Primary Factors Affecting Water Quality and Quantity in Four Watersheds in Eastern Puerto Rico

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Abstract

As part of the U.S. Geological Survey (USGS) Water, Energy, and Biogeochemical Budgets (WEBB) program, four small watersheds in eastern Puerto Rico were monitored to identify and evaluate the effects of geology, landcover, atmospheric deposition, and other factors on stream water quality and quantity. Two catchments are located on coarse-grained granitic plutonic rocks, which weather to quartz- and clay-rich, sandy soils, and two are located on fine-grained volcanic rocks and volcaniclastic sediments, which weather to quartz-poor, fine-grained soils. These differing soil materials result in different hydrologic regimes. Soils on the granitic rocks have greater permeability than those developed on the volcaniclastic rocks, allowing more water infiltration and potentially greater landslide erosion rates. For each bedrock type, one catchment was covered with mature rainforest, and the other catchment was affected by agricultural practices typical of eastern Puerto Rico. These practices led to the erosion of much of the original surface soil in the agricultural watersheds, which introduced large quantities of sediment to stream channels. The agricultural watersheds are undergoing natural reforestation, like much of Puerto Rico. Eastern Puerto Rico receives large atmospheric inputs of marine salts, pollutants from the Northern Hemisphere, and Saharan Desert dust. Marine salts contribute over 80 percent of the ionic charge in precipitation, with peak inputs in January. Intense storms, mostly hurricanes, are associated with exceptionally high chloride concentrations in stream waters. Temperate pollution contributes nitrate, ammonia, and sulfate, with maximum inputs during northern cold fronts in January, April, and May. Pollution inputs have increased through time. Desert dust peaks in June and July, during times of maximum dust transport from the Saharan Desert across the Atlantic Ocean.

Keywords: Puerto Rico, Luquillo, landcover change, atmospheric deposition, hurricanes

Introduction

The U.S. Geological Survey (USGS) Water, Energy, and Biogeochemical Budgets (WEBB) program strives to understand the processes controlling fluxes of water, energy, and elements over a range of temporal and spatial scales. The WEBB program includes five field sites across the United States (Colorado, Georgia, Puerto Rico, Vermont, and Wisconsin) that vary in landform, hydrology, climate, and ecology. The Puerto Rico WEBB site represents a montane, humid-tropical environment. Precipitation, runoff, and water chemistry were monitored by the USGS in four small (3.3–26 km^2) watersheds (Icacos, Mameyes, Canóvanas, and Cayaguás) in eastern Puerto Rico from 1991 to 2005 (Figure 1). These data, in combination with data from the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Department of Agriculture–Forest Service (USDA-FS), can be used to understand how landscape, vegetation, long-range atmospheric deposition, and people interact to affect water quantity and quality and erosion processes in the watersheds. A regional synthesis of riverine discharge and water quality cannot succeed without high-quality characterization, utilizing a geographic information system (GIS) approach, of the landscape in which the rivers are embedded. The present report summarizes our efforts at such a characterization.

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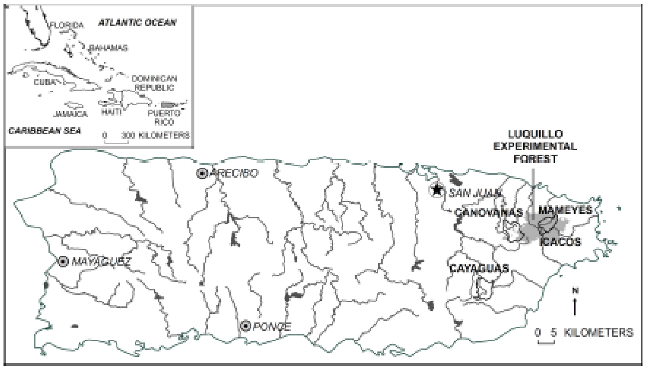

Figure 1. Location of Puerto Rico and study watersheds (outlined).

