection limits are described in Table 2. The average % relative difference of laboratory duplicates ranges from 0.7% to 4.8%, with values of NH_4^+ having the greatest uncertainty (Table 2). Changes in analytical methodology over time are documented in Table S1. Recent deployment of high-frequency water quality sensors that measure nitrate (NO_3^-), conductivity, temperature, dissolved oxygen, fluorescent dissolved organic matter and turbidity will provide new insights into controls on stream chemistry (Wymore et al., 2019).

TABLE 1 Major data sets for the Luquillo experimental Forest long-term catchment study

Data set number	Data set description	Location	Method	Freq.	Freq as reported	Primary data owner	DOI/URL
1	Geophysics	LEF	Ground penetrating radar	N/A	N/A	Xavier Comas	http://www.hydroshare.org/resource/94b4d04d22e04311a8a0d5d8cf37cf05Soil
2	Air temperature by 50-m elevation increment	LEF	HOBO temperature 250 to 1000 m elevation	15-min	Daily average	Alonso Ramírez	https://doi.org/10.6073/pasta/b14b442a87fff9dc22b68bc462be756b
3	Climate (5)	EVFS	Meteorological Instrumentation	5-min and continuous	Daily	Alonso Ramírez	https://doi.org/10.6073/pasta/e73e96da124481de01486a0dab0178dc
4	Climate	PE; SAB	Tipping bucket	5-min and continuous	Daily	Grizelle González	https://doi.org/10.6073/pasta/8d2ee3d7d5e3e8655063e738ae3700e2
5	Rainfall since 1975	EVFS	Openfall rainfall collector	Daily	Daily	Alonso Ramírez	https://doi.org/10.6073/pasta/3e34534da2a008d84269356442f772b8
6	NADP rainfall	EVFS	Belfort and NOAH IV	Continuous	Daily	NADP	http://nadp.slh.wisc.edu/data/sites/siteDetails.aspx?net=NTN&id=PR20
7	USGS rainfall	Rio Icacos	Tipping bucket	5-min	Daily	USGS	https://waterdata.usgs.gov/nwis/dv?referred_module=sw&site_no=50075000
8	Throughfall and rainfall	BEW	Multiple open collectors	Weekly	Weekly composite	Tamara Heartsill-Scalley	https://doi.org/10.6073/pasta/fe51799a303a8504c0562426fbc850c6
9	Cloud base level	SAB	Vaisala CL31 laser ceilometer	30 s	Hourly mean	Grizelle González	https://doi.org/10.2737/RDS-2017-0023
10	Temperature, relative humidity and cloud immersion	LEF	Meteorological Instrumentation, game camera	15-min	30-min	Martha Scholl	https://doi.org/10.5066/P9UQCN4T
11	Rain and throughfall chemistry	EVFS, BEW	Bulk rain, throughfall	Weekly	Weekly	William McDowell	https://doi.org/10.6073/pasta/8a6c85713bf55573c457d92076385bee
12	NADP rain chemistry	EVFS	Wet only	Weekly	weekly	NADP	http://nadp.slh.wisc.edu/data/sites/siteDetails.aspx?net=NTN&id=PR20
13	Soil chemistry by forest type	LEF	By depth	N/A	N/A	Miguel Leon	http://www.hydroshare.org/resource/9211abc0a4fe4611a7c72ac31c35840c
14	Litterfall chemistry	EV	Litterfall	Quarterly	Quarterly	Whendee Silver	https://doi.org/10.6073/pasta/bcbe47a10a08bc6ddca69fb2c59959ca
15	Stream flow	Rio Icacos	Broad crested weir	15-min	Daily average	USGS	https://waterdata.usgs.gov/pr/nwis/uv?site_no=50075000
16	Stream flow	Quebrada Guabá	Open channel stage	15-min	Daily average	USGS	https://waterdata.usgs.gov/pr/nwis/uv?site_no=50074950
17	Stream flow	Rio Mameyes	Open channel stage	15-min	Daily average	USGS	https://waterdata.usgs.gov/pr/nwis/uv?site_no=50065500
18	Stream flow	Rio Espiritu Santo	Open channel stage	15-min	Daily average	USGS	https://waterdata.usgs.gov/pr/nwis/uv?site_no=50063800
19	Stream flow	Rio Grande	Open channel stage	15-min	Daily average	USGS	https://waterdata.usgs.gov/pr/nwis/uv?site_no=50064200
20	Stream flow	Quebrada Sonadora	Open channel stage	15-min	Daily average	USGS	https://waterdata.usgs.gov/pr/nwis/uv?site_no=50063440
21	Stream flow	Quebrada Toronja	Open channel stage	15-min	Daily average	USGS	https://waterdata.usgs.gov/pr/nwis/uv?site_no=50063500
22	Stream flow	Rio Sabana	Open channel stage	15-min	Daily average	USGS	https://waterdata.usgs.gov/pr/nwis/uv?site_no=50067000

