ANALYSIS OF HYDROLOGICAL PROCESSES APPLYING THE HSPF MODEL IN SELECTED WATERSHEDS IN ALABAMA, MISSISSIPPI, AND PUERTO RICO

J. N. Diaz-Ramirez, W. H. McAnally, J. L. Martin

ABSTRACT. *The goal of this study was to evaluate the Hydrological Simulation Program – FORTRAN (HSPF) to gain more insight in the underlying causes and mechanisms of hydrological processes in an upland basin in Alabama and Mississippi (1,856-km² Luxapallila Creek), a humid subtropical watershed in coastal Alabama (140-km² Fish River), and a steep-slope tropical catchment in Puerto Rico (99-km² Rio Caonillas). For each watershed model, rainfall, potential evapotranspiration, and streamflow time series from January 1999 to December 2000 were used to calibrate model parameters and 2001 time series were applied to verify model results. In each study area, actual evapotranspiration was the main mechanism of water loss followed by river discharge. Annual baseflow values ranged from 58% of total discharge in Luxapallila Creek basin to 84% of total discharge in Fish River watershed. In Luxapallila Creek and Fish River, interflow was the primary mechanism of direct runoff; however, surface runoff was the main process of direct runoff in Rio Caonillas. The HSPF model was successfully adapted to model daily streamflow processes in Luxapallila Creek basin and Rio Caonillas catchment with coefficient of determination and Nash and Sutcliffe coefficient values between 0.61 and 0.71 for the entire period; however, the Fish River watershed model performance was poor. The poor performance is likely due to the lack of rainfall time series available within the watershed boundaries. In general, this study showed the robustness of the HSPF model in extreme environments (small catchments vs. large basins, flat vs. hilly areas, low vs. moderate/high runoff potential, tropical marine vs. humid subtropical climates).*

Keywords. *HSPF, Lumped hydrologic modeling, Mississippi, Alabama, Puerto Rico, Tropical and subtropical hydrological processes.*

This research assessed hydrological processes using a computer model in three different watersheds located in Puerto Rico, Mississippi, and Alabama. Hydrologic processes included precipitation on land (liquid/solid), surface runoff, infiltration, evaporation, transpiration, and groundwater flow. Many physiographic characteristics (climate, soils, topography, and vegetation) are involved in hydrologic processes and make the tracking of water very complex. Hydrologic modeling provides a representation of the water processes and its controlling factors.

The Hydrological Simulation Program – FORTRAN (HSPF) (Bicknell et al., 2001), is a conceptual, continuous, lumped parameter watershed model supported by the U.S. Environmental Protection Agency (USEPA) and U.S. Geological Survey (USGS). The HSPF model has been successfully applied worldwide and used extensively in the United States, the Caribbean, Africa, China, India, and Europe. Extensive and successful applications of HSPF components (hydrology, erosion, sediment transport, and instream water quality) in urban and rural areas around the world have been reported (e.g., Moore et al., 1988; Chew et al., 1991; Laroche et al., 1996; Fontaine and Jacomino, 1997; Carrubba, 2000; Zhang, 2001; Al-Abed and Whiteley, 2002; Engelmann et al., 2002; Doherty and Johnston, 2003; Johnson et al., 2003; Paul, 2003; Albek et al., 2004; Hayashi et al., 2004; Im et al., 2004; Chou et al., 2007; Diaz-Ramirez et al., 2008a,b; and Göncü and Albek, 2010).

The objective of this study was to apply the HSPF program to gain more insight into the underlying causes and mechanisms of hydrological processes (surface runoff, interflow, baseflow, streamflow, evapotranspiration, and deep percolation) in three different rural drainage areas (fig. 1): an upland basin in Alabama and Mississippi, a humid subtropical watershed in coastal Alabama, and a steep-slope tropical catchment in Puerto Rico. The HSPF model and its GIS interface, BASINS, were selected for this study because they are widely used for performing hydrologic transport analysis; input databases used to setup case studies in United States and Puerto Rico are downloaded via internet; time series utilized to evaluate model outputs in United States and Puerto Rico applications are downloaded by internet connection; pre and post processing of HSPF is done with graphical user interface programs; and the entire computer package is public domain software supported by USEPA and

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The authors are **Jairo N. Diaz-Ramirez, ASABE Member,** Assistant Research Professor, **William H. McAnally,** Research Professor, and **James L. Martin,** Professor, Department of Civil and Environmental Engineering, Mississippi State University, Mississippi State, Mississippi. **Corresponding author:** Jairo N. Diaz-Ramirez, Department of Civil and Environmental Engineering, Mississippi State University, P.O. Box 9546, Mississippi State, MS 39762; phone: 662-325-9885; e-mail: jd216@cee.msstate.edu.

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Figure 1. Location of drainage areas.

USGS. Study areas were selected on the basis of availability of background materials such as maps (land use, soils, geology, and topography) and hydro-meteorological data (rainfall, evapotranspiration, and streamflow); same source and date of maps; same periods of hydro-meteorological time series; and distinct hydrologic processes (rainfall intensity, spatial and temporal rainfall and evapotranspiration variability, rainfall-runoff and groundwater-runoff mechanisms).

HSPF

This section presents a brief summary of the capabilities and applications of HSPF for modeling hydrologic processes. A detailed description of HSPF can be found in HSPF Version 12 User's manual (Bicknell et al., 2001). The HSPF software is a conceptual, continuous, lumped parameter watershed model supported by U.S. Environmental Protection Agency (USEPA). The model simulates hydrologic and water quality processes in pervious or impervious areas. Water quality constituents simulated by HSPF include dissolved oxygen, biochemical oxygen demand (BOD), temperature, pesticides, conservatives, fecal coliforms, sediment detachment and transport, sediment routing, nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, and zooplankton (Donigian et al., 1995). The newest HSPF version runs under the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) software (USEPA, 2009a). BASINS platform offers pre and post processing for the HSPF.

Hydrological simulation in HSPF consists of five storage classes (interception, upper zone, lower zone, baseflow, and deep percolation), each allowing different types of inflow and outflow. Inflows and outflows are simulated in HSPF as water-balance accounting. Each pervious land segment (hydrologic response unit) considers the following processes: interception, evapotranspiration, surface detention, surface runoff, infiltration, shallow subsurface flow (interflow), baseflow, and deep percolation (Donigian et al., 1995). Surface detention and surface runoff are the only components simulated in impervious areas. Flows from pervious and impervious areas are routed into the channel network.

Rainfall abstractions via interception are simulated by assuming an interception storage capacity (about 0 to 5 mm) according to the type of vegetation on the land segment. Volume of interception storage must be filled before excess precipitation can reach the land surface; intercepted water is subsequently evaporated. Actual evapotranspiration (SAET) is an important value of the water balance, and it is simulated in response to the input time series for potential evapotranspiration (PET). Water evaporates first from the riparian vegetation (wetlands). Further SAET is satisfied sequentially by interception storage, upper zone storage, active ground water, and lower-zone storage, where each storage has a different resistance to evaporation. In this way the maximum potential of each storage is depleted either until all storages have contributed their maximum amount to evapotranspiration or until the PET has been fully satisfied.

HSPF uses both physical and empirical formulations to model the movement of water within each hydrologic response unit. Infiltration is based somewhat on the work of Philip (1957) along with empirical relationships and variables. These variables are related to U.S. Department of Agriculture (USDA) Natural Resources Conservation

Service (NRCS) hydrologic soil group (HSG) classifications, annual precipitation and soil characteristics of the study area. The percentage of infiltrated water that enters the groundwater storage can become active groundwater outflow or inactive groundwater (deep percolation). The proportion of deep percolation is user designated by model parameter DEEPFR. The remaining portion of the infiltrated water goes into the active groundwater storage. Active groundwater outflow (baseflow) is simulated using a simplified relationship that computes the volume and the energy gradient of the flow. Two parameters are used in simulating groundwater-runoff in HSPF: groundwater recession flow parameter, KVARY, and Groundwater recession rate, AGWRC.