Geology and Weathering Processes

The island of Puerto Rico is part of the Antilles Island Arc, which was formed by volcanism and sedimentation typical of a plate boundary. The island consists of a core of igneous rocks surrounded by younger sedimentary rocks (Figure 2). The Mameyes and Canóvanas watersheds are primarily underlain by marine-deposited, quartz-poor volcaniclastic rock, while the Icacos and Cayaguás watersheds are underlain by granitic rocks. The volcaniclastic rocks weather to clay-rich, fine-grained soils, whereas the granitic rocks weather to quartz- and clay-rich, sandy soils. Soils on the granitic rocks have greater permeability than those over the volcaniclastic rocks, allowing more water infiltration (Simon et al. 1990). The clay-rich soils of the volcaniclastic rocks are more cohesive than the quartz-rich soils over granitic rocks and thus are more resistant to erosion. Our studies suggest that these differences lead to a seven-fold greater physical erosion rate in the granitic soils. Brown et al. (1995) showed that the Icacos watershed is eroding at near steady state, with coarse material being mobilized from deep in the profile by landsliding. Thus, the high rates of physical erosion in the Icacos watershed do not reflect a recent acceleration of physical erosion. Chemical-erosion rates, in contrast, appear to be within a factor of two for all the different rock types and landcovers, and thus water chemistry of the rivers are not substantially different (R.F. Stallard, 2008, USGS, written commun.).

Landcover

Puerto Rico has undergone a rapid transformation in the past several centuries from pre-European conditions of relatively undisturbed forest, to intensive agriculture in the 19th and early 20th century, to an industrial economy since 1950. In the past 60 years, landcover of Puerto Rico has shifted from being almost entirely deforested to having forest covering about half of the island (Figure 3). Meanwhile, human population density of Puerto Rico has increased over threefold during the last century, resulting in one of the highest densities in the world. Accordingly, Puerto Rico may serve as a prototype for reforestation of tropical areas that are shifting from an agricultural to an industrial economy.

Two of the study watersheds are covered with mature rainforest (Icacos and Mameyes, Figure 1) and are within the Luquillo Experimental Forest (LEF), a forest preserve administered by the USDA-FS. Access to the LEF was historically very limited because of steep slopes, high annual rainfall, and designation as a reserve by the Spanish crown and later by the U.S. Government. Two watersheds (Cayaguás and Canóvanas) have been affected by agricultural activities typical of eastern Puerto Rico (pasture, coffee, tobacco, fruit crops), which led to the loss of much of the original surface layer of soil in these watersheds. Larsen and Santiago Román (2001) estimate that erosion in the Cayaguás watershed, which was intensely farmed for

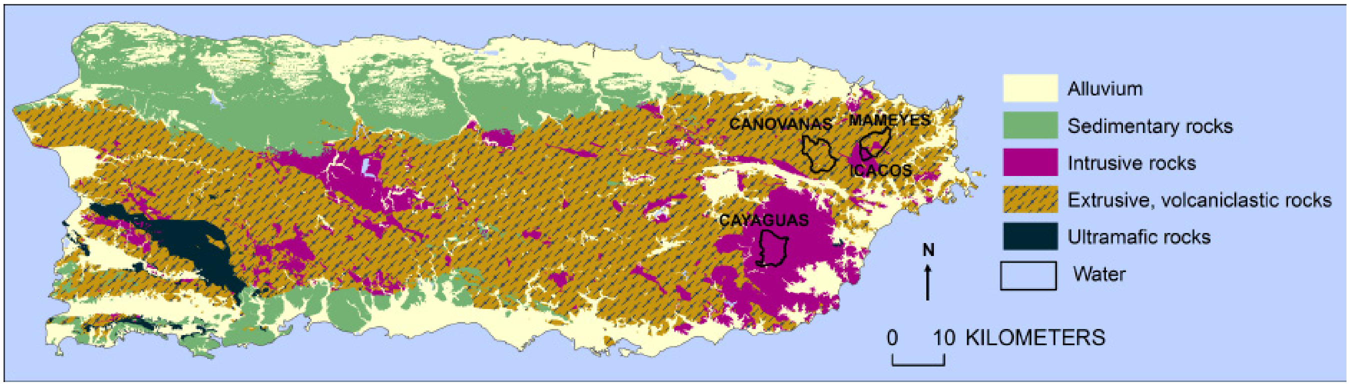

Figure 2. Geology of Puerto Rico and study watersheds (from Bawiec, 2001).

