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Forest Cover and Locality Regulate Response of Watershed Discharge to Rainfall Variability in Caribbean Region

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Abstract: Reforestation often occurs when the economy shifts from agriculture to industry and services such as tourism. However, there is a lack of coherent knowledge and investigation about the impact of reforestation in the tropics on hydrological variability as well as flood risks. It is unclear how changes in forest cover and pattern will affect flood risks and watershed response to future altered rainfall intensity. This study uses the Soil Water Assessment Tool (SWAT+) to simulate the impact of reforestation, the locality of forest, and the concentrated rainfall on the hydrology of the largest watershed in Puerto Rico. SWAT+ is a computer model simulating watershed hydrology driven by meteorological input and the characteristics of soils and land use. We hypothesized that increased forest cover, especially at low elevation range, would reduce flood risk and that reduced rain days while maintaining the mean annual rainfall invariant would increase stream discharge variability. We found that reforestation significantly reduced large discharges but increased small discharges; that forest at low elevation tended to reduce large and extreme discharges in comparison with forest at high elevation; and that more concentrated rainfall not only increased the rainfall variability but also increased the discharge variability. However, both the impact of shifting forest locality and the response of watershed to altered rainfall intensity strongly depended on geophysical factors such as ranges of elevation and slope. Moving forests to lower elevation in subbasins with steeper slopes showed a stronger reduction in extreme discharges than in subbasins with flatter slopes. On the other hand, subbasins with steeper slopes tended to response more strongly to more concentrated rainfall with greater increase in discharge variability than subbasins with flatter slopes. To cope with future increased climate variability, our results favor reforestation at lower elevation for watershed with large elevation ranges and steep slopes.

Keywords: hydrological variability; Puerto Rico; land use pattern; discharges; rainfall variability

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1. Introduction

Climate variability often refers to how the values of temperature or precipitation differ from the mean values [1]. Natural climate variability arises from perturbation-caused positive and negative feedbacks within the atmospheric system [2]. However, the main component of present climate variability is a result of human activities [3]. Warming increased the energy of the earth's system, and the progressive loss of glaciers and ice caps reduced the cooling of ocean water. These external forcings caused more frequent and extreme oceanic and atmospheric events such as localized high atmospheric pressure interwoven with mega tropical cyclones. Consequently, more frequent extreme weather conditions impact coastal and terrestrial ecosystems as well as human societies [4]. Alternating drought and extreme large rainfall brought about by major storms increased hydrological variability and flood risk and reduced the availability of water for terrestrial ecosystems and human consumptions [5].

Not only does hydrological variability link to climate processes but it also heavily depends on how terrestrial ecosystems respond to the climate variability [6]. The hydrological responses of terrestrial ecosystem to rainfall events are complex. Soil and vegetation hold and consume a portion of water, and runoff is generated when rainfall intensity exceeds the maximum infiltration rate of land matrix. The discharge of a catchment is a result of accumulated overland and subsurface flows [6].

Terrestrial ecosystem often acts as a buffer or filter to the rainfall variability [7]. The root system of vegetation, especially forest, facilitates the recharge of soil and aquifer, which hold water during large rainfall and release water gradually after. Surface roughness slows down overland flow, and the hydraulic conductivity of soil also governs the timing of subsurface flow. On the other hand, paved surface and bare land lack this filtering capacity, and the construction underground may block the subsurface flow. Thus, the discharge variability of a catchment depends not only on the rainfall variability but also on the composition and patterns of land cover, especially the forest cover and pattern [8]. Specifically, forest at critical locations within a basin may have more chances to regulate water flows and to affect the variability of stream discharges than at other locations [9].

In the tropics, the island Puerto Rico underwent profound land use changes and experienced increasing climate variability. Located at the east end of the Great Antilles and bounded by Atlantic Ocean in the north and Caribbean Sea in the south, the tropical island is greatly impacted by the more frequent alternation of severe drought and major tropical storms [10]. Tropical storms impact the island mostly during September with extreme rainfall [11,12], whereas severe droughts limit water supply and degrade the island ecosystem and harm human society [13]. Increasing droughts after 2000 (https://www.drought.gov/states/puerto-rico, accessed on 1 January 2024) have been observed, and rainy days have been shown to have decreased [14] from the 1950s onward, especially in the wet season. The patterns of severe drought/storms that impact Puerto Rico were found closely related to ENSO (El Niño and Southern Oscillation), NAO (North Atlantic Oscillation), and La Niña events [15,16]. Major hurricanes often follow severe droughts. For example, the recent severe drought during 2014–2016 in Puerto Rico is aligned with the strong ENSO event in the 2015–2016 period with a peak warming index of 2.2 (https://psl.noaa.gov/enso/mei/, accessed on 1 January 2024). This severe drought was followed by a Category 5 hurricane Irma and a high-end Category 4 hurricane Maria in 2017, which devastated Puerto Rico [10,17].

Industrialization started in the 1940s in Puerto Rico. As a result, urban expansion and forest recovery followed the abandonment of agriculture [18]. According to available land cover maps [19,20], forest grew from 42% of the land to 55%, and urban expanded from 14% to 17%, in the 10 year period from 2000 to 2010. The forest was more fragmented in mountains, especially in the west of the island. The demand for tourism at the coast often competes with forests for space, which challenges mangrove forest conservation. Land cover change not only modified the mean discharge but also altered flood risk [21]. It is unclear how the variability in rainfall is linked to the discharge variability of rivers under altered land use/cover.