(Continues)

TABLE 1 (Continued)

Data set number	Data set description	Location	Method	Freq.	Freq as reported	Primary data owner	DOI/URL
23	Stream flow	Rio Fajardo	Open channel stage	15-min	Daily average	USGS	https://waterdata.usgs.gov/pr/nwis/uv?site_no=50071000
24	Stream flow	Quebrada Prieta	Open channel stage	15-min	15-min	Alonso Ramirez	https://doi.org/10.6073/pasta/bc3c46b7ebc4f53c3cef1d9c052169df
25	Stream and groundwater oxygen and conductivity	LEF	HOBO loggers	15-min	15-min	William McDowell	http://www.hydroshare.org/resource/846fd1449f684382b2ac113c2e0e8422
26	Soil temperature, volume-weighted water content	EVFS	TDR - Campbell Scientific CS616	Hourly	Daily	Grizelle González	https://doi.org/10.2737/RDS-2019-0051
27	Stream chemistry	LEF	Grab samples	Weekly	Weekly	William McDowell	https://doi.org/10.6073/pasta/f9df56348f510da0113b1e6012fa2967
28	Regolith chemistry	LEF	Chemical analysis of regolith by depth	N/A	N/A	Maria Chapela-Lara	http://www.hydroshare.org/resource/70d6eeb63e154f8197467e1f7c91f55b
29	Lysimeter chemistry	EVFS	Tension lysimeters	Monthly	Monthly	William McDowell	https://doi.org/10.6073/pasta/44835db7c9f0d16602131aad9370ba1f

Note: Climate refers to combined rainfall, wind speed and direction and temperature. Location refers to general research site (see Figure 1): LEF – Multiple sites in the Luquillo experimental Forest; EVFS – El Verde Field Station; BEW – Bisley experimental watersheds; PE – East peak; SAB – USDA Sabana Field Station. Freq. (frequency) refers to frequency at which measurements are made and reported. Gap filling, accuracy and instruments used are described in more detail in the metadata for each individual data set. Time series measurements are on-going with the exception of data sets 10, 16, 20 and 21.

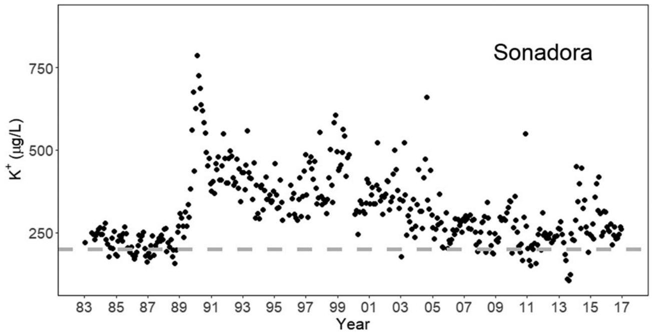

FIGURE 3 Exemplar stream chemistry data set showing average monthly concentrations of potassium (K^+) from weekly samples taken 1983–2017 in Quebrada Sonadora. Major hurricanes occurred in 1989 (Hugo) and 1998 (Georges). Dashed horizontal line is average concentration prior to hurricane Hugo in 1989.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

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 weathering products (e.g., SiO_2 and bicarbonate) due to the warm and wet environment that promotes rapid weathering in both lithologies (McDowell & Asbury, 1994; Murphy & Stallard, 2012; Shanley et al., 2011). Nitrogen concentrations are relatively high, with inorganic N dominated by NO_3^-, 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 is found in many well-drained forested catchments (McDowell & 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 & Asbury, 1994; Shanley et al., 2011). Hurricanes result in increased concentrations and fluxes of NO_3^- and K^+, but little change in other solutes (Schaefer et al., 2000; McDowell et al., 2013; Figure 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; data set 28), showing that weathering products may be transported to streams along deep flow paths with little opportunity for uptake by upland vegetation (McDowell, 1998). Aquatic biota can affect stream chemistry, as the assemblage of shrimp species has been shown experimentally to affect both NO_3^- and dissolved organic carbon concentrations (Crowl et al., 2001). Interpretation of stream chemistry is supported by groundwater (Luquillo, 2020; data set 25) and soil water chemistry (McDowell, 2015; data set 29).

