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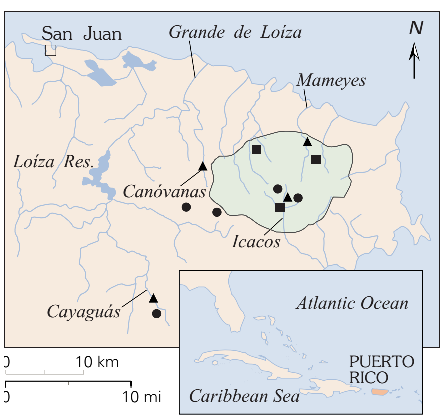
Luquillo Mountains, Puerto Rico

A Water, Energy, and Biogeochemical Budgets Program Site

The Puerto Rico research site consists of the 113 square-kilometer Luquillo Experimental Forest (LEF), administered by the U.S. Forest Service, and the nearby Río Grande de Loíza drainage basin, an urbanized and agriculturally-developed watershed. This combined region serves as a terrestrial laboratory for the study of issues related to the global loss of tropical forest, and the associated changes in land-use practices. Findings from the WEBB research help scientists understand how vegetation, landscape, and people interact to affect the quantity and quality of water and the erosion of the landscape. The results of this work can be applied not only to Puerto Rico, but also to many other regions, where deforestation and rapid land-use change are issues.

Puerto Rico was formed by volcanism and sedimentation characteristic of tectonic activity at a plate boundary, and the study watersheds were chosen to overlie volcanic rocks typical of such regions. Similar areas in the humid tropics include many parts of the Greater Antilles, Central America, Southeast Asia, and islands in the western Pacific to the Indian Ocean. Puerto Rico provides a glimpse into the future of tropical environments that are now undergoing deforestation. The island reached a maximum of deforestation during the 1940s and has been gradually reforested since then. Puerto Rico is a natural laboratory for analysis of how landscapes respond to and recover from massive land-cover change.



■ Weather station
▲ Streamflow-gaging station
● Rainfall station
▭ Luquillo Experimental Forest

The Luquillo study area is located in the eastern mountains of Puerto Rico.

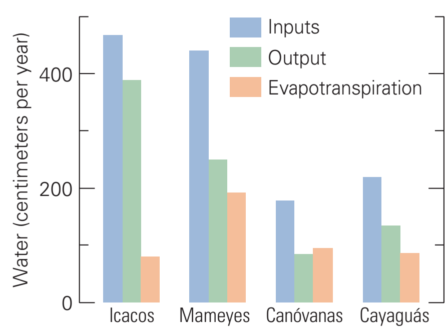
Water Budgets

Water used for public consumption may be the most important product of the Luquillo Mountains. Estimated as the cost paid by the consumer, water extracted from the streams that drain the Luquillo Mountains is worth about $25 million per year. Because of the importance of understanding where the water is most available and how the quantity changes with individual storms, season, and on annual to decadal time scales, water budgets have been developed. The budgets are used to show how much precipitation, stream runoff, and evapotranspiration have occurred in four watersheds in the study area during the 1990s. The water budgets are strongly controlled by elevation and orientation with respect to prevailing (trade) winds. Because of the steep gradients in these mountain watersheds, runoff is rapid and streamflow peaks are very brief.

Chemical and Physical Erosion

There are two types of erosion: chemical and physical. In chemical erosion, water dissolves and carries off elements from the bedrock, whereas in physical erosion, solid particles are removed by water, wind, and mass movement, such as landslides. When rocks are exposed to water, they decompose by reacting with the water and dissolved carbon dioxide, oxygen, nitric acid, sulfuric acid, and organic compounds. This is called "chemical weathering." As the rocks weather, some of the elements in minerals, such as feldspars, react and release dissolved sodium, potassium, magnesium, calcium, and some silicon. The volcanic rocks of eastern

Approximate water budgets for WEBB study watersheds. Inputs include rainfall, cloud drip, and septic tank infiltration. Outputs include stream discharge, groundwater flow, and public-supply withdrawals.



