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Rainfall, Runoff and Elevation Relationships in the Luquillo Mountains of Puerto Rico*

ANDRÉS R. GARCÍA-MARTINÓ,[1] GLENN S. WARNER,[2] FREDERICK N. SCATENA,[1] AND DANIEL L. CIVCO[2]

[1]*US. Department of Agriculture, Forest Service, International Institute of Tropical Forestry, Call Box 25000, Rio Piedras, Puerto Rico 00928-2500*
[2]*Department of Natural Resources Management and Engineering, University of Connecticut, Storrs, Connecticut 06269-4087*

ABSTRACT.—Long-terrn rainfall and discharge data from the Luquillo Experimental Forest (LEF) were analysed to develop relationships between rainfall, stream-runoff and elevation. These relationships were then used with a Geographic Information System (GIS) to determine spatially-averaged, mean annual hydrologic budgets for watersheds and forest types within the study area. A significant relationship exists between 1) elevation and mean annual rainfall; 2) elevation and the average number of days per year without rainfall; 3) annual stream runoff and the weighted mean elevation of a watershed; and 4) annual stream runoff and the elevation of the gaging station. A comparison of rainfall patterns between a high and a low elevation station indicated that annual and seasonal variations in rainfall are similiar along the elevational gradient. However, the upper elevation station had greater annual mean rainfall (4436 mm/yr compared to 3524 mn/yr) while the lower station had a greater variation in daily, monthly, and annual totals. Model estimates indicate that a total of 3864 mm/yr (444 hm^3) of rainfall falls on the forest in an average year. The Tabonuco, Colorado, Palm, and Dwarf forest types receive an estimated annual rainfall of 3537, 4191, 4167, and 4849 mm/yr, respectively. Of the average annual rainfall input, 65% (2526 mm/yr) is converted to runoff and the remaining 35% (1338 mm/yr) is lost from the system by evapotranspiration and other abstractions. In comparsion to other tropical forests, the LEF as a whole has more evapotranspiration than many tropical montane forests but less than many lowland tropical forests.

RESUMEN.—Mediante un análisis de regresión, se identificaron relaciones entre lluvia, descarga, y elevación, utilizando datos obtenidos de estaciones localizadas en la Estacion Experimental de Luquillo (EEL). Estas relaciones fueron integradas a un Sistéma de Informacion Geográfico para lograr un análisis espacial y balance de agua para las cuencas y tipos de bosque en el area de estudio. Existen relaciones significativas entre: 1) elevación y lluvia promedio anual: 2) elevacion y el número promedio de dias al año sin lluvia; 3) descarga promedio anual y la elevación promedio; y 4) descarga anual y la elevación de esa misma estación. Una comparación de datos de lluvia obtenidos en partes altas y bajas del bosque demostró un patrón de lluvia anual muy similar. La estación localizada a una mayor elevacion tuvo una mayor cantidad de lluvia promedio anual (4436 mm/yr vs. 3524 mm/yr), mientras que la estación localizada en la parte baja del bosque presentó una mayor variación en los datos de lluvia darios, mensuales y anuales. Utilizando los modelos desarrollados, podemos estimar un promedio de 3864 mm/yr (444 hm^3) de lluvia en el bosque. Los bosques de Tabonuco, Colorado, Palma de Sierra y Bosque Enano reciben un estimado de 3537, 4191, 4167 y 4849 mm/yr de lluvia. Del prumedio de lluvia recibida en todo el bosque, el 65% se convierte en escorrentía y el 35% se pierde por medio de la evapotranspiración u otras pérdidas. Al comparar este bosque con otros boques tropicales, la EEL presenta un grado de evapotranspiración mayor que el de muchos bosques tropicales de la montana, pero menor que el de muchos bosques tropicales de tierra baja.

INTRODUCTION

Spatial and temporal variations in the amount of annual rainfall in the Luquillo Mountains of Puerto Rico have been related to the distribution of plants and animals, the density and structure of forests, and the geomorphic processes of soil formation and erosion (Brown et al., 1983; Weaver, 1972, 1975, 1991; Frangi and Lugo, 1985; White, 1963; Wadsworth; 1951 b). While the importance of rainfall to this tropical rain forest is widely recognized, and earlier studies reviewed some of the available data (Lugo, 1986; Briscoe, 1966; Holben et al., 1979;

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Brown et al., 1983; McDowell et al., 1988), a forest-wide, spatially averaged synthesis of all the long-term rainfall and runoff data has been lacking. This paper analyzes long-term rainfall and stream discharge data to develop statistically sound relationships between rainfall, stream-runoff, and elevation. These relationships are then used with a Geographical Information System (GIS) to estimate spatially averaged annual water budgets for watersheds and forest types within the Luquillo Mountains.

Study Area

On the basis of aspect relative to the prevailing trade winds, Puerto Rico is commonly divided into windward and leeward climatic regions. The windward and eastern regions of the island have the highest mean annual rainfall, while the leeward southwestern regions typically have the lowest annual rainfall. The Luquillo Experimental Forest (LEF), located in the windward portion of the island (Fig. 1.) is one of the wettest areas on the island. The Forest, which is administered by the USDA Forest Service, covers an area of 11,491 hectares within the Sierra de Luquillo Mountains. Over a distance of 10 to 20 km, this mountain range rises from sea level to an elevation of 1075 meters.

