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THE EFFECTS OF CHANGING LAND COVER ON STREAMFLOW SIMULATION IN PUERTO RICO[1]

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ABSTRACT: This study quantitatively explores whether land cover changes have a substantive impact on simulated streamflow within the tropical island setting of Puerto Rico. The Precipitation Runoff Modeling System (PRMS) was used to compare streamflow simulations based on five static parameterizations of land cover with those based on dynamically varying parameters derived from four land cover scenes for the period 1953-2012. The PRMS simulations based on static land cover illustrated consistent differences in simulated streamflow across the island. It was determined that the scale of the analysis makes a difference: large regions with localized areas that have undergone dramatic land cover change may show negligible difference in total streamflow, but streamflow simulations using dynamic land cover parameters for a highly altered subwatershed clearly demonstrate the effects of changing land cover on simulated streamflow. Incorporating dynamic parameterization in these highly altered watersheds can reduce the predictive uncertainty in simulations of streamflow using PRMS. Hydrologic models that do not consider the projected changes in land cover may be inadequate for water resource management planning for future conditions.

(KEY TERMS: land use/land cover change; urbanization; surface water hydrology; Precipitation Runoff Modeling System; geospatial analysis; Caribbean.)

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INTRODUCTION

The mission of the U.S. Geological Survey (USGS) National Climate Change and Wildlife Science Center (NCCWSC) (http://nccwsc.usgs.gov/) is to provide integrated science that is useful to resource managers to understand the effect of climate change on a range of ecosystem responses. The NCCWSC manages the United States (U.S.) Department of the Interior (DOI) Climate Science Centers (CSCs) (http://www.interior.gov/csc/index.cfm) which are tasked with prioritizing the delivery of fundamental scientific information and tools for the resource managers. The DOI launched the Landscape Conservation Cooperatives (LCCs) (http://lccnetwork.org/) to better integrate science and manage-

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ment to address climate change and other landscape scale issues. Together, the Southeast CSC (http://www.doi.gov/csc/southeast/index.cfm) and the Caribbean LCC (http://caribbeanlcc.org/) initiated the development of a hydrologic model for the island of Puerto Rico (PR) to provide resource managers with a tool to develop management strategies that address the impacts of climate and land cover change on water availability in PR.

The hydrologic impact of land cover change in PR is particularly important given the growth in population and urban areas associated with the shift from crop and pasture-based agriculture (Wadsworth, 1950) to industry (Dietz, 1986). Forest recovery, urban expansion, and agricultural decline in PR began around 1950 and are well documented (see del Mar López *et al.*, 2001; Helmer *et al.*, 2002; Helmer, 2004; Kennaway and Helmer, 2007; Martinuzzi *et al.*, 2007; Gould *et al.*, 2008). This pattern of land cover change is found in many tropical areas, including El Salvador, the Dominican Republic, Vietnam, Argentina, and parts of India (Grau *et al.*, 2003; Kauppi *et al.*, 2006). A temporally varying, spatially explicit, and process-oriented understanding of land cover change impact on hydrology will help to effectively manage water resources for societal benefit, environmental preservation, and the mitigation of event-based hazard risks.

Streamflow simulation using hydrologic models and calibration tools can achieve impressive statistical matches with measured streamflow, but the application of these results may be limited to the calibration period if significant anthropogenic changes occur outside the calibration period and are not accounted for in the hydrologic model parameterization. According to Milly *et al.* (2008), the assumption of stationarity — "the idea that natural systems fluctuate within an unchanging envelope of variability" — has long been compromised by human disturbances; thus, hydrologic models are incorrect to assume variables that are time invariant. This study quantitatively explores whether explicit inclusion of land cover change information in the parameterization of the Precipitation Runoff Modeling System (PRMS) (Leavesley *et al.*, 1983; Markstrom *et al.*, 2008), a distributed parameter, physical process simulation code, has an impact on simulated streamflow within the tropical island setting of PR. Furthermore, this study examines how the incorporation of this dynamic land cover information in PRMS yields a better understanding of hydrologic response in PR than one based on land cover descriptions that are held static throughout the period of simulation.

Past Studies

The effect of urban expansion (urbanization) on hydrology has long been a topic of study (Leopold, 1968). Alley and Veenhuis (1983) state that "man-made impervious cover has long been known to significantly affect the hydrologic response of a watershed." In addition to altering the ability of water to infiltrate into the soil and changing physical routing of water across the land surface, urbanization has been shown to affect heat budgets and evapotranspiration (Grimmond and Oke, 1991; Taha, 1997; Dow and DeWalle, 2000). The rate of conversion from rural to relatively impervious urban land within the U.S. is large (Alig *et al.*, 2004; White *et al.*, 2009). Alig *et al.* (2004) project that urbanization within the nation will continue for at least the next 25 years and that "developed area" will increase by as much as 79%, resulting in almost 10% of the U.S. land surface being converted to "developed" land cover.

Applications of hydrologic simulation codes that focus on the effect of urbanization on hydrology in the U.S. have been documented for a variety of geographic regions, such as the Piedmont (Hejazi and Moglen, 2008), Midwest (Tang *et al.*, 2005; Choi and Deal, 2008), coastal New England (Schiff and Benoit, 2007), Pacific Northwest (Cuo *et al.*, 2009), Southern California (Beighley *et al.*, 2008), Southeastern U.S. (Ferguson and Suckling, 1990; Viger *et al.*, 2011), and Northeastern PR (Wu *et al.*, 2007). In general, these studies either treat land cover as a static quantity within the simulation, examining changes in hydrologic response due to different static characterizations of land cover (Wu *et al.*, 2007; Beighley *et al.*, 2008; Choi and Deal, 2008; Cuo *et al.*, 2009) or they treat the impervious area as a dynamic input (Hejazi and Moglen, 2008; Viger *et al.*, 2011).

Land cover changes that occur over several decades can have substantial impacts on hydrology and need to be considered to more accurately represent actual conditions. In the study by Viger *et al.* (2011), the potential effects of long-term urbanization and climate change on the freshwater resources of the Flint River watershed, Georgia, were examined using PRMS. They demonstrated that land use can be an important moderator in hydrologic response: increases in imperviousness changed the negative trends in surface runoff seen under climate change conditions alone to positive ones. Although they treated impervious area as a dynamic input, they noted potential problems with using temporally constant values for vegetation type, vegetation density, interception, and radiation transmissivity. Policy makers, natural resource managers, and the public have the need to assess impacts of historical, current, and projected anthropogenic changes on the water resources on which they and ecosystems depend. Without accounting for these dynamic changes it may be difficult to develop hydrologic models for evaluation and predictive purposes. These dynamically changing properties occur in all watersheds and often are not accounted for single simulations at the watershed scale.

Objectives

The objective of this study was to improve the understanding of the hydrology of PR by implementing PRMS models that reflect the agricultural decline, urban expansion, and forest recovery since the 1950s for the entire island. The dynamic parameter capabilities within PRMS provide the ability to vary landscape characteristics at any location on a daily or longer time step within the model domain, making PRMS an ideal tool to study the effects of changing land cover on streamflow. PRMS results that incorporate dynamic land cover parameterizations will be useful in the assessment of historical, current, and projected water resources and hydrologic processes in PR. Application of any hydrologic simulation code for PR is especially challenging due to the sparse and/or inaccurate information available in PR to drive hydrologic simulations. The following two sections of this study give an overview of the study area and PRMS, respectively. This is followed by the methodology used to set up PRMS. Results are presented and discussed for both static and dynamic land cover parameterizations in PRMS. The study will finish with a conclusion to summarize and reinforce the findings of this research.