THE WEBB PROGRAM

The Water, Energy, and Biogeochemical Budgets (WEBB) Program was started in 1991 at five small watersheds in the United States to examine water, energy, and biogeochemical fluxes and to determine the effects of atmospheric deposition, climatic variables, and human influences on watershed processes. The five sites are at Loch Vale, Colorado; Luquillo Experimental Forest, Puerto Rico; Panola Mountain, Georgia; Sleepers River, Vermont; and Trout Lake, Wisconsin. These sites are supported, in part, by other programs in the USGS, other Federal and State Agencies, and Universities.

U.S. Department of the Interior
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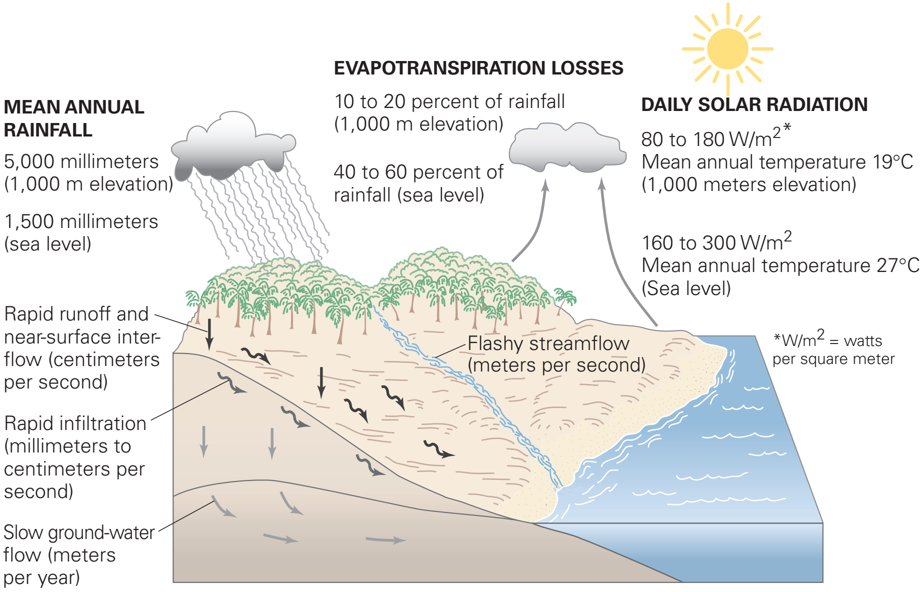


This representation of hydrologic and climatologic characteristics of eastern Puerto Rico shows how elevation increases precipitation and enhances runoff.

Puerto Rico also contain abundant silicon, iron, and aluminum. The weathering of minerals in the rocks forms the clays and reddish iron minerals that typify regional soils and stream sediments.

Water from streams in the LEF is sweet tasting and refreshing. This flavor comes from the substances dissolved in the water called solutes. These solutes include inorganic ions, which are the electrically charged components of dissolved salts, natural organic compounds and ions, and neutral constituents including, silica and gases, such as oxygen, nitrogen, and carbon dioxide.

The composition of water that falls as rain on the forest changes dramatically as it passes over and through the soil into streams. The composition of rain water falling on the LEF is controlled primarily by salts from the ocean. When waves break and bubbles burst, droplets of seawater enter the atmosphere. In addition, marine algae release sulfur gases to the atmosphere. The gases become sulfuric acid. Lesser contributions of sulfuric acid, nitric acid, and ammonia come from air pollution from North America and Europe, and Sahara dust contributes calcium and sulfate from Africa. The composition of the water changes immediately upon falling through the leafy canopy of forest trees, picking up leaf exudates and feeding communities of plants and bacteria growing on leaf surfaces, branches, and trunks. The composition of the water again changes as it falls on and soaks through soil. Roots and associated fungi remove plant nutrients from the water.

