AWRA American Water Resources Association
Advancing Water Resources Research and Management
Third International Symposium on Tropical Hydrology
San Juan, Puerto Rico, July 12-16, 1998

WATER BUDGETS OF FORESTED AND AGRICULTURALLY-DEVELOPED WATERSHEDS IN PUERTO RICO

Matthew C. Larsen[(1)] and Iris M. Concepción[(2)]

Abstract:

Accurate assessment of water budgets is critical for effective management of water resources, especially on small, densely-populated islands with extremely limited storage capacity such as Puerto Rico. A water budget defines a balance between inputs, outputs, and storage. The water budgets described herein provide a generalized summary of the inputs, extractions, and outputs from four watersheds in and near the Luquillo mountains using rainfall, runoff, and public-supply extraction data as well as estimates of groundwater losses and inputs such as cloud drip and infiltration from septic tanks. Mean annual rainfall accumulation during a 7-year study (1991 to 1997) ranged from 1,722 mm in the Canóvanas watershed, to 4,235 mm in the Icacos and Mameyes watersheds; the Cayaguás watershed had 2,172 mm. Combined runoff, groundwater flow and withdrawals ranged from 47 to 73 percent of inputs (combined rainfall, cloud drip and septic tank infiltration). Evapotranspiration, calculated as the water budget residual, amounted to 27, 40, 44, and 53 percent of total moisture inputs in the Icacos, Cayaguás, Mameyes, and Canóvanas watersheds, respectively.

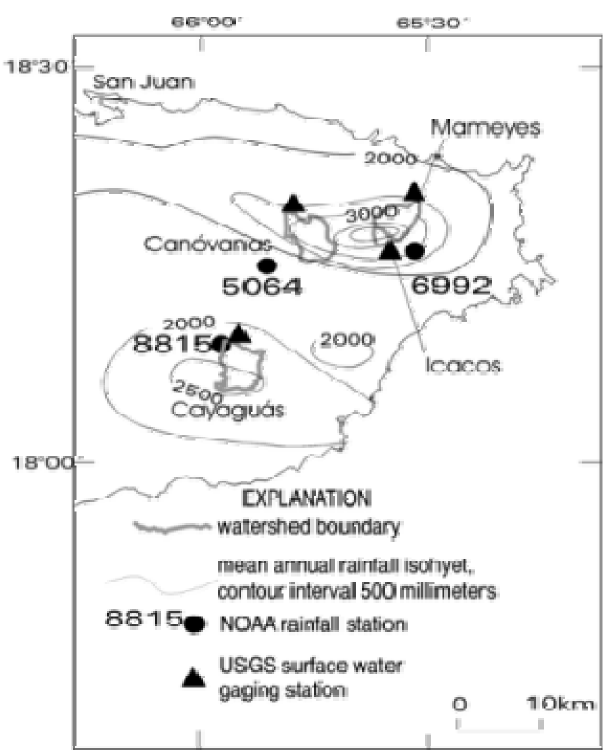
Introduction

A water budget, in the most basic form, defines a balance whereby a surplus occurs when inputs exceed combined extractions and outputs, and a deficit occurs when extractions and outputs exceed inputs. An accurate water budget is critical for effective management of water for public supply, agricultural and industrial uses, and hydroelectric power generation. Limited storage capacity on small, densely-populated islands is exacerbated by the high sediment loads of river systems in which the Puerto Rican reservoirs have been constructed (Zack and Larsen, 1993). Population growth and industrial development increase the demands on water resources. At the same time, public and private resistance to strategies such as dam construction, aqueduct systems for transporting water across long distances, and transfer of water from agriculture to urban distribution networks has also grown (Milliken and Taylor, 1981). Future conflicts among varying water-resource interests are likely to become more complex as demand for water outstrips supply.

This paper presents water budgets for the Canóvanas, Cayaguás, Icacos, and Mameyes watersheds, located in eastern Puerto Rico. A generalized summary of the inputs, extractions, and outputs from each watershed using data and estimates for the period 1991 to 1997 is provided. These four watersheds represent typical forested and agriculturally-developed settings and each overlies one of two dominant bedrock types that occur in Puerto Rico and elsewhere in island-arc systems.