STUDY AREA

PR is the smallest of the Greater Antilles Islands, located in the northeastern Caribbean Sea (Figure 1). The main island is approximately 8,900 square kilometers (km^2) with a thin strip of coastal plains, 8- to 16-km wide, surrounding steep igneous upland. These major physiographic regions cover approximately 10 and 86% of the island area, respectively, with the remainder in a karst area in the north (Boccheciamp, 1978). The combination of strong weathering of the volcaniclastic rock that makes up much of the island with relatively steep slopes has resulted in most river valleys becoming deeply incised (Murphy and Stallard, 2012). Bedrock is exposed to a small degree

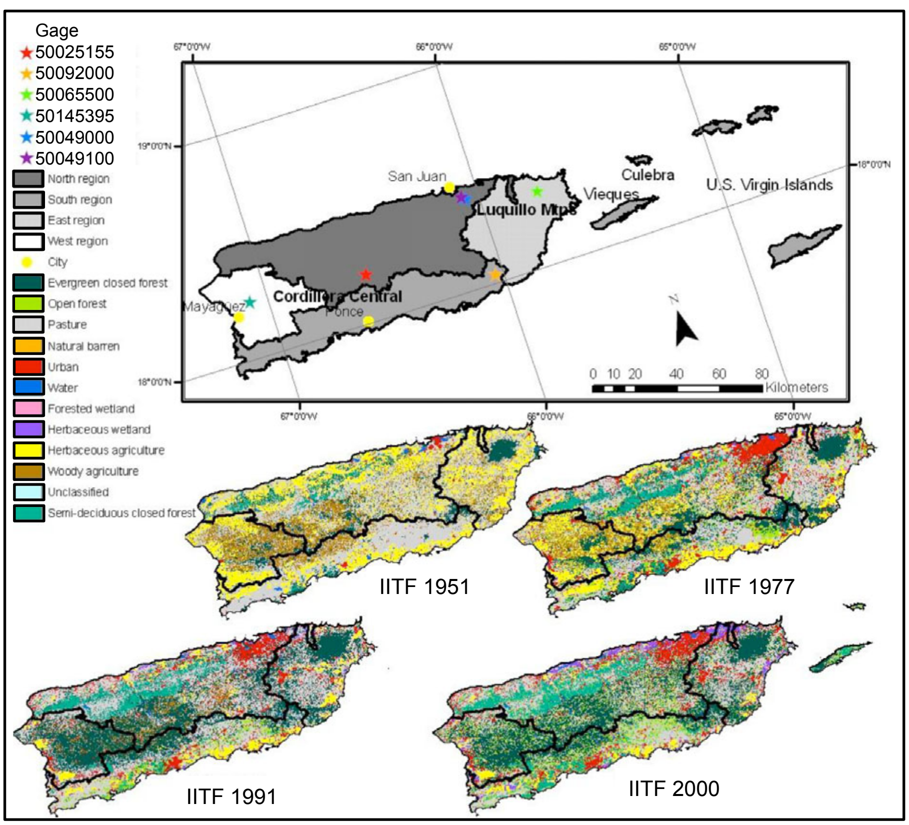

FIGURE 1. Map of Puerto Rico with Geographic Locations and Land Cover. The land cover snapshots were created by the USDA Forest Service International Institute of Tropical Forestry (IITF) for years 1951, 1977, 1991, and 2000. The black lines on each map divide the island into four climate regions.

(e.g., Scatena and Lugo, 1995). Soil in the mountains is a result of the weathering of the volcaniclastic rock, creating clay. Soil on the coastal plains is mostly sand from sedimentary sources, with very little loam (USDA, 1994).

PR follows the Caribbean weather pattern created by the easterly trade winds from the Atlantic Ocean. Average annual rainfall in PR is 1,778 mm with large interannual variability due to broad-scale storm patterns (Calvesbert, 1970). In general, the Caribbean rainfall season is bimodal, with an early rainfall season from May through June and a late rainfall season from August to November. Short-term climate changes from El Niño and La Niña occur in the area (Taylor *et al.*, 2002; Angeles *et al.*, 2007). The island-wide dry season is from January to April. Orographic effects are a major control on temperature and precipitation, with heaviest rain in the humid-tropical central mountains and to a lesser degree along the northern coasts; dry tropical climates exist along the southern coastal plain (Boccheciamp, 1978; Larsen and Simon, 1993). Other mesoscale phenomena, such as sea breezes, mountain-top convection, and standing gravity waves, affect the local weather with frequent smaller storms (Carter and Elsner, 1997). Temperatures in PR are fairly constant spatially and temporally. Average temperatures range from 24 to 29°C year-round (Calvesbert, 1970). Transpiration happens all year since most of the forest is evergreen (Weaver *et al.*, 1973; Lugo *et al.*, 1978; Miller and Lugo, 2009).

There are four mountain ranges within PR (Figure 1). Three of these comprise the Cordillera Central, which begins about 60 km southwest of San Juan and extend west through the center of the island, dominating the landscape of the southern two-thirds of the island. Maximum elevation of the Cordillera Central is 1,300 m. Annual rainfall in the upper elevations of the windward slopes (to the north) usually falls within the range of 2,000-2,500 mm (Calvesbert, 1970; Helmer *et al.*, 2002). The southern, particularly the southwest, side of the Cordillera Central receives much less rain (Helmer *et al.*, 2002). The fourth range, the Luquillo Mountains, dominates the geomorphology of the northeastern part of the island and is the wettest region of the island with annual rainfall over 4,500 mm in the upper elevations. Maximum elevation of the Luquillo Mountain range is 1,100 m. These mountain ranges naturally divide PR into four climatic regions: a moderate region north of the Cordillera Central, a dry region south of the Cordillera Central, a wet region east of the Cordillera Central surrounding the Luquillo Mountains, and a moderate region west of the Cordillera Central.

PR has a population density of 438 persons/km^2 (Martinuzzi *et al.*, 2007), which is similar to relatively urbanized settings like the state of New Jersey. Most of the population of the island is concentrated along the coasts. Martinuzzi *et al.* (2007) define 16% of the island as urban with 960 persons/km^2, and 48% of the island as sparsely populated rural with less than 195 persons/km^2. The largest city is San Juan, located along the north coast on the eastern half of the island (see Figure 1). Eight of the 10 most populous cities on the island are located within San Juan's greater metropolitan area. Notable exceptions are Ponce, located in the south, and Mayagüez, which is at the west end of the island. Large precipitation events can create sudden increases in streamflow, resulting in landslides that affect homes, transportation, power and communications in the mountainous interior, and floods that affect people and infrastructure on the populated coastal plains (Larsen and Simon, 1993).

Prior to European settlement in the 16th Century, PR was likely 95% forested, with broadleaf trees, moist soils, and very dense vegetation. Forest cover in PR reached a low of about 6% in the late 1940s because it was plowed over for agricultural development (Birdsey and Weaver, 1987), specifically plantation sugar production. At this time, crops and pasture were evenly divided covering 84% of PR (Wadsworth, 1950). In 1948, tax incentives from PR's government encouraged investment in industry which rapidly changed the economy from predominantly agriculture based to industrial based (Dietz, 1986). Although some of the intensively cultivated lands were transitioned to hay or intermittently grazed pasture, much of it was left unmanaged or protected. This allowed forest land cover to increase to 40% of the island (Birdsey and Weaver, 1987) with forest types varying by elevation. On the rainier northern side of the island, they range from subtropical moist to wet to rain forests. On the south side of the island, lower montane wet and rain forests are also found. Semideciduous forests occur on the coasts (Helmer *et al.*, 2002). The dominant type of forests is a moist broadleaf evergreen in character (Helmer *et al.*, 2002).

PR land cover changes from 1951 to 2000 are shown cartographically in Figure 1 and are summarized in Table 1. The shift to an industrial economy brought residents from rural to urban areas, resulting not only in rapid urban expansion around the cities but also reversion of former agriculture zones to forest (del Mar López *et al.*, 2001; Helmer, 2004; Parés-Ramos *et al.*, 2008). Typical of islands in the humid tropics, there are few locations in PR with no anthropogenic effects (Wohl *et al.*, 2012). Incorporating these changes into a hydrologic model may not only decrease the predictive uncertainty, but is crucial for planning adaptation of the hydrological system for future conditions (Buytaert *et al.*, 2009).

TABLE 1. Land Cover Percentages for the Main Island of Puerto Rico.

	Percent Land Cover Type[1]							
Year	Urban	Pasture	Herbaceous	Woody Agriculture	Forests (open/closed)	Forested Wetland	Herbaceous Wetland	Water[2]
1951	1.7	36.7	22.9	18.6	16.9	0.9	0.2	2.1
1977	9.8	31.5	8.9	12.6	33.6	0.9	0.5	2.1
1991	14.3	34.7	3.4	1.6	43.3	0.9	0.8	1.0
2000	15.4	34.7	1.1	2.2	44.8	0.9	0.8	1.1

[1]Adapted from Kennaway and Helmer (2007).
[2]Also includes unclassified and natural barren, which are very small amounts.

