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Water Withdrawn From the Luquillo Experimental Forest, 2004

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Abstract

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This study quantifies the amount of water withdrawn from the Luqillo Experimental Forest (LEF) in 2004. Spatially averaged mean monthly water budgets were generated for watersheds draining the LEF by combining long-term data from various government agencies with estimated extraction data. Results suggest that, on a typical day, 70 percent of water generated within the forest is diverted before reaching the ocean. This is up from an estimated 54 percent in 1994. Analysis showed that up to 63 percent of average monthly stream runoff is diverted from individual watersheds during drier months. Watersheds with large water intakes have the most dramatic decrease in streamflow, particularly the Río Espiritu Santo watershed, where 82 percent of median flow is diverted.

Keywords: Water budgets, hydrologic connectivity, geographic information systems (GIS), Puerto Rico, Caribbean National Forest, Luquillo Experimental Forest, dams.

Contents

Introduction

Owing to greater water demand associated with increasing urban and suburban development in northeastern Puerto Rico, there is widespread concern that water withdrawals are compromising the ecological integrity of streams draining the Luquillo Experimental Forest (LEF), also known as the Caribbean National Forest (CNF). This report develops a set of water budgets to characterize spatial and temporal variation in water availability and water withdrawal in the LEF and surrounding areas and compares them to similar budgets that were calculated in 1994.

The LEF includes 11,269 ha and is located in northeastern Puerto Rico about 50 km from the capital city of San Juan (fig. 1). It is also the only tropical rain forest in the USDA National Forest System, and was designated as a biosphere reserve by the Man and Biosphere Program of the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1976. Rapid urban and suburban development occurred from 1978 to 1995 in areas surrounding the forest (Ramos-González 2001). Zoning policies have been implemented to protect the forest from development. A buffer zone was created around the forest mainly for agricultural and conservation use (Lugo et al. 2000); however, it has been found that more than 40 percent of land is in violation of its intended use, with urban and suburban development encroaching upon the forest (Lugo et al. 2004).

Nine rivers drain the LEF (fig. 1), and a previous water budget found that, on a typical day in 1994, over half of all water flowing from the LEF was extracted for municipal use (Naumann 1994). Between 1994 and 2004, at least six new points of water withdrawal (e.g., intakes) have been added on rivers draining the LEF to meet present and projected municipal water demand. Four intakes have been added within the forest, and two intakes have been added outside of the forest on the Río Fajardo, Río Mameyes, Río Espíritu Santo, and Río Blanco (Ríos 2004). Two intakes draw particularly large amounts of water: the intake at Río Mameyes (outside of the forest) is permitted to extract 5 million gallons per day (mgd) (18 939 m^3/day), and the intake at Río Fajardo is permitted to extract 12 mgd (45 455 m^3/day) (Ortiz-Zayas et al., in press).

The water-permitting process is handled by two agencies: the USDA Forest Service and the Puerto Rico Department of Natural Resources and the Environment (DNRE). The Forest Service permits rights of way for land used to build a water intake within the LEF, and the DNRE permits the amount of water that may be extracted. Water permits are usually designed to maintain the Q99 (amount of flow equaled or exceeded 99 percent of the time).

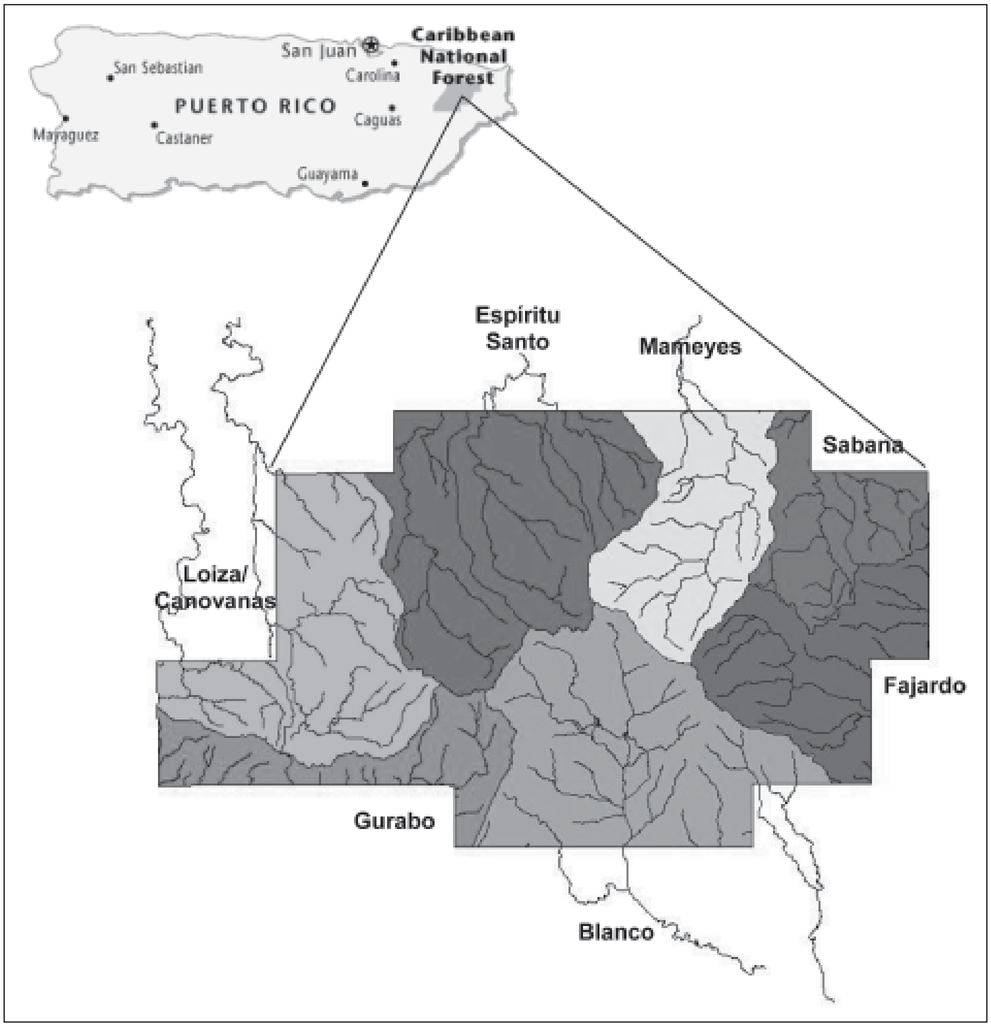

Figure 1—Watersheds draining the Luquillo Experimental Forest. The Río Grande and Río Espíritu Santo join near the estuary. The Río Grande is located on the west side of the Espíritu Santo watershed. The Río Canóvanas and Canovanillas join the Río Grande de Loíza watershed. The Río Canóvanas is east of the Río Canovanillas.