Study Area

Puerto Rico is the smallest island of the Greater Antilles, located about 1,700 km southeast of Miami, Florida. The island is in the trade-wind belt at the boundary between the Caribbean Sea and the Atlantic Ocean at 18°N, 66°W. Because of tectonically-controlled geologic complexity and strong orographic control on island rainfall distribution, a variety of land use, topographic, and soil characteristics exist in the relatively small (8,655 km^2) area of Puerto Rico. Several major bedrock types that typify island arc systems throughout the world have been mapped in Puerto Rico (Donnelly, 1989). These include the Cretaceous marine-deposited volcaniclastic rock and Tertiary intrusive rock that underlie the four study watersheds.



Eastern Puerto Rico includes a 113-km^2 forest preserve, the United States Forest Service-administered Luquillo Experimental Forest (LEF) in which the Icacos and Mameyes watersheds are located (Figure 1). The LEF is an area of relatively undisturbed forest and allows for the determination of water budgets with minimum anthropogenic effects. The Canóvanas and Cayaguás watersheds are located just west of the LEF, within the Río Grande de Loíza basin. Land use is typified by pasture and secondary forest with small clusters of houses. Mean annual rainfall in the four watersheds ranges from about 1,700 mm to greater than 4,000 mm per year, varying with elevation (Calvesbert, 1970). Much of the annual precipitation occurs in medium to high intensity showers associated with easterly waves and tropical disturbances.

Figure 1. Map of eastern Puerto Rico showing mean annual rainfall isohyets and location of study watersheds. Rainfall data from Calvesbert (1970).

Table 1. Precipitation and surface-water gaging stations used to determine water budgets for four watersheds in eastern Puerto Rico.

Watershed name, drainage area, km^2	Rainfall station ID	Rainfall station name	Surface water gaging station ID
Cayaguás, 26	668815	San Lorenzo 3 S	50051310
Canóvanas, 26	665064	Juncos	50061800
Icacos, 3	666992	Pico del Este	50075000
Mameyes, 18	666992	Pico del Este	50065500

Methods

Simplified water budgets were developed for this study using precipitation, mean daily runoff , and public supply withdrawal data for water years 1991 through 1997 (Table 1). Groundwater flow rates at the basin outlets were approximated using hydraulic conductivity values published for alluvial aquifers in the Caguas valley. Watershed-scale evapotranspiration (ET) rates were estimated using the common practice of calculation as the residual of water inflow minus water outflow (Likens and others, 1977). ET losses were estimated to be the residual of rainfall and other inputs (cloud drip, infiltration from septic tanks) minus runoff plus other losses (groundwater flow, public supply withdrawals). This technique is problematic as this residual value includes all the uncertainties of the water budget as well. It assumes that other components of the budget are accurate.

Monthly and annual precipitation accumulation data were obtained from the National Weather Service (NWS-NOAA) at stations in and near each watershed (Figure 1). Because the spatial distribution of rainfall stations was limited to the NWS-NOAA network, it was not ideal for the determination of watershed-scale precipitation input. Furthermore, the Pico del Este station, used to represent rainfall inputs for the Icacos and Mameyes watersheds, may under represent rainfall accumulation because of its location on a windswept, 1,051-m-elevation ridgetop (García and others, 1996).

A significant part of annual moisture input in tropical montane cloud forests (the highest elevations in the eastern mountains of Puerto Rico) is delivered by condensation and direct contact of cloud droplets (Bruijnzeel and Proctor, 1993). This input of water, known as cloud drip, or horizontal precipitation, is conveyed by clouds moving with the trade winds. In the Luquillo mountains, the annual moisture input of cloud drip has been estimated to be 10 percent of precipitation (Weaver, 1972).