This study aimed at an overarching question how reforestation and forest patterns modulate the watershed hydrology and its response to altered rainfall variability. Specifically: how does reforestation affect the large discharges with flood risks; how does the locality or pattern of forest affect the large discharges; and how does increasing rain intensity alter the discharge variability in tropical watersheds? We hypothesized that the increased forest cover and forest allocated at low elevation tend to reduce the large discharges and that the reduced rain days with increased rain intensity would increase the variabilities of both rainfall and discharge in streams. We applied the hydrological model SWAT+ (Soil Water Assessment Tool) to the watershed of Rio Grande de Loiza, the biggest watershed in Puerto Rico. SWAT+ is a computer model aimed to simulate watershed hydrological processes with input of spatial patterns of soil and land use as well as managerial plans. After the calibration and validation of the model, we simulated the discharge rate with two land use/cover maps of 1991 and 2010. We then generated two hypothetical land use patterns with forest allocated to the highest and the lowest elevation, respectively, and ran SWAT+ to investigate how forest locality affects the discharges. As the third part of the study, we generated rainfall with reduced rain days but maintained the mean annual rainfall of the stations in the watershed to investigate how increased rainfall intensity would affect the variability of stream discharges.

2. Materials and Methods

The Rio Grande de Loiza in Puerto Rico has the greatest drainage basin of 72,688 ha (Figure 1). Located in eastern Puerto Rico, the mountainous part of the watershed intercepts a great amount of moisture carried by the eastly trade wind. The annual rainfall at the rain gauge of RQC00668815 (200 m a.s.l.) is 2402 mm (1981–2010), the greatest among the seven stations within the watershed. The wetland near the river mouth is mostly occupied by mangroves. A reservoir, Lake Loíza, is located at the lower reach of the river down the city of Caguas with the dam built in 1953. The original capacity of the reservoir is 26.8 mm^3. According to the report in 2011, the reservoir water was diverted and supplied to San Juan metropolitan area with a mean rate of 394,000 m^3 d^{-1} [22]. Other water extractions from the lake and streams are unknown.

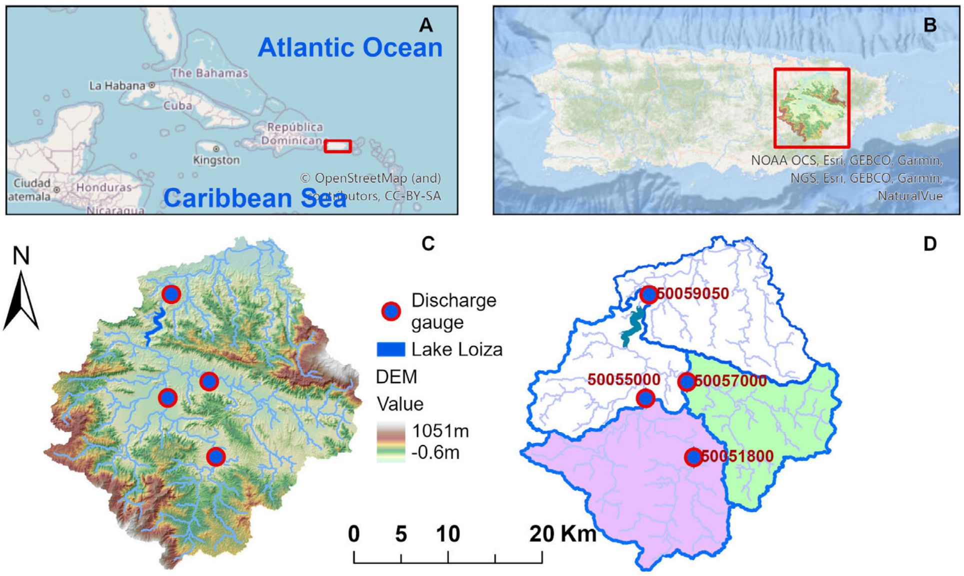

Figure 1. Location of the watershed of Rio Grande de Loiza in the Caribbean (**A**) and Puerto Rico (**B**); distribution of DEM, streams, reservoir, and gauges of discharge within the watershed (**C**); major subbasins and codes for discharge gauges (**D**). 50055000 (Rio Grande de Loiza at Caguas) and 50057000 (Rio Gurabo at Gurabo) are two upper-reach subbasins, and 50051800 (Rio Grande de Loiza at Highway 183) is a subbasin of 50055000. Maps were created in ArcGIS Pro 3.2 (ESRI, Redlands, CA, USA).

The Soil Water Assessment Tool (SWAT+) is a hydrological model built as a plugin to QGIS to simulate the hydrological processes of a watershed by computing evapotranspiration, surface runoff, subsurface flow, sediment yield, and nutrient dynamics driven by daily meteorological records [23,24]. Hydrological response unit (HRU), the basic spatial unit of SWAT+, was formed as the result of overlaying the delineated subbasins, soil map, land use map, and slope ranges. Therefore, land use composition and configuration as well as geophysical factors such as elevation and slope interplay to determine watershed stream discharge. Specifically, we used the QSWAT+ 2.0.6 and SWAT+ model of 60.5.2 associated with QGIS 3.16 (QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.org, accessed on 1 January 2024). The model was set up with a DEM of 20 m resolution. The soil map of Puerto Rico Soil Survey Geographic Database (SSURGO) and land use/cover maps of 1991 and 2010 were used to generate HRU. The result of the watershed delineation and HRU generation gave 40 subbasins, 75 channels, and 875 HRUs based on the land use/cover map of 1991.