The LEF, as an entity of the U.S. National Forest System, must adhere to the Multiple Use/Sustained Yield Act of 1960. Major water interests in the LEF include extractive users, people using streams for recreation, ecological integrity, and preservation of biodiversity. Balancing water needs is a continuing problem in northeastern Puerto Rico because of high water demand, low water storage capacity, the flashy nature of storm flows, and a high rate of loss from pipes (Hunter and Arbona 1995, Pringle and Scatena 1998). In Puerto Rico, 43 percent of water diverted for municipal water supplies is lost in delivery because of leaky pipes (Quiñones 2004). There is concern that water extraction for municipal use is failing to leave enough water in streams for other uses. Therefore, the goal of this study is to develop an updated water budget with current data and tools, such as geographic information systems (GIS), and to evaluate the spatial and temporal variation in water availability and effects of withdrawal.

Previous Research

Naumann (1994) developed a water use budget for the LEF in 1994 by using estimates of rainfall and evapotranspiration (ET) for each forest type and life zone found within the LEF based on an earlier study by Lugo (1986). Runoff was calculated as the difference between estimates of rainfall and ET (Naumann 1994). Estimates of streamflow from Hansen et al. (1985) were also used in the Naumann (1994) study. All of these early estimates were based on aerial averages; a GIS was not available to produce spatially averaged values.

Water withdrawals in the Naumann (1994) study were based on available information from Puerto Rico Aqueduct and Sewer Authority (PRASA) and the existing water permits. For those gravity-driven intakes where records of the withdrawal were not available, annual withdrawal was estimated by using a pipe flow equation developed by Swamee and Jain (Streeter and Wylie 1979):

$$Q = -0.955\ D^2 \sqrt{gDh_f/L}\ \ln(E\ /\ 3.7\ D + 1.775\ v/D\ \sqrt{gDh_f/L})$$

where

Q = flow (m^3/s),

g = acceleration of gravity (9.08 m/s^2),

D = pipe diameter (m),

h_f = elevation difference between the intake and water treatment station or storage tank (m),

L = length of pipe from the intake to water treatment station or storage tank (m),

E = pipe roughness (m) = 0.00025 m (value for cast iron), and

V = viscosity of water ($1.13 \times 10^{-6}\ m^2/s$).

This pipe flow equation was calibrated to a water intake on the Río Sabana. The pipe roughness coefficient was used because it gave the best estimate of water withdrawal. Naumann's (1994) water budget estimated an average annual rainfall of 339 cm/yr, ET of 132 cm/yr, and stream runoff of 207 cm/yr for the entire forest. It should be noted that this water budget was calculated without the use of GIS.

The first GIS-based water budget for the LEF was published in 1996 (García-Martinó et al. 1996). This budget differed from the 1994 budget by Naumann in that it only considered the area within the forest boundary, and did not explicitly include water extraction. The budget did develop spatially explicit regression equations of rainfall and streamflow by using all of the available long-term data. These budgets also assumed that groundwater recharge is minimal and ET is equal to mean annual rainfall minus mean annual runoff. The water budget estimated an average annual rainfall of 386 cm/yr. Of this, 65 percent is converted to runoff and 35 percent is lost to ET (García-Martinó et al. 1996).

Larsen (1997) calculated water budgets for four watersheds that drain parts of the LEF: Cayaguas, Canóvanas, Icacos, and Mameyes (fig. 1: Río Canóvanas and Río Cayaguas drain into the Río Grande de Loíza basin, and Río Icacos is a tributary of the Río Blanco). Unlike previous water budgets, this budget evaluated groundwater. Results showed that groundwater flow through steeply sloping uplands was minimal and confirmed the early assumptions that stream runoff can be estimated from the difference between rainfall and ET. The study did show that groundwater flow through faulted bedrock may be important in the coastal plain region of the area.

Ortiz-Zayas (1998) evaluated the importance of groundwater to the Mameyes watershed and also found that positive groundwater flux occurs in low-elevation coastal plain reaches. This study also indicated that in these lower elevation reaches, the river recharges groundwater at discharges above Q90 (0.4 m^3/s) and receives groundwater when streamflow is below Q90.

Purpose of the Study

Since these initial studies were completed, urbanization and water withdrawals from the forest have increased, and we have better GIS layers. None of these studies looked at seasonal variations. The purpose of this study was to determine spatially averaged, mean monthly and annual water budgets for each watershed draining the LEF, and the LEF as a whole. Specific objectives were to (1) update previous water budgets by including new intakes and improvements in GIS, (2) characterize the temporal and spatial variation in streamflow caused by water withdrawals, and (3) evaluate the relative impacts of water withdrawal on different streams at different times of the year.

Study Site

The climate of Puerto Rico is dominated by the northeast trade winds in the summer and by northwest cold currents in the winter. Orographic precipitation is generated by the collision of the trade winds with the Sierra de Luquillo and Central Mountain ranges. This causes heavy rains in the north and east sections of the island and dry conditions in the south and west sections of Puerto Rico (García-Martinó et al. 1996). The average annual rainfall for Puerto Rico ranges from 1.5 to 5 m, depending on elevation and location on the island. The average annual temperature is 19 °C at 1000 m and 27 °C at sea level[1] (Luquillo LTER 2006).

Elevation within the LEF ranges from 100 to 1075 m above sea level (Naumann 1994). There are four major forest types within the LEF: tabonuco forest at elevations less than 600 m above sea level, colorado forest between 600 and 750 m, palm forest at elevations greater than 750 m, and dwarf forest between 750 and 1075 m above sea level (Naumann 1994). The LEF also contains four of the six life zones found on the island: subtropical wet forest, lower montane wet forest, lower montane rain forest, and subtropical rain forest (Ewel and Whitmore 1973).

There is very little groundwater storage in the northeastern area of Puerto Rico, and there are no natural lakes on the island (see footnote 1). Nine major rivers have their headwaters within the LEF: Río Mameyes, Río Fajardo, Río Sabana, Río Blanco, Río Gurabo, Río Canóvanas, Río Canovanillas, Río Grande, and Río Espíritu Santo. Río Canóvanas and Río Canovanillas drain into the Río Grande de Loíza watershed, and the Río Grande joins the Río Espíritu Santo near the estuary (fig. 1).

These rivers are geomorphologically typical of montane streams in the Greater Antilles of the Caribbean (Ahmad et al 1993): The headwaters of these streams flow in steep, narrow, boulder-lined channels. Fine sediment is generally lacking, and flood flows are common. Storms cause sharp rises in the hydrograph. High flows usually last for a few hours, but can last as long as a few days during very large storms (Naumann 1994).

Río Mameyes to the border of the LEF, and a tributary, Río la Mina, are designated as wild and scenic rivers according to the Wild and Scenic Rivers Act. The Río Icacos, a tributary of the Río Blanco, also holds such designation (NPS 2005).

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[1] Larsen, M. 2003. Water resources in Puerto Rico. Presentation at third annual public symposium for long term ecological research in Puerto Rico. San Juan, PR: University of Puerto Rico.