It can be assumed that all water introduced into septic tanks eventually infiltrates into soil where it exits the watershed as groundwater, surface water, or ET. Septic tanks are used by 78 percent and 89 percent of households in the Canóvanas and Cayaguás watersheds, respectively (U.S. Dept. of Commerce, 1991). Using population data from the 1990 U.S. Census and mean water consumption of 170 liters/person/day, the maximum volume of water derived from septic tanks in the Canóvanas and Cayaguás watersheds was estimated (Dopazo and Molina, 1995). It is possible that septic tank inputs are as much as 100 percent greater than those indicated here. In recent years, the Puerto Rico Aqueduct and Sewer Authority has produced, on average, almost 2 m^3 of public supply water for every 1 m^3 consumed, with the balance attributed to such factors as antiquated monitoring systems, illegal hookups, and leaks in the distribution network.

Table 2. Groundwater discharge at the surface_water gaging station outlet for four watersheds in eastern Puerto Rico, estimated using the range of hydraulic conductivity values published for alluvial deposits derived from intrusive and volcaniclastic bedrock in the Caguas valley (Puig and Rodríguez, 1993).

	Canóvanas		Cayaguás		Icacos		Mameyes	
	Low	High	Low	High	Low	High	Low	High
Hydraulic conductivity, m/day	1.49	4.21	3.60	13.0	3.60	13.0	1.49	4.21
Stream wetted perimeter, m	18		11		8		16	
Area of groundwater discharge, m²	54		44		24		64	
Groundwater discharge, m^3/day	81	227	158	574	86	313	96	269
Groundwater discharge, mm/y	1	3	2	8	10	35	2	6

Mean daily discharge data from USGS surface water gaging stations in each of the watersheds were used to calculate monthly and annual runoff for the 7-year study period (Table 1). These stations may slightly under represent total watershed discharge because of unmonitored groundwater flow at the gaging site. Additionally, during the highest flow events, the reliability of discharge data decreases because discharge measurements are rarely possible.

Groundwater flow rates at the basin outlets were approximated using hydraulic conductivity values published for alluvial aquifers in the Caguas valley (Puig and Rodríguez, 1993)(Table 2). In addition, saturated hydraulic conductivity was assessed in shallow soils in the Icacos and Mameyes watersheds with a Guelph permeameter (Reynolds and Elrick, 1985).

Hydraulic conductivity values published for alluvial aquifers in the Caguas valley ranged from 1.49 to 4.21 m/day in alluvium derived from volcaniclastic bedrock, and from 3.6 to 13.05 m/day in alluvium derived from granodiorite (Puig and Rodríguez, 1993). These alluvial deposits were assumed to represent alluvium at the study watershed outlets because of the comparable bedrock types from which the alluvium was derived. Massive unweathered bedrock crops out in the stream channel at the surface-water gaging sites for each river. The depth to bedrock in the vicinity of the channels at these locations was estimated at no greater than 4 m (Simon *et al* 1990). Groundwater flow through valley fill was considered negligible as the stream channels at the gaging stations are incised within narrow valleys with steep gradients measured perpendicular to the channel axis. At the Canóvanas and Icacos stations, the baseflow water surface is 3 m below the channel banks and valley slopes have gradients of 11 to 15°. At the Mameyes gaging station, the baseflow water surface is 4 m below channel banks and valley slopes are 15 to 20°. Valley slopes are 5 to 10° at the Cayaguás gaging station and baseflow water surface is 4 m below the channel banks. To calculate groundwater flow the hydraulic conductivity was multiplied by a cross sectional area approximated as the wetted perimeter of the channel at the basin outlet, times 3 to 4 m depth below channel banks. Although groundwater flow through faulted bedrock has been shown to be important along the coastal plain where extensive wetland recharge areas exist (Blume and others, 1981), in these steeply sloping uplands it can be reasonably assumed that groundwater flow through bedrock is minimal.