Puerto Rico has a subtropical maritime climate that is influenced by global synoptic systems and local orographic effects. Between June and November weather patterns in the Luquillo Mountains are dominated by the northeast trade winds (Colón-Dieppa and TorresSierra, 1990). During the winter months, specifically December to May, Northern cold fronts influence the island's weather. At the base of the Luquillo Mountains average monthly temperature ranges between 23.5°C to 27°C (Brown et al., 1983). On the mountain peaks, average monthly temperatures range between 17°C and 20°C. Wind velocities on these peaks range between 8 and 18 km/hr with peak velocities occurring during January, April, and September. At the base of the mountains, velocities vary between 1.5 and 3 km/hr throughout the year.

The LEF contains four of the six Holdridge Life Zones found in Puerto Rico (Ewel and Whitmore, 1973). These are the subtropical wet, lower montane wet, lower montane rain, and subtropical rain forest ecosystems. In addition, the 11,491 ha forest has been divided into four forest types based on the dominant tree species in each type (Wadsworth, 1951). These are Tabonuco, Colorado, Sierra Palm, and the Dwarf forest. The Tabonuco forest occupies areas generally below 600 masl. The Colorado forest occurs in areas above the cloud condensation level, which is approximately 600 masl and is generally found on sandy soils underlain by granodioritic bedrock. The Sierra Palm forest occurs on steep windward slopes, riparian areas, and areas with poor drainage. The Dwarf forest ecosystem is only located on the highest mountain peaks and has short, stunted vegetation. In addition to rainfall, this forest gains between 2 and 4 mm of water per each 25 mm of rainfall, or about 10% of average annual rainfall, from the condensation of cloud droplets on plants (Weaver, 1972).

METHODS

Hydrologic Data and Statistical Analysis

Over the past 70 years, eighteen rain gages have been located within or adjacent to the LEF (Fig. l). While most stations are part of the National Oceanic and Atmospheric Administration (NOAA) network, other stations have been maintained by the USDA Forest Service, the University of Puerto Rico, the US Geological Survey, and the US Fish and Wildlife Service (Table 1). Three statistical comparisons were investigated using rainfall data from these rain gages:

1) A comparison of annual and daily rainfall at two long-term stations, El Verde (EV) at 400 masl and Pico del Este (PE) at 1051 masl. These stations had 15 or more years of record, and were compared because they represent extremes that exist within the LEF. 2) Regression relationships between elevation and mean annual rainfall for all available stations. 3) Regression analysis of elevation with the mean number of days per year without rainfall, the maximum number of connective days without rainfall, and

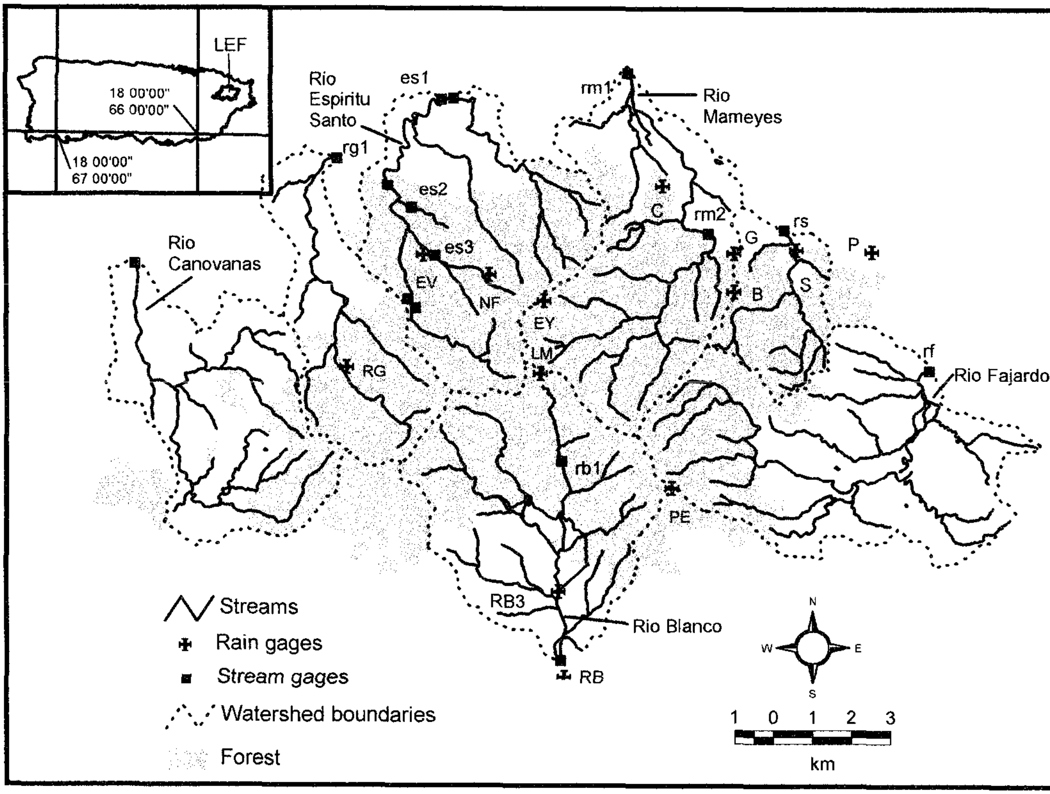


FIG. 1. Rain gages and stream gages in the Luquillo Experimental Forest.

the number of days per year without rainfall with a 10 year recurrence interval.