3 | FUTURE OF EXPERIMENTAL CATCHMENT RESEARCH IN THE LEF

Future work in the Luquillo catchments should focus on three primary objectives. First is a continuation of the long-term weekly rainfall,

TABLE 2 Analytical methods for water chemistry currently used by the Luquillo experimental forest long-term catchment study

Analyte	Unit reported	Typical range	Method	Regression	Points	MDL	Duplicate %	% recovery
SiO_2	mg SiO_2/L	0.05–35	Colorimetric	Linear	4–7	0.02	0.7	97.6
PO_4^{3-}	μg P/L	3–200	Colorimetric	Linear	4–7	2	2.4	100.4
NH_4^+	μg N/L	5–200	Colorimetric	Linear	4–7	5	4.8	100.6
Na^+	mg Na/L	0.1–15	IC	Quadratic	4–7	0.02	1.2	95.5
K^+	mg K/L	0.05–7	IC	Quadratic	4–7	0.01	1.7	101.5
Mg^{2+}	mg Mg/L	0.02–7	IC	Quadratic	4–7	0.02	1.9	95.2
Ca^{2+}	mg Ca/L	0.1–10	IC	Quadratic	4–7	0.10	2.7	98.4
Cl^-	mg Cl/L	0.12–15	IC	Quadratic	4–7	0.03	1.4	94.6
NO_3^-	mg N/L	0.02–3	IC	Quadratic	4–7	0.004	3.0	98.8
SO_4^{2-}	mg S/L	0.04–8	IC	Quadratic	4–7	0.02	2.3	98.4
TDN	mg N/L	0.1–10	TOC	Linear	4–7	0.05	4.1	94.7
DOC	mg C/L	0.1–20	TOC	Linear	4–7	0.10	1.8	96.9
DON	mg N/L	0.05–1	Difference	N/A	N/A	Variable	4.8	94.7
TDP	μg P/L	3–300	FIA	Linear	4–7	2.0	2.4	100.4
pH	unit	4–10	Electrochemical	Linear	3	N/A	N/A	N/A
Conductance	μmhos	0–500	Electrochemical	Linear	2	N/A	N/A	N/A

Note: Methods and instrumentation typically apply to most of the period of record. TDN is total dissolved nitrogen; DOC is dissolved organic carbon; DON is dissolved organic nitrogen. TDP is total dissolved phosphorus. Method refers to the analytical method used: IC is ion chromatography (Thermo Scientific Dionex ICS 1000/1100, Sunnyvale, CA); TOC is analysis of DOC and TDN with a Shimadzu Total organic carbon analyser (TOC-VSH or TOC-LSH; Shimadzu corporation, Kyoto, Japan); colorimetric is discrete colorimetric analyser, either SmartChem 200 (Unity scientific, Brookfield, CT) or seal AQ2 (seal analytical, Mequon, WI). FIA is flow injection analysis and colorimetric detection (Lachat 8500; Hach USA) with 2 cm cell. DON is measured as the difference between TDN and the sum of NO_3-N and NH_4-N. for changes in methods over the period of record, see Table S1. Regression refers to the type of regression used to develop the standard curve. Points refers to the number of calibration points used in the standard curve. MDL is method detection limit, the minimum concentration of a substance that can be measured and reported with 99% confidence that the analyte concentration is greater than zero. Duplicate % is the average value of % relative difference of laboratory duplicates. % recovery is the result of instrument performance checks with commercial standards.

throughfall and stream chemistry (data sets 8, 11 and 27), which represent one of the longest records of tropical catchment function in the world. These data sets are essential to track long-term trends in tropical montane watersheds. Second, global climate and atmospheric models predict a changing seasonality for the Luquillo Mountains and Puerto Rico including an increase in both the frequency and intensity of dry periods and droughts (Chadwick et al., 2016; Ramseyer et al., 2019) as well as hurricanes (Kossin et al., 2020). Understanding how tropical watershed- and ecosystem-scale processes respond to fluctuations between extremes in precipitation will be necessary to produce accurate models of water and solute export to the near coastal environment. Third, understanding how variable redox conditions control solute and greenhouse gas fluxes along hillslope to stream channel transects will be vital for predicting impacts of precipitation extremes. Changing redox conditions will drive the form of solutes (e.g., ammonium vs. nitrate) and the relative contributions of carbon dioxide, methane and nitrous oxide to greenhouse gas emission inventories.

4 | DATA SET FUNDING AND CONTRIBUTIONS

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DATA AVAILABILITY AND DATA OWNERSHIP

This Data Note describes 29 datasets with ownership and access information provided in Table 1. The datasets originate from a variety of sources and thus data and metadata formats vary. All data are freely available. Collaboration on any aspect of tropical catchment hydrology and biogeochemistry at Luquillo Experimental Forest is welcome, as the data collection efforts are expected to continue. Updated data sets are typically published within 2 years of collection, or more frequently. Authors of this data note or data set owners in Table 1 should be contacted to develop collaborations or to answer questions about the data.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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