Flow routing takes place in two regimes: on the overland flow plane and in the river channel network. Overland flow is modeled using the Chezy-Manning equation along with empirical equations relating outflow depth and volume of surface detention. Parameters used in these equations include the Manning's n for the overland flow plane, the length of the overland flow plane, and the slope of the overland flow plane. Manning's n values can be extracted from hydrology and hydraulic literature (Haan et al., 1994; Sturm, 2001). The length and slope values are calculated using topographic maps or digital elevation models. HSPF employs the "kinematic wave" routing technique to move water from one reach to the next in the river channel network (RCHRES module). Flow is modeled as unidirectional. Complete mix is assumed by the model in streams and lakes (Bicknell et al., 2001). For each reach, a fixed relationship is assumed between water level, surface area, volume and discharge (FTABLE) which is specified by the user. HSPF calculates hydraulic variables such as hydraulic radius, shear stress and velocity, assuming that the cross-section of the reach is constant throughout the reach.

In summary, the HSPF model uses physical concepts (i.e., mass conservation), empirical equations (i.e., linear and power relationships), physical data (i.e., rainfall, evaporation, slope and length of land surface, drainage area, hydraulic characteristics of the channel network), and parameters (i.e., interflow, infiltration) to simulate water quantity and quality from rural and urban watersheds. Most of the parameters are conceptual and must be calibrated usually against streamflow and concentration records measured at the outlet of the watershed. Table 1 shows definition and range of HSPF parameters used in simulating rainfall-runoff and groundwater-runoff processes in drainage areas not impacted by snow melt processes.

HSPF has been applied in different zones around the world since the 1980's (Donigian et al., 1995; Singh and Woolhiser, 2002). Extensive reviews of HSPF applications can be found in Borah and Bera (2004) and Liu (2006). HSPF watershed applications in Puerto Rico, Mississippi, and Alabama can be found in Diaz-Ramirez et al. (2008a,b), Duan et al. (2008), Lehrther (2006), and El-Kaddah and Carey (2004). One application of the HSPF model was on the 98.8-km^2 Rio Caonillas catchment near Jayuya, Puerto Rico, in which the model was used to simulated hydrology and suspended sediment transport (Diaz-Ramirez et al., 2008b). Puerto Rico is a tropical mountainous island located in the Caribbean. The Rio Caonillas catchment has extreme climate and physiographic conditions, such as rainfall intensity more than 25 mm h^{-1}and average soil slope of 38%. The HSPF model was calibrated and validated for daily flows and suspended sediment data collected by the U.S. Geological Survey (USGS) since 1999 to 2001. Daily streamflow model performance resulted in coefficient of determination (R^2) from 0.55 to 0.74 and Nash and Sutcliffe coefficient (NS) from 0.54 to 0.74. Daily suspended sediment concentration model performance resulted in R^2 from 0.32 to 0.34 and NS from -0.12 to 0.34. However, monthly suspended sediment concentration analysis resulted in higher goodness-of-fit values (R^2 from 0.72 to 0.77 and NS from 0.44 to 0.75). According to the researchers, the suspended sediment catchment model performed very well in the wet season (September to November), where the majority of the sediments are exported from the drainage area.

The impact of land use datasets on HSPF hydrology and sediment simulation was evaluated by Diaz-Ramirez et al. (2008a). The authors set up the model using climate and

Table 1. HSPF parameter definition (USEPA, 2000; 2009b).

			Calibration Scenarios			
Name	Definition	Range	Water Balance	High/Low Flow Distribution	Storm Flow	Seasonal Discrepancies
LZSN (mm)	Lower zone nominal soil moisture storage	50.8-381.0	X			
INFILT (mm h^{-1})	Index to infiltration capacity	0.25-25.0	X	X	X	
SLSUR (%)	Slope of overland flow plane	0.1-30.0			X	
NSUR	Manning's n (roughness) for overland flow	0.05-0.50			X	
LSUR (m)	Length of overland flow	30.5-213.4			X	
KVARY (mm^{-1})	Variable groundwater recession	0.0-127.0				X
AGWRC	Base groundwater recession	0.92-0.999		X		
DEEPFR	Fraction of groundwater inflow to deep recharge	0.0-0.5	X	X		
BASETP	Fraction of remaining evapotranspiration from baseflow	0.0-0.2		X		X
AGWETP	Fraction of remaining evapotranspiration from active groundwater	0.0-0.2				X
CEPSC (mm)	Interception storage capacity	0.0-10.2				X
UZSN (mm)	Upper zone nominal soil moisture storage	1.27-50.8				X
INTFW	Interflow inflow parameter	1.0-10.0			X	
IRC	Interflow recession parameter	0.3-0.85			X	
LZETP	Lower zone evapotranspiration parameter	0.0-0.9	X			X

physiographic data from the Luxapallila Creek drainage area, a 1,856.1-km^2 basin located in Alabama and Mississippi. Three land use databases were used in this project: The Geographic Information Retrieval and Analysis System (GIRAS), the Moderate Resolution Imaging Spectroradiometer land cover product (MODIS MOD12Q1), and the National Land Cover Dataset (NLCD). The authors concluded that choosing the right land use dataset will impact the modeling of sediments and, potentially, other water quality constituents that are related with agricultural activities.

Duan et al. (2008) evaluated the effects on land use changes on Saint Louis Bay watershed using the HSPF model. The study area is a coastal watershed located in southern Mississippi. Two main tributaries reach the bay, the Jordan River (609 km^2) and the Wolf River (931 km^2). The authors used the 1977 GIRAS land use data and the 1992 NLCD land use dataset to assess the impact of land use changes on streamflow, sediments, water temperature, and dissolve oxygen of the watersheds. Jordan River and Wolf River watersheds present similar land use distribution (~70% forest land, ~20% crop land, and ~10% wetlands). When land use datasets were used, the authors found significant changes in total outflows of sediments in each watershed; however, no significant changes were found in streamflow, water temperature, and dissolve oxygen were found.

Lehrter (2006) applied the HSPF model in the Weeks Bay watershed located in southern Alabama using input gauge rainfall time series from 2000 to 2001. He calibrated daily streamflow simulations using data from the USGS Fish River station (02378500). Calibrated parameter values were validated at the USGS Magnolia River (02378300). He found R^2 of 0.49 for calibrated and 0.36 for validated sub-watersheds. Lehrter pointed out that in many storm events the magnitude of peak discharge was not well simulated; however, baseflow and time of peak were well tracked by the model.

El-Kaddah and Carey (2004) published an HSPF case study in the Cahaba River watershed, Alabama. The 472,675-ha watershed was setup to evaluate hydrologic and nitrogen processes. The authors concluded that the hydrologic model performed well in simulations of hydrograph shape, peak flows, and seasonal and low flows. Also they declared that total nitrogen concentrations exported by the watershed were less well modeled. Reasons for this included lack of nitrogen source information available to the model. In addition, the authors suggested the use of the most comprehensive module available in HSPF to calculate nitrogen processes. Finally, the researchers recommended the use of the HSPF model to large-scale studies for a better understanding of the watershed-scale processes.

Study Areas

The HSPF model was applied to the Luxapallila Creek basin (Alabama and Mississippi), Fish River watershed (Alabama), and Rio Caonillas catchment (Puerto Rico). Table 2 shows main environmental characteristics of the study areas. The Luxapallila Creek basin (fig. 2) is located in northern Alabama and Mississippi with an average basin slope of 2%, and average annual precipitation of 1,385 mm. At the USGS 02443500 station, the basin has a drainage area of 1,856.1 km^2. Seasonal fluctuations in rainfall result in maximum river discharges from January to April and minimum discharges from August to September. Seasonal temperatures vary widely in the basin from average daily values around 4°C in January to roughly 27°C in August. Elevations in the study area range from 45 to 274 m above mean sea level. In table 2, the National Land Cover-NLCD data developed in 2001 (USEPA, 2008) shows that the basin is primarily forest land (59.3%) followed by wetlands (11.6%), upland shrub land (11.5%), agriculture land (12.0%), urban land (5.3%), barren land (0.1%), and grass

Table 2. Selected environmental characteristics of study watersheds.