Mean dailv stream flow values were obtained from US Geological Survey records for nine watersheds located within or adjacent to the LEF (Fig. 1 and Table 2). Two statistical relationships were investigated using this data: 1) Regression relationships between mean annual runoff and the elevation of the gage. 2) Regression relationships between the weighted mean elevation of the watershed (WME) and mean annual runoff. The WME of a watershed or forest type was calculated as the average elevation of each 30 m by 30 m cell within the watershed or forest type.

The best fit curves for all the derived relationships were selected by comparing the partial residual estimated sum of squares *(PRESS),* the coefficient of determination (R^2), the error mean squared (EMS) and the *F* statistic (SAS, 1985). When comparing linear versus polynomial fits, all the regression diagnostic-parameters were compared. When comparing exponential and power curves with the simple regressions (linear and polynomial), only the R^2 was used, since the *PRESS* and EMS statistics can not be directly compared when the data are transformed.

GIS Analysis

Digital Elevation Models (DEM) for each of the five 7½′ topographic maps that cover the forest were obtained from the US Geological Survey. These DEM’s have a 30 × 30 m resolution, and were projected onto Universal Transverse Mercator (UTM) coordinates. Vector coverages of the ownership boundary and forest types at the LEF were provided by the Caribbean National Forest. The boundaries for each of the nine watersheds analyzed were drawn on the topographic maps, digitized as vector coverages, and transformed into a raster image

TABLE 1. Stations used in the development of the relationship between rainfall and elevation.

Name	ID	Years of record	Source	Elev (m)	Mean rainfall (mm/yr)	DNR[6] per year
El Verde	EV	19	UPR[1]	400	3524	97
Pico del Este	PE	24	NOAA[2]	1051	4436	38
Rio Grande	RG	20	Brown et al., 1983	107	2640	
Rio Blanco Upper	RBU	13	NOAA	439	3752	92
Rio Blanco[4]	RB	16	Brown et al., 1983	35	2545	131
Paraiso	P	43	Brown et al., 1983	101	2333	—*
Rio Blanco 3	RB3	18	Brown et al., 1983	152		—
Rio Blanco 4	RB4	27	Brown et al., 1983	549	3870	—
Catalina	C	4	Briscoe, 1966	200	3240	—
Bisley[5]	B	4	scatena[3] and Snyder et al., 1987	285	3208	—
Gurabo	G	4	Briscoe, 1966	250	3140	—
Sabana	S	4	Briscoe, 1966	100	2879	—
North Fork	NF	5	Snyder et al., 1987	675	4160	—
South Fork	SF	5	Snyder et al., 1987	570	3424	—
East Fork	EF	3	Snyder et al., 1987	510	3840	—
West Fork	WF	4	Snyder et al., 1987	625	3990	—
La Mina	LM	8	Brown et al., 1983	716	4700	—
El Yunque	EY	4	Snyder et al., 1987	1030	4426	—

[1] Terrestrial Ecology Division, University of Puerto Rico.
[2] National Oceanographic Administration, San Juan office.
[3] Luquillo Long Term Ecological Research Site data base, F.N. Scatena.
[4] Elevation and mean annual rainfall are average of stations R. Blanco 1 and R. Blanco 2a from Brown et al., 1983,
[5] Elevation and mean annual rainfall are average of Bisley stations from Scatena.
[6] Average days with no measurable rain.
* No data available.

TABLE 2. Hydrologic budget for 10 watersheds with USGS long term streamflow data.

Watershed name	USGS gage #	Drain. area (ha)	Elev. at gage (m)	WAE (m)	Ave. rain[1] (mm/yr)	Ave. runoff[2] (mm/yr)	ET =[3] Rain – Run.
Rio Grande (rg1)	642	1912	39	516	3732	2203	1529
Rio Espiritu Santo (esl)	638	2243	9	458	3743	2309	1434
Rio Espiritu Santo (es2)	635	17	153	339	3401	1706	1695
Rio Espiritu Santo (es3)	6344	265	390	598	4203	2381	1822
Rio Blanco (rbl)	750	333	636	687	4153	3607	546
Rio Mameyes (rml)	657	3093	10	359	3318	2093	1225
Rio Mameyes (rm2)	655	1752	92	503	3747	2990	757
Rio Fajardo (rf)	710	3845	46	272	3149	1473	1676
Rio Sabana (rs)	670	1001	101	322	3329	1743	1586

[1] From eq. 1.
[2] From USGS discharge data.
[3] Average rainfall minus average runoff.

TABLE 3. Water inputs and outputs from four forest types inside the LEF.

