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An Improved Water Budget for the El Yunque National Forest, Puerto Rico, as Determined by the Water Supply Stress Index Model

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Quantifying the forest water budget is fundamental to making science-based forest management decisions. This study aimed at developing an improved water budget for the El Yunque National Forest (ENF) in Puerto Rico, one of the wettest forests in the United States. We modified an existing monthly scale water balance model, Water Supply Stress Index (WaSSI), to reflect location watershed conditions, by incorporating a new empirical evapotranspiration (ET) equation derived from global eddy covariance data for rainforests. Modeling results indicated that the mean water yield was about 1795 mm yr^{-1} for the ENF region, representing approximately 63% of the annual precipitation. We found a wide range of the estimates for all key hydrological fluxes, particularly ET, among those reported in the literature. The large differences in both the magnitude and seasonality of fluxes are a result of differences in estimation methods and physical watershed boundaries used among these studies. The present modeling study that used the updated data products and modeling techniques provided an improved annual water budget with a smaller uncertainty compared to previous studies. Future studies should focus on quantifying water budgets, especially ET and precipitation, across a topographic gradient at a fine spatiotemporal scale.

Keywords: tropical rainforests, water budgets, evapotranspiration, water yield, WaSSI model

Tropical rainforests cover about 12% of the earth's land area and play an important role in global hydrological and energy cycling, biodiversity conservation, and mitigating global climate change (FAO 1993, Choudhury and DiGirolamo 1998, Kumagai et al. 2005, Hansen et al. 2013). Forests provide a stable supply of high-quality water for irrigation, hydro-electric power generation, and domestic drinking (Bruijnzeel and Scatena 2011). Studies indicated that the hydrological cycle in tropical rainforests has been greatly altered by increasing human activities (i.e., land use change and water withdrawal) and climate change (Kumagai et al. 2004, Bruijnzeel and Scatena 2011, Wohl et al. 2012). Many studies (Wohl et al. 2012, Van Beusekom et al. 2015, Khalyani et al. 2016) have projected that continued rapid hydrological change would seriously threaten drinking water supply and the health of aquatic ecosystems (Caldwell et al. 2012). An accurate quantification of the water budgets is a prerequisite for land managers to develop effective climate change adaptation and mitigation strategies in the tropical rainforest region (Wohl et al. 2012, Clark et al. 2014).

As the only tropical rainforest in the National Forest System (NFS) of the United States, El Yunque National Forest (ENF) in Puerto Rico, also known as the Luquillo Experimental Forest and previously known as the Caribbean National Forest, offers

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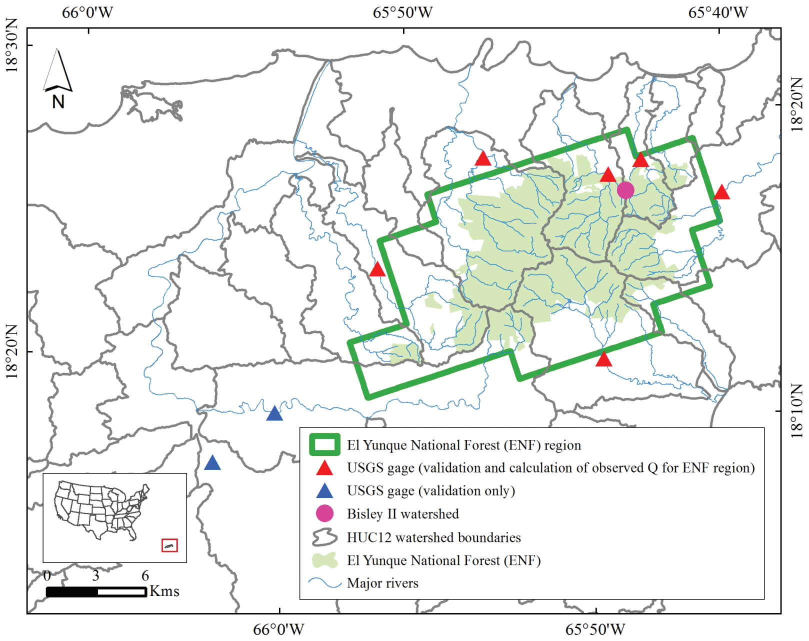

Figure 1. Locations of El Yunque National Forest, streamflow gaging stations, and 12-digit Hydrologic Unit Code (HUC12) watersheds.

an ideal location for managing rainforests for multiple ecosystem services. Although ENF constitutes one of the smallest forests in the US NFS, it is a source of fresh water for 780,000 residents, or about 20% of the population of Puerto Rico (Crook et al. 2007). In recent years, the watershed hydrology of ENF has been affected by increasing anthropogenic water use pressure associated with the population growth and economic development (del Mar López et al. 2001, Crook et al. 2007, Martinuzzi et al. 2007). For example, the population in and around ENF has doubled and urban area has increased more than 25 times during the past 60 years (Thomlinson et al. 1996, Thomlinson and Rivera 2000, Gould et al. 2012). In turn, the number of water intakes in and around the ENF region has increased to meet the needs of the growing population and industry. For some of the forested watersheds, these intakes diverted up to 35% of the streamflow in drought months (Crook et al. 2007). Previous studies have predicted that water supply in this region would likely continue to decline in the future as a result of decreased precipitation and increased temperature (Van Beusekom et al. 2015, Khalyani et al. 2016). Hydrologic changes will not only seriously impact the domestic, industrial, agricultural, and energy water uses but could also threaten aquatic ecosystem functions (Van Beusekom et al. 2015). Therefore, a comprehensive assessment of water budgets in the ENF region can provide useful information for the communities depending on the water supply from the ENF, and government agencies in charge of administering water resources (Harris et al. 2012).

There have been few efforts in developing a complete water budget for the ENF region due to the rugged terrain, and the conclusions have been highly inconsistent and even contradictory due to the differences among data sources, study methods, investigation periods, and spatial scales (van der Molen 2002, Holwerda et al. 2006, Van Beusekom et al. 2015). For example, estimated mean annual evapotranspiration (ET) ranged from 1006 mm yr^{-1} for the ENF region (Figure 1) when using an energy balance model (Harmsen et al. 2009, 2010) to 2420 mm yr^{-1} for a small watershed (Bisley II) (Figure 1) derived from the watershed water balance method (Schellekens et al. 2000). Both the highest (Crook et al. 2007) and lowest (Wu et al. 2006) ET rates have been reported to be in March. In some cases, observed annual runoff (Q) by USGS gage stations for Icacos Basin even exceeded annual precipitation (P) derived from a rainfall-elevation equation (Crook et al. 2007). There is a clear need to study the water balances in the ENF region using the best available data and hydrological modeling techniques. In addition, there is an urgent need to compare the uncertainties in estimating hydrological processes and fluxes for the ENF region across various studies so that future monitoring efforts can focus on these knowledge gaps (Juston et al. 2013).

We adopted a monthly water and carbon balance model (Water Supply Stress Index, WaSSI) (Sun et al. 2008, 2011b) in this study

Management and Policy Implications

El Yunque National Forest (ENF) provides water for over 20% of the entire population of Puerto Rico. Understanding of the magnitude and seasonal variation of the water budgets (i.e., precipitation, evapotranspiration, and streamflow) for ENF can provide useful information for land managers as they process water permits. This study provided an improved complete annual water budget with a smaller uncertainty and a more accurate estimate of seasonal variability than reported in the literature using the best available data products and modeling techniques. About 63% of annual precipitation (i.e., 1795 mm) becomes streamflow, representing the wettest forests within the US National Forest System. We also found strong seasonal variations in the water yield, with the highest value in May and the lowest value in March. These findings suggest that water resource managers need to consider both the volume and timing of the water extraction to maintain the ecological integrity of forest streams. In addition, we identified uncertainties and challenges in estimating forest water loss (i.e., evapotranspiration). Our study suggests that changes in forest composition and structure due to forest management and climate change are likely to increase the uncertainty of projections of future water balances for rainforests in the study region.

to simulate watershed water budgets using limited input parameters and variables. The objective of the original WaSSI model was for quantitatively assessing the relative magnitude of water supply and human water demand. The *WaSSI* index was defined as the ratio between the sum of all water demand or withdrawal (m^3) and total water supply volume (m^3) for each watershed. The WaSSI model has been tested, validated, and applied at the 8-digit Hydrologic Unit Code (HUC8) and 12-digit Hydrologic Unit Code (HUC12) watershed scale across the continental United States (Caldwell et al. 2012, Sun et al. 2015b, Duan et al. 2016), the Yangtze River basin in China (Liu et al. 2013a, Liu et al. 2013b), and Rwanda (McNulty et al. 2016). Compared to other hydrological models, such as SWAT and RHESSys (Tague and Band 2004, Arnold and Fohrer 2005), WaSSI can be easily implemented at a regional scale and a model comparison study suggests that WaSSI has a similar predictive capacity to more complex models (Caldwell et al. 2015) even though WaSSI requires fewer input climatic variables and no model calibration (Sun et al. 2011b, Duan et al. 2016). Therefore, the WaSSI model provides a powerful tool for simulating the watershed hydrology in data-limited areas such as the ENF region.