Methods

Runoff Calculation

Average monthly runoff per unit area for each watershed was calculated from long-term daily runoff from 17 U.S. Geological Survey stream gages (fig. 2). Average monthly runoff for each stream gage was divided by basin area. Runoff volume per drainage area was compared for gages within the same watershed, and one gage was chosen as the representative stream gage for the entire watershed, based on the longest data record (table 1). In some watersheds (Espíritu Santo, Fajardo, Canóvanas, Gurabo, and Sabana), water intakes are located above the stream gage chosen. Analysis demonstrated that using an alternate gage would not yield different results in the case of the Espíritu Santo or Gurabo watersheds. In the case of the Río Fajardo, the intake has not actually begun operation, and therefore has not altered streamflow at the gage used. Alternate gages were not available for the Canóvanas or Sabana; however, the amount of water withdrawn above these gages is very small. Therefore, runoff estimates do not include the reduction of streamflow due to water withdrawal. ArcView 3.2a™[2] (a GIS) was used to merge watersheds that drain into the same basin and to calculate each basin area. Average monthly and annual runoff volumes for each basin were calculated by multiplying runoff volume per drainage area from the representative stream gage by total basin area.

Runoff is reported in centimeters per year to be comparable to rainfall depth and data from other studies. To convert runoff to volume per time, multiply the given number (cm/time) by drainage area (cm^2). See table 2 for drainage areas.

Rainfall Calculation

A rainfall-elevation regression equation developed by García-Martinó et al. (1996) was applied to a 25-meter digital elevation model (DEM) of the LEF to calculate average annual rainfall. This equation relates average annual rainfall depth with elevation for 18 rain gages within the LEF. No difference existed between rain gages located on the windward or leeward side of the forest, suggesting that rainfall is uniform over the forest and varies consistently with elevation (García-Martinó et al. 1996). Watershed boundaries were overlaid on the resulting grid, and average annual rainfall was calculated for each watershed.

[2] The use of trade or firm names in this publication is for reader information, and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

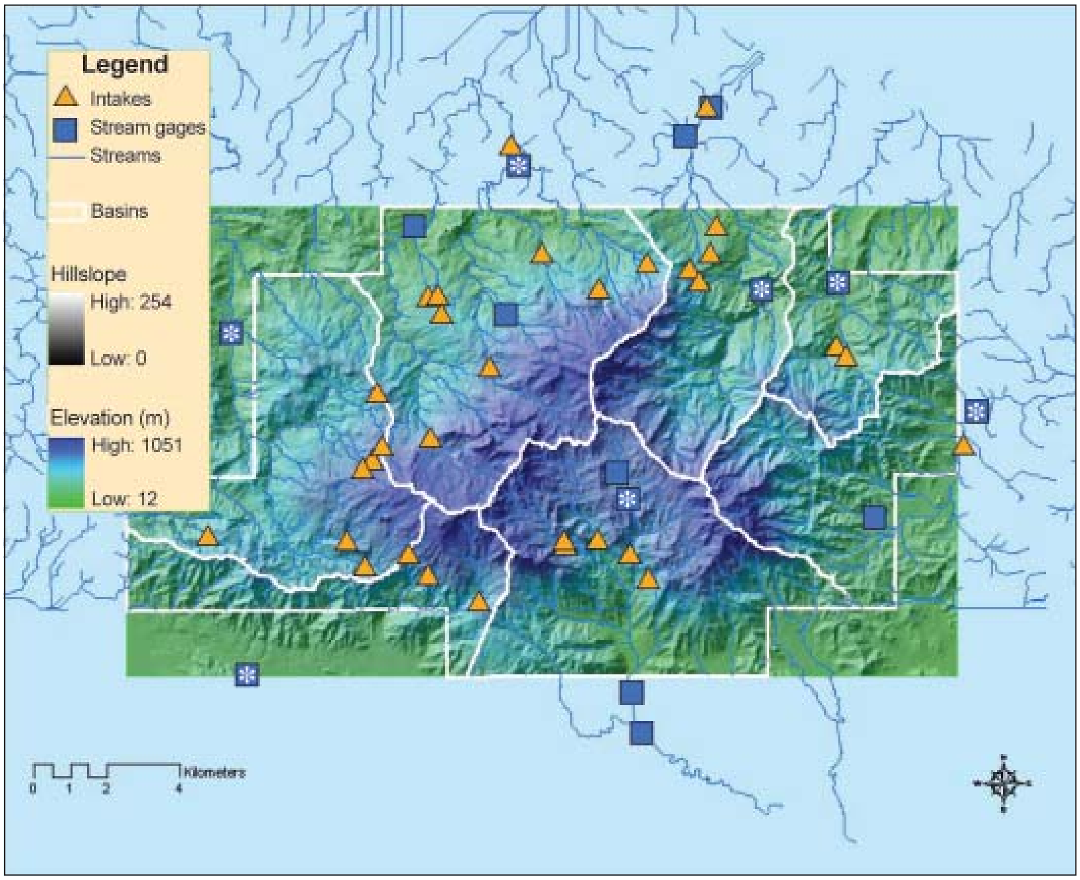

Figure 2—U.S. Geological Survey stream gages. Stream gages used in analyses are marked with an asterisk. Water intakes are shown in relation to stream gages for reference. Watersheds, clockwise from the left, bottom corner of the Luquillo Experimental Forest are: Gurabo, Canóvanas (Loíza), Espiritu Santo, Mameyes, Sabana, Fajardo, Blanco.

Table 1—U.S. Geological Survey flow gages on streams draining the Luquillo Experimental Forest

Watershed	Gage	Latitude	Longitude	Drainage area	Period of record	Operation
				Square miles	*Years*	
Blanco	50074950	18 17’02"	65 47’20"	0.12	11	1992-2002*
	50075000	18 16’38"	65 47’09"	1.26	57	1945-2002*
	50076000	18 13’45"	65 47’06"	12.3	3	1982-1985
	50077000	18 13’09"	65 46’57"	17.6	5	1972-1977
Canovanas/ Loiza	**50061800**	18 19’08"	65 53’21"	9.84	33	1967-2002*
Espiritu Santo	50063440	18 19’24"	65 49’03"	1.01	16	1984-2002*
	50063800	18 21’37"	65 48’49"	8.62	44	1966-2002*
	50064200	18 20’42"	65 50’30"	7.31	26	1967-2002*
Fajardo	**50071000**	18 17’56"	65 41’42"	14.9	42	1961-2002*
	50070500	18 16’21"	65 43’18"	3.69	5	1995-2001
	50072000	18 19’11"	65 39’07"	21.6	6	1960-1966
Gurabo	**50055750**	18 14’02"	65 53’07"	22.3	12	1990-2002*
	50057000	18 15’30"	65 58’05"	60.2	41	1959-2002*
Mameyes	**50065500**	18 19’46"	65 45’04"	6.88	26	1967-2002*
	50066000	18 22’27"	65 45’50"	13.4	3	1997-2002*
	50065700	18 22’03"	65 46’14"	11.8	18	1966-1985
Sabana	**50067000**	18 19’52"	65 43’52"	3.96	21	1979-2002*

Note: Gage used in analyses are in bold. Gages marked with * are currently operating.