To run SWAT+ for Rio Grande Loiza Watershed, we used eight weather stations within and in close distance to the watershed. The data were downloaded from National Climate Data Center, which included RQC00661590 (CANOVANAS), RQC00669521 (TRUJILLO ALTO 2 SSW), RQC00664276 (GURABO SUBSTATION), RQC00661309 (GAGUAS 1 W), RQC00665064 (JUNCOS 1 SE), RQC00668822 (SAN LORENZO FARM 2 N), RQC00668815 (SAN LORENZO 3 S), and RQC00664115(GUAVATE CAMP). Of the eight stations, RQC00661590, RQC00669521, RQC00665064, and RQC00664276 have daily maximum and minimum temperature observations. The missing values of rainfall were filled by means of scaling values from stations with maximum correlation, a method similar to that in the R 4.2 package of 'fillGap' (R Foundation for Statistical Computing, Vienna, Austria). The missing values of temperature were filled with regression on time (with multiple harmonic waves) as well as the rainfall in the previous 2 days.

The daily discharges from 4 USGS gauges (Figure 1) of Rio Grande de Loiza at Highway 183 San Lorenzo (USGS code 50051800), Rio Grande de Loiza at Caguas (50055000), Rio Grande de Loiza below Loiza damsite (50059050), and Rio Gurabo at Gurabo (50057000) were used for calibration, validation, and subsequent analyses. The discharges at 50055000 and 50057000 were from the two major subbasins in the upper reaches of the watershed (Figure 1). We hereafter refer to these subbasins using their corresponding gauge codes.

SWAT+ model must be calibrated and validated before simulation, and we used the daily climate and discharge data from 1987 to 1991 to calibrate the model. The calibration was carried out by means of SWAT+ Toolbox. Four parameters were chosen to be optimized: *cn2*, the curve number controlling the proportion of surface runoff during a rainfall event; *k*, the saturated soil hydraulic conductivity; *flo_min*, the threshold groundwater level to allow baseflow; and *alpha*, the parameter controlling baseflow timing. To validate the model, we used monthly discharges from 1981 to 2010 for all four gauges.

To investigate the impact of land cover changes on the variability of stream discharges, we simulated the discharges of the three subbasins of 50055000, 50057000, and 50059050 with the land use/cover maps of 1991 [25] and NOAA C-CAP for 2010 [19], respectively. The calibrated model was run for each of the land use/cover maps. We used the standard deviation of daily discharge as the measure of discharge variability, and the impact of the land use change can be derived by comparing discharges between land use maps.

Two hypothetical land use scenarios were generated by manipulating forest and pasture covers based on the 1991 land use map while maintaining other land use types unchanged in the two upper-reach subbasins of 50055000 and 50057000. The *high forest* scenario was created by moving the forest to top elevation but pasture to low elevation, and the *low forest* scenario was achieved by moving forest to low elevation and pasture to top elevation. The calibrated SWAT+ was run for these two scenarios to investigate how the forest locality affects the stream discharges.

The scenarios of reduced rain days were generated with a method similar to the rainfall generator embedded in SWAT+. The conditional probabilities of rain today given yesterday wet, and rain today given yesterday dry were computed from the rainfall sequence for each of the 12 months. The daily rainfall amount was fitted to a Weibull minimum distribution. The probability of rain given yesterday wet was reduced by different percentages and the scale parameter of the Weibull minimum distribution was increased accordingly to maintain mean annual rainfall largely unchanged. The altered rainfall scenarios were then applied to simulate watershed discharges. QGIS was used for spatial data preparation. Rainfall analyses, scenario generation, and discharge analyses were carried out with Python 3.10 and R 4.2 [26].

3. Results

3.1. Calibration and Validation of SWAT+

The calibration of SWAT+ yielded the Nash–Sutcliffe model efficiency coefficient (NSE) of 0.532 for daily discharges from 1987 to 1991 at the gauge 50059050. The validation of model (Figure 2) was performed by comparing the simulated and observed monthly discharges from all four gauges during 1981–2010. The NSE varied from 0.58 for 50051800 to 0.83 for 50057000.

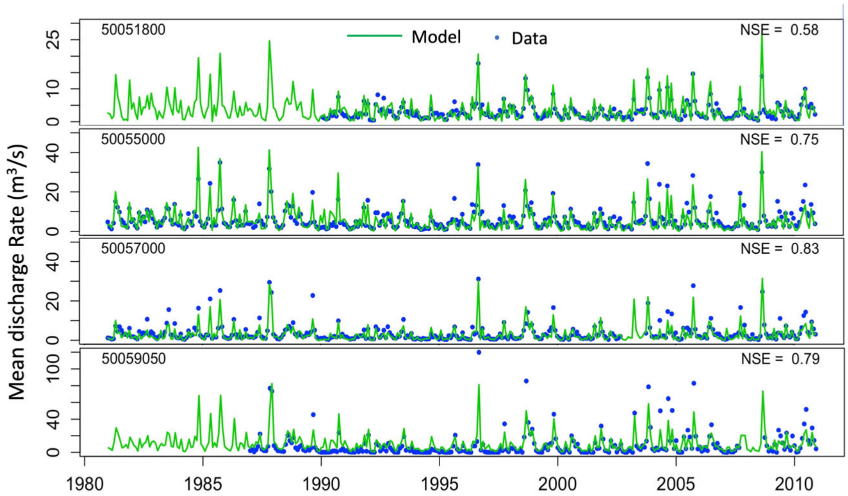

Figure 2. Validation of SWAT+ for monthly discharges at four stream gauges during 1981–2010. NSE, Nash–Sutcliffe efficiency.