The original evapotranspiration (ET) algorithm of the WaSSI model was intended to capture relationships among ET, climate, and vegetation across broad land cover types (e.g., deciduous forest, grassland, and cropland) (Sun et al. 2011a). Previous studies demonstrated that the control mechanisms of ET in the tropical region are different from the temperate and arid region (Bruijnzeel and Scatena 2011). Thus, modifications of the ET model are necessary before applying the WaSSI model in the ENF region.

The overall goal of this study was to develop a more accurate water budget for the ENF region than the previous studies by using updated meteorological data and a modified WaSSI model. Our specific objectives were to 1) modify the WaSSI model by incorporating a new ET algorithm using eddy flux observations from multiple tropical rainforests; 2) quantify the annual and monthly water budgets at the entire ENF scale; and 3) evaluate the uncertainties of the annual water balances developed for ENF by this and previous studies.

Methods

Study Area

The ENF region is located in northeastern Puerto Rico, with an area of 224 km^2 (Figure 1). National Forest covers about half of the ENF region (113 km^2), with the rest being mainly covered by commonwealth and private forests. The grassland, wetland, urban, crop, and barren lands account for only 5% of the total land area in the ENF region. The ENF is the only tropical rainforest in the National Forest System in the United States. It is distributed in the Sierra de Luquillo Mountains (Figure 1), with elevation ranging from 100 to 1075 m above sea level (a.s.l.) (Naumann 1994). ENF has a subtropical maritime climate, with annual mean temperature ranging 24–27°C, and a reported mean annual precipitation ranging between 3000 and 4000 mm (Garcia-Martino et al. 1996, Harris et al. 2012). Mean monthly temperature in ENF varies slightly throughout the year, with a low temperature of 24°C in December–February and a high temperature of 27°C in July–August (Figure 2a). Precipitation in the form of rainfall is distributed fairly evenly throughout the year, with May and November being relatively wet and January–March being relatively dry (Schellekens et al. 2000) (Figure 2b).

ENF is the headwaters of nine major rivers, including the Río Mameyes, Río Fajardo, Río Sabana, Río Blanco, Río Gurabo, Río Canóvanas, Río Canovanillas, Río Grande, and Río Espíritu Santo (Figure 1). These rivers are typical of montane streams in the Greater Antilles of the Caribbean, with steep, narrow, and boulder-lined headwaters (Ahmad et al. 1993). A lack of fine sediment in flood flow is common. There is very little change in groundwater storage, and thus groundwater contributes little to streamflow in the ENF (Larsen 1997, Ortiz-Zayas 1998). No natural lakes were found in the ENF (Crook et al. 2007).

There are four major forest types in ENF: tabonuco, colorado, palm, and elfin forests (Brown et al. 1983, Harris et al. 2012). The tabonuco forests, dominated by *Dacryodes excelsa*, are found across elevations below 600 m a.s.l and cover nearly 70% of ENF. The tabonuco forests develop on deep and well-drained acid clay soils. The colorado forests occur in areas between 600 and 750 m a.s.l. and are usually found on sandy soils underlain by granodioritic bedrock. The colorado forests, dominated by *Cyrilla racemiflra*, cover about 17% of the ENF. The palm forests that cover 11% of the ENF are found on steep windward slopes, riparian areas, and areas with poor drainage at elevations greater than 750 m a.s.l. The palm forests are dominated by the sierra palm (*Prestoea montana*). The elfin forests characterized by short and stunted woody vegetation (i.e., *Ocotea spathulata* and *Tabebuia rigida*) are located on the highest mountain peaks, and only occupy about 2% of ENF. Soils in the palm and elfin forests are guayabota-ciales-picacho association, which is continuously wet, unstable, and susceptible to slippage (Brown et al. 1983). The bedrocks of the palm and elfin forests are intrusive igneous (Fletcher and Brantley 2010). Mean monthly leaf area index (LAI) for the ENF region as estimated from Moderate Resolution Imaging Spectroradiometer (MODIS) products (MOD15A2) was about 3 m^2 m^{-2} and had slight seasonal variation because the study area was mainly covered by evergreen rainforests (Figure 2d).

WaSSI Model and Modifications

The original WaSSI model was developed to simulate water cycles and examine impacts of multiple stresses, including climate change, land cover/land use change, and water demand, on watershed hydrology and supplies (Sun et al. 2008). Details of the WaSSI model are found in the User's Guide (Caldwell et al. 2013). The model simulates monthly water fluxes (i.e., ET, infiltration, soil water storage, snow accumulation and melt, Q, base flow, and groundwater) for each of the land cover categories in a watershed at the USGS HUC8 or HUC12 scale. Predicted water flux is then aggregated across the entire basin using an area-weighted averaging method to maintain water volume balance (Sun et al. 2011b, Caldwell et al. 2012) (Figure 3). As a semi-distributed model, WaSSI only considers proportion of land covers among (or within) watersheds. Infiltration, soil-water storage, Q, and groundwater were estimated based on the algorithms from the Sacramento Soil Moisture Accounting Model (SAC-SMA) (Burnash et al. 1973, Burnash 1995) and the 11 soil parameters derived from State Soil Geographic Data Base (STATSGO; Natural Resources Conservation Service 2012). The basic design of the SAC-SMA model includes two water storages in the lower soil zone that generates fast base

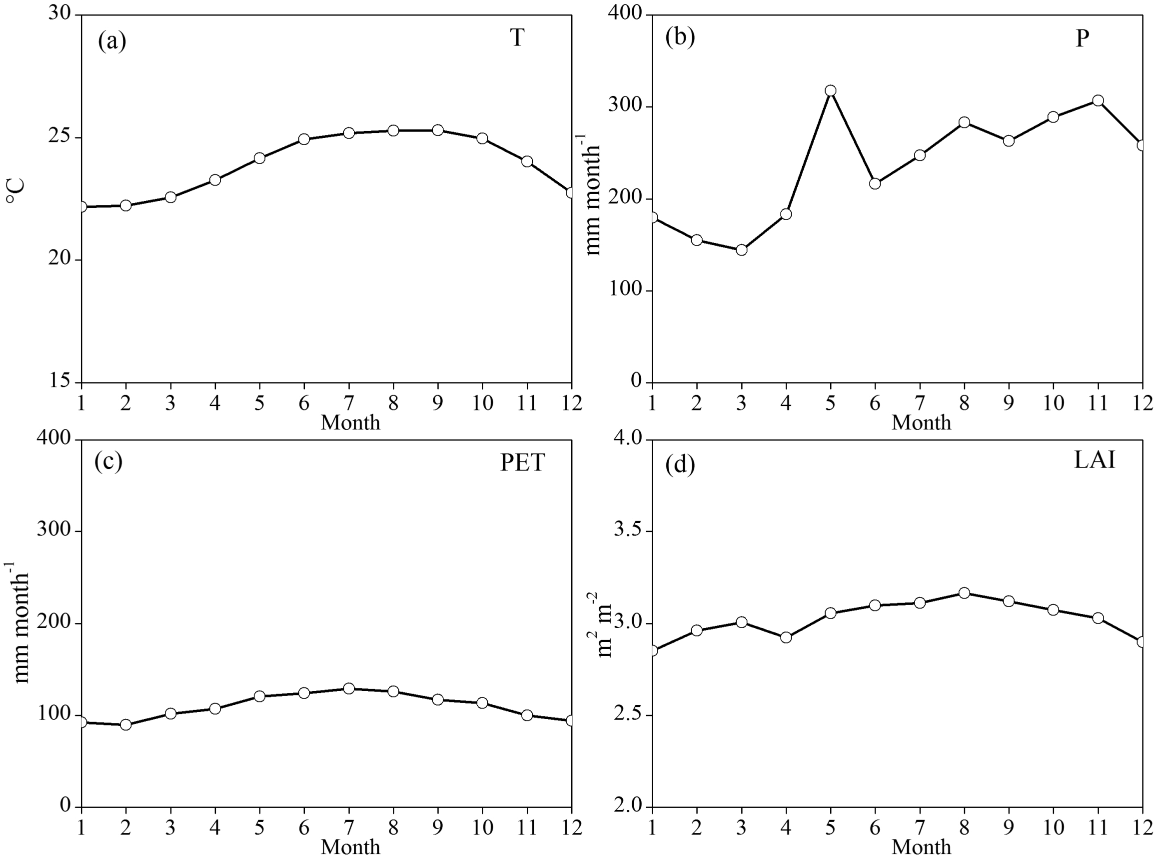

Figure 2. Seasonal variations of (a) temperature (T), (b) precipitation (P), (c) potential evapotranspiration (PET), and (d) leaf area index (LAI) for the El Yunque National Forest region. The monthly T and P were obtained from the spatial climate database developed by parameter–elevation regressions on independent slopes model (PRISM). The monthly PET was generated by the Hamon model embedded in the WaSSI model. The monthly LAI was derived from MODIS LAI products (MOD15A2).