Characteristic	Luxapallila Creek	Fish River	Rio Caonillas
Total area (Km^2)	1856.1	140.1	98.8
Average land slope (%)	2	3	38
2001 NLCD Land use distribution (%)			
Wetlands	11.6	14.3	0.0
Urban	5.3	9.7	4.8
Barren or mining	0.1	0.6	0.3
Forest	59.3	29.9	67.7
Upland shrub land	11.5	6.5	1.4
Grass land	0.1	7.6	25.8
Agriculture - Cropland	4.8	19.1	0.0
Agriculture - Pasture	7.2	12.3	0.0
Main channel longitude (km)	90	26	26.7
Main channel slope (%)	0.3	0.2	3.6
Mean annual precipitation (mm)	1,385	1,623	1,930
Annual streamflow yield (m^3 s^{-1} km^{-2})	4.8	5.6	9.9
High flows / Low flows (month)	January-April/August-September	March/May	September-November/February-April
Hydrologic soil groups (%)			
A	0	17	1
B	8	83	66
C	92	0	27
D	0	0	6
Geology	Unconfined semiconsolidated sediment aquifer (sand and clay)	Unconfined sand and gravel aquifer	Unconfined fractured-rock aquifer

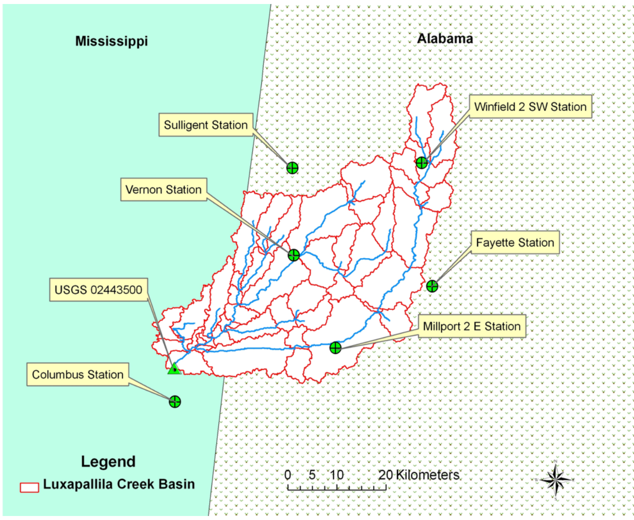

Figure 2. Location of the Luxapallila Creek streamflow and weather stations.

land (0.1%). The study area is mainly sandy loam soils in HSG C (USDA-NRCS, 2009). Luxapallila Creek watershed is located on the outcrop areas of the Black Warrior River aquifer (Miller, 1990). Rainfall recharges the aquifer and baseflow moves quickly into channel system. Deep percolation is small in the study area (Miller, 1990).

Fish River watershed (fig. 3) is located in the coastal area of Alabama and it is a tributary of Weeks Bay. The 140.1-km^2 watershed has slopes that range from 0 to 4%. Annual mean precipitation is around 1,623 mm. Monthly precipitation values are evenly distributed throughout the year. Hurricanes, tropical storms, and summer showers are the main source of rainfall in the watershed. Seasonal

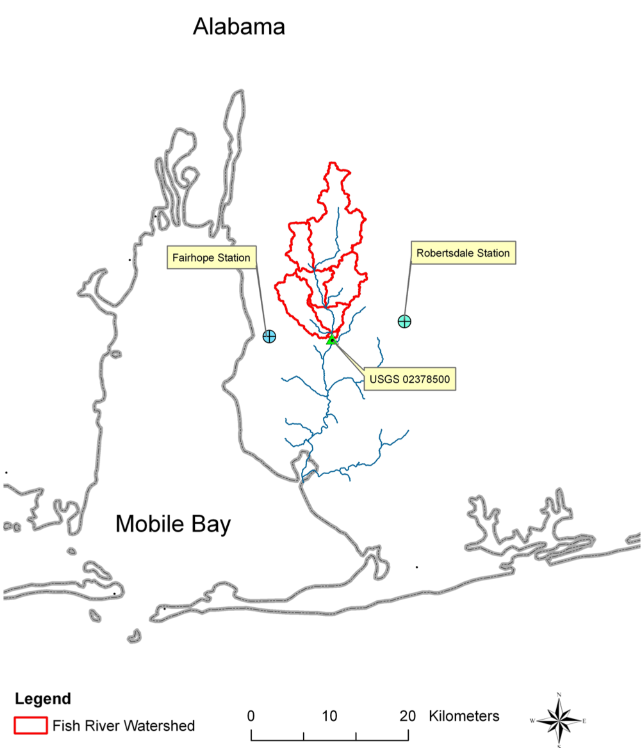

Figure 3. Location of the Fish River streamflow and weather stations.

temperatures vary widely in the watershed with average daily values around 10°C in January to about 28°C in August. Elevations in the study area range from 14.7 to 68.7 m above mean sea level. The 2001 NLCD land use distribution shows that the watershed is primarily agricultural (31.4%) followed by forest land (29.9%), wetlands (14.3%), urban areas (9.7%), grass land (7.6%), upland shrub land (6.5%), and barren land (0.6%). In general, soils in the area are well drained or excessively drained with HSGs B/A (USDA-NRCS, 2009). The aquifer system beneath the Fish River watershed is divided into two geological units (Dowling et al., 2004): a) Aquifer zone A2, the Miocene/Pliocene aquifer system with a thickness of 100 m and a ground water residence time around 40 years; b) Aquifer zone A3, the lower unit is roughly 250 m thick and has a water residence time of more than 50 years. The recharge in the highly permeable sediments of the A2 aquifer was calculated by Dowling et al. (2004) between 240 and 560 mm yr^{-1}.

The Rio Caonillas catchment (fig. 4) is a mountainous tropical island catchment with mean slope values ranging from 10.3% to 54.9%. The 98.8-km^2 watershed is located in central Puerto Rico. Precipitation in the watershed is highly variable, both seasonally and areally. Average annual precipitation values in the catchment range from 1,700 to 2,000 mm, and heavy rainfall events occur mainly from September to November. Average daily temperature values vary from around 19°C in January to roughly 24°C in August. Elevations in the study area range from 300 to 1,338 m above mean sea level. 2001 NLCD land use is distributed as 67.7% forest land, 25.8% grass land, 4.8% urban areas, 1.4% upland shrub land, and 0.3% barren land. Hydrologic soil group B makes up 66% of the total area (USDA-SCS, 1982). Runoff is very rapid, and erosion is severe in areas without permanent vegetative cover. Soils on the Rio Caonillas watershed are above relatively impermeable bedrock (plutonic rocks) (Briggs and Arkers, 1965). Water budgets calculated in the Luquillo Mountains of Puerto Rico show that little water (less than 1% of total outputs) is lost through ground water recharge (Larsen and Concepción, 1998; García-Martinó et al., 1996). Luquillo Mountains and Río Caonillas watershed present a similar bedrock formation (Helmer et al., 2002).

Figure 5 shows observed streamflow yield duration curves for daily time series at each watershed outlet, 01 January 1999 – 31 December 2001. Streamflow was normalized against area to make the flow independent of the size of the watershed. Duration curves were developed using USGS streamflow data at 02443500 Luxapallila Creek, 02378500 Fish River, and 50026025 Rio Caonillas. Annual streamflow yields were 4.8 m^3 s^{-1} for Luxapallila Creek, 5.6 m^3 s^{-1} for Fish River, and 9.9 m^3 s^{-1} for Rio Caonillas. It is observed in figure 5 that daily streamflow yield distribution was very different at each watershed. Highest flow yields between 0% and 25% of the time were produced by Rio Caonillas catchment followed by Luxapallila Creek and Fish River. Flow yield distribution between 25% and 80% of time showed that Rio Caonillas had the greatest flows, with the Fish River flows intermediate. Low flow values (values lower than 90% of time flow exceedance) of Fish River and Rio Caonillas were an entire magnitude greater than those of the Luxapallila Creek.