3.2. Impact of Land Use Change on Daily Discharges

Land use/cover of the three subbasins of 50055000, 50057000, and 50059050 featured reforestation from 1991 to 2010. Forest mostly emerged from the previous grassland. While agricultural land use remained relatively small and constant, urbanization and urban sprawl continued (Table 1).

Table 1. Land cover fractions within three subbasins of the Rio Grande de Loiza watershed.

Watershed	Year	Forest	Pasture	Agriculture	Urban
50055000	1991	0.46	0.37	0.00	0.16
	2010	0.60	0.18	0.00	0.21
50057000	1991	0.34	0.41	0.07	0.17
	2010	0.46	0.30	0.01	0.25
50059050	1991	0.42	0.36	0.02	0.19
	2010	0.55	0.20	0.01	0.24

The changes in land use altered the hydrology of the watershed. Simulated daily discharges of the three subbasins (Figure 3 upper panels) showed the prevailing patterns of decreased large discharges with the land use of 2010 compared to those with the land use of 1991.

Bootstrapping was applied to regress the difference in simulated daily discharge between 2010 and 1991 land use maps on the log-transformed daily discharges with land use of 1991 (Table 2). The slopes of the regression are significantly smaller than zero as the 95% confidence intervals are in the negative range, implying the prevailing reduced big discharges with the land use of 2010. Specifically, the mean slope ranges from −0.082 for 50057000 (Rio Gurabo at Gurabo) to −0.349 for 50055000 (Rio Grande de Loiza at Caguas). The mean slope of −0.323 for 50059050 (Rio Grande de Loiza below the dam) is largely a combination of the two upper-reach subbasins. However, the intercepts are significantly greater than zero, i.e., 0.017 for 50057000 to 0.133 for 50059050, implying the increased small discharges (baseflow) with the land use of 2010. The superposition of the increased small but reduced large discharge makes the mean discharges with the land use of 2010 slightly decreased compared to those with the land use of 1991 (5.24 vs. 5.29 $m^3\ s^{-1}$ for 50059050).

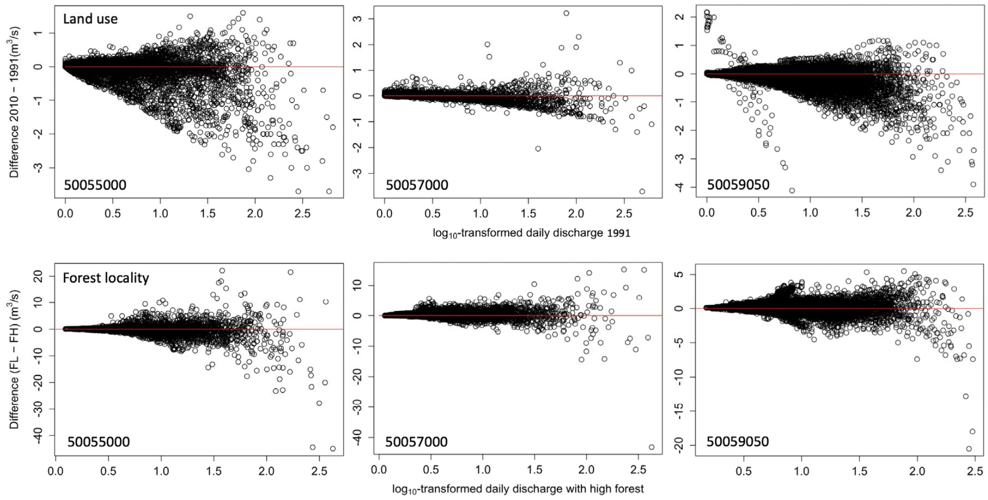

Figure 3. For three subbasins of the Rio Grande de Loiza watershed, differences in daily discharges between 2010 and 1991 land use versus the log-transformed daily discharges based on 1991 land use (upper panels, land use), and differences in daily discharges between *low forest* and *high forest* scenarios versus the log-transformed daily discharges with the *high forest* scenario (lower panels, forest locality). FL, FH—*low forest*, *high forest* scenarios. The horizontal red line shows zero difference in discharge. Points below the lines indicate discharge reduction, whereas those above the lines show increases in discharge.

Table 2. Coefficients of bootstrapping regression of difference in daily discharge between 2010 and 1991 land use on log-transformed daily discharges with land use of 1991 (upper), and coefficients of bootstrapping regression of difference in daily discharge between *low forest* and *high forest* land use scenarios on log-transformed daily discharges with the *high forest* scenario.

