Executive Summary

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Puerto Rico is in a state of rapid, ongoing change. Locally, agricultural lands are undergoing reforestation, while coastal areas are becoming heavily urbanized. The area is also changing because of the introduction of nonnative species, water supply projects, and the construction of roads and other infrastructure. Superimposed on these local phenomena are slower, larger scale changes, such as the deposition of airborne pollutants and natural and human-induced climate change. Owing to the island's steep topography, low water-storage capacity, and dependence on trade-wind precipitation, Puerto Rico's people, ecosystems, and water supply are vulnerable to extreme weather such as hurricanes, floods, and droughts. Eastern Puerto Rico offers a natural laboratory for separating geologic and land-cover influences from regional- and global-scale influences because of its various bedrock types and the changing land cover surrounding intact, mature forest of the Luquillo Experimental Forest (which is contiguous with El Yunque National Forest). Accordingly, a multiyear assessment of hydrological and biogeochemical processes was designed to develop an understanding of the effects of these differences on local climate, streamflow, water quality, and ecosystems, and to form the basis for a long-term and event-based program of climate and hydrologic monitoring.

Focusing on small watersheds allows for integrated studies of hydrologic and chemical processes, owing to minimal spatial variability of geology, land use, and climate. For two decades, the U.S. Geological Survey has been evaluating the processes controlling fluxes of water, energy, and elements throughout a range of temporal and spatial scales in small watersheds at five sites in different parts of the nation. The Water, Energy, and Biogeochemical Budgets Project in eastern Puerto Rico represents a montane, humid-tropical environment, in which lie four watersheds of differing geology and land use. Two watersheds are located on coarse-grained granitic rocks (Icacos and Cayaguás), and two are located on fine-grained volcanic rocks and volcaniclastic sedimentary rocks (Mameyes and Canóvanas). For each bedrock type, one watershed is covered with mature rainforest (Icacos and Mameyes); the other is undergoing reforestation after being used as agricultural land (Cayaguás and Canóvanas). These watersheds, like most of the rest of Puerto Rico, were subjected to intensive agriculture in the 19th and early 20th century, but they have been undergoing reforestation as a result of a shift from an agricultural economy to an industrial one and subsequent human migration to urban areas (discussed in chapters A and B in this volume).

Puerto Rico lies directly in the path of the easterly trade winds, which deliver steady rainfall to the mountains and steer weather systems called tropical waves toward the island. Hurricanes and tropical storms derived from these systems typically deliver the majority of yearly rainfall and occur from May to December (chapter C). Northern cold fronts can also deliver heavy rainfall for several days at a time, typically from December through February. These storms vary greatly in frequency and intensity, contributing to substantial interannual variation in precipitation and stream discharge. The largest storms can have profound geomorphic consequences, such as landslides, debris flows, deep gullying on deforested lands, excavation and suspension of sediment in stream channels, and delivery of a substantial fraction of annual stream sediment load (chapters F and G). Past deforestation and agricultural activities in the Cayaguás and Canóvanas watersheds led to profoundly accelerated erosion and soil loss, and this material continues to be remobilized during large storms.

Rainfall varies greatly over small distances in eastern Puerto Rico owing to differences in elevation, topographic position, aspect, and proximity to the ocean. The Icacos and Mameyes watersheds, located on the eastern side of the Luquillo Mountains, are the wettest of the four watersheds studied, and their highest elevations receive more than 4,000 millimeters of rain annually (chapter C). Precipitation increases with elevation in these watersheds. The Canóvanas and Cayaguás watersheds, located on the western side of the Luquillo Mountains, are considerably drier, and precipitation and elevation are not correlated. Precipitation and runoff in all watersheds show large interannual variation and are highest in years when major storms—such as Hurricanes Hortense (1996) and Georges (1998)—strike eastern Puerto Rico. These large storms typically produce similar runoff in all of the study watersheds, suggesting that higher annual runoff in the eastern, windward side of the Luquillo Mountains (which includes the Mameyes and Icacos watersheds) is caused by smaller, more-routine rain events. When one considers watershed-wide water budgets, the windward or leeward aspect of a watershed is more important than differing geology and land cover.

Regional weather patterns and consequent sources of air masses influence the type and timing of atmospheric contributions to eastern Puerto Rico. Nitrogen loads in precipitation at a National Atmospheric Deposition Project site in eastern Puerto Rico have roughly doubled since measurements began in 1985 (chapter D). Eastern Puerto Rico also receives marine salts and Saharan Desert dust in rainfall. The proportion of material delivered by these sources varies seasonally; deposition of marine salts is greatest in January, whereas material from North America is deposited primarily in January, April, and May, and Saharan Desert dust peaks in June and July. Saharan dust typically contributes enough alkalinity in June and July to neutralize acidity in precipitation. During large storms, entrainment of ocean spray and foam can lead to highly elevated concentrations of chloride in stream waters (chapter E).