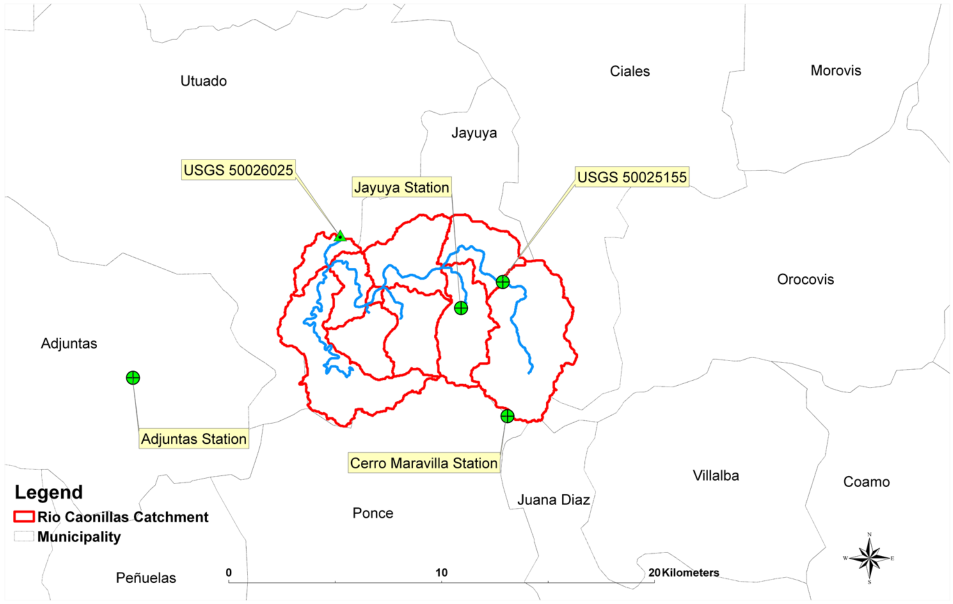

Figure 4. Location of the Rio Caonillas streamflow and weather stations.

The drainage basin of the Luxapallila Creek has a low slope (2%) and moderately high runoff potential. The Black Warrior aquifer crops out in the Luxapallila Creek basin where precipitation recharges the regional aquifer (Southeastern Coastal Plain). The unconfined aquifer consists of semiconsolidated sediments including coarse to fine sand along with beds of gravel and limestone with maximum thickness of 1,500 m (Renken, 1996). Groundwater-runoff can drain quickly and baseflow is scant in the Luxapallila Creek basin. The Fish River watershed has soils with low runoff potential and low slope (3%). The sand absorbs most of the storm-runoff potential. The Fish River drainage area is located in a sand and gravel aquifer, which has a high hydraulic conductivity, but it is thin (100 m), so the water table constantly recharges the river system. Rio Caonillas has a steep topography (38% average slope) along with moderately low/high runoff potential. Rio Caonillas drainage area is located in an area of plutonic rocks, which has a very low hydraulic conductivity. The aquifer is 15 to 90 m thick (Olcott, 1999). As a consequence, runoff and baseflow are high.

Groundwater-runoff (baseflow) processes are function of study area soils, topography, channel configuration, and geology (Fetter, 2001). There are several approaches to estimate baseflow recession in a drainage area (Chapman, 1999; Fetter, 2001; Eckhardt, 2004). This study will use the

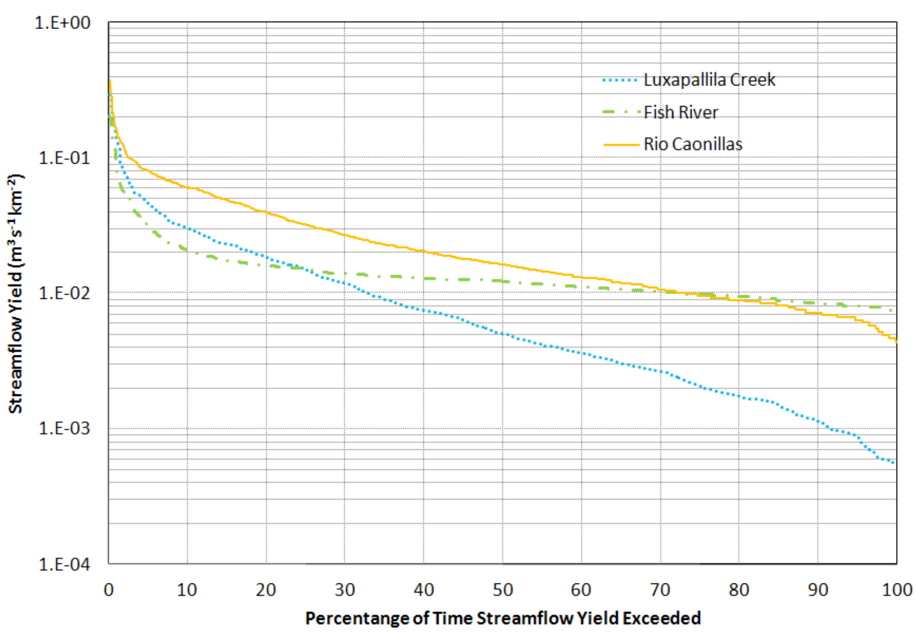

Figure 5. Observed streamflow yield duration curves for daily time series (01 Jan. 1999-31 Dec. 2001).

HSPF model results to quantify the surface runoff and baseflow volumes on study areas.

Methodology

Model Application

The Hydrological Simulation Program – FORTRAN (HSPF) was used to simulate hydrologic processes in this study. The Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) platform offers GIS tools to display and calculate physiographic data (topographic, land use, soils, watershed boundaries, and land slope). Spatial and climatic data including topography, land use, soil properties, and reach characteristics were established using the BASINS/HSPF GIS interface. Detailed hourly meteorological data were processed using the WDMUtil software (also part of the BASINS suite) and then incorporated into the watershed data management file (.wdm) specific for each model. BASINS' automatic delineation tool subdivided the Luxapallila Creek basin into fifty sub-drainage areas, Fish River watershed into seven sub-drainage areas, and Rio Caonillas catchment into ten sub-drainage areas. Table 3 depicts the datasets and methods used in this study. Databases, sources, and methods used in this research were consistent across the study areas.

Model Evaluation

This study used two different periods to evaluate the HSPF model performance in each drainage area. Calibration was done by perturbing select HSPF parameters defined in table 1 from the period 01 January 1999 to 31 December 2000. Verification, the process of evaluating calibrated HSPF parameters without further parameter modification, was performed from 01 January 2001 to 31 December 2001. Calibration and verification were accomplished using an hourly time step. Daily streamflow values were recorded at the outlet of each study area by USGS stations: 02443500 Luxapallila Creek, 02378500 Fish River, and 50026025 Rio Caonillas. Simulated daily streamflow values were evaluated against observed values in each drainage area.

The Generation and Analysis of Model Simulation Scenarios for Watersheds (GenScn) software (Kittle et al., 2001) was used to evaluate the HSPF outputs. Visual evaluation was performed using hydrographs, scatterplots, and duration curves of observed and simulated streamflow data. To date, modeling professionals (developers and users) have not reached consensus on which criteria are best for evaluating model performance (Bergman et al., 2002; Donigian, 2002; Krause et al., 2005; McCuen et al., 2006; Jain and Sudheer, 2008). McCuen et al. (2006) and Krause et al. (2005) recommended the use of different efficiency and error index criteria to effectively evaluate hydrology model outputs. Several efficiency and error index criterion are reported in the scientific literature; however, every criterion has pros and cons and should be taken into account in model evaluation (Legates and McCabe, 1999; Krause et al., 2005; McCuen et al., 2006; Moriasi et al., 2007). The following numerical criteria were used to evaluate observed streamflow data versus simulated streamflow data by HSPF: the R^2, NS, mean relative error (MRE), and root mean square error (RMSE). The RMSE, NS, and R^2 equations are more sensitive than MRE measure to large errors because the squaring process gives uneven weight to peak flows (Legates and McCabe, 1999; Krause et al., 2005; Moriasi et al., 2007). Performance rating of model results depends on the process simulated (flow, sediments, pesticide, or water quality). This study followed performance ratings developed by Donigian (2002) and Moriasi et al. (2007) for streamflow simulations (table 4).