Table 2—Drainage areas of watersheds and the entire forest

Watershed	Area
	Hectares
Blanco	4 618
Mameyes	2 732
Fajardo	2 659
Espiritu Santo	4 992
Gurabo	1 788
Sabana	1 785
Canovanas/Loiza	3 843
Total forest to administrative boundary	22 417
Espiritu Santo to intake E-19	3 272
Mameyes to intake M-17	3 750
Fajardo to intake F-18	3 229

Average monthly rainfall was derived by determining the proportion of rainfall that occurs in each month based on the rainfall pattern at the El Verde rain gage, as was done by Wang et al. (2003). This method is acceptable because seasonal rainfall patterns are similar throughout the LEF (García-Martinó et al. 1996).

Intakes

Water extraction volumes from intakes were estimated from USDA Forest Service rights-of-way and Puerto Rico Department of Natural Resources and the Environment water franchises, when available. When permit data were not available, extraction volume was estimated by using the aforementioned pipe-flow equation, using field data from Naumann (1994) and updated information when appropriate. Extraction volumes were estimated for 34 intakes, 14 of which were not included in Naumann (1994).

Intake locations were projected from x,y coordinates in Puerto Rico state plane meters to NAD 27 for Puerto Rico and converted to a shape file. Intakes without established global positioning system (GPS) locations were digitized onscreen by using information from paper maps as a reference.

Because intakes are referred to by different names and numbers in the previous water budget study (e.g., Naumann 1994) and in Forest Service permit files, table 3 standardizes names used for all known intakes on streams draining the forest. These intakes are shown and labeled on figure 3. This will allow future investigators seeking to update the water budget to easily compare data.

Water Budget

Average monthly and average annual water budgets were calculated for each watershed and the LEF as a whole. The equation used was:

$$R = P - ET;$$

where

R = runoff,

P = precipitation, and

ET = evapotranspiration.

In practice, precipitation and runoff were measured or estimated, and ET was calculated as the remainder: $ET = P - R$. The ET, rainfall, and runoff volumes were then compared to other estimates. Water extraction was subtracted from runoff to calculate the amount of water remaining in streams.

Table 3—Estimated water withdrawal for water intakes on streams draining the Luquillo Experimental Forest

Study ID	Forest Service ID	Naumann ID	Stream	Watershed	Owner	Pipe calculation	Permit
						– – – Gallons per day	*– – –*
B-10	10		Rio Cubuy	Blanco	PRASA	951,120	501,120
B-Ka	K	7	Rio Cubuy	Blanco	PREPA		
B-Kb	K	8	Rio Sabana	Blanco	PREPA		
B-Kc	K	9	Rio Icacos	Blanco	PREPA		3,580,703
B-Kd	K	10	Rio Prieto	Blanco	PRASA		3,580,703
C-15	15		Rio Cubuy	Canovanas	PRASA		192,000
C-2	2	23	Quebrada Los Santos	Canovanas	PRASA	660,500	
C-c	C		Creek	Canovanas	Private		165
C-l	L		Quebrada Aguacate	Canovanas	Private		299
C-m	M		Spring	Canovanas	Private		150
C-n	N		Quebrada La Motilla	Canovanas	Private		440
C-o	O	19	Spring	Canovanas	Private	329,193	1,872
E-16	16	15	Rio Espiritu Santo	Espiritu Santo	PRASA	3,353,883	950,000
E-19			Rio Espiritu Santo	Espiritu Santo	PRASA	20,772,461	
E-3	3		Tribitary Of Quebrada Jimenez	Espiritu Santo	PRASA	619,817	187,200
E-6	6	16	Rio Grande	Espiritu Santo	PRASA	14,941,683	
E-6*	6*		Rio Grande	Espiritu Santo	PRASA		200,000
E-9	9	0	Quebrada Jimenez	Espiritu Santo	PRASA		249,874
E-d	D		Creek	Espiritu Santo	Private		40
E-p	P		Rio Grande	Espiritu Santo	Private	85,337	
E-q	Q		Creek	Espiritu Santo	Private		200
E-x		12	Quebrada Grande	Espiritu Santo	PRASA	264,200	
E-xx		13	Quebrada Colberg	Espiritu Santo	PRASA	74,594	
F-18			Rio Fajardo	Fajardo	PRASA		12,000,000
G-7	7	25	Rio Gurabo	Gurabo	PRASA	1,241,740	
G-f	F	24	Quebrada Grande	Gurabo	Private	92,393	1,370
G-g	G	26	Creek	Gurabo	Private	291,677	
M-17			Rio Mameyes	Mameyes	PRASA		5,000,000
M-a	A	5	Quebrada Catalina	Mameyes	Private		200
M-b	B		Quebrada Tabonuco	Mameyes	Private	1,678	120
M-l	I	1	Quebrada Linguete	Mameyes	Private	475,560	17,875
M-y			Quebrada La Maquina	Mameyes	Gov't		60,480
S-1	1	2	Rio Cristal	Sabana	PRASA	792,600	
S-11	11	3	Rio Sabana	Sabana	PRASA	792,600	

Note: Intake identifications are given from the USDA Forest Service and Naumann (1994). GPD = gallons per day, PRASA = Puerto Rico Aqueduct and Sewer Authority, PREPA = Puerto Rico Electric Power Authority. Intake 6* is a temporary sump-pump that is currently in operation.