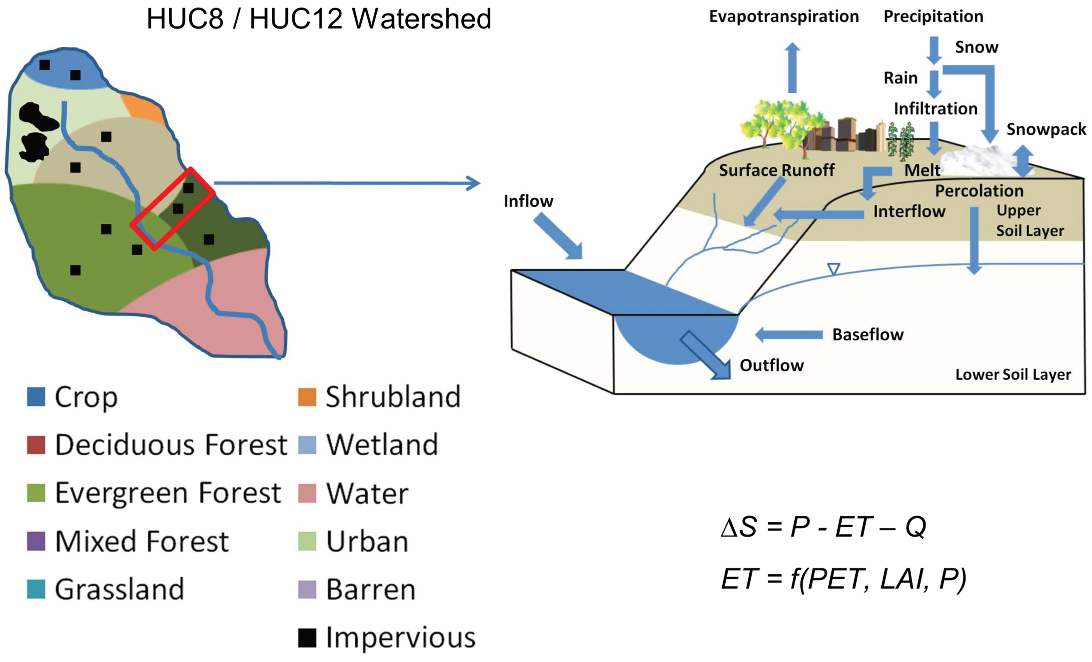

Figure 3. Schematic diagram illustrating the hydrological processes simulated by a monthly water balance model, Water Supply Stress Index Model (WaSSI). ΔS = change in surface and groundwater storage; Q = streamflow or water yield; ET = evapotranspiration; P = precipitation, and LAI = Leaf Area Index.

Table 1. Characteristics of the eddy covariance flux research sites for tropical forests.

Site ID	Latitude (°N)	Longitude (°E)	Precipitation (mm yr^{-1})	ET (mm yr^{-1})	PET (mm yr^{-1})	Mean Leaf Area Index	Elevation (m)	Data period	Country location
BR-Ji2	−10.08	−61.93	1651	1063	1418	4.5	195	2000–2002	Brazil
BR-Ma2	−2.61	−60.21	2621	970	1444	4.1	67	2000–2006	Brazil
BR-Sa1	−2.85	−54.95	1593	1091	1413	3.5	90	2002–2004	Brazil
BR-Sa3	−3.01	−54.97	1174	1173	1461	3.3	100	2000–2003	Brazil
VU-Coc	−15.44	167.19	2734	1051	1371	4.3	1	2001–2004	Vanuatu

flow and primary groundwater flow. The primary groundwater flow rate is estimated using a solution of Darcy's equation for an unconfined homogeneous aquifer (Dingman 1993). Partitioning of rainfall into groundwater is constrained by the soil moisture conditions in the upper layer and the percolation of the lower soil layer. The rainfall above the water capacity of the upper soil layer will infiltrate into the lower soil layer to become groundwater and generate base flow (Koren et al. 2003).

In the original WaSSI model, the monthly ET formula was derived empirically using eddy flux and sapflow measurements at multiple sites from grassland to subtropical conifer forests (Sun et al. 2011a). The general ET equation captures general relationships among ET, climate, and vegetation across broad land cover types at the monthly scale. ET was calculated as follows:

$$\begin{aligned} ET = 0.0222 \times PET \times LAI + 0.174 \\ \times P + 0.502 \times PET + 5.31 \times LAI \end{aligned} \quad (1)$$

where PET is potential ET, which was calculated by Hamon's method as a function of air temperature and daytime length (Hamon 1963), LAI is leaf area index, and P is precipitation.

In this study, we developed a new monthly ET formula to replace the original ET formula embedded in the WaSSI model based on the observations from five eddy flux sites dominated by tropical evergreen rainforests (Table 1). Regression models that relate ET, PET, P, and LAI were developed using the SAS's regression procedure (SAS System version 9.2 for Windows, SAS Institute Incorporation, Cary, NC, USA, 2002–2003). Different combinations of the independent variables (P, LAI, and PET) were tested to derive the best fit of observed data. We modified the ET formula to reduce the uncertainty associated with modeling unique ecosystems such as tropical rainforests in the ENF region using the original generalized ET equation. The average elevation of these five eddy flux sites used to derive the new monthly ET formula was lower than that of ENF (91 m vs. 423 m). However, they represent the best available stations in the global network of micrometeorological tower sites (FLUXNET, http://fluxnet.fluxdata.org/) that have similar climate and ecosystem structures found in the ENF region (Fang et al. 2016, Liu et al. 2017). Table 1 provides descriptions of the four eddy flux sites (i.e., BR-Ji2, BR-Ma2, BR-Sa1, and BR-Sa3) located in Brazil and one site (i.e., VU-Coc) located in Vanuatu.

Required input data to the WaSSI model include soil properties, land covers, LAI, P, and air temperature (T). The 1 km×1 km STATSGO soil data were used to derive the 11 soil parameters required by the SAC-SMA model (Miller and White 1998). The 15 m×15 m land cover data for the year 2001 were provided by the Puerto Rico GAP Analysis project (Gould et al. 2008). The monthly 1 km×1 km LAI data over 2000–2011 were derived from MOD15A2. The multi-year mean monthly LAI by land cover type was computed by overlaying the land cover data with MOD15A2 LAI. Monthly 450 m×450 m P and T data over 1963–1995 were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) that used observed climate data from 15 weather stations in and around the ENF (Daly et al. 2003). These datasets represent the best spatially explicit climate data available for the ENF region to date. All the spatially explicit input data were transformed from their native grid resolution to the HUC12 watershed level by an area-weighted mean approach.

We run the modified WaSSI model over all the HUC12s in Puerto Rico with the flow originating from ENF region first. Then we estimated the Q and ET for the study area from a total of 11 HUC12 watersheds bordering ENF region (Figure 1) by an area-weighted averaging method.

WaSSI Model Validation

The simulated Q (unit: mm) for each HUC12 watershed was validated against the monthly streamflow data recorded at the US Geological Survey (USGS) gages (USGS-Q) that are located near the outlet of the HUC12 watershed. Eight out of sixteen USGS gages (http://waterwatch.usgs.gov/) were chosen to validate the WaSSI model performance (Table 2 and Figure 1). We understand that some gages are not located exactly at the outlet of their HUC12 watersheds, and thus the modeled Q may not be the exact as the observed Q at these USGS gages. However, these eight USGS gage stations represent the best available gages that have similar drainage areas to their HUC12 watersheds.

In this study, coefficient of determination (R^2), root mean square error (RMSE), and Nash-Sutcliffe efficiency (NSE) were used to evaluate the performance of the WaSSI model. It is commonly accepted that the lower the RMSE and the larger the R^2, the better the model performance. NSE, indicating how well the plot of observed versus simulated data fits the 1:1 line (Nash and Sutcliffe 1970, Moriasi et al. 2007), is computed as follows:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{mean})^2} \right] \quad (2)$$

where Y_i^{obs} is the ith observation for the constituent being evaluated, Y_i^{sim} is the ith simulated value for the constituent being evaluated, Y_{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations. The NSE can range from negative infinity to 1.0, where the closer NSE is to 1.0, the better the model fits to observations. NSE values that are greater than 0.50, 0.65, and 0.75 for prediction of monthly streamflow were considered to be indicative of satisfactory, good, and very good model performance, respectively (Moriasi et al. 2007). Negative

Table 2. USGS streamflow gaging stations on the main rivers draining ENF.

Gage Station	Lat (°N)	Long (°E)	Drainage area (km^2)	Data period	Gaged river	Validated HUC12	HUC12 area (km^2)	Mean elevation (m)	Elevation range (m)
50055000	18.24	–66.01	233	1959–2015	Río Gurabo	Rio Grande de Loiza at Carraizo Dam	139	181	30–750
50057000	18.26	–65.97	156	1959–2014	Río Gurabo	Río Gurabo	132	164	40–1049
50061800	18.32	–65.89	26	1967–2015	Río Canóvanas	Río Canóvanas	45	323	0–959
50063800	18.36	–65.81	22	1966–2015	Río Espíritu Santo	Rio Espiritu Santo near mouth	64	380	1–1066
50065500	18.33	–65.75	18	1967–2014	Río Mameyes	Rio Mameyes near mouth	40	290	–1–1056
50067000	18.33	–65.73	10	1979–2014	Río Sabana	Rio Sabana at mouth	19	204	–1–677
50071000	18.30	–65.69	39	1961–2014	Río Fajardo	Rio Fajardo near mouth	67	182	0–1040
50076000	18.23	–65.78	32	1982–2014	Río Blanco	Río Blanco near mouth	70	294	0–1038

Table 3. Uncertainties of the annual water budgets for the ENF region.