HYDROLOGIC MODEL

The USGS PRMS is used to simulate land-surface hydrologic processes, including evapotranspiration, runoff, infiltration, interflow, snowpack, and soil moisture on the basis of distributed climate information, such as temperature, precipitation, and solar radiation (SR), as well as land use and other characteristics of the model domain. PRMS is a modular, deterministic, distributed-parameter, physical-process model (Figure 2). In addition to runoff, shallow subsurface, and groundwater fluxes, PRMS simulates hydrologic water budgets at the watershed scale with temporal scales ranging from days to centuries. The reader is referred to Leavesley *et al.* (1983) and Markstrom *et al.* (2008) for a complete description of PRMS.

The distributed parameter capabilities of PRMS are provided by partitioning the watershed into Hydrologic Response Units (HRUs). Each HRU is assumed to be homogenous with respect to its hydrologic response. PRMS is conceptualized as a series of reservoirs (soil zone, shallow subsurface, and groundwater; see Figure 2) whose outputs combine to produce runoff. For each HRU, a water balance is computed each day and an energy balance is computed twice each day. Surface, subsurface, and groundwater flows from each HRU are routed to an associated stream network. Once in the network, water is routed to the watershed outlet (or the coast, in the case of this study). In this study, runoff refers to the local flow

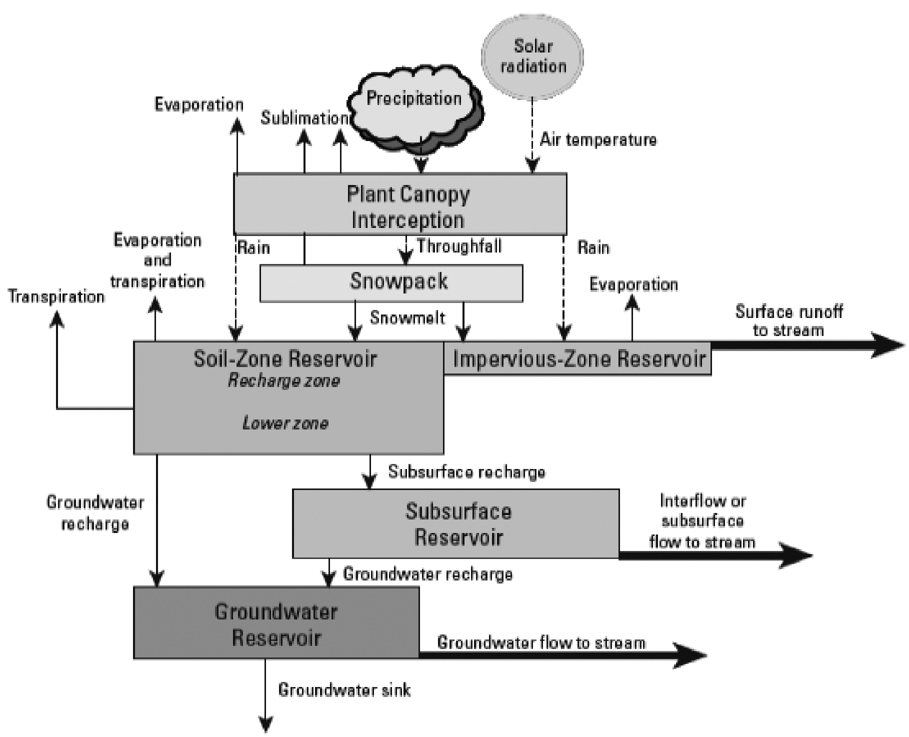

FIGURE 2. Overview of the Precipitation Runoff Modeling System Conceptualization of Components and Fluxes (taken from Markstrom *et al.*, 2008).

produced by each HRU and streamflow refers to the aggregated, routed runoff in the stream network.

In addition to a suite of topographic parameters (such as elevation, slope, and aspect), the soils, vegetation type and density, and imperviousness characteristics of each HRU are described by PRMS parameters. Traditionally, PRMS parameters were static for the period of simulation. Over long periods, land-cover-related parameters can become obsolete as conditions on the landscape change, creating difficulty for appropriate calibration of PRMS (LaFontaine *et al.*, 2013). This study explores approaches for dealing with the dynamic nature of land cover within the period of simulation.

METHODS

The following sections describe the methodology followed in this study which includes: HRU delineation and parameterization using static land cover; interpolation of daily climate values from weather stations to the HRUs; PRMS calibration and evaluation under static land cover conditions; PRMS simulations using dynamic land cover parameterization; and methodology used to simulate streamflow for the entire island of PR.

HRU Delineation and Parameterization

Spatial delineations of the HRUs and a routing network for PR were taken from the Geospatial Fabric for National Hydrologic Modeling (GF) (Viger and Bock, 2014). These features were created as part of the GF manufacturing process, which aggregates the flow lines of the NHDPlus Dataset (USEPA and USGS, 2008). NHDPlus is based on the 1:100,000 scale National Hydrography Dataset. This is chiefly done by defining a set of Points of Interest (POIs), aggregating the minimally sufficient set of flow lines needed to connect each hydrologically consecutive pair of POIs into a single routing segment, and dividing the local contributing area associated with the segment into “left-bank” and “right-bank” HRUs. POIs correspond to stream gages, reservoir and lake outflows, and major river confluences, among other features. Within PR, there were 243 segments and 489 HRUs.

The GF provided the static parameters for the HRUs, describing topographic, vegetation, and soils characteristics based on NHDPlus, National Land Cover Database (NLCD2001) (Homer *et al.*, 2007), and STATSGO (USDA, 1994), with resolutions of 30, 30, and 1 km, respectively. Parameters derived from NLCD2001 include percent of HRU area that is impervious, summer and winter cover density, and values indicating the depth of precipitation interception by vegetation for rain in summer and winter. These parameters are all average values for the associated HRU. The dominant cover type (bare, grass, shrub, or tree) is also determined for each HRU. Soils parameters related to available water-holding capacity and texture are derived from the STATSGO soils database (Wollock, 1997). For model calibration, the value for a given HRU parameter was held constant for the duration of the simulation period, and PRMS was used to simulate the hydrology of PR under constant land cover conditions.

Climate Inputs

PRMS requires daily inputs of precipitation, maximum temperature, and minimum temperature for each HRU. A multiple linear regression (MLR) method was used to distribute daily measured precipitation and maximum and minimum temperature data from a group of climate stations (daily mean value) to each HRU in PR (Hay *et al.*, 2000, 2006a, b; Hay and Clark, 2003) based on the longitude (x), latitude (y), and elevation (z) of the HRU.

To account for seasonal climate variations, the MLR Equation (1) was developed for each month and for each dependent variable (the climate variables [CV]: precipitation, maximum and minimum temperature) using the independent variables of x, y, and z (xyz). The monthly MLR equations describe the spatial relations between the monthly dependent CV and the independent xyz variables. Equation (1) describes a plane in three-dimensional space with “slopes” b_1, b_2, and b_3 intersecting the CV axis at b_0. Note that for each month the best MLR equation for a given CV did not always include all the independent variables (i.e., x, y, and z).

$$\mathrm{CV} = b_1\,x + b_2\,y + b_3\,z + b_0 \tag{1}$$

To estimate the daily value of each CV for each HRU, the following procedure was followed: (1) mean daily values of each CV and corresponding mean x, y, and z values from a set of stations were used with the “slopes” of the monthly MLRs in Equation (1) to estimate a unique y-intercept ($b_0$est) for that day and (2) Equation (2) was then solved using b_1, b_2, and b_3 from Equation (1) and the x, y, and z coordinates from the HRUs:

$$\mathrm{CV}_{(\mathrm{HRU})} = b_1\,x_{(\mathrm{HRU})} + b_2\,y_{(\mathrm{HRU})} + b_3\,z_{(\mathrm{HRU})} + b_0\mathrm{est} \tag{2}$$

In past studies (Hay *et al.*, 2000, 2006a, b; Hay and Clark, 2003) the “slopes” in Equation (1) were determined using nearby climate stations. For this study, daily maximum and minimum temperatures and precipitation data from 46 climate stations in PR were compiled from the National Weather Service cooperative observer network for water years (WYs) 1952-2012. The 46 climate stations were found to have approximately 70% of their data missing from 1952 to 2012. Murphy and Stallard (2012) estimated the error in measured precipitation in PR to be approximately 15%. This combination of poor quantity and quality of station data made it difficult to use station data to estimate “slopes” of the monthly MLRs in Equation (1) for each CV. Therefore, “slopes” were calculated using mean monthly CVs calculated at each HRU using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly *et al.*, 2003) maps.