Results and Discussion

In spite of the close proximity of the watersheds, their mean annual precipitation and runoff vary considerably because of orographic effects and the nature of convection. In the tropics the main cause of convection is rising air, which is responsible for most precipitation (Nieuwolt, 1977). Convective cells are of limited areal extent. The predominantly convective nature of tropical cloudiness is therefore a major factor for the notorious spatial and temporal variability of tropical rainfall (Hastenrath, 1991). Annual runoff from the four watersheds has fluctuated substantially, varying by 1,000 to 2,400 mm during the several decade period of record of each stream. The years 1991 to 1997 were a period of low runoff for all of the watersheds. The 1994 water year was significant because it was the lowest runoff year for the Canóvanas, Icacos, and Mameyes Rivers and was the third lowest for the Cayaguás River since continuous monitoring by the USGS began in 1978. In addition to the temporal variability seen in annual runoff of the four streams, the spatial variability is significant as well. For example, runoff from the Canóvanas watershed has never equalled or exceeded that of the Icacos for the available record. The Canóvanas gaging station is only 12 km from that of the Icacos, but the Canóvanas basin is located on the west side of the Luquillo mountains in a rainshadow (Figure 1). Seasonal moisture variability is apparent in all of the study watersheds. March and April are the lowest runoff months and hurricane season months of September, October, and November are the months with greatest runoff in all of the watersheds.

A minimum estimate of groundwater discharge at the basin outlets for the four watersheds can be approximated by using saturated hydraulic conductivity in soil and saprolite. According to McDowell and others (1992), this value is about 10^{-4} cm/s at a shallow wellfield in the Icacos watershed, and 10^{-5} cm/s at a shallow wellfield in the Mameyes watershed. Three shallow tests (20 cm or less) by the authors using a Guelph permeameter yielded the same conductivity values: 10^{-4} cm/s in soil in the Icacos watershed and 10^{-5} cm/s in soil in the Mameyes watershed. These rates are equivalent to 0.1 and 0.01 m/day, respectively, in the Icacos and Mameyes watersheds and represent a probable minimum groundwater flow velocity. Maximum groundwater flow rates estimated in each of the four watersheds using the highest hydraulic conductivity values published by Puig and Rodríguez are only a few millimeters per year (Table 2). If the saturated hydraulic conductivity values are used, annual groundwater losses are a fraction of a millimeter in each watershed.

Documented public supply withdrawals are minimal in each of the four watersheds. Surface-water withdrawals in the Canóvanas basin average 43 mm per year and only 3 mm annually in the Cayaguás basin (Table 3). In the Mameyes watershed, 4 mm or less is annually withdrawn for USFS facilities in the LEF (Table 4). The Icacos watershed has no withdrawals.

Combined public supply withdrawals and groundwater flow represent less than 1 percent of mean annual rainfall in the Cayaguás watershed for the 7-year study period. They total less than 3 percent in the Canóvanas basin, and are negligible in the Icacos and Mameyes basins. As these components of the water budgets are reasonably certain and of low magnitude, ET loss can be plausibly estimated as the residual of inputs minus outputs, keeping in mind the uncertainties of rainfall accumulation and discharge measurements that were discussed above.

Table 3. Approximate water budget, in mm, by water year in the Canóvanas and Cayaguás watersheds, eastern Puerto Rico. Withdrawals include private and public surface-water intakes. Other inputs are via septic tanks estimated at 170 liters/person/day. Cloud drip is moisture from cloud condensation (at 600 m and above) estimated at 10 percent of measured precipitation (Weaver, 1972). In the Canóvanas watershed, this value was reduced to 0.17 of the calculated total as only this portion of the watershed is both above 600 m elevation and forested. ET is calculated as the residual of inputs minus losses and includes any errors in data.