Subbasin	**Slope**		**Intercept**	
	Value	**95% Confidence Interval**	**Value**	**95% Confidence Interval**
		Difference between 2010 and 1991 land use		
50055000	−0.349 ± 0.018	[−0.384, −0.314]	0.079 ± 0.005	[0.069, 0.089]
50057000	−0.082 ± 0.010	[−0.1009, −0.063]	0.017 ± 0.001	[0.014, 0.020]
50059050	−0.323 ± 0.010	[−0.344, −0.303]	0.133 ± 0.007	[0.120, 0.147]
		Difference between low forest and high forest		
50055000	−0.943 ± 0.155	[−1.239, −0.624]	0.403 ± 0.082	[0.241, 0.566]
50057000	−0.007 ± 0.123	[−0.235, 0.262]	0.323 ± 0.053	[0.214, 0.423]
50059050	−0.265 ± 0.048	[−0.361, −0.168]	0.387 ± 0.039	[0.307, 0.460]

3.3. Impacts of Forest Locality on Daily Discharges

The simulated difference in daily discharge between *high forest* and *low forest* scenarios (Figure 3 lower panel) showed that the forest at low elevation tends to reduce the large discharges. The pattern is especially obvious for the discharges at 50055000 and, subsequently, at 50059050 but is weak and hardly observable at 50057000. After the removal of the 'outliers' with criteria for the difference in discharge smaller than −40 for 50055000 and 50057000 and −10 for 50059050, bootstrapping was applied to regress the difference in the discharge between the two forest locality scenarios on the log-transformed discharge with the high forest scenario.

The coefficients of the bootstrapping regression (Table 2) show that the slope for 50055000 is −0.943 ± 0.155, with the 95% confidence interval of [−1.239, −0.624]. Since the confidence interval is negative, we can infer that the slope is significantly less than 0. The same argument applies to the slope of 50059050, for which the slope of −0.265 ± 0.048 is also significantly less than 0. Thus, the large discharge is significantly reduced with forest at low elevation. However, this pattern is not true for 50057000, where the slope of

−0.007 ± 0.123 with 95% confidence interval of [−0.235, 0.262] is not significantly different from zero.

3.4. Response of Stream Discharges to Altered Rainfall Variability

The conditional probabilities of rain and the parameters of Weibull minimum distribution for each of the 12 months were shown in Table 3 for the meteorological station RQC00668815 during 1981–1990 (Table 3). The same set of parameters were derived for each station in the periods from 1991 to 2000 and from 2001 to 2010. The mean monthly rainfall was regressed on the conditional probabilities of rain in the day given wet or dry in the day before as well as the scale of Weibull minimum distribution. The equation for RQC00668815 during 1981–1990 is as the following,

$$P = -281.4 + 24.06\lambda + 277.24p_w + 59.89p_d, \quad R^2 = 0.990 \tag{1}$$

where P is the mean monthly rainfall, λ is the scale of the Weibull minimum distribution, and p_w and p_d are the probabilities of rain given yesterday wet and dry, respectively. The R^2 for the eight stations was found in the range from 0.952 to 0.990 with a mean of 0.980. The model fit was shown in Figure 4. In generating rainfall scenarios, we decreased the p_w by 10 to 60% at a step of 10%. To keep the monthly rainfall relative stable, we increased the λ accordingly. Specifically, $\Delta\lambda = -\frac{c_{p_w}}{c_\lambda}\Delta p_w$ where c_{p_w} and c_λ are the coefficients before p_w and λ, respectively.

Table 3. The rainfall parameters for RQC00668815 during 1981–1990. k and λ are the shape and scale of Weibull minimum distributions, respectively. p_w and p_d are the conditional probabilities of rain today given yesterday wet and dry, respectively. P is the mean monthly precipitation.

Month	k	λ	p_w	p_d	P (mm/month)
January	1.191	4.741	0.936	0.378	106.8
February	0.986	5.643	0.909	0.408	120.0
March	0.901	5.372	0.894	0.277	117.7
April	0.885	5.632	0.899	0.306	126.0
May	0.855	10.423	0.935	0.362	275.3
June	0.917	8.667	0.925	0.413	210.2
July	0.967	9.568	0.973	0.467	260.5
August	0.864	7.774	0.939	0.533	216.5
September	0.831	9.438	0.921	0.351	235.0
October	0.877	9.403	0.935	0.383	243.3
November	0.724	8.085	0.915	0.537	252.8
December	0.851	7.042	0.961	0.423	204.3

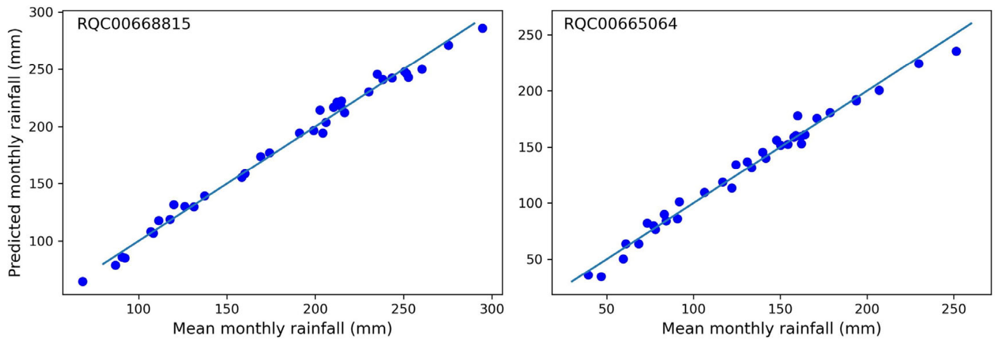

Figure 4. The fit of monthly rainfall on the scale of the Weibull minimum distribution and the conditional probability of rain in a day given the condition of the day before for two stations in the period of 1981–1990.