Because infrequent, large storms play a major role in erosion of landscapes and can lead to a change in hydrologic flow paths, the Water, Energy and Biogeochemical Budgets Project focused on high-runoff events; we sampled 263 storms, including all major hurricanes that occurred between 1991 and 2005 (chapter C, appendix 1). Nearly 5,000 routine and event samples were analyzed for parameters that allow determination of denudation rates based on suspended and dissolved loads; 860 of these samples were analyzed for a comprehensive suite of chemical constituents. Of samples analyzed for comprehensive chemistry and for sediment, 543 were collected at runoff rates greater than 1 millimeter per hour, 256 at rates exceeding 10 millimeters per hour, and 3 at rates exceeding 90 millimeters per hour. Streams have rarely been sampled during events with such high runoff rates.

The rivers studied are generally similar in water-quality characteristics. Most chemical constituents show similar trends in the four watersheds, which imply considerable similarity in runoff generation and flow-path structuring despite differences in geology, soils, land cover, and weathering styles (chapter E). The rivers with lowest mean-annual runoff rates and highest ratios of evapotranspiration to runoff (Cayaguás and Canóvanas) tend to have higher concentrations of nonbioactive constituents. These developed watersheds typically have higher concentrations of nutrients (potassium, nitrate, ammonium ion, phosphate), perhaps indicating additional agricultural or wastewater sources. Projecting watershed yields to a common, intermediate mean-annual runoff (1,860 millimeters per year) generally decreased or did not change the range of yields of constituents that are the primary indicators of chemical weathering, biological activity on the landscape, or atmospheric contributions (dissolved bedrock, sodium, silica, chloride, dissolved organic carbon, and calcium), further indicating no dominant influence of either geology or land cover (chapter H). Magnesium and inorganic carbon showed a dependence on geology, possibly due to the presence of carbonates or mafic rocks. Projected yields of nutrients and particulate constituents (suspended solids and particulate organic carbon), however, were far in excess of equilibrium yields, and they were much greater for developed landscapes as compared with forested watersheds, consistent with the known effects of land clearing, agricultural activities, and domestic wastewater inputs.

Physical and chemical weathering rates of the four watersheds studied are high. Bedrock in the Icacos (granitic rock) and Mameyes (volcaniclastic rock) watersheds have some of the highest documented rates of chemical weathering of silicate rocks in the world (chapter I). Physical denudation rates based on mass balances are higher than expected for a steady-state system; this excess is substantial in all watersheds except the Mameyes (forested watershed on volcaniclastic bedrock; chapter H). Deforestation and agriculture can explain the accelerated physical erosion in the two developed watersheds (Canóvanas and Cayaguás). Physical erosion rates of the granitic watersheds are seven-fold as great as those for the volcaniclastic watersheds, owing to greater permeability and thus higher rates of water filtration and greater susceptibility to landsliding (chapters C and F). The reason for such high rates of physical erosion in the Icacos watershed (forested watershed on granitic bedrock) is unclear but may be related to changes in forest quality or to the history of road construction. The elevated physical erosion drives an increased particulate organic carbon flux, one that is large and is important to the carbon cycle. This increased flux is also sustainable because soil-carbon replacement is rapid.

It is crucial to understand long-term geomorphical, hydrological, and biogeochemical processes in tropical regions, because these regions occupy about a quarter of Earth's land surface, yet they contribute a substantially higher fraction of the water, solutes, and sediment discharged to the world's oceans. Nearly half of Earth's population lives in the tropics, and therefore development stresses are intense and can potentially harm soil resources, water quality, and water supply and in addition increase landslide and flood hazards. Small watersheds in eastern Puerto Rico provide an excellent opportunity to examine these processes and their connection to climate, geology, and land cover. The 15-year Water, Energy, and Biogeochemical Budget dataset, which includes discharge, field parameters, suspended sediment, major cations and anions, and nutrients, is available from the U.S. Geological Survey's National Water Information System (*http://waterdata.usgs.gov/nwis*). The dataset provides a baseline for characterizing future environmental change and will improve our understanding of the interdependencies of land, water, and biological resources and their responses to changes in climate and land use. Because eastern Puerto Rico resembles many tropical regions in terms of geology and patterns of development, implications from this study are transferable to other tropical regions facing deforestation, rapid land-use change, and climate change.

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