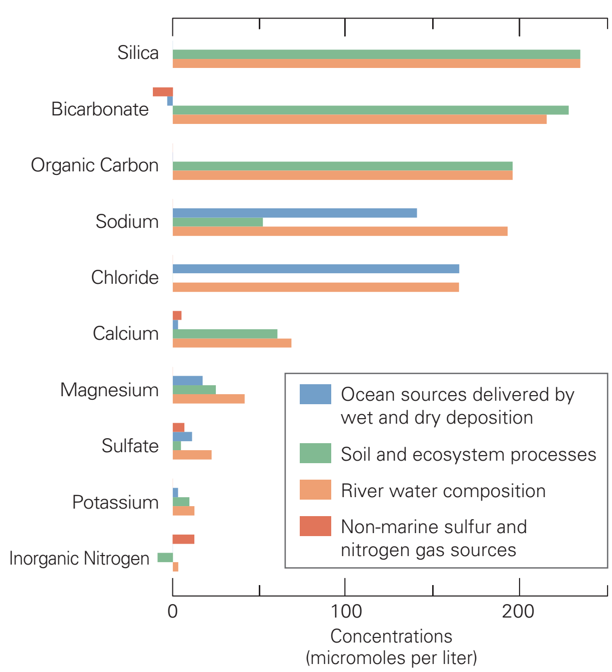
Plants promote chemical weathering through release of root exudates and through respiration and decay, which add carbonic, nitric, and organic acids to soil water. These acids react with bedrock and release various ions and silica from the rock into the soil water, while also forming the clay minerals that become soil and the fine sediment carried by the streams.

> In the Luquillo Mountains, chemical weathering of the bedrock, which is promoted by plants, contributes to most of the dissolved load of rivers and forms soils, which in turn, when physically eroded, become the suspended and bed loads in rivers.

The composition of water that enters from the rain and dust, and streamflow that leaves the Icacos watershed is shown in the figure to the left. All the chloride in the Icacos water was assumed to come from sea salt. In acquiring these ions, the water has nourished the forest and has carried a small part of the Luquillo Mountains to the ocean. The Luquillo Mountains have eroded about 5 centimeters since Columbus first visited the island 500 years ago.

Chemical weathering is important in understanding nutrient cycling and forest dynamics, but also in making abundant regolith (loose material, including soil) available for physical erosion. In eastern Puerto Rico, two classes of physical erosion are identified: surficial erosion, where particles are transported from the ground surface, and landsliding, where particles are excavated deeply as a moving mass of rock and soil. A variety of chemical techniques are used to understand the rates of physical and chemical erosion. Many of these rely on natural radioactive isotopes to estimate rates or relative importance of chemical or physi-

Discharge weighted average concentrations of solutes in the Icacos River ranked according to concentration. Inorganic nitrogen combines nitrate and ammonia. Non-marine sulfur and nitrogen gases are presumably derived mainly from human activities. The negative values correspond to ecosystem losses of nitrogen and for bicarbonate to the acid brought in by rain. Sodium, calcium, magnesium, potassium, and ammonia are positive ions (cations). Bicarbonate, chloride, sulfate, and nitrate are negative ions (anions). Organic carbon is a mix of ions and molecules. Silica is a molecule.



cal processes. The concentration of the radioactive cosmogenic isotope, beryllium-10, in quartz grains that occur in sediment in river channels and on hillslopes has been measured. The beryllium-10 forms as the slow, steady rain of cosmic-ray neutrons strikes atoms in quartz and other minerals in soil and bedrock within a meter or so of the ground surface. The concentration of beryllium-10 is related directly to erosion rate. The results of this work indicates that in the Icacos watershed the fine-grained sediment appears to be derived from surficial erosion, whereas much of the coarse-grained sediment comes from landslides. Beryllium-10 was also used to estimate what the erosion rate of an area was before it was deforested.