The daily rainfall sequences were generated for each station in the period of 1980 to 2010. Figure 5 shows the rainfall sequence generated for RQC00668815 in the period of three years from 2006 to 2008. The altered rainfall scenarios with the reduction in continuous rain days showed that the rainfall variability increased (Figure 6), whereas the mean annual rainfall was largely unchanged.

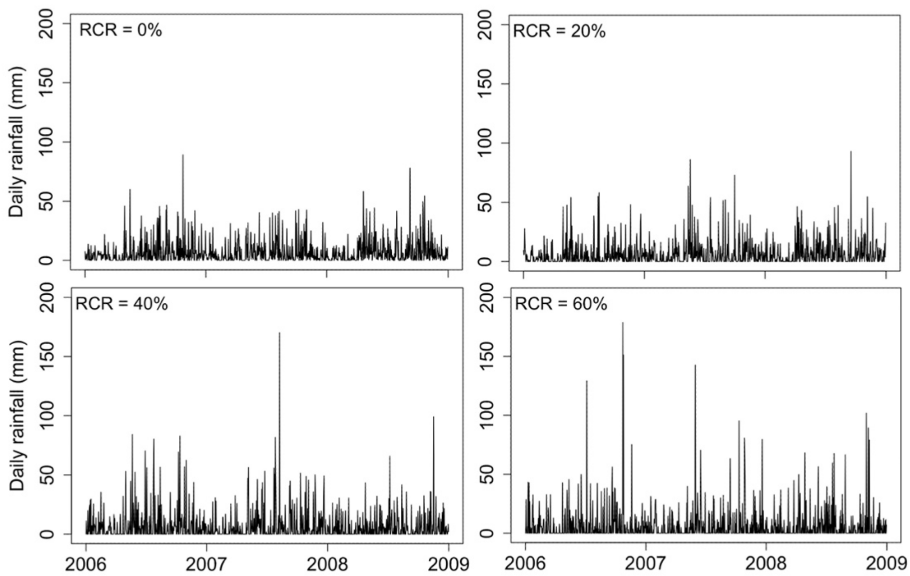

Figure 5. Simulated daily rainfall for RQC00668815 in the period of 1 January 2006–31 December 2008 with various reductions in continuous rainfall probability (RCR).

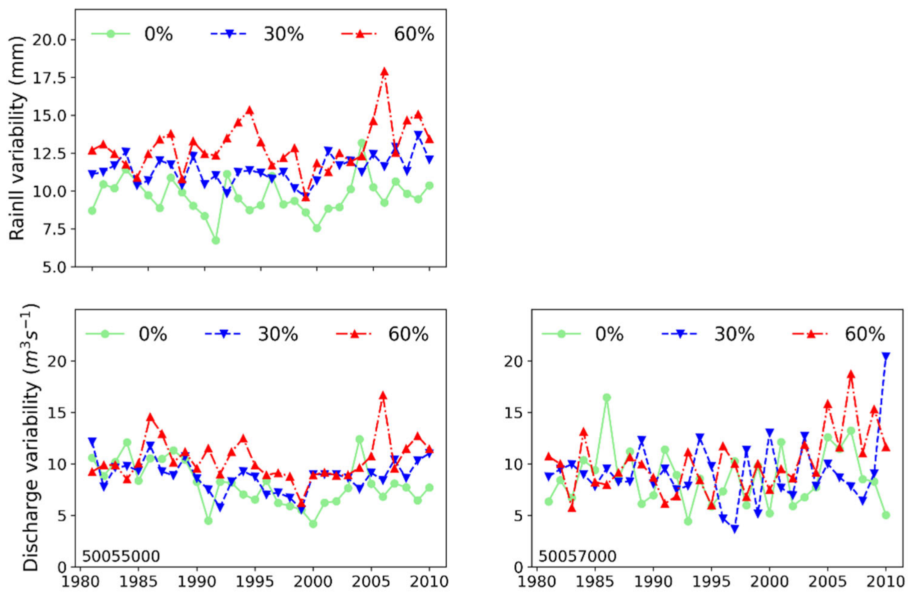

Figure 6. Variability of generated rainfall with three levels of reduction in continuous rainfall probability (0, 30, and 60%) and corresponding discharge variability at the two upper-reach subbasins.

SWAT+ simulated discharges at 50055000, 50057000, and 50059050 corresponding to the reduction in continuous rain days (Figures 6 and 7). However, the intercept and slope of the regressions of discharge variability on the reduction in the probability of continuous rain days are quite different among the three subbasins. Rio Gurabo at Gurabo has the greatest intercept (8.54 m^3 s^{-1}), whereas Rio Grande de Loiza at Caguas has the steepest slope (0.044). The downstream outlet below the dam showed the smallest intercept and slope.