Manual calibration of HSPF hydrologic parameters was used for the three study areas. Manual calibration consisted of adjusting the parameters that govern water balance, seasonal flows, and storm events following HSPF author's guidelines (USEPA, 2009b). The calibration process for each watershed was done when error measures (RMSE and MRE) were minimized, efficiency criteria (NS an R^2) were maximized, and the parameter values were within the range specified by the literature and supported by the knowledge of watershed physiographic characteristics.

Results and Discussions

This section presents HSPF parameter estimation values found in this research and comparisons with calibrated parameters found in the literature (table 5). In HSPF, the general water balance is affected by LZSN, LZTEP, and DEEPFR (table 1). LZSN (lower zone nominal soil moisture storage) is related to rainfall and soil characteristics of the study area (USEPA, 2000). LZSN is a conceptual parameter that needs to be calibrated but no specific guidelines are

Table 3. Databases and methods used in each watershed.

Dataset	Luxapallila Creek	Fish River	Rio Caonillas
Soil map	STATSGO2	STATSGO2	SSURGO
Land use	2001 NLCD	2001 NLCD	2001 NLCD
Digital elevation model	30-m resolution	30-m resolution	30-m resolution
Rainfall stations	NWS Fayette, Millport 2 E, Sulligent, Vernon, Winfield 2 SW, and Columbus	NWS Robertsdale and Fairhope	NWS Jayuya & Cerro Maravilla, and USGS 50026025 & 50025155
Spatial rainfall distribution	Station proximity	Station proximity	Station proximity
Potential evapotranspiration	NOAA Haleyville and Hamon temperature method	NOAA Robertsdale & Fairhope, and Hamon temperature method	Pan evaporation from NOAA Adjuntas and monthly pan coefficients from Harmsen et al. (2004)
Stream characteristic (FTABLE)	National Hydrography Dataset and ground truthing	National Hydrography Dataset and ground truthing	National Hydrography Dataset and ground truthing
Area discretization (sub-watersheds)	50	7	10

Table 4. General performance ratings for selected statistics for different time steps.

Statistic	Performance Rating				Source
	Poor	Fair	Good	Very Good	
R^2 (daily)	0.52-0.61	0.62-0.72	0.73-0.81	0.82-1.00	Donigian, 2002
R^2 (monthly)	0.52-0.64	0.65-0.76	0.77-0.85	0.86-1.00	Donigian, 2002
NS (monthly)	<0.50	0.50-0.65	0.65-0.75	0.75-1.00	Moriasi et al., 2007
MRE (%)[a]	>±25	±15-±25	±10-±15	<±10	Donigian, 2002; Moriasi et al., 2007

[a] Limitation: relevant to monthly and annual errors rather than storm event differences.

presented in the literature. Calibrated LZSN values were similar in Fish River and Luxapallila Creek but lower in the Rio Caonillas drainage area. All calibrated LZSN values were in the range declared by HSPF developers. LZETP (index to lower zone evapotranspiration) is a parameter which defines the actual evapotranspiration opportunity from the lower zone (root zone of the soil profile). LZETP value ranges by vegetation are suggested by HSPF authors (USEPA, 2000). In this study, calibrated LZETP values were in the range suggested by HSPF developers (table 1). Simulated actual evapotranspiration values were calibrated using data from published studies (Harmsen et al., 2002; Lu et al., 2003). Actual evapotranspiration opportunity decreased in the following vegetation order: wetlands, forest land, upland shrub land, grassland, cropland, urban areas, and barren land. The last parameter adjusted for the water balance was the fraction of infiltrated water that goes to deep aquifers (DEEPFR). DEEPFR was very low in Rio Caonillas catchment compared to the other two drainage areas due to the relatively impermeable volcanic rocks located beneath the aquifer.

The next step in the hydrology model calibration was to adjust HSPF parameters related to storm flow volume and rate. In HSPF, infiltration rates are related to HSG classification (USEPA, 2000). HSG class placement is based on soil's runoff potential, texture, bulk density, strength of soil structure, clay mineralogy, and organic matter (USDA-NRCS, 2007). Expected value (mm h^{-1}) for each HSG classifications are 10.0-25.0 (A), 2.5-10.0 (B), 1.25-2.5 (C), and 0.25-1.25 (D) (USEPA, 2000). This study calculated the average of HSG by subwatershed in each drainage area. Luxapallila Creek basin showed soils mainly with HSG C (table 2) with a final calibration value of infiltration rate (INFILT) of 2.5 mm h^{-1}. Fish River soils showed higher infiltration rates than Luxapallila Creek due to HSGs B (83 of total area) and A (17% of total area). Final calibration value of INFILT in Fish River ranged from 10.0 to 25.0 mm h^{-1} showing soils with lower runoff potential than Luxapallila Creek soils. HSG classes in Rio Caonillas catchment ranged mainly in C (66% of total area) and B (27% of total area) with small areas in D (6%) and A (1%). Rio Caonillas HSG distribution shows soils mainly with moderately low runoff potential when thoroughly wet. Final HSPF INFILT calibrated values were in the expected range of HSGs B and C. In general, every model represented different infiltration rates that were associated to HSG classification ranges of study areas (table 5).

Storm runoff volumes are affected by slope (SLSUR) and length (LSUR) of overland flow. SLSUR and LSUR values for each study area were extracted from 30-m resolution digital elevation models. Rio Caonillas is a steep catchment with average soil slope of 38%. HSPF authors recommend a maximum SLSUR value of 30%; however, this study used the value that represents the physical conditions of the area. LSUR value of Rio Caonillas catchment was shorter than the other two study areas due to steeper landscape conditions (table 5). The Manning's coefficient for runoff (NSUR) calibrated for each study area varied by land use type. Calibrated NSUR values in this research were the same across the study areas and in the range provided by HSPF authors (tables 1 and 5). The highest NSUR values corresponded to wetlands, forest land, upland shrub land, and grassland. The lowest NSUR value was assigned to urban areas. The higher the NSUR value the lower the runoff volume generated by land use class.

HSPF calculates direct runoff as sum of surface runoff and interflow. Parameters dealing with surface runoff were previously analyzed. Interflow parameters are INTFW (interflow inflow parameter) and IRC (interflow recession parameter). INTFW calculated the amount of water entering the soil profile, and the higher the INTFW parameter the smaller the surface runoff. In this study, the INTFW parameter was higher in Fish River than Luxapallila Creek and Rio Caonillas (table 5). Fish River watershed soils showed lower runoff potential than the other two study areas (table 2). The IRC parameter affects the rate at which interflow is discharged from storage (USEPA, 2000). The storm peak recedes slower as the IRC parameter value increases. Calibrated IRC values were the same for Luxapallila Creek and Fish River. Rio Caonillas showed a higher IRC value than the other two drainage areas. In figure 5 (flow duration curves), Rio Caonillas storm events recessed slower than Fish River and Luxapallila Creek ones, and it is expected that Rio Caonillas IRC parameter value should be higher than the ones found in the other two study areas.