Fluvial Sediment and the Effects of Humans on Landscape

Intense agricultural practices of the 19th and early 20th century have resulted in high suspended-sediment yields in the Loíza basin many decades after farming had been abandoned. Soil was eroded from the hillslopes, mainly by landsliding, while they were being farmed and was then deposited at the base of the hillslopes near stream channels. Since then, stormflows have episodically moved the sediment from the base of the hillslopes downstream where it is deposited in reservoirs or in estuaries and in coastal waters where coral reefs are located. The sediment and associated contaminants degrade the water quality and are harmful to aquatic organisms in these areas.

To understand these processes, the four Luquillo WEBB study watersheds were paired to compare and contrast the effects of land use as well as bedrock geology on fluvial sediment yield (combined suspended and bedload sediment). During the period 1991 to 1995, sediment concentration, which was calculated as sediment yield normalized to runoff, was about 3.5 times greater in the two watersheds in secondary forest and pasture compared to sediment concentration in the watersheds in primary forest. However, the influence of lithology was almost as great: sediment concentration in intrusive-bedrock (quartz diorite and granodiorite) watersheds was about 3.2 times higher than sediment concentration in volcaniclastic-bedrock (volcanic sandstone, mudstone, and breccia) watersheds. These contrasts highlight the well-known impact of land use on sediment concentration and yield but stress the strong control of bedrock geology as well. Most importantly, the high sediment yields in the watersheds that were converted to pasture and secondary forest, even after 60 years of forest reestablishment, provide a glimpse into the future of tropical watersheds elsewhere that are now undergoing deforestation.

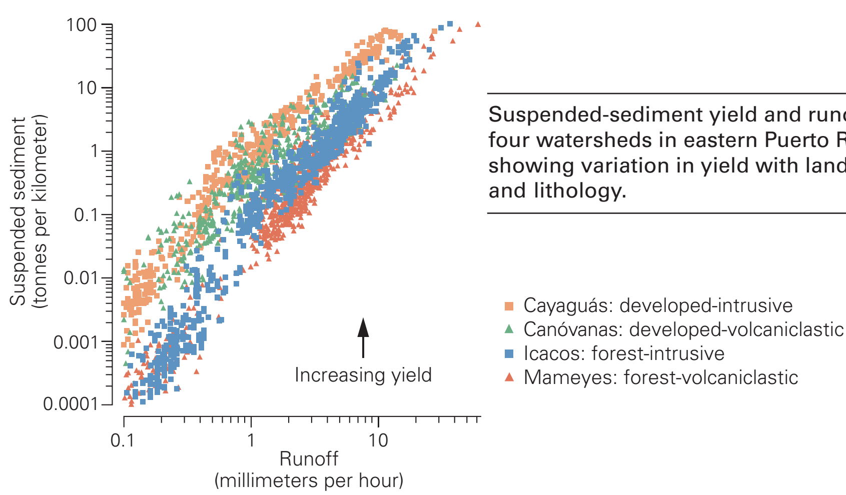
Watershed	Watershed drainage area (km^2)	Type of bedrock	Principal land use	Mean annual runoff (mm)	Mean annual fluvial sediment yield (tonnes per km^2)	Mean annual sediment concentration (kg/mm of runoff)
Mameyes	17.8	Volcaniclastic	Primary forest	2,441	227	93
Canóvanas	25.5	Volcaniclastic	Secondary forest, pasture	672	225	335
Icacos	3.3	Intrusive	Primary forest	3,193	954	299
Cayaguás	26.4	Intrusive	Pasture, secondary forest	1,111	1,163	1,047

Watershed characteristics and mean fluvial sediment yield (combined suspended and bedload sediment) for water years 1991 to 1995.

Landslides in a Tropical Setting

Landslides are common in steep mountainous areas of Puerto Rico, where mean annual rainfall is high and intense storms are frequent. In general, when rainfall exceeds 200 millimeters in 24 hours, landslides occur. Each year, landslides cause extensive damage to property and occasional loss of life. The increasing population of Puerto Rico (3.9 million in 1999) increases stress on the natural environment and physical infrastructure; this makes human populations more vulnerable to landslide hazards. Maps of recent landslides, which were developed from 1:20,000 scale aerial photographs in combination with a geographic information system, were used to evaluate the frequency and distribution of shallow landslides. Several types of landslides were documented. Rainfall triggered debris flows, shallow soil slips, and slumps were most abundant. Hillslopes that are most prone to landsliding have been modified by humans. The hillslopes exceed 12 degrees in gradient, are greater than 300 meters in elevation, and face the east-northeast. Areas along road corridors are also particularly vulnerable. The rate of landsliding disturbance is increased from 5 to 8 times in a 170 meter wide swath along highways in the Luquillo Mountains.