Forest type	Area (ha)	WAE[1] (m)	Average[2] rainfall (mm/yr)	Average[4] runoff (mm/yr)	Average[5] ET (mm/yr)
tabonuco	5787	402	3537	1830	1707
colorado	3476	720	4191	3197	994
sierra *palm*	1856	711	4167	3158	1009
dwarf	372	897	4849[3]	3958	1144
Weighted average			3879	2526	1245

[1] Weighted Average Elevation.
[2] From Eq. 1.
[3] Including a 10%. contribution from cloud moisture.
[4] From Eq. 4a.
[5] Rainfall minus runnoff.

using Arc Info, IDRISI, and ERDAS software. A complete characterization for each watershed was performed by Garcia-Martinó (1996) and is described in Civco et al., (1995). The final grid image consisted of 1336 rows and 944 columns.

Following the development and selection of regression relationships between rainfall

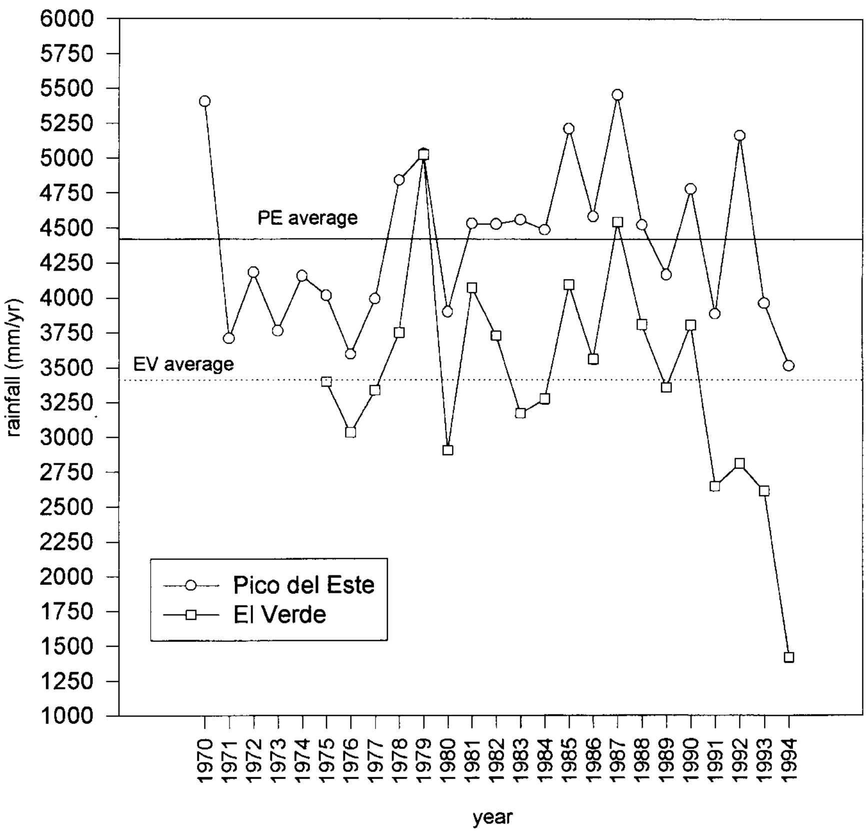


FIG. 2. Total and average annual rainfall for Pico del Este (PE) and El Verde (EV).

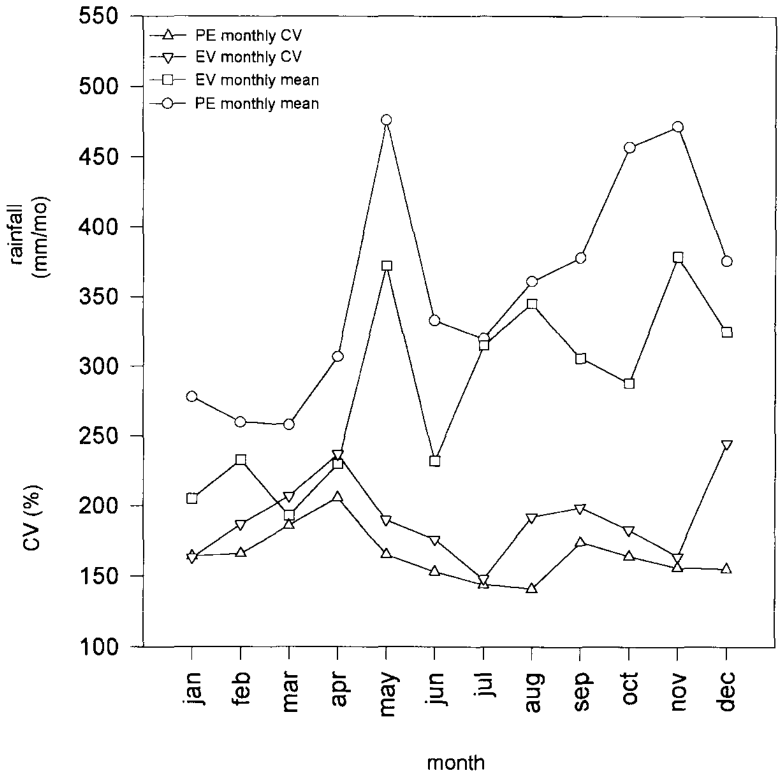


FIG. 3. Monthly average rainfall and coefficient of variation (CV) for Pico del Este (PE) and El Verde (EV) rain gages from long data.

and elevation, the GIS was used to apply the regression equations to each 30 × 30 meter cell within the forest. The resulting image was then overlaid with images of the watershed boundaries, the LEF property boundary, and forest types to calculate average annual rainfall for each of the forest types, selected watersheds, and the entire forest.