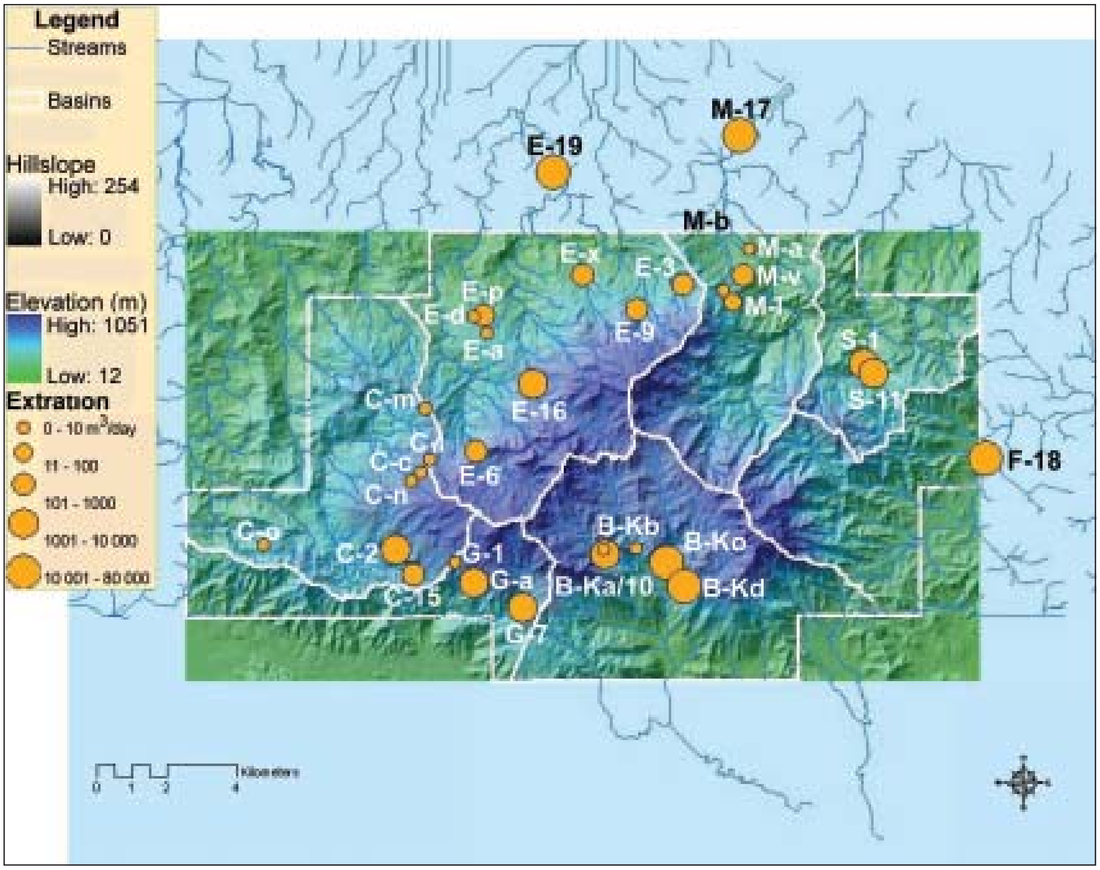

Figure 3—Water intakes on streams draining the Luquillo Experimental Forest. Watersheds are delineated in white and are clockwise, from the left: Canóvanas (Loíza), Espíritu Santo, Mameyes, Sabana, Fajardo, Blanco, and Gurabo. Intakes are depicted with solid circles. Circle size corresponds to the withdrawal capacity of each intake.

Several large water intakes are located outside of the LEF on streams that drain the LEF. Large intakes are located in the Río Espíritu Santo, Mameyes, Fajardo, and Río Grande de Loíza drainages. ArcView was used to digitize the area including all intakes on each river and to calculate the area of each basin draining into the last intake on each river. Water budgets were calculated to include the water withdrawal of these intakes by using the extended areas and methods above.

The annual water budget model ($R = P - ET$) does not account for soil moisture. However, the water budget is based on long-term data; therefore, soil moisture should be relatively constant. Also, groundwater contributions to streamflow are small in the LEF (Larsen 1997, Ortiz-Zayas 1998).

Results

Water Intakes

Estimates of water withdrawal were generated for 33 gravity-fed dams and 1 French drain-style intake. Thirty-one of these are located within the LEF administrative boundary (fig. 3). In seven cases, information was available for the pipe-flow equation in addition to a permit; therefore, two estimates of water withdrawal were generated (table 3). For water budget calculations, the water permit was preferred over the pipe-flow equation estimation because the permit is the legal extraction volume. Pipe-flow equation estimates were used for eight intakes.

In the Río Fajardo drainage, two intakes are currently located within the LEF, and another is under construction just outside of the LEF. The new intake is expected to begin operation in the near future. Once the new intake is operating, the two other intakes will supposedly cease operation. Therefore, for this analysis, the two existing intakes are ignored, and the new intake is considered.

In the Río Espíritu Santo drainage, two intakes are named "E-6." E-6 is the actual intake and E-6' is a temporary sump-pump that has failed to go out of operation. For this analysis, both are considered because it is unclear whether PRASA has any intention of removing intake E-6'.

Current estimates suggest that in 2004, 66.4 mgd (2.52×10^5 m^3/day) of water were withdrawn from streams draining the LEF. Ten years earlier, 51 mgd (1.93×10^5 m^3/day) were withdrawn from the same area (Nauman 1994).

Water Budget for the LEF

Average annual rainfall is estimated as 358 cm/year for the LEF. Average monthly rainfall for the LEF ranges from 18 to 40 cm/month. March is the lowest average rainfall month and November is the highest average rainfall month. All ranges hereafter indicate the lowest and highest rainfall (or runoff) months; specifically, March and November. Average monthly rainfall for each watershed is presented in table 4.

Average annual runoff is estimated as 228 cm/yr, or 63 percent of annual rainfall. Average monthly runoff for the LEF ranges from 12 to 28 cm/month. Average monthly runoff for each watershed is presented in table 4. Runoff is presented here in centimeters per time so that it can be compared to rainfall. Runoff is converted to centimeters per time by dividing volume per time by surface area of the drainage basin (see table 2 for drainage areas).

Table 4—Average monthly and annual rainfall, runoff, and evapotranspiration for each watershed draining the Luquillo Experimental Forest, and the forest overall

	Month												
Basin	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**Annual**
Rainfall	*Centimeters*												
Blanco	30	41	37	26	22	19	26	37	26	30	37	37	370
Espiritu Santo	30	41	37	26	22	19	26	37	26	30	37	37	370
Fajardo	27	38	34	24	21	17	24	34	24	27	34	34	338
Grande de Loiza	29	40	36	25	22	18	25	36	25	29	36	36	360
Gurabo	29	40	36	25	22	18	25	36	25	29	36	36	360
Mameyes	29	39	36	25	22	18	25	36	25	29	36	36	355
Sabana	26	35	32	23	19	16	23	32	23	26	32	32	319
Total forest	29	40	36	25	22	18	25	36	25	29	36	36	358
Runoff													
Blanco	38	45	39	34	30	24	27	37	28	32	36	42	411
Espiritu Santo	21	30	27	19	15	13	14	22	15	18	22	21	238
Fajardo	19	22	17	10	7	7	8	17	11	10	12	17	157
Grande de Loiza	13	14	11	8	5	4	4	8	5	6	8	12	97
Gurabo	11	10	7	3	2	2	2	6	6	5	8	11	74
Mameyes	28	35	27	24	16	16	17	27	22	21	24	27	283
Sabana	18	26	20	12	8	8	8	23	14	13	14	18	182
Total forest	23	28	23	18	14	12	13	21	15	16	20	23	228
Evapotranspiration													
Blanco	0	0	0	0	0	0	0	0	0	0	2	0	0
Espiritu Santo	9	11	10	7	7	5	12	16	11	12	16	16	132
Fajardo	8	16	17	14	14	10	16	17	13	18	23	17	182
Grande de Loiza	16	27	26	18	17	14	21	28	20	24	29	24	263
Gurabo	18	30	29	22	20	16	24	30	20	24	29	25	286
Mameyes	1	4	9	1	6	2	8	9	3	7	12	9	72
Sabana	8	9	12	10	11	8	14	10	9	14	18	14	136
Total forest	6	12	13	7	8	6	12	15	10	12	17	13	130

By subtracting average annual runoff (prior to withdrawals) from average annual precipitation, average annual evapotranspiration for the LEF is estimated as 130 cm/yr, or 36 percent of average annual rainfall. Average monthly evapotranspiration for the LEF ranges from 6 to 17 cm/month. Average monthly evapotranspiration for each watershed is presented in table 4.