The results from Equation (1) using the PRISM data produced several dominant MLR relations in PR, which were consistent with the four climatic regions defined by the mountain ranges described earlier. Therefore, PR was divided into four regions (referred to as the North, South, East, and West) and “slopes” were calculated for each of the four regions (see Figure 1 for geographic outlines of the regions). This resulted in four separate PRMS models for PR that were parameterized and calibrated. Other researchers have found similar climate regions in PR as the ones presented here (e.g., Veve and Taggart, 1996; Carter and Elsner, 1997; Harmsen *et al.*, 2004).

The adjusted R^2 associated with the MLRs for precipitation in the North, South, East, and West regions are 0.74, 0.74, 0.86, and 0.72, respectively. The East and West regions have similar precipitation “slopes” in the z direction (elevation); showing higher mean monthly precipitation for the same elevation than the other regions. The South region has the lowest z precipitation “slope” and the North region falls in the middle. For all regions, the adjusted R^2 associated with the MLRs for maximum temperature and minimum temperature are approximately 0.9. The regions do not have significantly different “slopes” for the temperature MLRs, indicating that the temperature relations to x, y, and z are similar across the island.

PRMS Calibration under Static Land Cover Conditions

A “default” application of PRMS was developed for each of the four climate regions using the static parameterization scheme described earlier. For each region, designated “default” parameters, defined through a parameter sensitivity analysis, were calibrated using the Luca software (Hay and Umemoto, 2006). Luca uses a multiple objective, stepwise, automated calibration strategy with the Shuffled Complex Evolution global search algorithm (Duan *et al.*, 1992, 1994) to calibrate parameters in a PRMS model. This multiple objective, stepwise calibration procedure assures that intermediate model fluxes as well as the water balance are simulated consistently with measured values (Hay *et al.*, 2006b).

For each of the four climate regions, six steps were used in the calibration procedure. Table 2 lists the calibration dataset, objective function, and PRMS parameters calibrated for each step in the process. The parameters calibrated in each step were determined from a single parameter sensitivity analysis conducted using Monte Carlo techniques.

The first two steps in the calibration procedure adjusted the parameters that control the computation of SR and potential evapotranspiration (PET), respectively, using mean monthly values as the calibration dataset. The mean monthly SR values for each region were derived from the National Solar Radiation Database using measurements at San Juan from 1961 to 1990 (NSRDB, 1992). The mean monthly PET values for each region were derived from mean monthly PET point values based on Harmsen *et al.* (2004). The sum of the absolute difference of monthly measured and simulated SR and PET was used as the objective function.

The third step in the calibration procedure adjusted the parameters to match the volume of measured streamflow (Table 2) using monthly streamflow calculated for the “best” gage in each region as the calibration dataset. The normalized root mean square error of monthly measured and simulated streamflow was used as the objective function.

Researchers have noted that due to the sparse data in the tropics, poor model performance may be due to the lack of enough high-quality data rather than a lack of understanding (Buytaert *et al.*, 2009; Wohl *et al.*, 2012). It was questionable if any of the streamflow records in PR would be adequate for PRMS calibration. Previous experience by the authors has shown that if a simple monthly water balance model (MWBM) could not be calibrated accurately with monthly streamflow information, then a calibrated daily PRMS model would not be accurate. Therefore, a MWBM was used to identify the “best” gage in each region for PRMS model calibration.

Streamflow records from the USGS National Water Information System (NWIS) network were pulled using the USGS Downsizer (Ward-Garrison *et al.*, 2009). The Downsizer retrieved data for 74 gages in PR, 16 of which could be considered relatively free of anthropogenic effects and would therefore be potential candidates for use in model calibration (see Falcone, 2011). These 16 gages were identified by

TABLE 2. Parameters Calibrated in Each Step of the Calibration Process.

Step	Calibration Dataset	Objective Function	PRMS Parameters Used to Calibrate Model State	Parameter Description
1	Observed mean monthly solar radiation	Sum of the absolute difference	dday_intcp_hru	Intercept in temperature degree-day relationship
			dday_slope_"month"	Slope in temperature degree-day relationship
2	Observed mean monthly potential evapotranspiration	Sum of the absolute difference	jh_coef_hru_"month"	Monthly air temperature coefficient used in Jensen-Haise computations
3	Monthly measured flow with 15% error bounds	NRMSE	adjust_rain	Precipitation adjust factor for rain days
			psta_nuse	Binary indicator for using station in precipitation distribution calculations
			psta_freq_nuse	Binary indicator for using station in precipitation frequency calculations
4	Monthly measured flow with 15% error bounds	NRMSE	K_coef	Travel time of flood wave from one segment to the next downstream segment
			slowcoef_lin	Linear coefficient in equation to route gravity-reservoir storage down slope for each HRU
			soil_moist_max	Maximum available water-holding capacity of soil profile
			soil_rechr_max	Maximum available water-holding capacity for soil recharge zone
			tsta_nuse	Binary indicator for using station in temperature distribution calculations
5	Daily high flows with 15% error bounds	NRMSE	fastcoef_lin	Coefficient to route preferential flow storage down slope
			pref_flow_den	Fraction of the soil zone in which preferential flow occurs
			sat_threshold	Water-holding capacity of the gravity and preferential flow reservoirs
			smidx_coef	Coefficient in nonlinear surface runoff contributing area algorithm
6	Daily low flows with 15% error bounds	NRMSE	gwflow_coef	Linear coefficient to compute groundwater discharge from each groundwater reservoir
			soil2gw_max	Maximum amount of capillary reservoir excess routed directly to the groundwater reservoir
			ssr2gw_rate	Linear coefficient used to route water from the gravity reservoir to the groundwater reservoir

Note: HRU, Hydrologic Response Unit; NRMSE, normalized root mean square error; PRMS, Precipitation Runoff Modeling System.

Falcone (2011) to be the least-disturbed watersheds for PR. Two of these sixteen gages are located in the North region, five are in the South, seven are in the East, and two are in the West.

For each of the 16 gages, a MWBM (McCabe and Markstrom, 2007) based on the Thornthwaite methodology (Thornthwaite, 1948) was run for WYs 1971-2008. Split sample calibration was used to determine which gages could be used for model calibration; available data for each gage were separated into a set used for model calibration and an independent set for evaluation of MWBM performance. The coefficient of determination (R^2) for the evaluation years was used to determine how well measured streamflow values were simulated by the model and the "best" gage in each region was determined based on the R^2 results. Figure 1 identifies the "best" gage for each region: 50025155 (North region), 50092000 (South region), 50065500 (East region), and 50141395 (West region), with R^2 values ranging from 0.56 to 0.65. The "best" gage for each region was used to derive the monthly runoff volumes for calibration of the water balance parameters (see Table 2) for all HRUs in a given region.

When possible, each region's PRMS model was calibrated using the middle portion of the record from the "best" gage; allowing an evaluation period before and after the calibration period. Gage 50025155 in the North region has anomalously large streamflow for the year 1996 presumed to be due to a gage malfunction since none of the nearby gages show similar patterns, therefore WYs 1998-2006 were used for calibration. Figure 3 shows the period of record, calibration, and evaluation periods for the "best" gages.

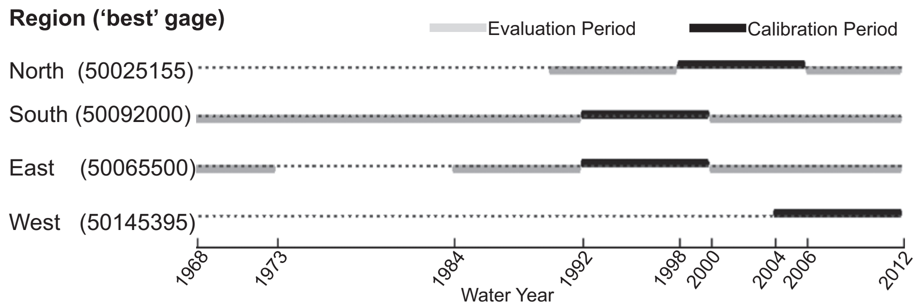

FIGURE 3. Period of Record for Streamflow Gages Used for Model Calibration.

Eight years of record were selected for the calibration period (Figure 3) to ensure robustness in the results (Yapo *et al.*, 1996).

The streamflow measurements for "best" gages in each region are rated as "fair" in the NWIS database, indicating that approximately 95% of the discharges are within 15% of the true value (see http://wdr.water.usgs.gov). To account for this measurement error in the calibration, the PRMS models were calibrated with an error range of 15% in the calibration datasets.