	1991	1992	1993	1994	1995	1996	1997	Mean
Canóvanas watershed								
Rainfall	1,624	1,996	1,797	1,260	1,744	2,277	1,357	1,722
Other inputs: septic tanks (78 % of households)	10	10	10	10	10	10	10	10
Other inputs (cloud drip)	28	34	31	21	30	39	23	29
Total inputs (rainfall + septic tanks + cloud drip)	1,662	2,040	1,838	1,291	1,784	2,326	1,390	1,761
Runoff	706	732	792	368	762	1,259	881	786
Withdrawals	46	43	44	43	36	40	45	43
Groundwater flow	3	3	3	3	3	3	3	3
Total outputs (surface runoff, withdrawals, and groundwater flow)	755	778	839	414	801	1,302	929	831
Total outputs/total inputs	0.45	0.38	0.46	0.32	0.45	0.56	0.67	0.47
ET estimated as residual of inputs-outputs	906	1,262	998	877	982	1,024	461	930
ET, percentage of total inputs	55	62	54	68	55	44	33	53
Cayaguás watershed								
Rainfall	2,021	2,436	2,208	1,909	1,877	2,903	1,850	2,172
Other inputs: septic tanks (89 % of households)	5	5	5	5	5	5	5	5
Total inputs (rainfall + septic tanks)	2,026	2,441	2,213	1,914	1,882	2,908	1,855	2,177
Runoff	677	1,365	1,656	940	920	2,083	1,577	1,317
Withdrawals	4	5	2	2	2	1	1	3
Groundwater flow	8	8	8	8	8	8	8	8
Total outputs (surface runoff, withdrawals, and groundwater flow)	689	1,378	1,666	950	930	2,092	1,586	1,327
Total outputs/total inputs	0.34	0.56	0.75	0.50	0.49	0.72	0.85	0.60
ET estimated as residual of inputs-outputs	1,337	1,063	547	964	951	816	269	850
ET, percentage of total inputs	66	44	25	50	51	28	15	40

The approximated 7-year water budgets indicate that most of the water entering the Cayaguás, Icacos, and Mameyes watersheds exits as runoff, leaving a balance of 44, 23, and 43 percent, respectively, that can be assigned to ET (Tables 3,4). In contrast, slightly less than half of water inputs to the Canóvanas basin exits as runoff and ET represents 56 percent of water inputs. The low ET estimated for the Icacos watershed is probably the result of two factors: low solar radiation inputs in this high-elevation (>600 m) watershed , and low tranport: the watershed faces away from prevailing winds.The monthly distribution of rainfall, runoff, and the difference between them, which is mainly ET, are temporally and spatially variable. During a 1994 drought, runoff, as a fraction of rainfall, was at a minimum in the Canóvanas basin. The difference between rainfall and runoff in the Cayaguás basin was not as pronounced as in the Canóvanas.

Conclusions

Watershed-scale data summarized for a 7-year period in eastern Puerto Rico indicate large inter-annual variation with annual rainfall accumulation as much as 27 percent below to 34 percent above the 1990's mean. Runoff during the same period varied even more, ranging from 53 percent below to 60 percent above the 1990's mean in the Canóvanas watershed. Interannual variation of runoff in the Cayaguás watershed was comparable to that of the Canóvanas watershed while only ranging from 33 percent below to 19 percent above in the Mameyes watershed.

Mean annual precipitation for the 7-year study period ranged from 1,722 mm in the Canóvanas watershed to 4,235 mm in the Icacos and Mameyes watersheds. Mean annual runoff ranged from 786 mm in the Canóvanas watershed to 3,839 mm in the Icacos watershed. Average ET during the 7-year period was estimated to have ranged from 27 percent of total moisture inputs (rainfall, cloud drip) in the Icacos watershed to 53 percent of total moisture inputs in the Canóvanas watershed. Runoff was 3 to 7 percent below moisture inputs determined for the Icacos watershed in 1996 and 1997. This difference probably results from the decrease in accuracy of stage-discharge relations at rare, high-magnitude peak flows. To complicate matters, rainfall data quality may be severely compromised during high magnitude runoff events associated with hurricanes.

Simplifed water budgets can be developed with basic data commonly available through public sources administered by Federal agencies such as the USGS and NWS-NOAA. The budgets allow water and other resource managers to gage the use and availability of this critical resource over the short term when seasonal fluctuations are important and over the long term when regional variations in weather may prevail.

Table 4. Approximate water budget, in mm, by water year in the Icacos and Mameyes watersheds, eastern Puerto Rico. Cloud drip is moisture from cloud condensation (at 600 m `and above) estimated at 10 percent of measured precipitation (Weaver, 1972). In the Mameyes watershed, this value was reduced to 0.36 of the calculated total as 0.64 of the watershed area is below 600 m elevation. Withdrawal is surface water consumed at U.S. Forest Service facilities in the Mameyes watershed. ET is calculated as the residual of total inputs minus combined runoff and groundwater flow and includes any errors in the data.