Study region	Area (km^2)	Time periods	Annual water budgets ($mm\ yr^{-1}$)			Relative error (%)			Reference
			P	Flow (Q)	ET	P	Q	ET	
ENF region	224	1963–1995	2843[a]	1903[c]	940[b]	—	—	—	Observed water budgets in this study
			2843[a]	1337[b]	1506[a]	0	30	60	Original WaSSI model results in this study
			2843[a]	1795[b]	1048[a]	0	6	11	Improved WaSSI model results in this study
ENF region	224	2009–2014	2297[a]	646[a]	1006[d]	19	66	7	Harmsen et al. (2009, 2010)
ENF region	224	2000–2013	—	—	1449[d]	—	—	54	Mu et al. (2011)
ENF	113	2003–2004	2892[a]	—	1012[d]	2	—	8	Wu et al. (2006)
ENF region	224	2004	3580[a]	2280[c]	1300[b]	26	20	38	Crook et al. (2007)
ENF	113	1994	3879[a]	2526[a]	1245[b]	36	33	32	Garcia-Martino et al. (1996)
ENF	196	1900–1980	3775[a]	2005[a]	1770[b]	33	5	88	Lugo (1986)
	113	1900–1980	3465[a]	2193[a]	1272[b]	22	15	35	
			3300[a]	1925[a]	1375[b]	16	1	46	
Bisley II catchment	0.06	1996–1997	3584[c]	1284[c]	2300[b]	26	33	145	Schellekens et al. (2000)
			3584[c]	1284[c]	1093[d]	26	33	16	

[a]Statistical method; [b]Water balance method; [c]Observation; [d]Energy balance model.

values of NSE indicate that using the mean of the observations provides a better fit than the model.

Water Budget Uncertainty Analysis

We examined the uncertainties of estimated water budgets for the ENF region for this and previous studies. We used the relative error, defined as the ratio of the absolute difference between simulated and observed values to the observed value of water balance components (i.e., P, Q, and ET), to demonstrate the uncertainties in estimating water balances (i.e., estimation errors) for the ENF region. The mean USGS-Q during 1963–1995 for the six gage stations bordering ENF region (Figure 1) was calculated and then was averaged to represent the observed Q for the ENF region. The P in the ENF region is highly variable in space because of the steep topography (Garcia-Martino et al. 1996, Van Beusekom et al. 2015). For example, the annual P can vary from less than 2000 mm to nearly 5000 mm over a distance of 5–8 km. As a result, the observed P from few weather stations cannot represent the actual precipitation for the whole ENF region. We thus used the P from PRISM, which interpolates P based on elevation, to represent observed P in this study. Additionally, we calculated observed annual ET (USGS-ET) for the ENF region by using the water balance approach (i.e., PRISM-P minus USGS-Q). The watershed water balance method estimated ET as the difference between P, Q, and changes in surface and groundwater storage (ΔS): $ET = P - Q \pm \Delta S$. The water balanced equation can be simplified as ET = P – Q (Brown et al. 2008, Sun et al. 2011b, Hao et al. 2015) because the changes in soil water storage were negligible over a long-term mean annual period (e.g., 1963–1995 in this study), and the exchanges of deep groundwater and streamflow in the ENF region are small (Larsen 1997, Ortiz-Zayas 1998). However, evidence showed that the ΔS could not be ignored at a monthly scale (Wang et al. 2010). Thus, the annual ET at the regional scale can only be estimated by the watershed water budget method or modeling approach (Wang et al. 2010). The annual USGS-ET derived from the watershed water budget method is perhaps most close to the actual regional ET, assuming negligible water withdrawals. Previous ET estimates by models were highly inconsistent for the ENF region (Schellekens et al. 2000, Wu et al. 2006, Harmsen et al. 2009) (Table 3). Streamflow characteristics of some watersheds in the ENF region may have been altered by water management practices such as water withdrawal. Anthropogenic withdrawal may lead to an overestimation of USGS-ET because the USGS-Q may be lower than natural Q.

Results

WaSSI Model Modifications and Validation

The new monthly ET formula derived from the five eddy flux tower observations dominated by tropical evergreen rainforests was as follows:

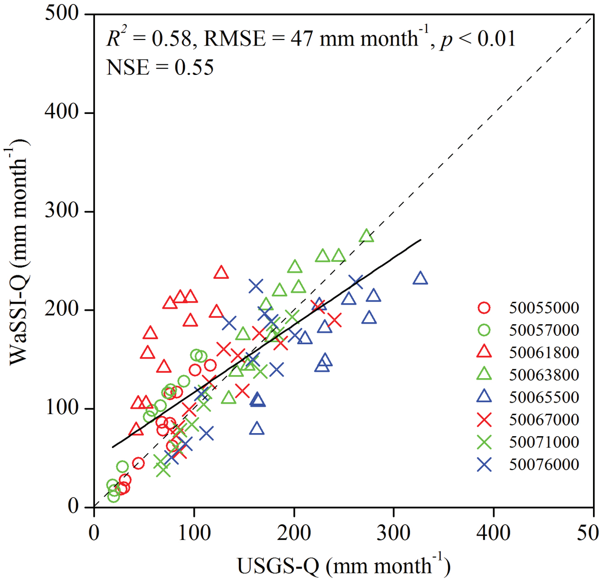

Figure 4. A comparison of simulated mean monthly streamflow (Q) by WaSSI against the USGS observed mean monthly Q. Dashed line is the 1:1 line, and solid line indicates the best linear fit.

$$ET = 28.6 + 0.55 \times PET - 0.032 \times P + 1.47 \times LAI\,(R^2 = 0.25,\ p < 0.0001) \qquad (3)$$

where PET is potential ET, which was calculated by Hamon's method as a function of air temperature and daytime length (Hamon 1963), LAI is leaf area index, and P is precipitation.

The modified WaSSI model performed satisfactorily for the ENF region, as indicated by the significant correlations between the modeled and observed mean monthly Q across all sites (R^2=0.58, RMSE=47 mm month^{-1}, p<0.01) with NSE as 0.55 (Figure 4). Overall, the modeled mean monthly Q matched well with the observations for most of the eight watersheds (Figure 5). However, the model performance was not satisfactory at three USGS gage stations (50057000, 50061800, and 50065500), as indicated by the negative NSE values. Specifically, we found an underestimation of 27.8% at station 50065500, and an overestimation of 47.4% and 118.5% at stations of 50057000 and 50061800, respectively. The underestimation of Q may be due to the overestimation of ET by the modified ET equation, as discussed in WaSSI Model Validation. The overestimation of Q might be caused by water withdrawal for drinking water supply that was considered in the WaSSI model for this study.

Observed and Modeled Water Budgets for the ENF Region

The mean precipitation (i.e., PRISM-P) for the ENF region was 2843 mm yr^{-1}, with monthly values ranging from 144 mm in March to 317 mm in May (Figure 6). The observed (USGS-Q) and modeled Q were 1903 ± 593 mm yr^{-1} (mean ± one standard

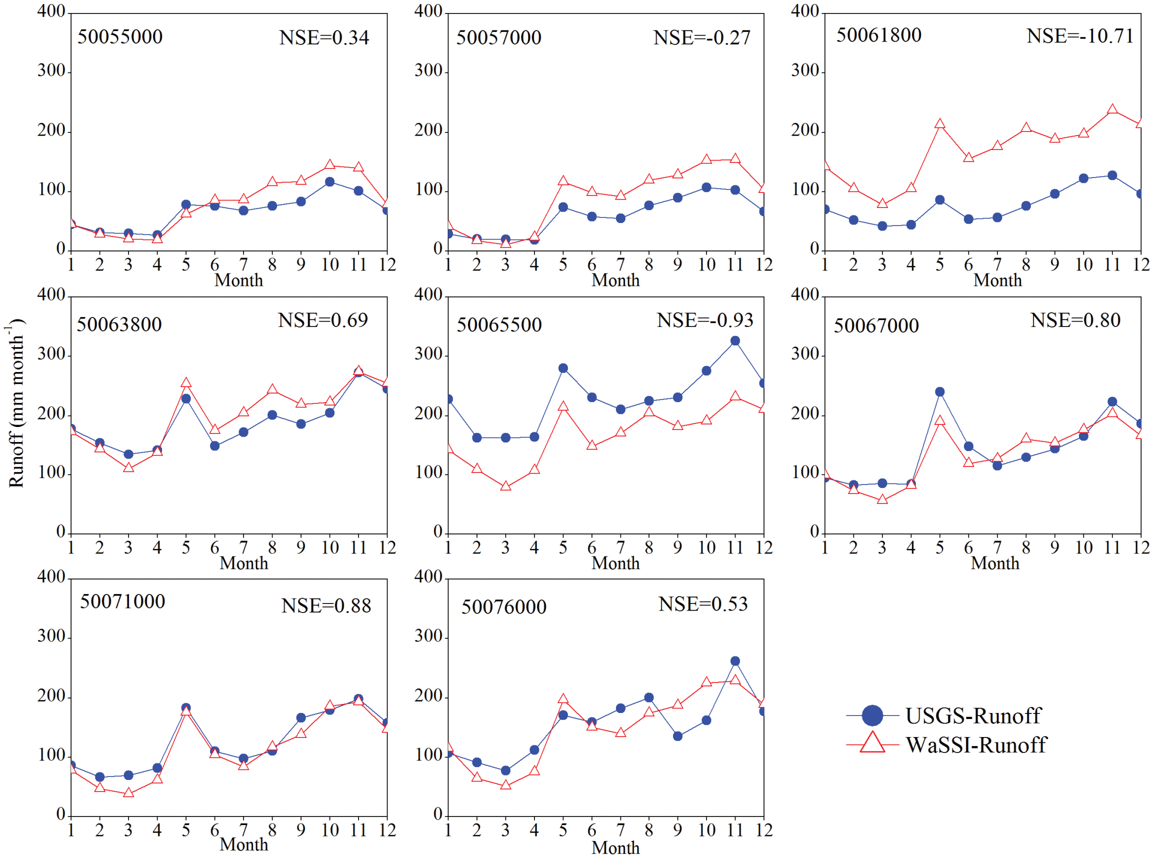

Figure 5. Seasonal variation of WaSSI modeled monthly streamflow (Q) and observed Q at USGS gage stations.