two centuries, lowered the mean surface elevation in the watershed by 660 mm and introduced massive amounts of sediment to river channels, where much of it was deposited as alluvium. This sediment continues to be remobilized during large storm events. The Cayaguás and Canóvanas watersheds have since undergone some degree of reforestation, which can change hydrology of watersheds by increasing evapotranspiration and decreasing streamflow (Jackson et al. 2005).

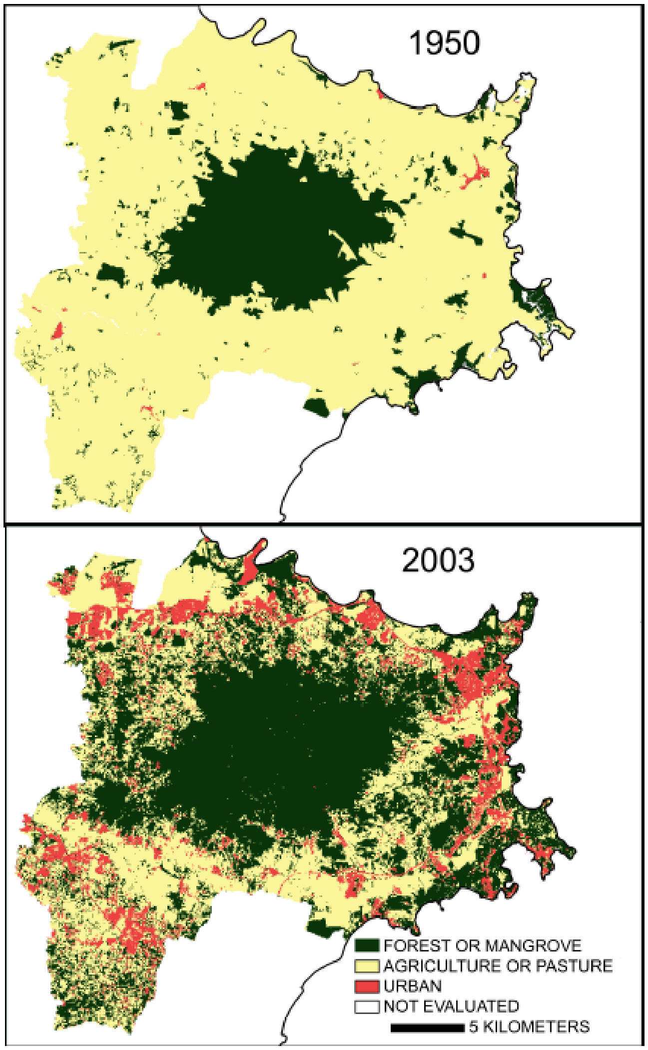

Figure 3. Landcover in northeastern Puerto Rico in 1950 and 2003 (W.F. Gould, 2008, USDA-FS, written commun.).

Hurricanes

Puerto Rico lies directly in the path of the easterly trade winds and receives as much as 70 percent of yearly rainfall from tropical disturbances imbedded in the trade winds, which are strongest from May through December. Storms range from tropical waves to hurricanes. Major tropical disturbances affect the Caribbean about nine times a year. Hurricanes impact Puerto Rico about once every 10 years (Figure 4). The most recent hurricanes that caused substantial damage in eastern Puerto Rico were Hugo in 1989, which had winds over 200 km/hr, and Georges in 1998, with winds of 240 km/hr. Rainfall associated with Georges totaled 630 mm in the central mountains and triggered extensive flooding and debris flows (Larsen and Webb 2009).