The fourth step in the calibration procedure calibrates the PRMS parameters associated with streamflow timing (Table 2). The PRMS models were calibrated with an error range of 15% in the calibration datasets based on reported streamflow measurement estimates. The normalized root mean square error of measured and simulated streamflow was used as the objective function.

The fifth and sixth calibration steps adjust the parameters that influence the high and low flows, respectively (Table 2). The high and low flows were determined using the Indicators of Hydrologic Alteration software (Richter *et al.*, 1996). All considered the general 15% streamflow measurement error. The normalized root mean square error of measured and simulated high (low) streamflow was used as the objective function.

PRMS Evaluation under Static Land Cover Conditions

The PRMS models for the four climatic regions were calibrated and evaluated for the periods shown in Figure 3 using the static parameterization scheme described earlier. Calibration of SR and PET parameters was the first two steps in the stepwise calibration procedure. Mean monthly simulations of SR and PET for the calibration and evaluation periods were nearly identical to those produced from the calibration datasets. This is similar to previous studies using this calibration methodology (see figures 6-7 in Hay *et al.*, 2006b; figure 6 in Markstrom *et al.*, 2012; and figure 13 in LaFontaine *et al.*, 2013).

Steps 3-6 calibrated parameters associated with streamflow volume, timing, and high and low values. Measured and simulated annual streamflow (WYs 1953-2012) from the calibration and evaluation periods at the "best" gages in the North, South, East, and West regions are shown in Figure 4. Annual streamflow values were simulated accurately for the calibration periods with the exception in the West region. Simulation accuracies during the evaluation periods were variable.

The monthly biases in simulated streamflow for each region are summarized in Figure 5 for the calibration and evaluation periods. A positive monthly bias indicates that the simulated was greater than the measured streamflow. The West region has no data outside the calibration period for evaluation (see Figure 3 for dates of the calibration and evaluation periods). In general, the median monthly bias for the calibration periods tends to be close to zero, with exception for some of the months in the South and West regions. In the North and West regions, the mean magnitude of the median biases in the drier months (January through April, and July and December) and the mean magnitude of the median biases in the wetter months (May through June and August through November) are approximately equal to the mean magnitude of the median biases in all months, indicating the models perform similarly in dry and wet conditions. In the South and East regions, the models perform better in the drier months, with only one-quarter of the mean magnitude of the median biases coming from the drier months in the South region, and one-tenth of the mean magnitude of the median biases coming from the drier months in the East region.

The biases for the pre-calibration evaluation period (dark gray) are generally larger and have greater absolute medians than the post-calibration evaluation period (light gray), especially in the northern region. As noted earlier, forest recovery, urban expansion, and agricultural decline in PR began around 1950.

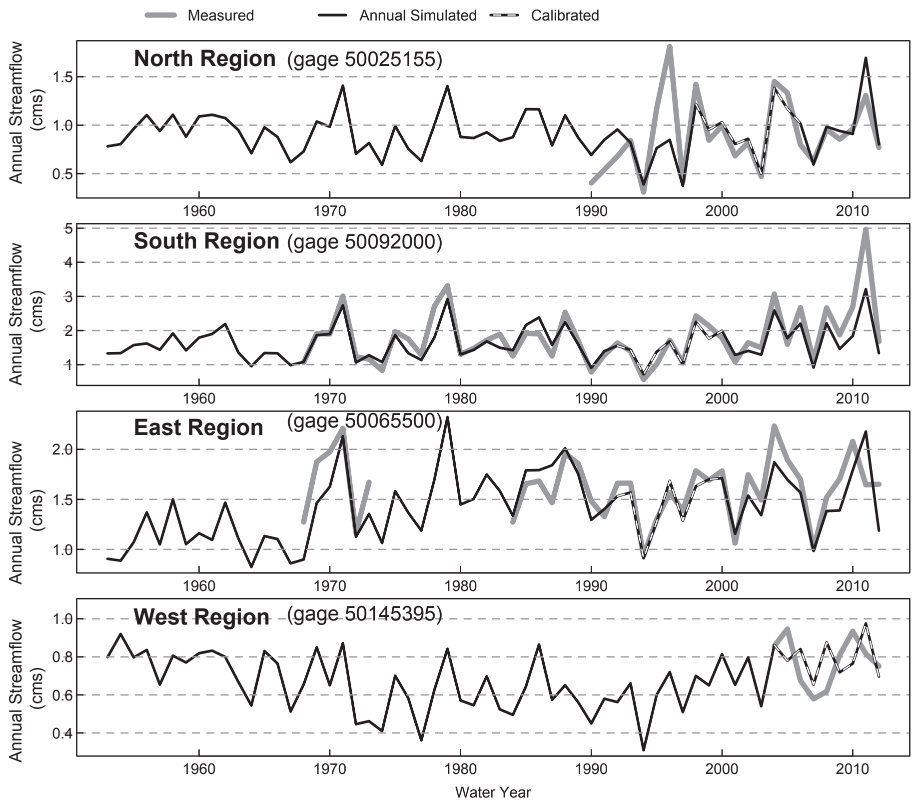

FIGURE 4. Annual Measured and Simulated Streamflow during the Calibration and Evaluation Periods at the "Best" Gages in the North, South, East, and West Regions of Puerto Rico.

This land cover change is not represented by the static parameterization used in the PRMS model calibrations. The PRMS PR models all used static land cover derived from NLCD2001 for parameter derivation, which is more similar to the actual land cover in the post-calibration evaluation period. Land-cover-based parameters that change through the period of simulation may result in an overall better model, especially prior to the 1990s in PR (see Figure 1 and Table 1 for qualitative and quantitative description of land cover changes prior to the 1990s, respectively). These dynamically changing properties occur in all watersheds and are generally not accounted for in single hydrologic model simulations at the watershed scale.

PRMS Simulations Using Dynamic Parameterization

PRMS simulations using dynamic parameters provide the capability of varying landscape characteristics at any location and on any day of a simulation. The dynamic land cover parameters for PR were derived from four United States Department of Agriculture (USDA) Forest Service International Institute of Tropical Forestry (IITF) (shown in Figure 1) land cover maps with dates of 1951, 1977, 1991, and 2000. Parameter sets derived from the IITF 1951, 1977, 1991, and 2000 datasets were used to create static parameter sets representing land cover for each of those four years. To create dynamic parameter sets in which the parameters changed on a yearly basis, parameter values for interceding years were linearly interpolated yearly (and linearly extrapolated after year 2000) for each HRU.

The 1951 land cover map is a digitization of a 1:150,000 scale paper map of land cover in 1951 (Brockman, 1952; Kennaway and Helmer, 2007). The 1977 land cover map was created from non-orthorectified air photo mosaics of 1977 and 1978, which were manually interpreted to derive land cover maps. The USDA IITF team mosaicked the quadrangles and generalized them to PR land cover types (Ramos and Lugo, 1994). The 1992 land cover map is from the Landsat 5 TM images of 1991 and 1992. Missing areas in the imagery were filled from the 1977 land cover map (Helmer *et al.*, 2002). The 2000 land cover map was made from 18 Landsat 7 ETM+ images collected during 1999-2003. Multiple years were used for the 2000 land cover map to overcome issues with cloud cover and image availability. There are two scenes from 1999, eight from 2000, seven from 2001, and one from 2003 (Martinuzzi *et al.*, 2007; Gould *et al.*, 2008). The spatial distribution of the land cover types for each of the mapped points in time is shown