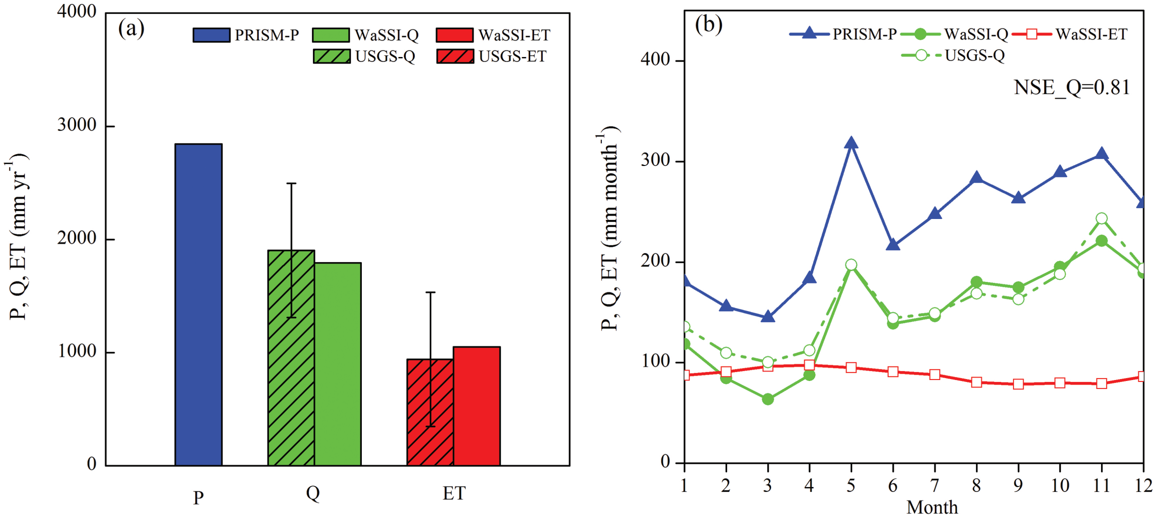

Figure 6. Observed and WaSSI modeled water budgets for (a) mean annual and (b) monthly time-step for the El Yunque National Forest region. Error bar represents the standard deviation of observed annual Q between 1963 and 1995. NSE_Q represents the Nash-Sutcliffe coefficient between the observed and modeled values.

deviation, hereafter) and 1795 mm yr^{-1}, respectively, with the interannual trends similar to that of the P (R^2=0.64, p<0.001). The NSE between the observed and modeled monthly Q was 0.81 (Figure 6b), indicating a good performance of WaSSI model in capturing the Q's seasonality for the ENF region. The modeled ET was also comparable to the observed (USGS-ET) on an annual mean scale (1048 vs. 940 ± 593 mm yr^{-1}), yet with slight seasonal variations (78 to 97 mm month^{-1}).

Uncertainties of the Estimated Water Budgets and Comparisons to Previous Studies

The quantification methods together with the resultant estimates of annual water balance components (i.e., P, Q, and ET) varied greatly across this and previous studies in the ENF region (Table 3). For example, Lugo (1986) calculated the P as the area-weighted mean P of major forest types, life zones, or elevation intervals. Other studies (Garcia-Martino et al. 1996, Wu et al. 2006, Crook et al. 2007) estimated the P by a rainfall-elevation regression equation derived from 18 rain gages. The streamflow has been derived either by using the observations from the USGS gage stations (Schellekens et al. 2000, Crook et al. 2007) or by the curve number method of the USDA Natural Resource Conservation Service (US Soil Conservation Service 1973, Fangmeier 2006, Harmsen et al. 2009). The annual or seasonal ET rates have been estimated either by the differences between P and Q or by energy balance models (Wu et al. 2006, Mu et al. 2011), with annual P, Q, and ET estimates ranging from 2297 to 3879 mm yr^{-1}, 646 to 2526 mm yr^{-1}, and 1006 to 2300 mm yr^{-1}, respectively, across this and previous studies.

When comparing with previous studies, the present modeling analysis showed improved estimates of water budgets (Table 3). The relative errors of P, Q, and ET were less than 2%, 6%, and 11%, respectively, in the current study. The largest relative errors of P, Q, and ET in the others reached up to 36% (Garcia-Martino et al. 1996), 66% (Harmsen et al. 2009, 2010), and 145% (Schellekens et al. 2000), respectively. The estimated ET of previous studies and this study generally had much lower accuracy than P and Q. For example, the mean relative error of ET estimated by all the studies was 1.9 and 2.4 times that of Q and P, respectively (Table 3). In particular, the accuracy of ET estimated with the revised ET equation was much higher than the original ET formula in WaSSI model. Also, our ET estimates had much lower relative estimation error than the widely used global MODIS-ET products (6% vs. 54%).

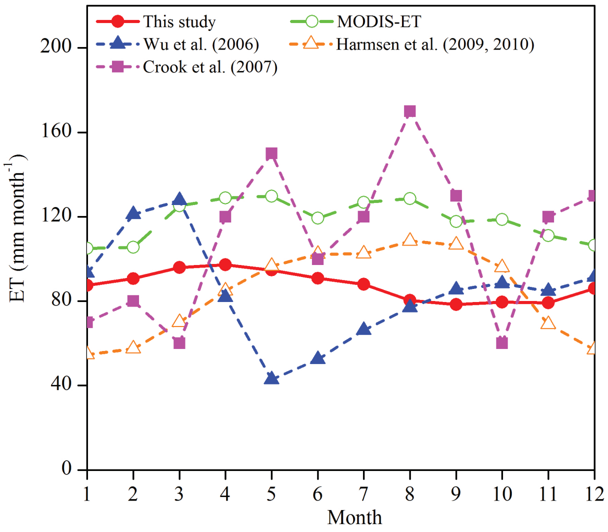

Figure 7. A comparison of mean monthly ET modeled by WaSSI and reported values by previous studies (Wu et al. 2006, Crook et al. 2007, Harmsen et al. 2009, 2010, Mu et al. 2011) for the El Yunque National Forest region.

The monthly patterns of ET estimates also varied greatly across this study and previous studies (Figure 7). This study showed that the ET fluctuated slightly by month while the other studies indicated large seasonal variations. For example, Wu et al. (2006) reported that the ET estimates by an energy balance model peaked in March and bottomed in May. The widely used global MODIS-ET products revealed a typical bell-shaped pattern of monthly ET estimates (Mu et al. 2011).

Discussion

WaSSI Model Validation

This study indicated that the modified WaSSI model with a new ET algorithm performed better than the original generalized WaSSI model (Sun et al. 2011a). The modeled ET (1048 mm yr^{-1}) for the ENF region was much closer both to the site-observed ET (i.e., 705–1066 mm yr^{-1}) by van der Molen (2002) and the USGS-ET (940 mm yr^{-1}) derived by the watershed water balance method. Also, the relative error of ET estimates from the new ET equation was much lower than that from original model as compared with USGS-ET (11% vs. 60%) (Table 3). As a result, the mean Q estimates by the modified WaSSI model (1795 mm yr^{-1}) were also much closer to the mean observed USGS-Q (1903 mm yr^{-1}) than the estimates by the original WaSSI model (i.e., 1337 mm yr^{-1}). The new ET equation (Eq. 3) suggests that ET is mainly limited by energy (i.e., surface net radiation) instead of soil water availability (Budyko 1974, Hasler and Avissar 2007, Costa et al. 2010) because it is more strongly correlated with PET than P. The new ET equation (Eq. (3)) also suggests that the relationship between P and ET in the rainforests is negative. It is plausible that higher cloudiness associated with higher P may reduce solar radiation in the tropical climate zone. Note that the actual relative errors of ET estimates from the new and original ET equation could be larger than reported here, owing to the possible overestimation of USGS-ET, because the USGS-Q may be lower than natural Q due to water withdrawal.