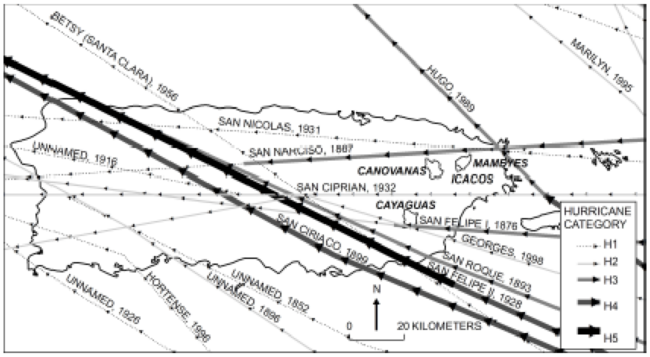

Figure 4. Hurricanes that have passed over or near Puerto Rico since 1850 (study watersheds outlined; data from National Oceanic and Atmospheric Administration 2006).

Atmospheric Inputs

The precipitation chemistry from the National Atmospheric Deposition Program (NADP) site at El Verde (National Atmospheric Deposition Program 2007), within the LEF in eastern Puerto Rico, is dominated by three major sources of solutes (Figure 5):

- Marine salts, which contribute about 82 percent of the ionic charge, including chloride, sodium, and magnesium;
- Temperate pollution from the Northern Hemisphere (10 percent), primarily nitrate, ammonia, and sulfate derived from pollution and natural sources—nitrogen loads have doubled since measurements began in 1985 (Stallard 2001); and
- Saharan Desert dust (5 percent), primarily from calcium carbonate.

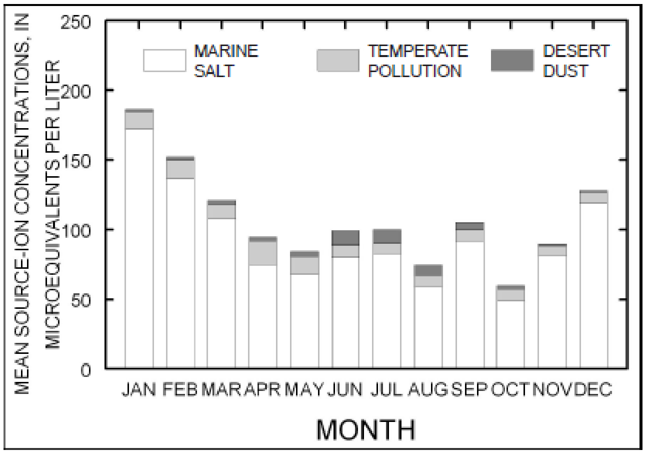

Figure 5. Mean monthly contributions of marine, temperate, and desert sources to rain chemistry in eastern Puerto Rico (data from NADP site at El Verde, 1985–2006; National Atmospheric Deposition Program 2007).

Massive sandstorms blowing off the Saharan Desert can blanket hundreds of thousands of square kilometers of the Atlantic Ocean. Although this dust fall has been going on for millions of years, the clearing of land south of the Sahara may be an additional contribution (Shinn et al. 2000). The transport of dust, pollution, and pathogens are affecting the health of coral, amphibians, and people (Shinn et al. 2000, Stallard 2001, Kuehn 2006). Moreover, the dust may play a role in decreasing the frequency and intensity of hurricanes formed over the Atlantic Ocean (Dunion and Velden 2004).

Stream chemistry was sampled during several large storms. Results indicate that some storms, mostly hurricanes, can contribute extremely large marine salt inputs. Hurricanes Hortense (1996) and Georges (1998) had comparable total rainfall, but Georges was shorter and more intense (Figure 6). Hortense produced 333 mm total runoff from the Mameyes watershed with an average stream-water chloride concentration of 111 micromoles/liter (µM), while Georges produced 317 mm total runoff with an average chloride concentration of 455 µM (R.F. Stallard, 2008, USGS, written commun.). Georges deposited the equivalent of 0.3 mm of seawater over the entire Mameyes watershed. This hurricane, and several other large storms, were missed in the NADP sampling, which occurs weekly. These results suggest that NADP may underestimate chloride inputs at El Verde, confounding mass-discharge programs such as LOADEST (Runkel et al. 2004).