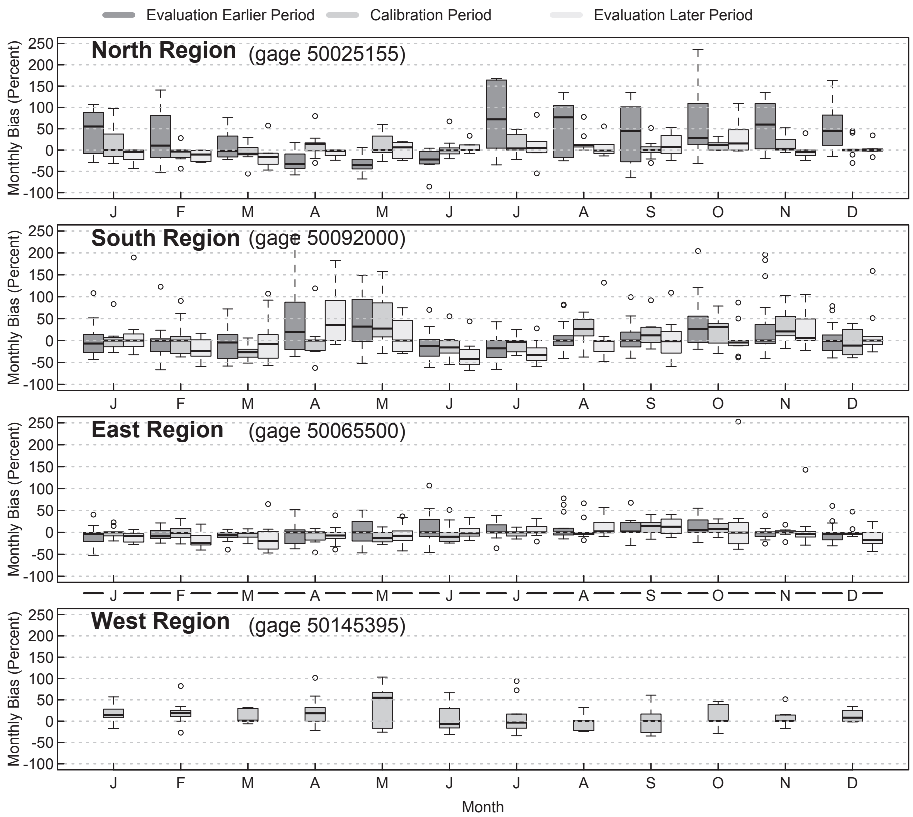

FIGURE 5. Monthly Bias (percent) between Measured and Simulated Streamflow Calculated Using the Early (dark gray) and Later (light gray) Evaluation Periods and the Calibration Period (medium gray) for the "Best" Gages in the North, South, East, and West Regions of Puerto Rico.

TABLE 3. PRMS Parameters Affected by Changing Land Cover.

PRMS Parameter	Parameter Description	Source
cov_type	Dominant cover type of each HRU (bare, grass, shrub, or tree)	PRMS cover type per land cover type that is dominant in each HRU
covden_sum	Plant canopy density during summer as a fraction of HRU area	Canopy density per land cover type from NLCD2001 or from merge of NLCD2001 density and year 2000 IITF land cover
covden_win	Plant canopy density during winter as a fraction of HRU area	Canopy density multiplied by canopy leaf-loss percent per land cover type
srain_intcp	Depth of precipitation interception by vegetation for rain in summer in each HRU	Depth of precipitation interception in summer per land cover type
wrain_intcp	Depth of precipitation interception by vegetation for rain in winter in each HRU	Depth of precipitation interception in winter per land cover type
hru_percent_impv	Fraction of each HRU area that is impervious	NLCD2001 imperviousness surface or percent of urban land cover type in each HRU

Note: PRMS, Precipitation Runoff Modeling System; HRU, Hydrologic Response Unit; NLCD, National Land Cover Database; IITF, International Institute of Tropical Forestry.

in Figure 1 and a numerical summary of the maps for the main island of PR is given in Table 1.

The PRMS parameters affected by changing land cover describe the land cover type, seasonal canopy density, seasonal rain-storage capacity, and impervious-land percent for each HRU (see Table 3). The canopy leaf loss in winter, cover type, and depth of precipitation interception in summer and winter were assigned per cover type, and not calculated. The IITF datasets do not provide the impervious-land percent or seasonal canopy density found in the NLCD2001 products. Impervious area was assumed to be 100% wherever the urban land cover type existed. Canopy densities were calculated by comparing the NLCD2001 cover density per IITF 2000 cover type and are listed in Table 4. The per-cover type densities were assumed to be constant for all years in the IITF sequence. After calculating mean canopy density for

TABLE 4. IITF and NLCD Land Cover Type Comparison.

IITF Land Cover Type	NLCD Land Cover Type	Canopy Density from IITF Land Cover (%)[1]	Canopy Density from NLCD Land Cover (%)[2]	Canopy Leaf Loss in Winter (%)	PRMS Cover Type	Depth of Precipitation Interception in Summer (mm)	Depth of Precipitation Interception in Winter (mm)
Urban	Urban	7.6	2.9	100	Bare	0	0
Pasture	Pasture	12.5	0	100	Grass	0.5	0.5
Herbaceous agriculture	Agriculture	3.1	3.9	100	Grass	0.5	0.5
Woody agriculture	N/A	39.2	N/A	0	Tree	0.5	0.5
Open forest	Shrub	35.4	15.8	60	Shrub	1.3	1.3
Evergreen closed forest	Evergreen forest	55.5	65.9	0	Tree	1.3	1.3
Semideciduous closed forest	N/A	59.9	N/A	60	Tree	1.3	0.5
Forested wetland	Forested wetland	42.6	53.6	60	Tree	1.3	1.3
Herbaceous wetland	Herbaceous wetland	3.1	0	100	Shrub	1.3	1.3
Water	Water	6.1	0	100	Bare	0	0

Notes: IITF, International Institute of Tropical Forestry; NLCD, National Land Cover Database; PRMS, Precipitation Runoff Modeling System.
[1]From merging the NLCD2001 density with the year 2000 IITF land cover map.
[2]From merging the NLCD2001 density with the NLCD2001 land cover map.

each IITF cover type, the area-weighted average of these cover type densities was determined per HRU. Any holes or unclassified areas in the IITF land cover maps are filled in from the surrounding areas.

PRMS Simulations for Puerto Rico

The relative changes in the adjusted parameters from the calibration procedure described above were used to adjust the parameters in the HRUs located in the ungaged areas of each region. This resulted in a PRMS model for each of the four PR regions with calibrated parameters based on the “best” gage in each region. Each of these PRMS models was run for WYs 1953-2012 (with 1952 for initialization) with static land cover parameter sets based on the (1) NLCD2001 dataset and (2) each of the four IITF land cover datasets. PRMS was then run using dynamic land cover parameters (based on an interpolation derived from the IITF land cover datasets over time). No parameter calibration was carried out for these alternate scenarios in addition to that described in the Hydrologic Model calibration section.

RESULTS

The following sections describe the results from the PRMS simulations for each region in PR with land cover parameters based on the (1) NLCD2001 dataset and (2) each of the four IITF land cover datasets. In these PRMS models, all parameter values remain static for the specified time period. Use of static parameter values over broad temporal and spatial scales may be insufficient to evaluate the hydrologic response when changes in climate or landscape are substantial. Therefore, results from a PRMS model simulation using dynamic land cover parameters are shown to illustrate that accounting for these dynamic changes is important for hydrologic model evaluation and predictive purposes.

Simulations Based on Static Land Cover

The PRMS model for each of the four regions was run for the period of record (WYs 1953-2012, with 1952 for initialization) using land cover parameters derived from NLCD2001. Figure 6 shows the annual simulated runoff for each region. Overall, the East region has the most runoff and the South and North regions have the least. Although the West and East regions have similar precipitation elevation “slope” relations from the MLRs (increasing precipitation with elevation), the West is lower in average elevation than the East. As a result, the West region receives much less precipitation than the East and in general less runoff. The total drainage areas for the North, South, East, and West regions are 3,700, 2,625, 1,265, and 1,632 km^2, respectively. Therefore, changes in the North region’s streamflow will have the largest contribution to total streamflow for PR.

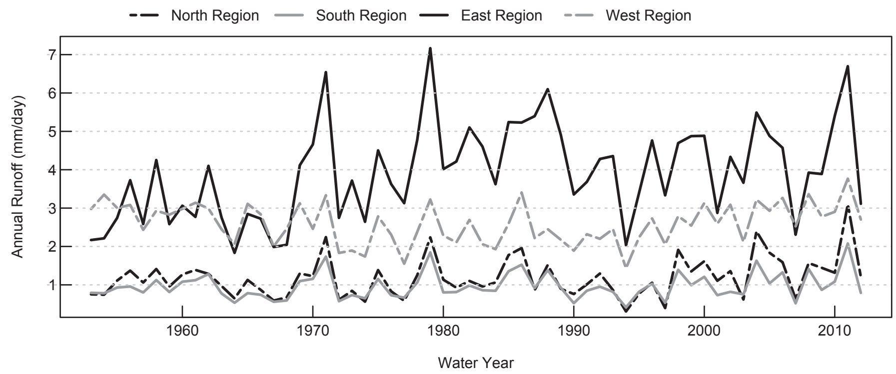

FIGURE 6. Annual Simulated Runoff for Each Region Using Static Land Cover Parameters Derived from National Land Cover Database 2001.