Once the water balance and storm flow parameters were calibrated, the high-flow/low-flow distribution of the series was adjusted. HSPF parameters that affect this distribution were INFILT, AGWRC, DEEPFR, and BASETP (see table 1). INFILT and DEEPFR values were previously explained. The AGWRC parameter depends on watershed physiographic characteristics (e.g., climate, soils, geology, topography), (USEPA, 2000). The AGWRC is the ratio of current groundwater discharge to groundwater discharge 24 hours earlier (Bicknell et al., 2001). This complex conceptual parameter was adjusted through calibration. The final AGWRC value found in each study area was in the range of possible values declared by HSPF developers and it was comparable to cited studies (tables 1 and 5). The fraction of remaining evapotranspiration from baseflow parameter, BASETP, affects actual evapotranspiration from riparian vegetation. Luxapallila Creek and Fish River wetland areas were affected with BASETP value of 0.03. The remaining areas in these two watersheds did not contribute to this kind of evapotranspiration from riparian vegetation. Rio

Caonillas catchment showed a small BASETP value of 0.001 across of land uses. The reason for using a lumped BASETP value in Rio Caonillas was due to large landuse in forest land (67.7%) and grass land (25.8) that probably some is near to the channel network.

Finally, the HSPF hydrologic calibration process was focused on seasonal discrepancies that were affected by KVARY, BASETP, AGWETP, CEPSC, UZSN, and LZETP parameters (table 1). BASETP and LZETP parameter values were previously analyzed. The groundwater recession flow parameter, KVARY, is used to descript non-linear groundwater recession rate (USEPA, 2000). KVARY (mm^{-1}) values found in this study ranged from 0.0 in Fish River to 101.6 in Luxapallila Creek with an intermediate value of 17.8 in Rio Caonillas. HSPF developers recommend plot daily flow duration curves to help in calculating the slope of the flow recession (USEPA, 2000). The flow recession slope is higher in Luxapallila Creek than Rio Caonillas and Fish River (fig. 5). This pattern was followed by KVARY values found in this study (table 5). The HSPF parameter that affects the fraction of remaining evapotranspiration from active groundwater, AGWETP, was calibrated only for wetland areas in Luxapallila Creek basin and Fish River watershed. It was assumed that water table was at or near the wetland areas where vegetation extracts water from groundwater. Rio Caonillas catchment land use distribution did not show wetland areas (table 2), and the effect of AGWETP was neglected. HSPF authors provide guidelines to determine the rainfall intercepted by vegetation (CEPSC) (USEPA, 2000). CEPSC values directly affect the runoff volumes generated in each simulated area. Higher CEPSC values resulted in smaller amounts of runoff volume generated. In this study, calibrated CEPSC values varied by vegetation type (table 5). This variation was the same among the study areas. CEPSC values ranged from 5.1 in forest land to 0.0 in barren land. The upper zone nominal soil moisture storage, UZSN, is related to land surface characteristics, topography, and LZSN value (USEPA, 2000). Decreasing UZSN value increases the direct overland flow. Rio Caonillas showed the highest UZSN value followed by Luxapallila Creek and Fish River(table 5). This parameter distribution suggests a higher generation of runoff in Rio Caonillas than the other two watersheds.

Three HSPF studies were found in the literature with applications in Luxapallila Creek basin, Fish River watershed, and Rio Caonillas catchment (table 5). Diaz-Ramirez et al. (2008a) HSPF calibration in Luxapallila Creek was done using hydro-meteorological data from 1985 to 1993; rainfall time series from National Weather System (NWS) Millport 2 E, Haleyville, and Sulligent; land use data collected between 1977 and 1980; and a 10-sub-watershed delineation. The current Luxapallila Creek calibration study used hydro-meteorological data from 1999 to 2000; rainfall time series from NWS Fayette, Millport 2 E, Sulligent, Vernon, Winfield 2 SW, and Columbus; land use data released in 2001; and a 50-sub-watershed delineation. Despite of the differences in modeling approach, eight (LZSN, DEEPFR, AGWETP, CEPSC, NSUR, INTFW, IRC, and LZETP) out of 15 HSPF parameters evaluated were the same in both studies. Information about slope and length of overland flow parameters was not reported in Diaz-Ramirez et al. (2008a). The remaining calibrated parameter values (INFILT, KVARY, AGWRC, BASETP, and UZSN) were close in both models.

Lehrter (2006) calibrated HSPF in Fish River using hydro-meteorological data from 2000 to 2001; rainfall time series from NWS Mobile Regional Airport and Fairhope, and USGS Fish River; and land use data collected between 1993 and 1995. No information about sub-watershed delineation was available. The current Fish River model was setup using hydro-meteorological time series between 1999 and 2000; rainfall data from NWS Fairhope and Robertsdale; land use data released in 2001; and a 7-sub-watershed delineation. Lehrter (2006) published only 5 parameter values out of the 15 used in the current evaluation. INFILT and AGWRC parameter values were close in both models. LZSN, UZSN, and IRC parameter values in Lehrter (2006) were distantly lower than those found in the current research (table 5).

Diaz-Ramirez (2004) calibrated HSPF in Rio Caonillas catchment using hydro-meteorological data from 1998 to 2001; rainfall time series from NWS Cerro Maravilla, Jayuya, and Dos Bocas; land use data collected in 1993; and a 3-sub-watershed delineation. The current Rio Caonillas catchment model was built using hydro-meteorological data between 1999 and 2000; rainfall time series from NWS Cerro Maravilla and Jayuya, and USGS 50026025 and 50025155; land use data released in 2001; and a 10-sub-watershed delineation. Despite of the differences in modeling approach, ten (LZSN, INFILT, SLSUR, LSUR, AGWRC, DEEPFR, AGWETP, CEPSC, NSUR, and LZETP) out of 15 HSPF parameters compared were close in both studies. The remaining HSPF parameter values (KVARY, BASETP, UZSN, INTFW, and IRC) showed marked differences in both models (table 5).

In general, differences found in current calibrated parameters and cited parameter models could be attributed to discrepancies in model setup and target model outputs. In addition, in models like HSPF with several parameters, different sets of model parameters can perform similar model results (Beven, 2001).

This section discusses annual HSPF outputs such as discharge (surface runoff, interflow, and baseflow), actual evapotranspiration (AET), deep groundwater, and storage. Simulated annual water balance for each study area is shown in table 6. In this research, the water loss (discharge, AET, and deep groundwater) from each study area equals the input rainfall adjusted for any changes in water storage. It can be seen that water balance components depicted discrepancies among the study areas. In Luxapallila Creek and Fish River, potential evapotranspiration (PET) was calculated using the Hamon method (Hamon, 1963). The Hamon method is a temperature based equation recommended by Lu et al. (2005) for the southeastern United States. After PET time series are calculated, HSPF computes AET as a function of five moisture storages (interception storage, upper zone, lower zone, baseflow, and active groundwater storage) and the PET. After meeting the evapotranspiration demand from the five storages for each land segment, AET is calculated as the sum of the five storages (Bicknell et al., 2001). In Puerto Rico, pan evaporation time series are widely used for estimating consumptive use (Harmsen, 2003). In order to compute PET time series in Rio Caonillas, this study used pan evaporation time series from NOAA Adjuntas station (fig. 4) and monthly pan coefficients calculated by Harmsen et al. (2004).

Table 5. Comparison of the calibrated parameter values reached in this study and the literature.