Overall, the annual WaSSI modeled Q for the ENF region was comparable to the observed USGS-Q and the monthly patterns were similar (Figure 6). However, the WaSSI model underestimated Q by 27.8% for gage station 50065500, where substantial portions of upper basins are in the cloud condensation zone (i.e., 600 m a.s.l.) (Figures 1, 4, 5, and Table 2) and overestimated Q at gage stations 50057000 and 50061800, located in the western part of the region, by 47.4% and 118.5%, respectively (Figures 1, 4, and 5). The underestimation of Q in the high-elevation watershed might be due to the overestimation of ET by the modified ET equation. The modified ET formula was developed by the eddy flux data mostly in Brazil tropical rainforests due to the lack of eddy flux data in the ENF region. In contrast to Brazil's forest conditions, about 30% of the forests in the ENF receive frequent cloud condensation (Brown et al. 1983). Previous studies suggested that although the cloud condensation accounts for a very small proportion of the total P for the ENF region (i.e., 3%–5%) (Weaver 1972, Holwerda et al. 2006), the frequency of condensation events could significantly affect ET rates (Bruijnzeel and Veneklaas 1998, Letts and Mulligan 2005, McJannet et al. 2007). A more recent study indicated that cloud-immersion frequency averaged 80% at sites above 900 m during nighttime hours and 49% during daytime hours (Bassiouni et al. 2017). Fog formations can reduce the solar radiation, lower vapor pressure deficit, and wet the leaf surfaces, resulting in lower forest ET rates (Bruijnzeel and Veneklaas 1998, Letts and Mulligan 2005, McJannet et al. 2007). Eddy flux observations of ET at the high-elevation sites in the ENF region are essential and needed to further improve the ET equation for a better quantification of the water balance for the island. The overestimation of Q in the western part of the study area may be partially attributed to anthropogenic effects (e.g., flow reduction by water withdrawal) on the runoff (Crook et al. 2007). USGS water use report (Molina-Rivera and Gómez-Gómez 2014) showed several large water intakes in the western part of the ENF region. The observed Q was likely to be lower than the natural streamflow when water withdrawal in the upstream area of the watershed occurred. Future study should quantify the water use–induced changes of hydrological cycles in these watersheds where flow regimes were disturbed.

Uncertainties of the Estimated Water Budgets in This and Previous Studies

Our results showed that the annual water budgets estimated in this study had smaller relative errors than previous studies in general (Table 3). There may be two reasons for this improvement. First, the input P data to WaSSI model were generated by the PRISM method specifically for the Puerto Rico region with a high spatial resolution (i.e., 450 m). This dataset provided more improved estimates of P at the ENF region scale (Daly et al. 2003, Van Beusekom et al. 2015) than that generated by the rainfall-elevation regression model (Garcia-Martino et al. 1996, Crook et al. 2007), area-weighted mean method (Lugo 1986), or global meteorological data with a coarse resolution (i.e., 1.00°×1.25°) (Mu et al. 2011). For example, Garcia-Martino et al. (1996) found that the rainfall-elevation regression equation tended to overestimate P in the high-elevation region. Zhang et al. (2015) demonstrated that the poor-quality climate data (global daily meteorological reanalysis dataset from NASA's Global Modeling and Assimilation Office [GMAO]) used by the MODIS algorithm caused the overestimation of MODIS ET in the subtropical and tropical forests (e.g., by 54% for the ENF region). Second, the monthly ET formula embedded in the modified WaSSI model was specifically developed for the ENF region by using the best available ET measurements for tropical rainforest ecosystems in the FLUXNET. The WaSSI model has proved to be successful in quantifying water balances with limited input data in the United States (Sun et al. 2011b, Caldwell et al. 2015, Sun et al. 2015a) and elsewhere (Liu et al. 2013a, 2013b). In contrast, the curve number method of the USDA Natural Resource Conservation Service (US Soil Conservation Service 1973, Fangmeier 2006) used to estimate Q by Harmsen et al. (2009, 2010) reportedly had high flow prediction errors during heavy rainfall periods (Kim and Lee 2008). These errors may have caused significant underestimation of the annual Q for the ENF region, where the stream discharge mainly occurs in storm events (Brown et al. 1983, Crook et al. 2007).

The variable estimations in water budgets might also be a result of the inconsistent spatial scales and study periods of the data sources among the various studies. For example, the ET calculated by Schellekens et al. (2000) for a small watertight (the leakage into or out of the catchment is negligible) watershed (i.e., Bisley II catchment, 0.06 km^2) (Van Dijk et al. 1997) in 1996–1997 was 2.4 times the observed ET across the ENF region (2300 vs. 940 mm yr^{-1}). The ET results from Schellekens et al. (2000) were calculated by the watershed water balance method, that is, $ET = P - Q$, with P from observation at a rain gage and Q from the daily discharge record. The overall error in ET estimates was estimated to be 12% (Schellekens et al. 2000). The relatively high ET rates in the Bisley II catchment during the 1996–1997 period may be explained by seaveral reasons: (1) the frequent occurrence of rainstorms of low intensity associated with frontal activity, (2) a highly effective net upward transport of evaporated moisture from the wetted canopy driven by the release of heat upon condensation, (3) the proximity of the site to the warm waters of the Atlantic Ocean, which may act as a source of advective energy brought in by the trade winds, and (4) a comparatively low aerodynamic resistance due to the broken forest canopies from the severe hurricane damages in 1989 and its location in highly dissected terrain (Schellekens et al. 2000).

Among all three hydrological fluxes examined (P, Q, and ET), we found larger uncertainty in ET estimates than among P and Q in this and previous studies. The ET estimates were all higher than the USGS-ET (Table 3). The actual relative error of ET estimates could be even larger than reported here, given that the USGS-ET may be overestimated due to water withdrawal in some of the watersheds and/or the omission of fog immersion, as discussed previously in WaSSI Model Validation.

The monthly patterns of ET estimates also varied greatly across various studies (Figure 7). For example, our modeling study indicated that the ET fluctuated slightly by month, which can be largely attributed to the small seasonal variations of the LAI and available energy (indicated by PET) (Figure 2) (Brown et al. 1983, Daly et al. 2003). The present result is reasonable, given that ET in tropical rainforests is limited by available energy (i.e., solar radiation) that varies only slightly by season (Zhang et al. 2001, Costa et al. 2010). For the other study with relatively smaller discrepancies in annual ET estimates, Wu et al. (2006) showed that the ET estimates by an energy balance model vary substantially by month and peaks in March. Wu et al. (2006) derived the key model input (i.e., cloud cover) from MODIS data, which cover only two days each month, and the entire month is not represented. Thus, the cloud cover data are apparently far from enough to reflect the actual cloud variability and thus may introduce uncertainties in monthly ET estimates.

Implications and Future Study

The modified WaSSI model has a great potential in simulating the watershed hydrology of tropical forest regions with limited data. The model requires only five widely available environmental variables (i.e., precipitation, air temperature, LAI, soil properties, and land cover) for parameterization. Particularly, the ET equation embedded in WaSSI was developed from the eddy flux observations over five tropical rainforest sites (Table 1) and it appeared to be more accurate in estimating ET for rainforests than the original generalized WaSSI model.

The uncertainties identified from this study have important implications for future data collection and in-depth hydrologic monitoring. First, the observed Q at the USGS gages may be lower than the natural streamflow value as induced by the water withdrawal for human uses in the upstream area of the watershed in some cases (Crook et al. 2007). Second, the ET equation derived from only five eddy flux sites in Brazil and Vanuatu may not accurately capture the relationship between ET, climate, and vegetation in the ENF region (Equation 3). For example, the coefficient for P is very small (i.e., –0.032), suggesting P may not be a major factor for ET. Other climatic factors such as radiation, sunshine hours, vapor pressure deficit, and wind may play important roles. The ET equation needs to be improved when new eddy flux data in tropical rainforests are available, especially at higher-elevation regions. Third, the present WaSSI model does not consider the impacts of understory vegetation information and tree density or height on the ET rate. Finally, the depth of the STATSGO soil data (i.e., 2.5 m) used in this study might be shallower than the actual soil depths, resulting in a possible bias of the WaSSI modeled Q by neglecting deep groundwater flow processes. However, this should not influence our Q estimates significantly because deep groundwater and surface water exchanges are shown to be negligible in the ENF region (Larsen 1997, Ortiz-Zayas 1998). Future forest hydrological studies in ENF should focus on quantifying water budgets of different forest ecosystem types across a topographic gradient with particular attention to quantifying forest ET at tree, stand, to watershed levels to better explain the control mechanism of ET in tropical rainforests. In addition, quantifying the effects of fog on precipitation on high elevations is needed to close the water budgets.

Conclusions

In this study, we developed a new water budget for the ENF region by applying an improved ecohydrological model (WaSSI). The WaSSI model was modified using a new ET algorithm derived from eddy flux observations for tropical rainforests. We identified the uncertainties of estimated water balances in this and other various studies. Results suggested that the modified WaSSI model adequately captured the magnitude and monthly patterns of the water budgets for the ENF region as compared with the original WaSSI model and previous studies. The uncertainty of the water budgets was overall smaller than the previous studies, suggesting that an integrated modeling had an advantage over other methods previously applied in Puerto Rico. The modified WaSSI model has a great potential in simulating the watershed hydrology of other tropical rainforest regions with limited data. Further, we conclude that the uncertainties of ET reported in the literature were much higher than that of P and Q for tropical forests in the ENF region. Accurately estimating ET remains the biggest challenge in constructing watershed water budgets and understanding the ecohydrological processes in rainforests. The knowledge gained from this study will be useful to land and water managers to maximize forest ecosystem services. The improved estimation of water balance at both the annual and monthly levels provides forest managers the much-needed information for sustaining water supply from forests.

Literature Cited

Ahmad, R., F. Scatena, and A. Gupta. 1993. Morphology and sedimentation in Caribbean montane streams: Examples from Jamaica and Puerto Rico. *Sediment. Geol.* 85(1):157–169. doi:10.1016/0037-0738(93)90080-O.