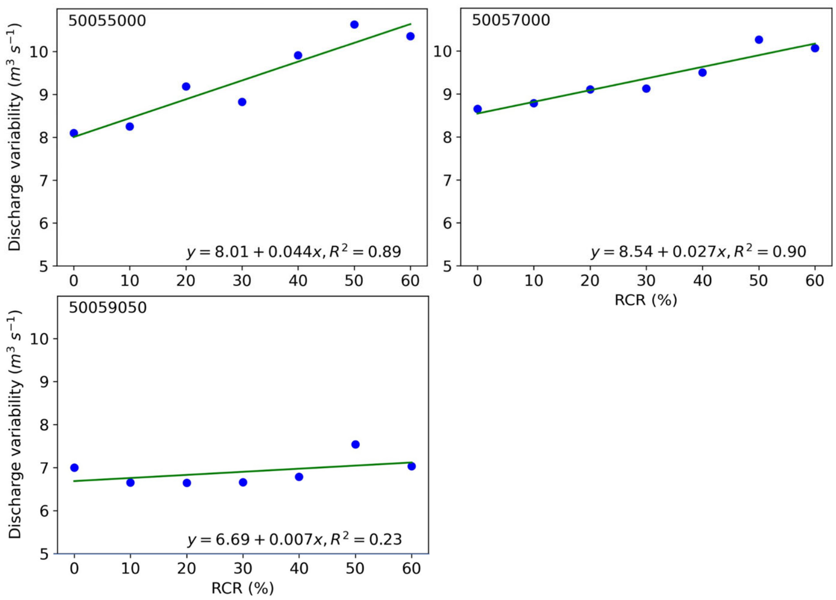

Figure 7. Mean discharge variability changes with the reduction in continuous rainfall probability (RCR) for the three subbasins.

4. Discussion

Land use/cover change has been identified as an important regulator of river discharges. Vegetation, especially forest, tends to slow down surface runoff, tends to intercept rainfall via leaves and stem flows, tends to facilitate the recharge of soils, and tends to increase baseflow [27,28]. Forest roots also allow soils to store more water than other vegetations and tend to reduce surface flow but increase baseflow [29], hence reducing the discharge variability. On the other hand, runoff coefficients for impermeable surfaces in urban and tilled agricultural land are much larger than that of forest. Therefore, the impermeable surfaces and tilled land have little or limited capacity to reduce the hydrological variability.

Reforestation in Puerto Rico has lasted for decades after the industrialization [30]. Forest cover increased from 15.7% in 1970s to 45.7% in 2014 [31]. The forest cover in Rio Grande de Loiza watershed increased by more than 10% over the period from 1991 to 2010. During the same period, cities of Caguas, Trujillo Alto, and Gurabo within the watershed expanded by 5~7% despite the stumbling economy. Our simulation shows that the effect of reforestation dominates over that of urban expansion so that the big discharge at the daily scale is reduced for all the three subbasins. The positive intercepts in Table 2 indicate that there were greater baseflows with 2010 land use than with 1991 land use. The ability to offset the big discharge differs among three subbasins and seems to depend on both the land use in 1991 and the land use change from 1991 to 2010. Rio Grande de Loiza at Caguas (50055000) has the largest negative mean slope (−0.349, Table 2); thus, its ability to offset the big discharge is the strongest. This is because that the subbasin had the highest forest cover in 1991 (46%) and the strongest increase in forest cover (14%) from 1991 to 2010. The subbasin of Rio Gurabo at Gurabo (50057000) has the weakest mean slope (−0.082) and thus the weakest ability to offset the big discharge because of its lowest forest cover in 1991 (34%) and the smallest increase (12%) from 1991 to 2010. Moreover, the subbasin of 50057000 had the biggest urban expansion from 17% to 25%. The discharge from the reservoir dam is mostly determined by the discharge at Rio Grande de Loiza at Caguas, which has much larger discharges than those of Rio Gurabo at Gurabo. Thus, the slope and intercept of 50059050 (Table 2) are in between and close to those of 50055000.

Forest cover is directly linked to the conversion of rainfall and runoff to baseflow. In the interior tropical forest of Puerto Rico, 39 to 45% of rainfall was converted into baseflow in streams [32]. The higher conversion ratio is connected to greater forest cover. Forest area has been identified as a one-parameter model of the variability of stream flows, and the greater the forest area, the more stable the stream flows [33]. Watersheds with greater forest cover also possess greater buffering capacity during flooding events [34]. A previous simulation study of mountainous watersheds in Puerto Rico showed that forest cover significantly decreased the big discharges [21]. The synthesis of hydrological consequences of reforestation in central America indicated that forest cover regulated the hydrological processes and ecosystem services [35]. In particular, increased forest cover reduced the risk of moderate floods and soil erosion. The comparison of peak discharges with forest land versus non-forest land [36] showed that forest decreased peak discharge by ~1 m^3 s^{-1} for moderate storm intensity. When storm intensity increased, this buffering capacity decreased. Our simulation showed a similar reduction in daily discharges with increased forest cover. However, the buffering capacity of forest in this study seems maintained for large discharge events.

The impact of altering forest locality also varied among subbasins. At Rio Grande de Loiza at Caguas (50055000) and Rio Grande de Loiza below the damsite (50059050), placing forest at low altitude significantly reduced discharge, especially the large discharge, in comparison with placing the forest at high elevation. However, the effect of shifting forest locality for the subbasin of Rio Gurabo at Gurabo (50057000) is not as significant as that for the other two subbasins.