Landslides are the dominant cause of hillslope erosion in forested and deforested landscapes and generally occur when rainfall exceeds 200 millimeters in a day. Road corridors are especially landslide prone.



Suspended-sediment yield and runoff for four watersheds in eastern Puerto Rico showing variation in yield with land use and lithology.

Landslide scar and deposit in the Icacos River near the USGS gaging station, Luquillo Mountains.

Despite being a hazard, landslides, under natural conditions, are important because of their role in controlling the sediment loads and chemistry of the pristine streams that drain the Luquillo Mountains. Landslides have this effect because of the periodic introduction of a large quantity of soil and weathered rock directly into stream channels where it often remains for weeks to months as streamflow gradually erodes the material.

Under natural conditions, landslide erosion exceeds erosion of soil by other processes, such as slopewash, which is the surficial mobilization of individual soil particles. For example, the Mameyes and Icacos rivers annually export from 227 to 954 tonnes of sediment per square kilometer, respectively, based on data collected by manual and automatic water sampling at USGS streamflow-gaging stations. According to recent data published by the Luquillo WEBB Project, slopewash ranges from 10 to 50 tonnes per square kilometer per year on steep slopes in the LEF. This erosion rate is far less than the total amount of sediment carried by rivers that drain the study area. Much of the above-mentioned fluvial sediment is instead mobilized by landslides.

—Matthew C. Larsen and Robert F. Stallard

SUMMARY

- Puerto Rico provides a glimpse into the future of tropical environments that are now undergoing deforestation. The island reached a maximum of deforestation during the 1940's and has been partially reforested since then. Puerto Rico is a natural laboratory for analysis of how landscapes respond to and recover from massive land-cover change.
- Landscapes that have been deforested have accelerated physical erosion rates; they have a 3.5 times higher rate of sediment yield when compared to their forested counterparts.
- Landslides are the dominant cause of hillslope erosion in forested and deforested landscapes and generally occur when rainfall exceeds 200 millimeters in a day.
- Runoff varies from 49 to 82 percent of inputs (mainly precipitation and cloud drip) and is strongly controlled by elevation and location with respect to prevailing (trade) winds.
- Streamflow in the Luquillo Mountains is chemically dilute and transport of mass is predominately physical, as sediment particles.
- The Luquillo Mountains have been eroded by 5 centimeters since Columbus first visited the island because of combined chemical and physical weathering of bedrock.

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COLLABORATORS

USGS Luquillo WEBB Project researchers work closely with scientists involved with the National Science Foundation-funded Long Term Ecological Research (LTER) program in the Luquillo Experimental Forest. Many of these scientists are based at the U.S. Forest Service International Institute of Tropical Forestry, and the University of Puerto Rico Institute for Tropical Ecosystem Studies, located in Río Piedras, Puerto Rico. USGS and LTER scientists cooperate by sharing data and research equipment and publishing research papers together.

Students and volunteers from a number of universities in Puerto Rico and in the United States have made many important contributions towards the success of the USGS Luquillo WEBB project by helping in the collection, processing, and archiving of data and samples. Graduate students have advanced our scientific understanding of important geochemical and hydrological processes and budgets by conducting research and publishing their results.

For more information about the Luquillo WEBB study visit:

http://pr.water.usgs.gov/public/webb

For more information or for reprints, please contact:

WEBB Site Coordinator
U.S. Geological Survey
651 Federal Drive, Suite 400-15
Guaynabo, Puerto Rico 00965-5703
(787) 749-4346 or mclarsen@usgs.gov.