Arnold, J.G., and N. Fohrer. 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modelling. *Hydrol. Process.* 19(3):563–572. doi:10.1002/hyp.5611.

Bassiouni, M., M.A. Scholl, A.J. Torres-Sanchez, and S.F. Murphy. 2017. A method for quantifying cloud immersion in a tropical mountain forest using time-lapse photography. *Agric. For. Meteorol.* 243:100–112. doi:10.1016/j.agrformet.2017.04.010.

Brown, S., A.E. Lugo, S. Silander, and L. Liegel. 1983. *Research history and opportunities in the Luquillo Experimental Forest*. U.S. Dept. of Agriculture, Forest Service, Southern Forest Experiment Station. Report. Gen. Tech. Rep. SO-44. 132 p.

Brown, T.C., M.T. Hobbins, and J.A. Ramirez. 2008. Spatial distribution of water supply in the coterminous United States. *J. Am. Water. Resour. Assoc*. 44(6):1474–1487. doi:10.1111/j.1752-1688.2008.00252.x.

Bruijnzeel, L., and F. Scatena. 2011. Hydrometeorology of tropical montane cloud forests. *Hydrol. Process*. 25(3):319–326. doi:10.1002/hyp.7962.

Bruijnzeel, L., and E.J. Veneklaas. 1998. Climatic conditions and tropical montane forest productivity: The fog has not lifted yet. *Ecology*. 79(1):3–9. doi:10.1890/0012-9658(1998)079[0003:CCATMF]2.0.CO;2.

Budyko, M.I. 1974. *Climate and Life*. Academic Press Inc., New York. 508 p.

Burnash, R.J.C. 1995. The NWS River Forecast System—catchment modeling. P. 311–366 in *Computer models of watershed hydrology*, Singh, V.P. (ed.). Water Resources Publications, Littleton, CO.

Burnash, R.J.C., R.L. Ferral, and R.A. Mcguire. 1973. *A generalized streamflow simulation system—conceptual modeling for digital computers*. Joint Federal and State River Forecast Center, US National Weather Service and California Department of Water Resources. 204 p.

Caldwell, P., G. Sun, S. McNulty, et al. 2013. *WaSSI Ecosystem Services Model*. Available online at http://www.forestthreats.org/research/tools/WaSSI/WaSSIUserGuide_english_v1.1.pdf; last accessed Aug. 15, 2015.

Caldwell, P., G. Sun, S. McNulty, E. Cohen, and J.M. Myers. 2012. Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US. *Hydrol. Earth Syst. Sci*. 16:2839–2857. doi:10.5194/hess-16-2839-2012.

Caldwell, P.V., J.G. Kennen, G. Sun, et al. 2015. A comparison of hydrologic models for ecological flows and water availability. *Ecohydrology*. 8(8):1525–1546. doi:10.1002/eco.1602.

Choudhury, B.J., and N.E. DiGirolamo. 1998. A biophysical process-based estimate of global land surface evaporation using satellite and ancillary data I. Model description and comparison with observations. *J. Hydrol*. 205(3):164–185. doi:10.1016/S0022-1694(97)00149-2.

Clark, K.E., M.A. Torres, A.J. West, et al. 2014. The hydrological regime of a forested tropical Andean catchment. *Hydrol. Earth. Syst. Sc*. 18(12):5377–5397. doi:10.5194/hess-18-5377-2014.

Costa, M.H., M.C. Biajoli, L. Sanches, et al. 2010. Atmospheric versus vegetation controls of Amazonian tropical rain forest evapotranspiration: Are the wet and seasonally dry rain forests any different? *J. Geophys. Res*. 115(G4):G04021. doi:10.1029/2009JG001179.

Crook, K.E., F.N. Scatena, and C.M. Pringle. 2007. *Water withdrawn from the Luquillo experimental forest, 2004*. US Department of Agriculture, Forest Service, International Institute of Tropical Forestry. Gen. Tech. Rep.

Daly, C., E.H. Helmer, and M. Quiñones. 2003. Mapping the climate of Puerto Rico, Vieques and Culebra. *Int. J. Climatol*. 23(11):1359–1381. doi:10.1002/joc.937.

del Mar López, T., T.M. Aide, and J.R. Thomlinson. 2001. Urban expansion and the loss of prime agricultural lands in Puerto Rico. *AMBIO*. 30(1):49–54. doi:10.1579/0044-7447-30.1.49.

Dingman, S.L. 1993. *Physical hydrology*, Prentice Hall, Englewood Cliffs, NJ. 646 p.

Duan, K., G. Sun, S. Sun, et al. 2016. Divergence of ecosystem services in US National Forests and Grasslands under a changing climate. *Sci. Rep*. 6:24441. doi:10.1038/srep24441.

Fang, Y., G. Sun, P. Caldwell, et al. 2016. Monthly land cover-specific evapotranspiration models derived from global eddy flux measurements and remote sensing data. *Ecohydrology*. 9(2):248–266. doi:10.1002/eco.1629.

Fangmeier, D.D. 2006. *Soil and water conservation engineering*. Thompson Delmar Learning, Clifton Park, NY.

FAO. 1993. *Forest resources assessment 1990: Tropical countries*. FAO.

Fletcher, R.C., and S.L. Brantley. 2010. Reduction of bedrock blocks as corestones in the weathering profile: Observations and model. *Am. J. Sci*. 310(3):131–164. doi:10.2475/03.2010.01.

Garcia-Martino, A.R., G.S. Warner, F.N. Scatena, and D.L. Civco. 1996. Rainfall, runoff and elevation relationships in the Luquillo Mountains of Puerto Rico. *Caribb. J. Sci*. 32:413–424.

Gould, W.A., C. Alarcon, B. Fevold, et al. 2008. *The Puerto Rico Gap Analysis Project Volume 1: Land cover, vertebrate species distributions, and land stewardship*. US Department of Agriculture, Forest Service, International Institute of Tropical Forestry. Gen. Tech. Rep.

Gould, W.A., S. Martinuzzi, and I.K. Parés-Ramos. 2012. *Land use, population dynamics, and land-cover change in eastern Puerto Rico*. US Geological Survey. Professional Paper 1789-B. 25–42 p.

Hamon, W.R. 1963. Computation of direct runoff amounts from storm rainfall. *Int. Assoc. Sci. Hydrol. Publ*. 63:52–62.

Hansen, M.C., P.V. Potapov, R. Moore, et al. 2013. High-resolution global maps of 21st-century forest cover change. *Science*. 342(6160):850–853. doi:10.1126/science.1244693.

Hao, L., G. Sun, Y. Liu, et al. 2015. Urbanization dramatically altered the water balances of a paddy field-dominated basin in southern China. *Hydrol. Earth. Syst. Sc*. 19(7):3319–3331. doi:10.5194/hess-19-3319-2015.

Harmsen, E.W., J. Mecikalski, A. Mercado, and P.T. Cruz. 2010. Estimating evapotranspiration in the Caribbean Region using satellite remote sensing. In *Proceedings of the AWRA Summer Specialty Conference, Tropical Hydrology and Sustainable Water Resources in a Changing Climate*. San Juan, Puerto Rico.

Harmsen, E.W., N.L. Miller, N.J. Schlegel, and J.E. Gonzalez. 2009. Seasonal climate change impacts on evapotranspiration, precipitation deficit and crop yield in Puerto Rico. *Agric. Water. Manag*. 96(7):1085–1095. doi:10.1016/j.agwat.2009.02.006.

Harris, N.L., A.E. Lugo, S. Brown, and T. Heartsill-Scalley. 2012. *Luquillo experimental forest: Research history and opportunities*. US Department of Agriculture. EFR-1. 152 p.

Hasler, N., and R. Avissar. 2007. What controls evapotranspiration in the Amazon basin? *J. Hydrometeorol*. 8(3):380–395. doi:10.1175/JHM587.1.

Holwerda, F., F. Scatena, and L. Bruijnzeel. 2006. Throughfall in a Puerto Rican lower montane rain forest: A comparison of sampling strategies. *J. Hydrol*. 327(3):592–602. doi:10.1016/j.jhydrol.2005.12.014.

Juston, J.M., A. Kauffeldt, B.Q. Montano, J. Seibert, K.J. Beven, and I.K. Westerberg. 2013. Smiling in the rain: Seven reasons to be positive about uncertainty in hydrological modelling. *Hydrol. Process*. 27(7):1117–1122. doi:10.1002/hyp.9625.

Khalyani, A.H., W.A. Gould, E. Harmsen, A. Terando, M. Quinones, and J.A. Collazo. 2016. Climate change implications for tropical islands: Interpolating and interpreting statistically downscaled GCM projections for management and planning. *J. Appl. Meteorol. Climatol*. 55(2):265–282. doi:10.1175/JAMC-D-15-0182.1.

Kim, N.W., and J. Lee. 2008. Temporally weighted average curve number method for daily runoff simulation. *Hydrol. Process*. 22(25):4936–4948. doi:10.1002/hyp.7116

Koren, V., M. Smith, Q.Y. Duan, et al. 2003. Use of a priori parameter estimates in the derivation of spatially consistent parameter sets of rainfall-runoff models. In *Calibration of watershed models (water science and application)*, Duan, Q., S. Sorooshian, H.V. Gupta, A.N. Rousseau, and R. Turcotte (eds.). AGU, Washington, DC.