The ability to intercept surface and subsurface flows depends also on the geophysical factors such as relative elevation and slope, as well as channelization of runoff [9]. The subbasin of 50055000 has higher elevation and steeper slope than 50057000 (Figure 8). In fact, the mean elevation and slope of 50055000 are 265.6 ± 247.8 m and 14.6 ± 14.4°, respectively, in comparison with 172.4 ± 125.2 m and 11.4 ± 9.5° for 50057000. The subbasin of 50059050 has mean elevation and slope as 208.2 ± 143.7 m and 12.9 ± 8.8°, respectively. Greater slopes may imply that the forest roots at higher elevation have less chance to offset subsurface flows before channelization, leaving more chances for forest at lower elevation to intercept runoff and subsurface flow. This explains why the subbasin of 50055000 has the strongest, whereas the subbasin of 50057000 has the weakest, and that of 50059050 has moderate capacity to reduce large discharges by relocating forest to low elevations.

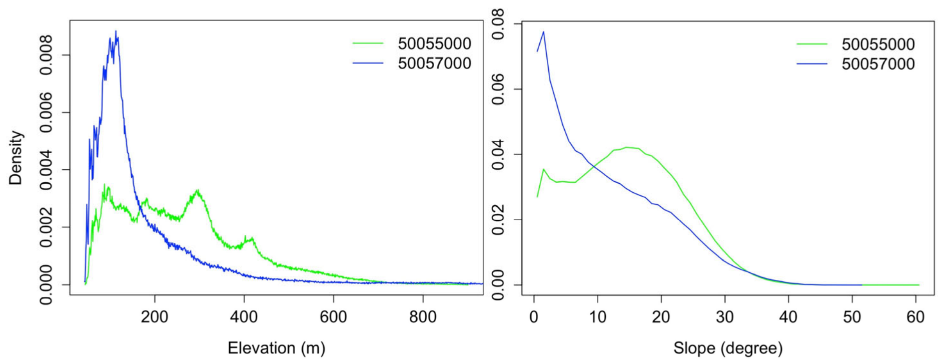

Figure 8. The elevation and slope distributions within the two upper-reach subbasins.

The spatial arrangement, location, and pattern of vegetation or green infrastructure, especially forests and woodlands, have been found to be important for flood risk management. It is important to have green infrastructure located in the path of surface and baseflow to maximize the effect on flood attenuation [9,37,38]. Cross-slope and scattered woody patches are found more effective to smooth the river flow. For example, riparian forest is more functional than upland forest as it has more chances to uptake water and to hinder the surface and subsurface flows [37].

Land use also affects the response of watersheds to changes in rainfall patterns. More forest cover tends to buffer the changes in rainfall variability. However, land use composition and pattern seem to be secondary compared with the geophysical factors: the subbasin of 50055000 had the greatest forest cover, yet its discharge variability has the steepest response to the changes in rainfall pattern (Figure 7). On the other hand, the subbasin of 50057000 has the least forest cover among the three subbasins, and the slope of response to changes in rainfall is not the highest.

Although more forests tend to offset large discharges, steeper slopes tend to generate more runoff as the stronger tangential gravity force tends to pull water down slope, leaving less water infiltrating soil layers [39]. This will provide less chance for baseflow to increase the variability of discharge [40]. Under the scenarios with reduced continuous raining days and more concentrated rainfall, watersheds with steeper slope and greater variation of elevation tend to amplify the effects of increased rainfall variability. In this study, the subbasin of Rio Grande de Loiza at Caguas (50055000) has the greatest and the subbasin of Rio Gurabo at Gurabo (50057000) has the flattest mean slope. Thus, the former has stronger response to decreased rainy days than the latter, despite the former having a larger forest cover. Our results thus imply that the geophysical factors dominate over the land use composition in watershed response to the altered rainfall variability. In addition to the elevation and slope differences, bigger watersheds tend to collect water with different timings of precipitation, which tend to yield less discharge variability. This might apply to the subbasin of 50059050, which has the weakest response to the scenarios with reduced continuous raining days.

5. Conclusions

Tropical watersheds in the Caribbean region are under progressively increasing seasonal and interannual climate variability, yet the land use within these watersheds features great deforestation/reforestation and urban expansion [41]. It is unclear how the changes in land use composition and pattern will affect the watershed response to increased climate variability.

In this paper, we applied Soil Water Assessment Tools (SWAT+), a computer model for watershed hydrology given land use, soil, and digital elevation model, to simulate the stream discharges of the biggest watershed in Puerto Rico. We aimed to explore how reforestation and forest locality would affect the large stream discharges and the responses of the watershed to altered rainfall variability.

We found that reforestation (12–14%) dominates over urban expansion (5~8%) to reduce large stream discharges and to increase baseflow in three major subbasins. Shifting forest to low elevation tended to reduce large stream discharges. Furthermore, the extent of changing forest locality depends strongly on the geophysical factors such as DEM and slope. A stronger reduction in large discharges with forest shifted to low elevation is associated with greater slope because the low-elevation forest has more chance to intercept overland and subsurface flows from steeper upper slopes. For subbasins with relatively flat slopes, shifting forest has limited effects on large discharges. We found increased rainfall and discharge variabilities are associated with reduced continuous rain days. The changes in discharge variability with reduced continuous rain days also depend on DEM and slope so that the steeper the slope, the stronger the increase in discharge variability. Hence to cope with the future increased climate variability, reforestation should mostly be placed at low elevation range for basins with steep slopes.

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