Water Budgets

Using the statistically valid relationship between rainfall and elevation, and measured discharges at gaged watersheds, mean annual water budgets for the gaged watersheds were calculated using the GIS and assuming that:

$$\text{Evapotranspiration} = \text{Mean Annual Rainfall} - \text{Mean Annual Runoff} \qquad \text{Eq. 1}$$

Mean annual water budgets for the four forest types within the Luquillo forest were also estimated using this relation and mean annual runoff, as estimated from a relationship with mean watershed elevation (Table 3). This simple approach assumes there is no change in water storage from year to year, and that there are no other significant inflows or outflows from the system. The approach also assumes that the withdrawals of water for municipal uses does not significantly affect stream discharge. While a considerable amount of water is withdrawn from the forest, this assumption is reason-

TABLE 4. Results of regressions between elevation and mean annual rainfall for eastern P.R.

Curve	*F*	EMS	Press	R^2	P
Quadratic	73.97	51382	1032631	91	0.0112
Linear	95.61	75019	1635919	86	0.0001
Power	101.46	0.0012	0.03	86	0.0001
Exponential	80.47	0.0014	0.03	83	0.0001

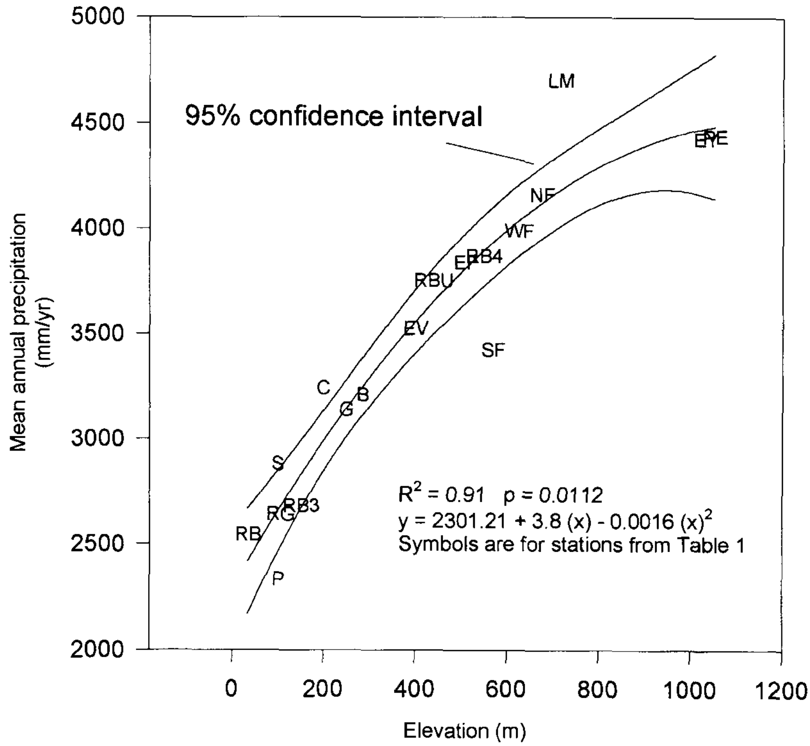


FIG. 4. Relationship between mean annual rainfall and elevation at 18 rain gages in the LEF.

able because most large water intakes are located downstream of the gaging stations used in this analysis (Naumann, 1994).

RESULTS AND DISCUSSION

Rainfall-Elevation Relationships

Annual and Daily Variations at Pico del Este (PE) and El Verde (EV). — Comparsions of the two long-term rainfall stations indicate that they have similar seasonal patterns but that the lower elevation station has a greater variation between years, during a single year, and among daily values. Mean rainfall and the coefficient of variation (CV) of annual values for EV and PE were 3418 mm/yr-22.6% and 4435 mm/yr-12.9% respectively. Annual values for EV ranged from 5023 mm to 1416 mm, while the range at PE was 5457 mm to 3517 (Fig. 2). Monthly peaks averaged 476 and 371 mm during the month of May, and 472 and 379 mm during the month of November for PE and EV respectively (Fig. 3). In addition, EV showed another peak in August. The monthly CV'S at both stations followed the seasonal rainfall pattern common for this region (Fig. 3). However, the EV station had a higher monthly CVS from February to December than the PE station.

At the PE station, daily median rainfall was 5 mm vs. 3 mm for the EV station. At PE, 90% of daily rainfall was below 29 mm, while 900/. was below 25 mm at EV. However, the two highest daily rainfalls measured at EV (308 mm on 8/31/79 and 500 mm on 12/8/87) were greater than the two highest daily rainfalls recorded at PE (266 mm on 4/21/83 and 256 on 1/6/92). At the PE station there was an average of 38 days per year with no rain, while 97 days per year had no rain at EV The CV of daily rainfall at EV (195%.) was higher than the CV for PE (168%), but mean daily rainfall was higher at PE (11.7 vs. 9.6 mm/d).