Kumagai, T., G.G. Katul, T.M. Saitoh, et al. 2004. Water cycling in a Bornean tropical rain forest under current and projected precipitation scenarios. *Water Resour. Res*. 40(1):W01104. doi:10.1029/2003WR002226.

Kumagai, T.O., T.M. Saitoh, Y. Sato, et al. 2005. Annual water balance and seasonality of evapotranspiration in a Bornean tropical rainforest. *Agric. For. Meteorol*. 128(1):81–92. doi:10.1016/j.agrformet.2004.08.006.

Larsen, M. 1997. *Tropical geomorphology and geomorphic work: A study of geomorphic processes and sediment and water budgets in montane humid-tropical forested and developed watersheds, Puerto Rico*. Ph.D. dissertation. Department of Geography, University of Colorado, Boulder, CO.

Letts, M.G., and M. Mulligan. 2005. The impact of light quality and leaf wetness on photosynthesis in north-west Andean tropical montane cloud forest. *J. Trop. Ecol.* 21(05):549–557. doi:10.1017/S0266467405002488.

Liu, C., G. Sun, S.G. McNulty, A. Noormets, and Y. Fang. 2017. Environmental controls on seasonal ecosystem evapotranspiration/potential evapotranspiration ratio as determined by the global eddy flux measurements. *Hydrol. Earth. Syst. Sc.* 21:311–322. doi:10.5194/hess-21-311-2017.

Liu, N., P. Sun, S. Liu, and G. Sun. 2013a. Coupling simulation of water–carbon processes for catchment: Calibration and validation of the WaSSI-C model. *Chin. J. Plant Ecol.* 37(6):492–502.

Liu, N., P.-S. Sun, S.-R. Liu, and G. Sun. 2013b. Determination of spatial scale of response unit for WASSI-C eco-hydrological model—a case study on the upper Zagunao River watershed of China. *Chin. J. Plant Ecol.* 37:132–141.

Lugo, A.E. 1986. *Water and the ecosystems of the Luquillo Experimental Forest*. US Dept. of Agriculture, Forest Service, Southern Forest Experiment Station. Gen. Tech. Rep. SO-63.

Martinuzzi, S., W.A. Gould, and O.M.R. González. 2007. Land development, land use, and urban sprawl in Puerto Rico integrating remote sensing and population census data. *Landsc. Urban. Plan.* 79(3):288–297. doi:10.1016/j.landurbplan.2006.02.014.

McJannet, D., J. Wallace, and P. Reddell. 2007. Precipitation interception in Australian tropical rainforests: II. Altitudinal gradients of cloud interception, stemflow, throughfall and interception. *Hydrol. Process.* 21(13):1703–1718. doi:10.1002/hyp.6346.

McNulty, S., E. Cohen, G. Sun, and P. Caldwell. 2016. Hydrologic modeling for water resource assessment in a developing country: The Rwanda case study. P. 181–203 in *Forest and the water cycle: Quantity, quality, management*, Lachassagne, P., and M. Lafforgue (eds.). Cambridge Scholars Publishing.

Miller, D.A., and R.A. White. 1998. A conterminous United States multilayer soil characteristics dataset for regional climate and hydrology modeling. *Earth. Interact.* 2(2):1–26. doi:10.1175/1087-3562(1998)002<0001:ACUSMS>2.3.CO;2.

Molina-Rivera, W.L., and F. Gómez-Gómez. 2014. *Estimated water use in Puerto Rico, 2005*. US Geological Survey. 37 p.

Moriasi, D.N., J.G. Arnold, M.W.V. Liew, R.L. Bingner, R.D. Harmel, and T.L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the Asabe*. 50(3):885–900. doi:10.13031/2013.23153.

Mu, Q., M. Zhao, and S.W. Running. 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote. Sens. Environ.* 115(8):1781–1800. doi:10.1016/j.rse.2011.02.019.

Nash, J.E., and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models, part I—a discussion of principles. *J. Hydrol.* 10(3):282–290. doi:10.1016/0022-1694(70)90255-6.

Natural Resources Conservation Service and US Department of Agriculture. 2012. *US General Soil Map (STATSGO2)*. Available online at https://datagateway.nrcs.usda.gov; last accessed 17 Jan. 2016.

Naumann, M. 1994. *A water use budget for the Caribbean National Forest of Puerto Rico*. USDA Forest Service.

Ortiz-Zayas, J.R. 1998. *The metabolism of the Río Mameyes, Puerto Rico: Carbon fluxes in a tropical rain forest river*. Ph.D. dissertation. Department of Environmental, Population and Organismal Biology, University of Colorado, Boulder, CO.

Schellekens, J., L. Bruijnzeel, F. Scatena, N. Bink, and F. Holwerda. 2000. Evaporation from a tropical rain forest, Luquillo Experimental Forest, eastern Puerto Rico. *Water Resour. Res.* 36(8):2183–2196. doi:10.1029/2000WR900074.

Sun, G., K. Alstad, J. Chen, et al. 2011a. A general predictive model for estimating monthly ecosystem evapotranspiration. *Ecohydrology*. 4(2):245–255. doi:10.1002/eco.194.

Sun, G., P. Caldwell, A. Noormets, et al. 2011b. Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model. *J. Geophys. Res.* 116(G3):G00J05. doi:10.1029/2010JG001573.

Sun, G., S.G. McNulty, J.A. Moore Myers, and E.C. Cohen. 2008. Impacts of multiple stresses on water demand and supply across the Southeastern United States. *J. Am. Water. Resour. Assoc.* 44(6):1441–1457. doi:10.1111/j.1752-1688.2008.00250.x.

Sun, M.T., G. Sun, C. Liu, J.A.M. Myers, and S.G. McNulty. 2015a. Future water budgets and water supply stress under climate change and urbanization in the upper Neuse River Basin, North Carolina, USA. *Am. J. Environ. Sci.* 11(4):175. doi:10.3844/ajessp.2015.175.185.

Sun, S., G. Sun, P. Caldwell, S. McNulty, E. Cohen, J. Xiao, and Y. Zhang. 2015b. Drought impacts on ecosystem functions of the US National Forests and Grasslands: Part II, assessment results and management implications. *Forest. Ecol. Manag.* 353:269–279. doi:10.1016/j.foreco.2015.04.002.

Tague, C.L., and L.E. Band. 2004. RHESSys: Regional hydro-ecologic simulation system—an object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling. *Earth. Interact.* 8(19):145–147. doi:10.1175/1087-3562(2004)8<1:RRHSSO>2.0.CO;2.

Thomlinson, J.R., and L.Y. Rivera. 2000. Suburban growth in Luquillo, Puerto Rico: Some consequences of development on natural and semi-natural systems. *Landsc. Urban. Plan.* 49(1):15–23. doi:10.1016/S0169-2046(00)00056-6.

Thomlinson, J.R., M.I. Serrano, T.d.M. Lopez, T.M. Aide, and J.K. Zimmerman. 1996. Land-use dynamics in a post-agricultural Puerto Rican landscape (1936–1988). *Biotropica*:525–536. doi:10.2307/2389094.

US Soil Conservation Service. 1973. *A method for estimating volume and rate of runoff in small watersheds.* US Department of Agriculture, Soil Conservation Service, Washington, DC. SCS-TP-149.

Van Beusekom, A.E., W.A. Gould, A.J. Terando, and J.A. Collazo. 2015. Climate change and water resources in a tropical island system: Propagation of uncertainty from statistically downscaled climate models to hydrologic models. *Int. J. Climatol.* 36(9):3370–3883. doi:10.1002/joc.4560.

van der Molen, M.K. 2002. *Meteorological impacts of land use change in the maritime tropics*. Ph.D. thesis, VU University, Amsterdam, The Netherlands.

Van Dijk, A.I., J.M.J. Schellekens, and M.M.A. Groen. 1997. *Geophysical survey of the Bisley I and II catchments, Luquillo Experimental Forest, Puerto Rico*, Work. Pap. 4, Fac. of Earth Sci., Vrije Univ., Amsterdam.

Wang, K., R.E. Dickinson, M. Wild, and S. Liang. 2010. Evidence for decadal variation in global terrestrial evapotranspiration between 1982 and 2002: 1. Model development. *J. Geophys. Res.* 115(D20):D20112. doi:10.1029/2009JD013671.

Weaver, P.L. 1972. Cloud moisture interception in the Luquillo Mountains of Puerto Rico. *Caribb. J. Sci.* 12(3/4):129–144.

Wohl, E., A. Barros, N. Brunsell, et al. 2012. The hydrology of the humid tropics. *Nat. Clim. Change*. 2(9):655–662. doi:10.1038/nclimate1556.

Wu, W., C.A. Hall, F.N. Scatena, and L.J. Quackenbush. 2006. Spatial modelling of evapotranspiration in the Luquillo Experimental Forest of Puerto Rico using remotely-sensed data. *J. Hydrol.* 328(3):733–752. doi:10.1016/j.jhydrol.2006.01.020.

Zhang, L., W. Dawes, and G. Walker. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resour. Res.* 37(3):701–708. doi:10.1029/2000WR900325.

Zhang, L., J. Tian, H. He, X. Ren, X. Sun, G. Yu, Q. Lu, and L. Lv. 2015. Evaluation of water use efficiency derived from MODIS products against eddy variance measurements in China. *Remote. Sens.* 7(9):11183–11201. doi:10.3390/rs70911183.