Parameter (unit)	Luxapallila Creek	Fish River	Rio Caonillas	Luxapallila Creek (Diaz-Ramirez et al., 2008a)	Fish River (Lehrter, 2006)	Rio Caonillas (Diaz-Ramirez, 2004)
LZSN (mm)	228.6 for all subwatersheds, land uses, and soils	254.0 for all subwatersheds, land uses, and soils	152.6 for all subwatersheds, land uses, and soils	228.6 for all subwatersheds, land uses, and soils	20.8 for all subwatersheds, land uses, and soils	127.0 for all subwatersheds, land uses, and soils
INFILT (mm h^{-1})	HSG B: 5.1 HSG C: 2.5	HSG A: 13, 22, 25.0 HSG B: 10.0	HSG B:3.8, 9.7, 10.2 HSG C: 2.5	2.8 for all subwatersheds, land uses, and soils	14.7 for all subwatersheds, land uses, and soils	10.2 for all subwatersheds, land uses, and soils
SLSUR (%)	1.2-10.3 variation by subwatershed	2.7-3.9 variation by subwatershed	1.0-63.7 variation by subwatershed	[a]	[a]	35-45 variation by subwatershed
LSUR (m)	76-122 variation by subwatershed	91-107 variation by subwatershed	46 for all subwatersheds, land uses, and soils	[a]	[a]	30.5 for all subwatersheds, land uses, and soils
KVARY (mm^{-1})	101.6 for all subwatersheds, land uses, and soils	0.0 for all subwatersheds, land uses, and soils	17.8 for all subwatersheds, land uses, and soils	45.7 for all subwatersheds, land uses, and soils	[a]	76.2 for all subwatersheds, land uses, and soils
AGWRC	0.97 for wetland areas 0.996 for remaining areas	0.997 for all subwatersheds, land uses, and soils	0.995 for all subwatersheds, land uses, and soils	Forest: 0.996 Agricultural: 0.990 Barren: 0.970 Wetlands: 0.996 Urban: 0.970	0.997 for all subwatersheds, land uses, and soils	0.999 for all subwatersheds, land uses, and soils
DEEPFR	0.2 for all subwatersheds, land uses, and soils	0.2 for all subwatersheds, land uses, and soils	0.03 for all subwatersheds, land uses, and soils	0.2 for all subwatersheds, land uses, and soils	[a]	0.03 for all subwatersheds, land uses, and soils
BASETP	0.03 for wetland areas 0.0 for remaining areas	0.03 for wetland areas 0.0 for remaining areas	0.01 for all land uses	0.03 for forest areas 0.0 for remaining areas	[a]	0.005 for all land uses
AGWETP	0.3 for wetland areas 0.0 for remaining areas	0.25 for wetland areas 0.0 for remaining areas	0.0 for all land uses	0.3 for wetland areas 0.0 for remaining areas	[a]	0.0 for all land uses
CEPSC (mm)	Wetlands: 3.8 Urban: 1.3 Barren or Mining:0.0 Forest: 5.1 Upland Shrub Land: 3.8 Grass Land: 3.8 Agriculture -- Cropland: 4.6 Agriculture -- Pasture: 4.6	Wetlands: 3.8 Urban: 1.3 Barren or Mining:0.0 Forest: 5.1 Upland Shrub Land: 3.8 Grass Land: 3.8 Agriculture -- Cropland: 4.6 Agriculture -- Pasture: 4.6	Urban: 1.3 Barren or Mining:0.0 Forest: 5.1 Upland Shrub Land: 3.8 Grass Land: 3.8	Forest: 5.1 Agricultural: 4.6 Barren: 0.0 Wetlands: 3.8 Urban: 1.3	[a]	Urban: 2.5 Barren or Mining:0.0 Forest: 5.1 Rangeland: 2.5 Agricultural: 5.1 Pasture: 2.5
UZSN (mm)	32.0 for all subwatersheds, land uses, and soils	50.8 for all subwatersheds, land uses, and soils	12.7 for all subwatersheds, land uses, and soils	Forest: 32.0 Agricultural: 13.7 Barren: 13.7 Wetlands: 32.0 Urban: 13.7	3.1 for all subwatersheds, land uses, and soils	Urban: 20.3 Barren or Mining: 7.6 Forest: 20.3 Rangeland: 20.3 Agricultural: 7.6 Pasture: 20.3
NSUR	Wetlands: 0.4 Urban: 0.15 Barren or Mining:0.25 Forest: 0.4 Upland Shrub Land: 0.4 Grass Land: 0.4 Agriculture -- Cropland: 0.2 Agriculture -- Pasture: 0.2	Wetlands: 0.4 Urban: 0.15 Barren or Mining:0.25 Forest: 0.4 Upland Shrub Land: 0.4 Grass Land: 0.4 Agriculture -- Cropland: 0.2 Agriculture -- Pasture: 0.2	Urban: 0.15 Barren or Mining:0.25 Forest: 0.4 Upland Shrub Land: 0.4 Grass Land: 0.4	Forest: 0.4 Agricultural: 0.2 Barren: 0.25 Wetlands: 0.4 Urban: 0.15	[a]	Urban: 0.3 Barren or Mining: 0.3 Forest: 0.3 Rangeland: 0.3 Agricultural: 0.3 Pasture: 0.3

Table 5 (con't). Comparison of the calibrated parameter values reached in this study and the literature.

INTFW	3.0 for all subwatersheds, land uses, and soils	4.0 for all subwatersheds, land uses, nd soils	1.0 for all subwatersheds, land uses, and soils	3.0 for all subwatersheds, land uses, and soils	[a]	Urban: 4.0 Barren or Mining: 2.0 Forest: 4.0 Rangeland: 4.0 Agricultural: 2.0 Pasture: 4.0
IRC	0.6 for all subwatersheds, land uses, and soils	0.6 for all subwatersheds, land uses, and soils	0.85 for all subwatersheds, land uses, and soils	0.6 for all subwatersheds, land uses, and soils	0.3 for all subwatersheds, land uses, and soils	0.3 for all subwatersheds, land uses, and soils
LZETP	Wetlands: 0.9 Urban: 0.3 Barren or Mining:0.1 Forest: 0.7 Upland Shrub Land: 0.6 Grass Land: 0.6 Agriculture -- Cropland:0.6 Agriculture -- Pasture: 0.6	Wetlands: 0.7 Urban: 0.3 Barren or Mining:0.1 Forest: 0.7 Upland Shrub Land: 0.7 Grass Land: 0.7 Agriculture -- Cropland:0.6 Agriculture -- Pasture: 0.6	Urban: 0.3 Barren or Mining:0.1 Forest: 0.6 Upland Shrub Land: 0.6 Grass Land: 0.5	Forest: 0.7 Agricultural: 0.6 Barren: 0.1 Wetlands: 0.8 Urban: 0.3	[a]	Urban: 0.1 Barren or Mining: 0.4 Forest: 0.8 Rangeland: 0.6 Agricultural: 0.7 Pasture: 0.6

[a] No information available.

In Luxapallila Creek basin, streamflow discharge accounted for 34.5% of total water losses. On a yearly basis, baseflow represented 57.9% of total discharge. Direct runoff was 42.1% of total streamflow. The surface runoff to interflow ratio was 0.26, indicating that interflow was the primary mechanism of direct runoff in the Luxapallila Creek basin. The HSPF parameter that influences interflow is INTFW and was calibrated to a value of 3.0. Soils in the study area have low infiltration rates ranging from 2.5 to 5.1 mm h^{-1} (table 5). Although this kind of soil conditions promotes surface runoff, interflow increased due to the low landscape slopes in Luxapallila Creek (2% on average). Low slope watersheds promote water to pond easier and quicker than steep soils, allowing more water passing through the soil profile and reach the interflow reservoir. On average, 58.2% of total precipitation was returned to the atmosphere via evapotranspiration. The study area has a humid subtropical climate with very hot summers and mild winters. These climate characteristics along with large areas cover by forest land, wetlands, upland shrub land, and cropland promote high levels of actual evapotranspiration rates. Deep groundwater losses through the aquifer were only 5.1% of the total input rainfall. The change in storage within the basin was not significant on an annual time scale (2.2% of total rainfall).

In Fish River watershed, the annual streamflow discharge accounted for 32.1% of total watershed outflow. Streamflow was primarily baseflow (84.0% of discharge). The surface runoff to interflow ratio was 0.06, indicating that interflow was the main mechanism of direct runoff in the Fish River watershed. In HSPF, the parameter that influences interflow is INTFW and was calibrated to a value of 4.0. The lack of simulated surface runoff is due to the well drained or excessively drained soils in the area (table 2). These classes of soils were represented in HSPF with infiltration rates from 10.0 to 25.0 mm h^{-1} (table 5). On annual basis, actual evapotranspiration accounted for 59.7% of total water losses. Fish River watershed has a humid, nearly subtropical climate with long summers reaching temperatures as high as 41°C. These climate characteristics along with large areas cover by vegetation derived in high actual evapotranspiration rates. Deep groundwater losses through the aquifer were only 7.3% of the total input rainfall. The change in storage within the Fish River watershed was not significant on an annual time scale (0.9% of precipitation).