On an annual basis, the volume of water extracted from the LEF is estimated at 25 cm/yr ($2.42x10^{10}$ gallons/year), or 7 percent of average annual rainfall and 11 percent of average annual runoff. Monthly extractions for each watershed are presented in table 5. The water diverted as a percentage of average monthly runoff ranges from 7 to 17 percent (table 5). The Espíritu Santo watershed has the highest percentage of runoff extracted (20 percent annually) and the Río Fajardo watershed has the least (0 percent from the LEF; however, a water intake is located just outside of the forest) (table 5).

Table 5—Water extraction within Luquillo Experimental Forest by volume and percentage of streamflow

	Month												
Basin	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**Annual**
	Centimeters												
Blanco	2	2	2	2	2	2	2	2	2	2	2	2	23
Espiritu Santo	4	4	4	4	4	4	4	4	4	4	4	4	47
Fajardo	0	0	0	0	0	0	0	0	0	0	0	0	0
Grande de Loiza	0	0	0	0	0	0	0	0	0	0	0	0	3
Gurabo	1	1	1	1	1	1	1	1	1	1	1	1	12
Mameyes	0	0	0	0	0	0	0	0	0	0	0	0	0
Sabana	1	1	1	1	1	1	1	1	1	1	1	1	12
Total forest	2	2	2	2	2	2	2	2	2	2	2	2	25
	Percentage of streamflow												
Blanco	5	4	5	6	6	8	7	5	7	6	5	5	6
Espiritu Santo	19	13	15	20	24	30	27	18	26	23	18	18	20
Fajardo	0	0	0	0	0	0	0	0	0	0	0	0	0
Grande de Loiza	2	2	2	3	4	6	6	3	5	5	3	2	3
Gurabo	9	10	14	31	43	54	52	16	17	19	13	9	16
Mameyes	0	0	0	0	0	0	0	0	0	0	0	0	0
Sabana	6	4	5	8	11	13	12	5	7	9	7	6	7
Total forest	9	7	9	11	14	17	15	10	13	13	11	9	11

Water Budget for Watersheds Including Large Intakes Outside of Forest Boundary

Results are given for watersheds with large dams on rivers draining the LEF; namely, the Río Espíritu Santo, Río Mameyes, and Río Fajardo drainages (table 6). In instances where only a part of a watershed drains into a large intake (Espíritu Santo and Fajardo), a water budget was calculated for the portion of the watershed that drains into the intake, to evaluate the effect of that intake on discharge. The Río Grande de Loíza is not evaluated, even though a large dam exists outside of the LEF, because the portion of the drainage included in the LEF is very small.

The portion of the Espíritu Santo watershed draining to intake E-19 generates 239 cm/yr (or 7.82×10^7 m^3/yr) of runoff. Average monthly runoff ranges from 13 to 30 cm/month. Of this, 95 cm/yr (or 7 to 8 cm/month) is extracted for municipal use. Forty percent of streamflow is diverted on an average annual basis, and average monthly streamflow diverted ranges from 26 to 60 percent.

The portion of the Fajardo watershed draining to intake F-18 generates 157 cm/yr (or 5.07×10^7 m^3/yr) of runoff. Average monthly runoff ranges from 7 to 22 cm/month. Of this, 51 cm/yr (or 4 cm/month) is extracted for municipal use. Thirty-three percent of streamflow is diverted on an average annual basis, and average monthly streamflow diverted ranges from 19 to 63 percent.

Intake M-17 lies on the Río Mameyes, outside of the LEF border. The area draining into the intake generates 281 cm/yr (or 1.05×10^8 m^3/yr) of runoff. Average monthly runoff ranges from 16 to 35 cm/month. Of this, 19 cm/yr (or 1 to 2 cm/month) is extracted for municipal use. Seven percent of streamflow is diverted on an average annual basis, and average monthly streamflow diverted ranges from 4 to 10 percent.

Discussion

Annual Water Budget for the LEF

The average annual water budget for the LEF, extending to the forest's administrative border, suggests that 36 percent of precipitation is lost to ET and 63 percent is converted to stream runoff. On an annual basis, 11 percent of the streamflow is diverted for human use. Lugo (1986) estimated ET by using three different methods, and the average of these methods was 42 percent. Another previous study estimated that 40 percent of average annual precipitation is lost to ET while 60 percent is converted to runoff (Naumann 1994); yet another found 35 percent of average annual precipitation is lost to ET while 65 percent is converted to runoff (García-Martinó et al. 1996).

Table 6—Runoff and water extraction by volume and percentage of streamflow for watersheds with large dams

	Month												
Basin	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**Annual**
	Centimeters												
Runoff													
Espiritu Santo	21	30	27	19	15	13	14	22	15	15	18	21	239
Fajardo	19	22	17	10	7	7	8	17	11	11	10	17	157
Mameyes	28	35	27	24	16	16	17	27	22	22	21	27	281
Water extaction													
Espiritu Santo	8	8	8	8	7	8	8	8	8	8	8	8	95
Fajardo	4	4	4	4	4	4	4	4	4	4	4	4	51
Mameyes	2	2	2	2	1	2	2	2	2	2	2	2	19
	Percentage of runoff												
Water extaction													
Espiritu Santo	38	26	30	40	47	60	54	37	52	46	37	37	40
Fajardo	23	19	26	42	58	63	51	25	38	44	37	24	33
Mameyes	6	4	6	6	9	10	9	6	7	8	7	6	7

Table 7 compares results of water budgets for five watersheds to the findings of García-Martinó et al. (1996). Watersheds Gurabo and Grande de Loíza were not included by García-Martinó et al. and therefore are not compared. In instances where more than one budget was given for a single watershed (e.g., three water budgets are given for the Espíritu Santo watershed), the budget for the sub-watershed with the largest basin area was used for comparative purposes. Average annual rainfall is relatively similar for the current study and García-Martinó et al. (1996). Slight differences can be attributed to rounding error and the use of GIS. Results for the percentage of average annual rainfall that is converted to runoff and ET are similar for watersheds Espíritu Santo, Fajardo, Mameyes, and Sabana. The methods used in this study do not accurately estimate streamflow for the Río Blanco drainage. The stream gage used to estimate average annual runoff was chosen because it has a long data record, but results show more runoff produced than rainfall, which is impossible. Apparently, there is not a linear relationship between basin size and runoff for the Río Blanco watershed as there is for the other watersheds. Therefore, it may be necessary to break up the Río Blanco watershed into subwatersheds to get a good estimate of runoff. However, the fact that the results for the other watersheds are consistent with García-Martinó et al. (1996)