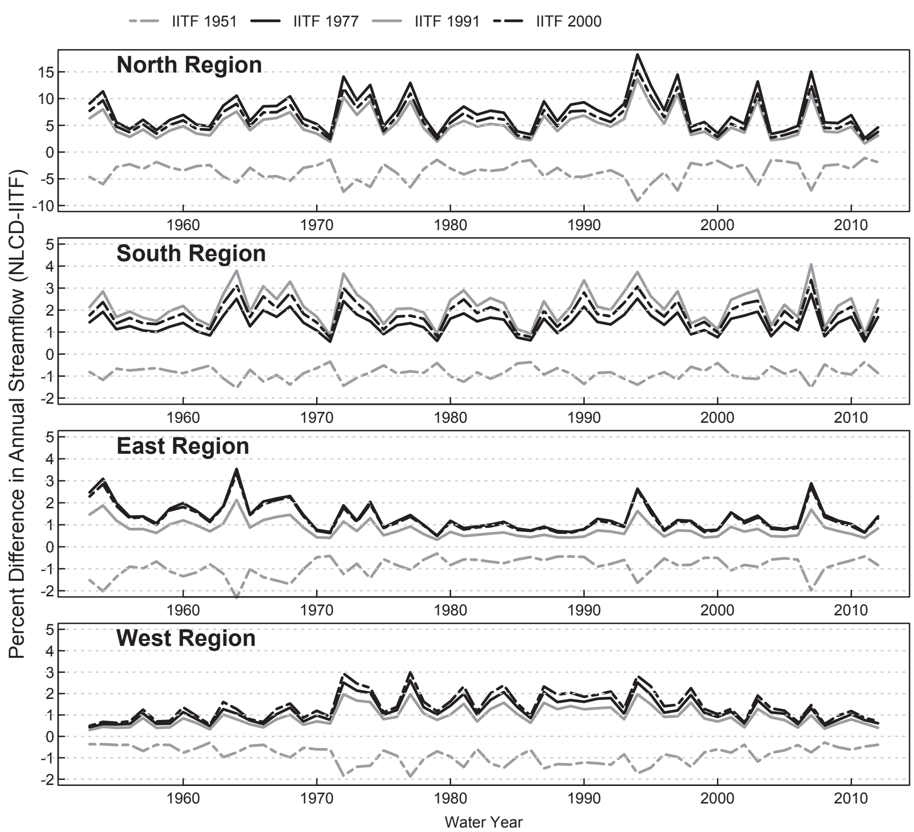

FIGURE 7. Percent Difference in Annual Streamflow Simulated Using Parameters Based on National Land Cover Database (NLCD) 2001 Land Cover and Each of the International Institute of Tropical Forestry (IITF) Land Covers (1951, 1977, 1991, and 2000) for the North, South, East, and West Regions.

The PRMS model for each of the four regions was run for the period of record (WYs 1953-2012, with 1952 for initialization) using each of the four IITF land cover datasets as a static land cover parameterization (16 PRMS simulations). Figure 7 shows the percent difference in the annual streamflow simulated using each of the IITF land cover parameterizations relative to values simulated using NLCD2001 land cover. Positive values indicate that the IITF land cover parameterization resulted in more streamflow than the parameterization based on NLCD2001 land cover. A consistent pattern is shown in all four regions with negative values using the earliest IITF land cover (1951, dashed gray lines) and positive values using the 1977, 1991, and 2000 IITF land covers (solid black, solid gray, and dashed black lines, respectively). This may reflect the large increase in urban land cover between 1951 and 1977, and continued state of greater urban land cover after 1977 (see Figure 1 and Table 1).

Note that the NLCD2001 HRU percent impervious values consistently fell between those calculated using the IITF 1951 and 1977 snapshot. Greenfield *et al*. (2009) report that the methodology by which NLCD2001 estimates percent impervious can underestimate the value by as much as 5.7% in the conterminous U.S. In the IITF and NLCD2001, designated urban areas are considered 100% impervious; green spaces, such as parks and lawns, on which infiltration occurs within urban areas are not recognized in the current study. Including a more detailed interpretation of the IITF and NLCD2001 output could reveal that the increases in streamflow are too steep because the hru_percent_imperv parameter values (Table 3) were consistently overestimated.

The most drastic urbanization occurred in the North region, which contains the city of San Juan (Figure 1). This is reflected in Figure 7 with significantly larger percent differences in streamflow in the North *vs*. the South, East, and West regions. Forest recovery occurred in the North, East, and West regions between 1951 and 1977, and continued between 1977 and 1991 when the urbanization slowed (Figure 1 and Table 1). This results in less streamflow with the 1991 land cover parameterization than with the 1977 land cover parameterization in all regions but the South. In contrast, the South region experienced much less forest recovery (it is a drier area with less inclination to be forested) and was still principally influenced by urbanization changes from 1977 to 1991. PRMS simulations in the South region produce more streamflow with the 1991 land cover parameterization (Figure 7 South region, solid gray line) *vs* the 1977 one (Figure 7 South region, solid black line). From 1991 to 2000, the effect of urbanization was greater than the effect of reforestation in all areas but the South, increasing the streamflow in the North, East, and West regions with the 2000 land cover parameterization over the 1991 land cover parameterization.

Simulations Based on Dynamic Land Cover

Based on the PRMS simulations using static land cover parameterizations for the four regions, one might interpret that using dynamic land cover parameterizations would not have a large impact on streamflow simulations for a large region (percent differences in Figure 7 are very small) unless the entire region has undergone extensive land cover change (North region being closest to this). In an attempt to determine if the uncertainty in simulated streamflow is reduced using dynamic parameterization, the range of PRMS simulations was compared at a stream gage in the North region that has experienced extensive land cover change over the period of simulation (WYs 1953-2012). The gage for the Río Piedras watershed (USGS Gage 50049100) was selected because the

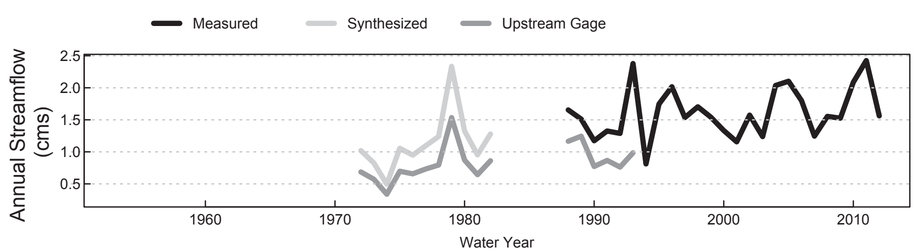

FIGURE 8. Measured and Synthesized Annual Streamflow at Río Piedras (USGS Gage 50049100) and Measured Annual Streamflow at Upstream Gage (USGS Gage 50049000).

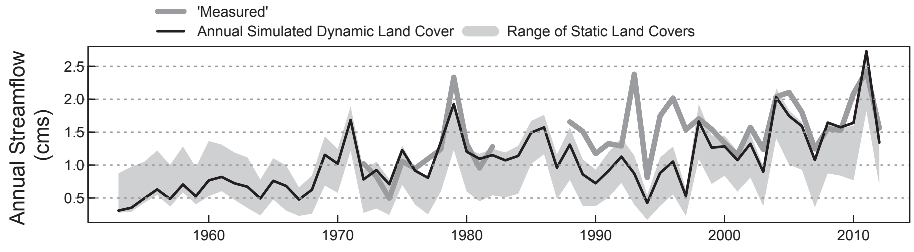

FIGURE 9. Annual Streamflow at Río Piedras (USGS Gage 50049100) Using “Measured,” Range of Simulated with Static Land Cover Parameters, and Simulated with Dynamic Land Cover Parameters.

watershed has had a large degree of urbanization over the simulation period being entirely contained within the current boundary of the San Juan municipality.

Unfortunately, there are substantial gaps in the streamflow measurement record for USGS gage 50049100. As noted earlier, there is a notable lack of high-quality streamflow data in PR. This has been noted as a growing concern; hydrologic data collection in the tropics is in rapid decline despite the pressing need for more and higher quality measurements (Wohl *et al.*, 2012). The missing streamflow records were filled using a correlation established with an upstream gage (USGS 50049000) to provide streamflow for evaluation that covers the IITF snapshots of land cover (years 1951, 1977, 1991, and 2000). This upstream gage contains 18% of the Río Piedras drainage (gage locations are shown in Figure 1). Both gages recorded measurements from WYs 1988 to 1993. A best-fit coefficient describing the monthly percent increase in streamflow from the upstream gage streamflow to the downstream gage was calculated and applied to produce synthesized data at USGS gage 50049100 from 1972 to 1982. The measurements for gages 50049100 and 50049000 and synthesized data based on the correlation are shown in Figure 8.