Elevation vs Mean Annual Rainfall. — The relationship between mean annual rainfall and elevation was compared using linear, polynomial, power, and exponential regres-

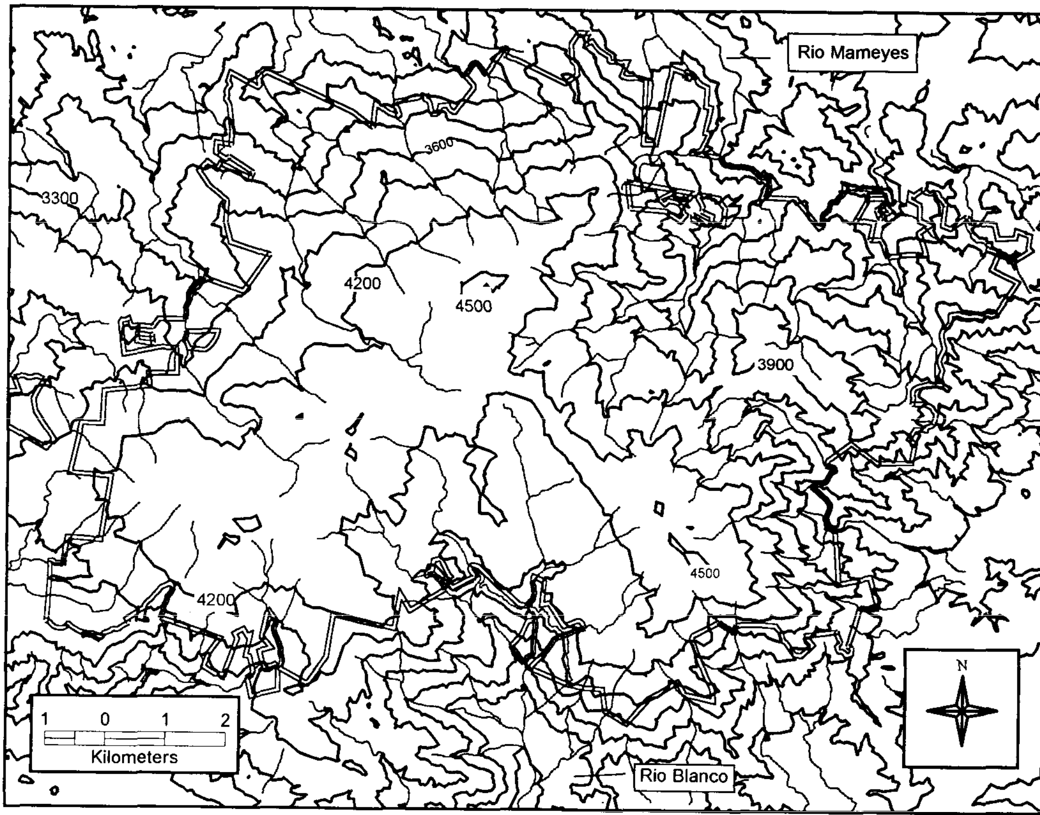


FIG. 5. Lines of equal rainfall (mm). A map produced by applying the rainfall-elevation relationship to a Digital Elevation Model.

sion models (Table 4). The second degree polynomial curve best fit the data (Eq. 2, Fig. 4).

$$\text{Mean Annual Rainfall (mm/yr)} = 2300 + 3.80\ \text{Elev. (masl)} - 0.0016\ \text{Elev (masl)}^{2.0]} \qquad \text{Eq. 2}$$

Using this relationship and a Digital Elevation Model, a map of rainfall contours was developed for the LEF (Fig. 5). This relationship was developed using data from different years and from stations with different lengths of record (Table 1), and it only estimates average annual rainfall over an elevation between 35 and 1050 masl. During extreme wet or dry years the relationship between elevation and rainfall may be different.

Although equation 2 is quite strong it should be used with caution because there is a data gap between 716 and 1030 masl and the equation tends to underestimate mean annual rainfall at lower elevations, while it overestimates rainfall at upper elevations (Fig. 6). Differences between measured and estimated values were compared with the aspect of each station but with no significant results. The relationship is consistent with a graphical analysis presented in Brown et al. (1983) but predicts higher rainfall for a given elevation than an equation developed by McDowell et al. (1994) based on 1 year of data collected by Holben et al. (1979) in the western portion of the forest.

Maps with contours of equal rainfall were develop by applying eq. 2 to a Digital Elevation Model (Garcia-Martinó, 1996).