	1991	1992	1993	1994	1995	1996	1997	Mean
Icacos watershed								
Rainfall	4124	4452	4399	3469	3933	4953	4315	4,235
Other inputs (cloud drip)	412	445	440	347	393	495	431	423
Total inputs (rainfall + cloud drip)	4,537	4,898	4,839	3,816	4,326	5,449	4,746	4,658
Runoff	3,248	3,575	3,383	2,191	3,805	5580	5091	3,839
Groundwater flow	35	35	35	35	35	35	35	35
Total outputs (surface runoff and groundwater flow)	3,283	3,610	3,418	2,226	3,840	5,615	5,126	3,874
Total outputs/total inputs	0.72	0.74	0.71	0.58	0.89	ex	ex	0.73
ET estimated as residual of inputs-outputs	1,254	1,288	1,421	1,590	486	(166)	(380)	1,208
ET, percentage of total inputs	28	26	29	42	11	na	na	27
Mameyes watershed								
Rainfall	4124	4452	4399	3469	3933	4953	4315	4,235
Other inputs (cloud drip)	148	160	158	125	142	178	155	152
Total inputs (rainfall + cloud drip)	4,273	4,613	4,557	3,594	4,074	5,132	4,470	4,387
Runoff	2,349	2,949	2,943	1,662	2,302	2785	2325	2,474
Withdrawals	4	4	4	4	4	4	4	4
Groundwater flow	6	6	6	6	6	6	6	6
Total outputs (surface runoff, withdrawals, and groundwater flow)	2,359	2,959	2,953	1,672	2,312	2,795	2,335	2,484
Total outputs/total inputs	0.55	0.64	0.65	0.47	0.57	0.54	0.52	0.56
ET estimated as residual of inputs-outputs	1,914	1,654	1,604	1,922	1,762	2,337	2,134	1,904
ET, percentage of total inputs	45	36	35	53	43	46	48	44

Notes: Withdrawal data reflect maximum extraction allowed under USFS permit for administrative and recreational facilities. ex = combined runoff and groundwater flow estimates exceed the combined rainfall and cloud drip inputs. Numbers in parenthesis are negative values. na = not applicable.

Acknowledgments

This work was funded by the Water, Energy, and Biogeochemical Budgets (WEBB) Program of the USGS. More information about WEBB can be obtained at http://dprsj1.er.usgs.gov/public/webb. Some of original work for this article was included in a doctoral thesis by Larsen. Special thanks are due T. Nel Caine, University of Colorado for his support and encouragement during Larsen's graduate studies.

References

Blume, H. C., B.M. Kendall, and J.C. Fedors, 1981. *Multifrequency radiometer detection of submarine freshwater sources along the Puerto Rican coastline.* Journal of Geophysical Research, 86 (C6) 5283-5291.

Bruijnzeel, L.A. and J. Proctor, 1993. *Hydrology and biogeochemistry of tropical montane cloud forests.* In: L.S. Hamilton, J.O. Juvik, and F.N. Scatena (Editors) Tropical montane cloud forests, Symposium proceedings, San Juan, Puerto Rico, May 31-June 5, 1993, UNESCO International Hydrological Programme, Paris, France, pp. 25-46.

Calvesbert, R.J., 1970. *Climate of Puerto Rico and the U.S. Virgin Islands;* U.S. Dept. of Commerce, Climatography of the U.S. no. 60-52, 28 pp.

Curtis, R.E., Zaida Aquino, P.L. Díaz, and R.J. Vachier, 1992. *Water Resources Data Puerto Rico and the U. S. Virgin Islands:* U.S. Geological Survey Water-Data Report PR 91-1, 520 p.

Díaz, P.L., Zaida Aquino, Carlos Figueroa-Alamo, R.J. Vachier, and A.V. Sánchez, 1993 to 1998, *Water resources data-- Puerto Rico and the U.S. Virgin Islands, Water year 1992 to 1997:* U.S. Geological Survey Water-Data Reports PR-92-1 to PR97-1.