Table 7—Comparison of water budget to García-Martinó (1996) findings

	Annual rainfall		Runoff		Evapotranspiration	
Study	**Current**	**Garcia**	**Current**	**Garcia**	**Current**	**Garcia**
	Centimeters		*– – – – – Percentage of rainfall – – – – – –*			
Blanco	373	415	45.0	86.9	55.0	13.1
Espiritu Santo	375	374	64.3	61.7	35.7	38.3
Fajardo	343	315	46.4	46.8	53.6	53.2
Mameyes	357	332	79.7	63.1	20.3	36.9
Sabana	322	333	57.2	52.4	42.8	47.6

allows confidence in the watershed-delineated water budgets. Furthermore, consistency in average annual water budgets suggests that the average monthly water budgets of this study are reasonable.

Because ET was calculated as the residual between rainfall and runoff, it was compared with other studies for consistency. Other estimates of ET are available for the Río Mameyes and Río Espíritu Santo watersheds; however, the estimates were made at different elevations, so some differences are expected. Wang et al. (2003) found 84 cm/year for subwatersheds of Bisley in the Mameyes Bisley and El Verde in the Espíritu Santo drainage. García-Martinó et al. (1996) found 122 and 75 cm/year for the Mameyes and 143, 169, and 182 cm/year for the Espíritu Santo (depending on subwatershed used). Schellekens et al. (2000) found 62 to 80 cm/year for the Bisley watershed (located within the Mameyes watershed), based on the water budget method for estimating ET. In the same study (Schellekens et al. 2000), 80 to 88 cm/year was estimated by using a combination of the Penman-Monteith equation and temperature fluctuation method. Current estimates of 72 cm/year for the Río Mameyes watershed and 132 cm/year for the Río Espíritu Santo watershed (table 4) are consistent with these previous studies.

For the entire LEF, it is estimated that approximately 11 percent of average annual streamflow is extracted for human use in 2004. However, the majority of stream discharge occurs during storm events; therefore, evaluating the percentage of annual streamflow withdrawn underestimates the ecological effect of water withdrawal on typical instream flow. Water extraction in streams draining the LEF results in a 40 percent decrease in the median flow (i.e., Q50 - X). Further, of the water generated within the LEF, 70 percent of the median flow is allocated for municipal use and fails to reach the ocean. This could be altering stream habitat for migratory shrimps and fishes, and also changing the dynamics of downstream transport of sediment, seston (suspended particles), and other food and energy sources to estuaries (Freeman et al. 2003, Ittekkot et al. 2000).

Return flow is not considered in the water budget owing to the fact that nearly all the wastewater treatment plants in the region are located at, or near, the estuary. Small water intakes within the forest divert water for local municipal use. Communities using these intakes probably have septic tanks, and most of this water is lost to evapotranspiration and groundwater. However, it is possible that a small amount of water may percolate back into the stream. Water diverted at larger intakes provides water for drinking-water plants outside of the forest. Water is returned from wastewater plants to estuaries. The area between water intakes and estuaries may run dry during certain parts of the year, depending on the proportion of flow diverted. As a result, saltwater intrusion may occur up to the lowest water intake in a watershed during such times. In addition, some water is treated at a wastewater treatment plant in a drainage different than that of its origin, resulting in interbasin exchange. This is the case for the new Fajardo wastewater treatment plant, which will treat water from four watersheds (Ortiz-Zayas et al., in press)

Monthly Water Budgets for the LEF

Monthly water budgets demonstrate that higher rainfall occurs from August to December, with a rainfall peak in November. A rainfall peak also occurs in May. March is the driest month of the year, which has important management implications: water diversion for human use should not exceed a level that would cause unacceptable stream habitat degradation during March. Runoff volume follows the monthly rainfall pattern: streamflow peaks in November with a second peak in May and is lowest in March. When water extraction is subtracted from average monthly flow, streamflow volume generally decreases for all watersheds. In general, streams with the largest intakes have the greatest reduction of instream flow. Water diverted from the forest ranges from 7 to 17 percent of average flow throughout the year, with up to 54 percent of flow diverted from individual watersheds (table 5). A much higher percentage of average flow is diverted when intakes outside of the forest are considered (table 6). For instance, 19 to 63 percent of flow is diverted from the Río Fajardo, and 26 to 60 percent of flow is diverted from the Río Espíritu Santo (table 6).

Assumptions and Error

This study assumes that seasonal variations in rainfall are uniform throughout the LEF. Specifically, that the percentage of annual rainfall, measured each month at the El Verde rain gage, represents the percentage of annual rainfall occurring each month throughout the forest. This is probably a good assumption owing to the statistically valid relationship between elevation and rainfall; however, some rain gages demonstrate small differences (such as a rainfall peak in October rather than November) which, when applied over a large area, may result in significant changes.

This study also assumes that permitted water extraction equals actual water extraction, which is not necessarily a safe assumption. However, as intakes are not gaged, there is no way of knowing how much water is actually withdrawn from streams. In cases where information required for the pipe flow equation is available, in addition to permit data, it has been found that pipes are capable of extracting more water than is permitted. In addition, this study does not include all illegal intakes or known intakes for which extraction volume is unknown, suggesting that actual water extraction is higher than estimated.

Results for the Río Blanco watershed are clearly flawed. The gage used for analyses is located high in the watershed, and this area produces more streamflow per unit area than other parts of the watershed. It may be necessary to break up the Río Blanco watershed into subwatersheds to reach a more accurate water budget.

Spatial Distribution

The effect of water withdrawal on instream flow is not uniform throughout the LEF. Watersheds with several intakes or large intakes have the greatest reduction in discharge. Most of the intakes within the forest boundary are small, with several extracting less than 1,000 gallons per day (3.8 m^3/day). These intakes are usually found higher in a watershed, whereas larger intakes are typically found lower in a watershed.

There seems to be a trend in northeastern Puerto Rico favoring one large intake low in a watershed over several small intakes higher in a watershed. The Río Fajardo watershed is an example of this. A new intake is currently under construction that is permitted to extract 12 mgd (4.55×10^4 m^3/day). This intake will replace two smaller intakes higher in the watershed (discussed below). Because the new intake is outside of the LEF, there is no instream flow reduction within the forest; however, 32 percent of average annual streamflow and 67 percent of the median flow will be diverted below the new intake (just outside of the forest). This highlights the importance of considering the area surrounding the LEF when making policy and management decisions for the LEF. Although the new Fajardo intake is outside of the CNF, it clearly affects aquatic environments for fauna within LEF by reducing connectivity between headwaters and estuaries.