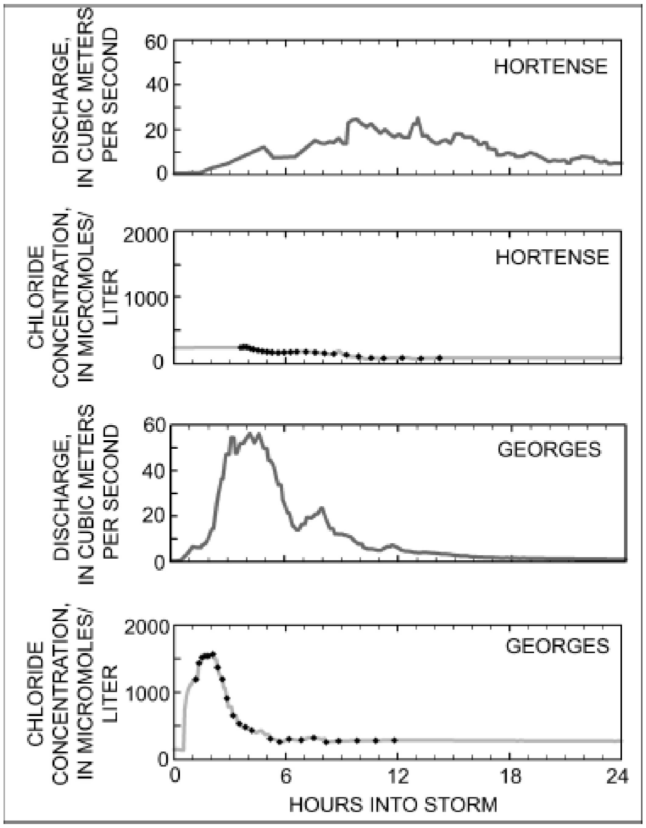

Figure 6. Discharge and chloride concentrations for the Río Mameyes during two hurricanes (R.F. Stallard, 2008, USGS, written commun.).

Summary

Eastern Puerto Rico is a changing environment. From within, it has a growing and urbanizing population. Forests are regrowing and increasing landscape-scale evapotranspiration at the same time that human populations are demanding more water. In addition, over the last several centuries, the climate appears to be getting drier (Zack and Larsen 1993). Water shortages are a major problem. In fact, during our study, droughts led to severe water rationing for the city of San Juan, with outages of more than 36 hours. This led to the hoarding of water in open containers and subsequent outbreaks of Dengue fever (Rigau-Pérez et al. 2001).

From afar, increasing temperate pollution, Saharan dust, and smog from the burning of African forests is changing the chemical landscape in Puerto Rico (Stallard 2001). Droughts, through dryness or warming, and along with the chemical changes, may contribute to the ongoing amphibian die-off (Stallard 2001, Burrowes et al. 2004).

Throughout Puerto Rico, floods caused by hurricanes and frontal storms damage infrastructure, and the associated suspended sediment clogs reservoirs and enters the ocean where it damages coral (Warne et al. 2005). The impact of large storms is affected by landcover and their intensity and frequency of occurrence. Presumably, ongoing forest recovery in Puerto Rico will lessen physical erosion. At the same time, however, the intensity or destructiveness of large storms may be increasing as a result of human-induced warming of the surface ocean (Emanuel 2005).

The 15-yr dataset described here provides the opportunity to evaluate and quantify the effects of these environmental conditions on the short-term quantity and quality of surface waters and provides a baseline for characterizing future environmental change. Implications from this study are transferable to other tropical regions where deforestation, rapid land-use change, and climate change are issues facing watershed managers and others concerned about the supply and quality of surface waters.

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