Elevation vs. Days Without Rain Per Year.— Daily rainfall data in digital format were available only for RB, EV, PE, and RBU stations (Table 1). Using this data set we found

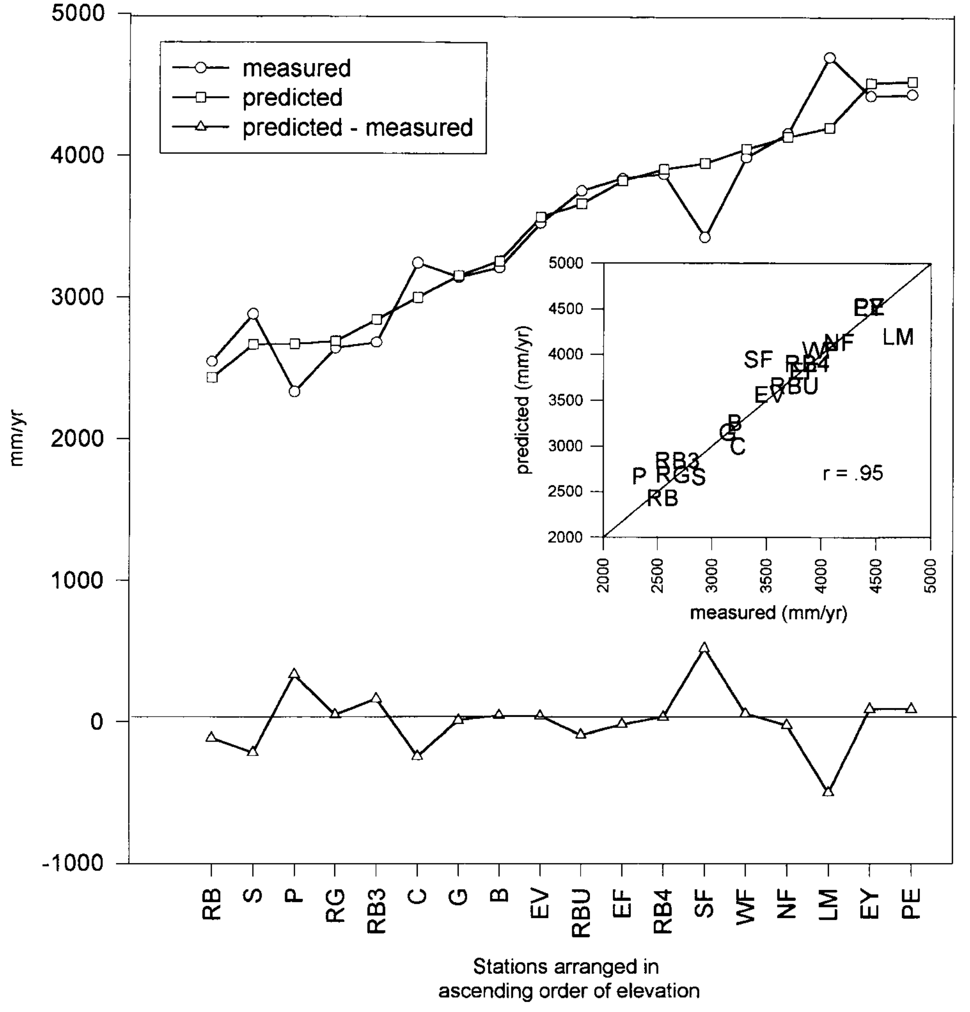


FIG. 6. Comparison between measured and calculated average rainfall for 18 rain gages in the LEF.

a significant relationship ($p= .0003$, $\alpha = .05$) between elevation and the mean number of days without rain per year (Eq 3, Fig. 7).

$$\text{Mean number of days per year with no rain} = 133.30 - 0.09 \text{ Elev (masl)} \qquad \text{Eq. 3}$$

Although this relationship is based on a limited sample, 99.9% of the variation was explained by the equation ($R^2 = 0.99$, $n=4$). As expected, the number of days with no rain decreased with increasing elevation and ranged from an average of 131 days/ year at 35 m to 38 days/year at 1051 m. Additional analysis indicated that the mean of the maximum number of consecutive days per year without rainfall, and the total number of consecutive days with no rain with a 10 year recurrence interval were not significant y related to elevation.

Stream Runoff-Elevation Relationships.—Gaging station elevation and the weighted mean elevation of the watersheds were positively and significantly correlated with mean annual stream runoff measured by the US Geological Survey.

$$\text{Mean Annual Runoff (mm/yr)} = 3.22 \text{ WAE (masl)} + 816.16$$
$$r^2 = 0.61 \qquad \text{Eq. 4a}$$