The greatest reduction of instream flow occurs in the Espíritu Santo watershed, where 82 percent of the median flow is extracted. The Fajardo watershed is also greatly affected by water withdrawal, as discussed above. Although the Río Mameyes has a large intake outside of the forest, only 11 percent of the median flow is extracted because of a minimum flow requirement of 5 mgd (1.89×10^4 m^3/day) (discussed below). Forty percent of the median flow is diverted in the Gurabo drainage, and 10 percent is diverted in the Blanco drainage, 15 percent in the Sabana drainage, and 9 percent in the Canóvanas (Loíza) drainage. Specific attributes of significant water intakes are discussed below according to the watershed within which they are located.

Río Fajardo

There are two currently operating water intakes in the Fajardo basin, which are used to supply the drinking water treatment plant for the Fajardo area (Ortiz-Zayas et al., in press). Together, these intakes are designed to remove 5 mgd (1.89×10^4 m^3/day); however, they are currently operating at 7 mgd (2.65×10^4 m^3/day) (Autoridad para el Financiamiento de la Infraestructura 1999). A new intake, which is intended to replace the two existing intakes is in development stages. This new intake will have the capacity to remove 12 mgd (4.55×10^4 m^3/day) and will move water into an off-stream reservoir. A tertiary regional wastewater treatment plant is also being built. This facility will replace four current wastewater treatment plants from four watersheds. It is estimated that an average of 9.2 mgd (3.48×10^4 m^3/day) will be returned to the Río Fajardo from the waste water treatment plant. The intake is designed to maintain a minimum flow of 0.1 m^3/s (Q99), and will cease water extraction during key times during night hours when migratory shrimp are most active. Overall, this new extraction scheme is expected to increase freshwater inputs to the estuary, but will decrease flow for 7.8 km below the intake. To manage the increased water volume downstream, a series of levees are being built to contain flood flows (Ortiz-Zayas et al., in press)

Río Blanco

Five intakes exist in the Río Blanco drainage, four of which are operated by the Puerto Rico Electric Power Authority (PREPA). The intakes are located on Río Icacos, Río Cubuy, Río Sabana, and Río Prieto; each intake is piped to the main hydropower plant. The Río Icacos is designated a wild and scenic river, which protects river flow. The PREPA has agreed to a minimum flow requirement of 4 cubic feet per second (cfs) (0.11 m^3/s) for the Icacos; however, zero flow has been observed below the intake (Cano 2003). A new intake, similar to the new Fajardo intake is being constructed outside of the CNF on the main stem of the Río Blanco (Cano 2003).

Río Mameyes

A new intake has been developed on the main stem of the Río Mameyes, which is considered a wild and scenic river from its headwaters to the border of the LEF. The intake is permitted to extract 5 mgd (1.89×10^4 m^3/day), but must maintain a minimum flow of 5 mgd (7.75 cfs or 0.22 m^3/s). This is less than Q99, which equals 8.5 cfs. The intake is a French drain, which prevents entrainment of migratory shrimp and fish.

Municipal Water Demand

The LEF is a relatively small system in comparison to adjacent urban development. All streams within the LEF are third order or smaller, and even though a large amount of water is carried by streams, the majority of water leaves the forest in short-duration, high-intensity flows that are not captured for storage by the water distribution systems (Scatena and Johnson 2001). Withdrawals alter the abundance and diversity of stream communities (Benstead et al. 1999, March et al. 1998). Water withdrawal is expected to increase in the future, creating management challenges in terms of maintaining the ecological integrity of a protected area (González-Caban and Loomis 1997). The U.S. Army Corps of Engineers (USACE 1993) projected water demand for each municipality outside of the LEF. Per capita demand is anticipated to slightly decrease over the 50-year period, suggesting an expectation of future water conservation practices. However, population size was expected to increase, therefore increasing overall water demand (USACE 1993).

According to the 2000 census (U.S. Census Bureau 2000), approximately 3.9 million people live in Puerto Rico. About 20 percent of this population depends on the LEF for water supplies (Naumann 1994). Based on estimates from USACE (1993), municipalities around the LEF (Canóvanas, Fajardo, Luquillo, and Río Grande) use an average of 85.5 gallons per person per day (0.32 m^3 per person per day) (for comparison, per capita water use in San Juan is about 160 gpd [0.61 m^3/day]). Therefore, about 780,000 people each use about 85.5 gpd, which results in daily water demand of 67 mgd (2.54×10^5 m^3/day). According to this analysis, the 34 known water intakes produce about 66.4 mgd (2.52×10^5 m^3/day).

Future Considerations

Future development (urban and suburban) and climate change will likely exacerbate pressures on aquatic ecosystems owing to water extraction. Northeastern Puerto Rico is a popular location for vacation homes and tourism. Tourism-related development is thought to require a higher per capita water demand owing to swimming pools and hotel operations. Puerto Rico currently has a pipe loss rate of about 43 percent (Quiñones 2003), and unless efficiency is increased, further development will likely fuel additional water withdrawal from streams draining the LEF. A larger population will also require additional wastewater treatment. Currently, water withdrawal results in dewatering of low-elevation reaches of some streams draining the LEF during several months of the year. During this time, effluent from wastewater treatment plants flows undiluted to the ocean. Clearly, this is an ecological, public health, and aesthetic problem. Interactions between further water withdrawal and additional wastewater treatment plant effluent are compounded by the fact that the tourist season coincides with lower average streamflow. Poor water quality owing to pollution may affect populations of estuarine and migratory biota. This, in addition to the adverse effects of dams on shrimp and fish migration and habitat availability, may result in landscape-scale ecological consequences. Drought years will exacerbate problems associated with the interaction of reduced instream flow and increased pollution.

Research suggests that water availability may be affected by urban development and regional climate change (e.g., Scatena 1998, Wang et al. 2003). The "urban heat island" is thought to increase regional temperatures of the LEF, thereby altering the hydrologic cycle. Scatena (1998) and Wang et al. (2003) suggested that an increase in carbon dioxide or temperature could potentially significantly alter the vegetation and hydrologic cycle of the LEF, which could alter the amount of water available for human use, recreation, research, and ecological purposes.

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English Equivalents

When you know:	Multiply by:	To find:
Centimeters (cm)	0.394	Inches
Meters (m)	3.28	Feet
Cubic meters (m^3)	35.3	Cubic feet
Kilometers (km)	0.621	Miles
Hectares (ha)	2.47	Acres
Hectares (ha)	10 000	Square meters
Liters (L)	0.264	Gallons
Cubic meters (m^3)	264	Gallons
Square meters per second (m^2/s)	10.76	Square feet per second
Cubic meters per second (m^3/s)	264	Gallons per second
Cubic meters per second (m^3/s)	35.3	Cubic feet per second

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