Donnelly, T.W. 1989. *Geologic history of the Caribbean and Central America.* In Bally, A. W., and Palemer A R., eds.: The Geology of North America--An Overview, Geological Society of America, The Geology of North America, v. A., pp. 299-321.

Dopazo, Teresa, and W.L. Molina, 1995. *Estimated water use in Puerto Rico, 1988-1989:* U.S. Geological Survey Open-file report 95-380, 31 pp.

García-Martino, A.R., G.S. Warner, F.N. Scatena, and D.L. Civco, 1996. *Rainfall, runoff, and elevational relationships in the Luquillo mountains of Puerto Rico.* Caribbean Journal of Science: 32 (4) 413-424.

Hastenrath, Stefan, 1991. *Climate dynamics of the tropics:* Kluwer Academic Publishers, Boston, 488 pp.

Likens, G.E., F.H. Bormann, R.S. Pierce, J.S. Eaton, and N.M Johnson, 1977. *Biogeochemistry of a forested ecosystem.* Springer-Verlag, New York, 146 pp.

McDowell, W.H., W.B. Bowden, and C.E. Asbury, 1992. *Riparian nitrogen dynamics in two geomorphologically distinct tropical rain forest watersheds:* subsurface solute patterns: Biogeochemistry 18: 53-75.

Milliken, J.G. and G.C. Taylor, 1981. *Metropolitan water management.* American Geophysical Union Water Resources Monograph Series 6, 180 pp.

Nieuwolt, S., 1977. *Tropical Climatology, An Introduction to the Climates of the Low Latitudes.* John Wiley and Sons, New York, 207 pp.

Puig, J.C., and J.M., Rodríguez, 1993. *Ground-water resources of the Caguas-Juncos valley, Puerto Rico:* U.S. Geological Survey Water Resources Investigation Report 91-4079, 52 pp.

Reynolds, W.D., and D.E. Elrick, 1985. *Measurement of field-saturated hydraulic conductivity, sorptivity and the conductivity-pressure head relationship using the 'Guelph Permeameter': Proceedings,* National Water Well Association Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone, Denver, Colorado, November, 1985, pp. 1-25.

Simon, Andrew, M.C. Larsen, and C.R. Hupp, 1990. *The role of soil processes in determining mechanisms of slope failure and hillslope development in a humid-tropical forest: eastern Puerto Rico,* in Kneuper, P.L.K., and McFadden, L.D., eds., Soils and Landscape evolution. Geomorphology, v. 3, pp. 263-286.

U.S. Department of Commerce, 1991. Census (1990) of population and housing: *Puerto Rico. U.S. Department of Commerce, Bureau of Census,* CPH 1-53, 199 pp.

Weaver, P.L., 1972, *Cloud moisture interception in the Luquillo mountains of Puerto Rico:* Caribbean Journal of Science, vol. 12, no. 3-4, p. 129-144.

Zack, Allen, and M.C. Larsen, 1994. *Island hydrology: Puerto Rico and the U.S. Virgin Islands.* National Geographic Research & Exploration: Water Issue, pp. 126-134.

Authors

1. Matthew C. Larsen, Research Hydrologist
Luquillo WEBB Project Chief
United States.Geological Survey, WRD
GSA Center Bldg.651
Federal Drive Suite 400-15
Guaynabo, Puerto Rico 00965-5703
Phone: (787) 749-4346 ext.: 280
Email: "mclarsen@usgs.gov"
Project Web Site: " http://pr.water.usgs.gov/public/webb/index.html"
USGS Water Resources of Puerto Rico and the U.S. Virgin Islands Web Site: "http://pr.water.usgs.gov/"

2. Iris M.Concepción, Hydrologist
United States.Geological Survey, WRD
GSA Center Bldg.651
Federal Drive Suite 400-15
Guaynabo, Puerto Rico 00965-5703
Phone: (787) 749-4346 ext.: 263
Email: "imcon@usgs.gov"