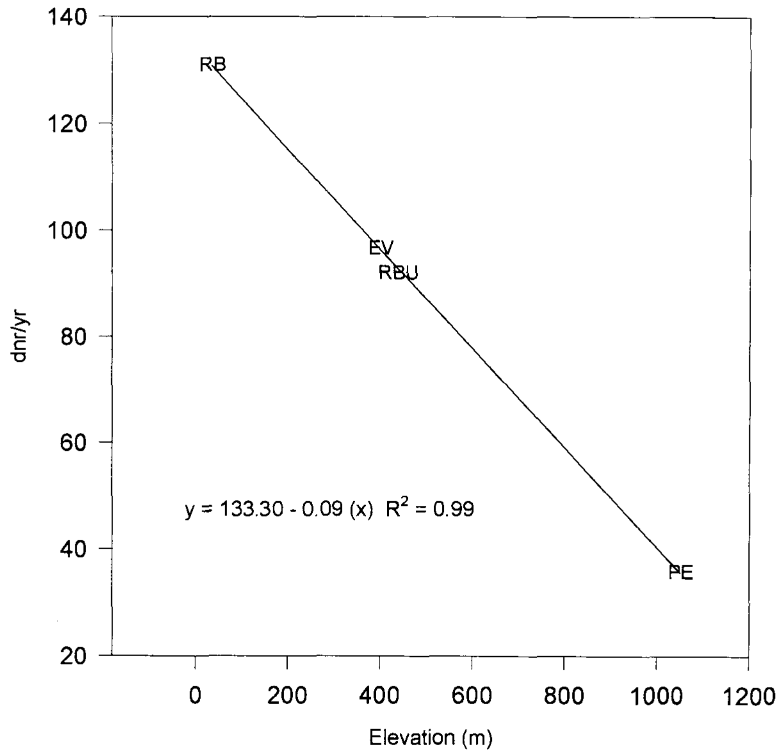
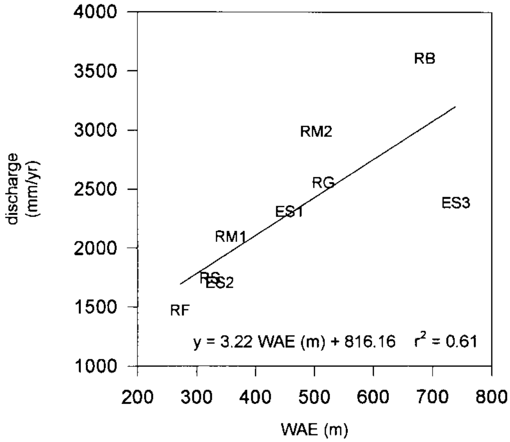


FIG. 7. Relationship between elevation and days with no rain per year for four rain gages located inside or adjacent to the LEF.

Mean Annual Runoff (mm/yr)
= 2.01 WAE (masl) + 1988.57
r^2 = 0.40 Eq. 4b

Although both relationships are strong, the regression using WME (Eq. 4a, Fig. 8a) is a better predictor than the relationship that uses elevation of the gage outlet (Eq. 4b, Fig. 8b). Higher confidence should also be placed on Eq.4a, since the WME accounts for the spatial distribution of elevation within the watersheds, while Eq. 4b has a large concentration of data points at lower elevations.

Mean Annual Hydrologic Budgets. — The total calculated volume of rainfall, measured runoff, and estimated ET for the long-term gaged watersheds in the area are given in Table 2. The inputs and outputs for each forest type as estimated from equation 2 and equation 4b appear in Table 3. In this analysis, water input from cloud interception has been added to the annual rainfall inputs of the cloud forest. This cloud water interception is considered to be 100/. of the total annual rainfall (Weaver, 1972) and represents an addition of 411 mm/yr of water to the cloud forest. On an average annual basis, the forest receives 3864 mm/yr of rainfall. Of this input, 65% is converted to stream runoff and 35% is recycled by evapotranspiration or lost by other abstractions. The largest amount of water falls in the Tabonuco forest (460/.), the forest type with the largest area. However, the higher elevation Colorado forest accounts for a larger percentage of the total runoff (360/.) leaving the forest. These estimates also suggest that the Tabonuco forest type has the highest percentage of rainfall that evapotranspires (40% of the total rainfall in this forest), compared to 25%, 26%, and 24% for the Colorado, Sierra Palm, and Dwarf forest respectively. In compassion to other tropical forests (Bruijnzeel 1990), the LEF as a whole (1245 mm/yr, Table 3) has more ET than many montane forests (avg. ET = 1055



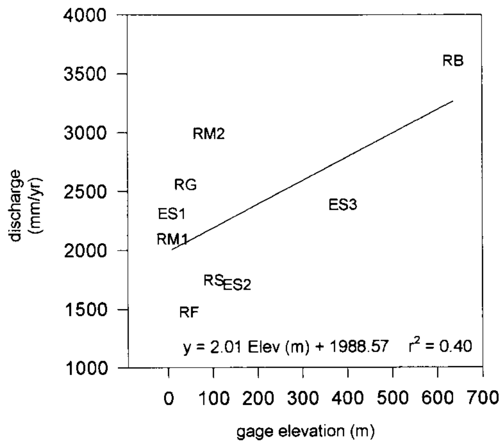


FIG. 8a. Relationship between the weighted average elevation (WAE) of the watershed and average runoff for 9 gage stations draining the LEF.

FIG. 8b. Relationship between the elevation at each stream gage station and the rage runoff for 9 gage stations draining the LEF.

mm/yr, s = 479, n = 13) but less ET than many lowland forests (avg ET = 1401 mm/yr, s = 1856, n = 22).

CONCLUSIONS

1) Although seasonal patterns were similar, the mean annual rainfall at Pico del Este (1051 masl) was much greater than at El Verde (400 masl). However, the variance of annual, daily and monthly values was higher for El Verde than Pico del Este. 2) There is a significant relationship between elevation and the number of days per year with no rain for four rain gages located at the LEF. 3) There was a significant and strong quadratic relationship between elevation and mean annual rainfall for 18 rain gages located at the LEE 4) There was a significant relationship between weighted-mean watershed elevation and mean annual runoff for streams located inside or adjacent to the LEF. 5) Reasonable estimates of mean annual rainfall, runoff, and evapotranspiration can be made for watersheds, forest types, and political units within the LEF using the developed regression relationships.

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