Figure 9 shows the "measured" and PRMS simulated streamflow using the five static (IITF 1951, IITF 1977, IITF 1991, IITF 2000, and NLCD2001) and one dynamic land cover parameterization in the North region's Río Piedras watershed. In the North region, the percent impervious area (a reflection of urbanization in the region) was lowest in the IITF 1951 snapshot and peaked in the IITF 1977 snapshot. While there is no measured streamflow for comparison prior to 1973, the effects of urbanization on simulated streamflow are clearly evident in the dynamic simulations. The range in the streamflow resulting from the five static parameterizations is shown by the gray band in Figure 9 and demonstrates the range of uncertainty associated with different land cover parameterization. The streamflow resulting from the dynamic parameterization falls within this gray band and accurately matches the measured streamflow, with the exception of WYs 1988-1997.

DISCUSSION

PRMS models were developed for four climatic regions covering PR. Each of these PRMS models was run for WYs 1952-2012 with five static land cover parameterizations based on snapshots in time (IITF 1951, 1977, 1991, 2000, and NLCD2001). A simulation using dynamic land cover parameterization was run for a highly altered watershed in the North region to illustrate the reduction in uncertainty that may be achieved when using the appropriate land cover. The following sections discuss the: (1) implications of data scarcity; (2) impervious area parameterization effects on streamflow; (3) human impacts on water supply; and (4) effects of scale when analyzing simulated streamflow.

Data Scarcity

The effects of land cover on streamflow simulations in the outer islands of PR were not assessed due to the lack of land cover data. The outer islands of Vieques, Culebra, and the U.S. Virgin Islands were included in the South region (see Figure 1) because their climates and land cover are most similar to that of the South (Veve and Taggart, 1996). Vieques and Culebra have IITF land cover for the year 2000 (see Figure 1). The U.S. Virgin Islands do not have any IITF land cover and are assumed to be similar to Vieques and Culebra in the year 2000. Therefore, the land cover parameters for the outer islands are from NLCD2001 in all of the IITF models in Figure 7 (and therefore do not contribute to South region IITF model bias from NLCD2001), except the year 2000 IITF land cover model in which all outer islands have parameters from Vieques and Culebra 2000 IITF land cover. Kennaway *et al.* (2008) mapped land cover in the U.S. Virgin Islands for 2000, but it was not part of the IITF land cover change dataset. Future hydrologic model applications could benefit from utilizing these data and future land cover change studies in the outer islands.

While data scarcity has been a consistent problem in developing every aspect of this modeling study in PR, the results indicate that hydrologic models developed for historic or future conditions that do not consider the past or projected changes in land cover may be inadequate. Finding land cover data sources to develop accurate dynamic parameterization can be problematic, but there are data sources becoming available that may alleviate this problem in some areas. For example, the completion of the USGS LandCarbon project (http://www.usgs.gov/climate_landuse/land_carbon/) will result in a continuous (1938-2100) annual set of land cover maps at 250-m resolution, for 16 land cover classes, for the conterminous U.S. Products like this, which are developed to be consistent with the NLCD data source, will make development of dynamic land cover parameterization datasets for PRMS relatively seamless within the conterminous U.S. PRMS models based on future climate projections, such as those made across the U.S. by Hay *et al.* (2011) and Markstrom *et al.* (2012), that also incorporate future land cover projections are crucial when planning adaptation of the hydrological system for future conditions (Buytaert *et al.*, 2009).

Impervious Area

The handling of impervious area within PRMS is particularly important in light of the physical growth of urban areas in PR and throughout the nation. Urbanization has long been held to result in an increase in the velocity and volume of surface runoff due to increasing impervious area which tends to be smoother, accelerating the runoff, and impeding the precipitation infiltration into the soil (Urbonas and Roesner, 1992). Past studies using hydrologic simulation models have demonstrated this phenomenon (e.g., Wu *et al.*, 2007; Viger *et al.*, 2011). Wu *et al.* (2007) examined the influence of land cover changes on streamflow in a northeastern PR watershed and concluded that complete urbanization in this watershed would result in increased surface runoff due to storm runoff going directly to the stream channels. Viger *et al.* (2011) examined the influence of long-term urbanization on streamflow in a watershed in Georgia and concluded that the impact of increasing impervious surfaces was to increase surface runoff. This phenomenon was demonstrated in the current study by comparing the PRMS simulations using the 1951 IITF land cover parameterization (least urbanized) with the later snapshots in Figure 7. PRMS simulations using the 1951 IITF land cover parameterization produced less streamflow in all regions than all other static land cover parameter datasets (Figure 7). This phenomenon has been recognized in PR and dams have been built to increase water storage capacity and help control the water supply (Wu *et al.*, 2007).

The current study did not consider the water storage capacity from dams or other small water bodies; there was no detention of surface runoff from impervious surfaces or storage ascribed to the newly impervious areas by PRMS. Many researchers (e.g., Alley and Veenhuis, 1983; Lee and Heaney, 2003; Wissmar *et al.*, 2004; Olivera and DeFee, 2007; Schueler *et al.*, 2009; Viger *et al.* 2011; LaFontaine *et al.*, 2013) have demonstrated that the presence of small water bodies can detain runoff from impervious surfaces, reducing peaks in streamflow response that might otherwise be expected to accompany an increase in impervious area within a watershed. This relatively fine-scale feature was not identified in the IITF land cover snapshots. An extension of PRMS developed in Viger *et al.* (2010) accounts for the effect of a large number of water-holding depressions in the land surface on the hydrologic response of a watershed. Properly characterizing this geographic feature in PR, and any change in this feature over time, is important for supporting effective natural resource management.

Human Impacts

The model bias shown in Figure 9, especially in WYs 1988-1997, could have many probable causes such as model error, precipitation under catch, and/or human impacts on the supply of water. In the Río Piedras watershed, a large amount of water is transferred into the watershed for human consumption (Lugo *et al.*, 2011). These transfers were not considered in PRMS, therefore PRMS should underpredict the measured streamflow. In addition, a very large (42%) water loss from leaky pipes was noted over a period of years (1991-1995) (Larsen, 2000), which may have contributed to increasing the volume of streamflow in the Río Piedras to well above what would be expected to be generated by precipitation that actually occurred within the watershed. The percent water loss went down drastically in the following years, to 15% in 2005 due to pipe repair (Molina-Rivera, 1998; Molina-Rivera and Gómez-Gómez, 2008; Lugo *et al.*, 2011). Understanding the impacts of water use on the hydrologic system for the past and potential future uses is crucial for water resources management planning.

Effects of Scale

The PRMS simulations based on static land cover illustrated the effect different land cover parameterizations can have on streamflow in PR. Notably, scale makes a difference: simulated streamflow for a large region with localized areas that have undergone dramatic land cover change may show negligible difference in total streamflow (note the small percent changes in Figure 7). But PRMS simulations using dynamic land cover parameterization for a highly altered watershed within the San Juan municipality in the North region (Río Piedras watershed) clearly demonstrates the effects of urbanization on simulated streamflow at the finer scale. The incorporation of dynamic land cover parameterization in highly altered watersheds has the ability to reduce the uncertainty in the PRMS simulations. A hydrologic model for historic or future conditions that does not consider the past or projected changes in land cover may produce significantly biased streamflow.

CONCLUSIONS

PRMS models were developed for PR, taking into consideration the large anthropogenic impacts, poor-quality climate data, and sparse streamflow records. This was accomplished by dividing PR into four climatic regions and using the least-altered and most reliable streamflow measurements to calibrate PRMS by region. The PRMS model for each region was used to simulate streamflow for WYs 1953-2012 using five static land cover parameterizations based on different snapshots in time (IITF 1951, 1977, 1991, 2000, and NLCD2001). The PRMS simulations based on static land cover illustrated consistent differences in simulated streamflow across the island. PRMS was then run using a dynamic land cover parameterization for a highly altered watershed located within the San Juan municipality. The PRMS simulations based on dynamic land cover parameterization illustrated the possible reduction in uncertainty that could be achieved in highly altered watersheds. Hydrologic models for historic or future conditions that do not consider the past or projected changes in land cover may be inadequate.

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