In Rio Caonillas catchment, streamflow discharge accounted for approximately 46% of outflow. Streamflow was primarily baseflow (67.2% of discharge). Direct runoff was only 32.8% of discharge, with surface runoff accounting for 19.3% of total streamflow and interflow accounting for 13.5% of total discharge. The surface runoff to interflow ratio was 1.4, indicating that surface runoff was the primary mechanism of direct runoff in Rio Caonillas drainage area. Surface runoff was higher than interflow due to the kind of soils within the catchment. Soil slopes averaging 38% have the potential of producing rapid storm runoff. HSG B and C soils make up 93% of the total area with potential rapid runoff. In addition, interflow volumes were lower than surface runoff volumes due to the low value of INTFW parameter (table 5). Actual evapotranspiration accounted for 52% of total water losses in the Rio Caonillas catchment. Puerto Rico is a tropical, wet island located in the Caribbean with average daily temperature ranging from 19°C in January to 24°C in August. This climate promotes high evapotranspiration rates. Water loss due to deep groundwater was only 1% of rainfall due to the relatively impermeable bedrock beneath the drainage area. Hydrologic studies performed in similar areas in Puerto Rico yielded comparable annual deep percolation rates (García-Martinó et al., 1996; Larsen and Concepción, 1998). The change in storage within the catchment was not significant on an annual time scale (1.1% of total rainfall).

In general, Rio Caonillas showed the highest annual precipitation rate followed by Fish River and Luxapallila Creek. Simulated actual evapotranspiration was the main mechanism of water loss in each study areas followed by discharge. The high rainfall amounts entering each watershed, large areas cover by different classes of vegetation, and high temperatures contributed to large amounts of actual evapotranspiration in each study area.

Table 6. Annual water balance.

Component	Luxapallila Creek (mm $year^{-1}$)	Fish River (mm $year^{-1}$)	Rio Caonillas (mm $year^{-1}$)
Rainfall	1,321.3	1,391.2	1,851.2
Discharge	455.3	446.0	849.2
Surface runoff	39.5	4.3	163.8
Interflow	152.4	67.0	114.7
Baseflow	263.4	374.7	570.7
Actual evapotranspiration	769.5	831.1	961.9
Deep groundwater	67.6	101.3	19.0
Storage	28.9	12.9	21.1

Mechanisms generating discharge (surface runoff, interflow, and baseflow) were different among the study areas and represent physical characteristics of each drainage area. An examination of the annual water budgets indicated that very little change in water storage occurred among the study areas (table 6).

Table 7 shows observed and simulated daily mean discharges. In Luxapallila Creek basin, simulated and observed daily mean discharges were close with MRE values between -9.01% and 0.79%. Long term flow discrepancies found in Luxapallila Creek were considered very good according to criteria from Donigian (2002) and Moriasi et al. (2007). The verification period showed around 60% higher flows than the calibration period; an indicator that the model was evaluated under different flow regimes. In Fish River watershed, long term discrepancies between observed and simulated daily mean discharges for the calibration and verification period ranged from -5.70% to 9.61%. These small discrepancies are considered very good by criteria from Donigian (2002) and Moriasi et al. (2007). In Rio Caonillas catchment, long-term flow errors varied from 3.00% (calibration period) to 11.00% (verification period). These values indicate that the model performance for long-term discrepancies ranged from very good to good. The verification period showed around 50% lower flows than the calibration period, showing that the model was evaluated under different flow periods.

Statistical results for best-fit calibration, verification, and total of daily and monthly flows are summarized in table 8. In Luxapallila Creek basin, R^2 and NS values were similar for the calibration and verification periods. R^2 values computed in this evaluation were classified as fair for daily and very good for monthly intervals (Donigian, 2002). Monthly NS values were rated very good by criteria from Moriasi et al. (2007). Negative MRE indicated that daily and monthly streamflow values were constantly overpredicted by the model. Monthly RMSE and MRE numbers were significantly lower than the ones computed using daily data. This tendency has been reported for several authors (Laroche et al., 1996; Moriasi et al., 2007; Diaz-Ramirez et al., 2008a,b). The statistical measures found for the HSPF model compare satisfactorily with published results by Diaz-Ramirez et al. (2008a). The HSPF evaluation performed by Diaz-Ramirez et al. (2008a) between 1994 and 2003 yielded daily R^2 and NS values of 0.68; on a monthly basis values increased to 0.77 for R^2 and 0.76 for NS. In modeling setup, the current study had differences with Diaz-Ramirez et al. (2008a) evaluation. For example, time framework evaluation was shorter in this study (1999-2000) than Diaz-Ramirez et al. (2008a) (1994-2003); the current study used six stations versus three stations used in the published study; area discretization was done using 50 sub-watershed in the current study versus 10 sub-watersheds in the cited document; land use data used in the current study was released in 2001 versus the land use map developed between 1977 and 1980 in Diaz-Ramirez et al. (2008a).

Comparison of HSPF results and observed streamflow data at the Fish River outlet are shown in table 8. HSPF underestimated (positive MRE) flow for the calibration period and overestimated (negative MRE) for the verification period. For the calibration period, R^2 values were 0.50 for daily intervals and 0.82 for monthly intervals. NS values for the calibration were 0.46 (daily) and 0.72 (monthly). According to guidelines provided by Donigian (2002) and Moriasi et al. (2007), HSPF simulated streamflow regimes poor for daily intervals and good to very good for monthly intervals. For the verification period, R^2 and NS values were similar to the calibration results. HSPF model performance increased as the evaluation time step increased (e.g., from a daily interval to a monthly interval). Evaluation of the hydrological component of HSPF in Fish River watershed has been done by Lehrter (2006). The author found a daily R^2 value of 0.49 for the 2000-2001 period. Aside time framework discrepancies between current study and cited work, land use, watershed discretization, and rainfall stations were different in both studies.

Numerical criteria are included in table 8 for evaluation of streamflow time series on daily and monthly intervals in the Rio Caonillas catchment. Daily MRE numbers were close to zero. In general, R^2 and NS values were fair for daily intervals and good to very good for monthly intervals. Diaz-Ramirez et al. (2008b) evaluated the hydrological component of HSPF in the Rio Caonillas catchment. Current study and published research used the same rainfall stations and time framework (calibration period from 1999-2000 and verification period for 2001), however, land use map and area discretization were different in both studies. For the calibration period, Diaz-Ramirez et al. (2008b) found that HSPF underestimated daily flows by 5.50%. In the current study, HSPF overestimated daily streamflows by 3.27% (MRE). For the 1999-2000 period, Diaz-Ramirez et al.

Table 7. Observed and simulated daily mean discharges.

Drainage Area	Statistic	Calibration (01/01/1999-12/31/2000)	Verification (01/01/2001-12/31/2001)	Total (01/01/1999-12/31/2001)
Luxapallila Creek	Observed discharge ($m^3 s^{-1}$)	20.31	32.04	24.22
	Simulated discharge ($m^3 s^{-1}$)	20.15	34.93	25.07
Fish River	Observed discharge ($m^3 s^{-1}$)	2.08	2.28	2.15
	Simulated discharge ($m^3 s^{-1}$)	1.88	2.41	2.05
Rio Caonillas	Observed discharge ($m^3 s^{-1}$)	3.00	2.00	2.67
	Simulated discharge ($m^3 s^{-1}$)	2.91	1.78	2.53

Table 8. Performance comparison statistics for daily and monthly streamflows.

Drainage Area	Statistic	Calibration (01/01/1999-12/31/2000) Daily	Calibration Monthly	Verification (01/01/2001-12/31/2001) Daily	Verification Monthly	Total (01/01/1999-12/31/2001) Daily	Total Monthly
Luxapallila Creek	R^2	0.61	0.96	0.64	0.93	0.62	0.95
	NS	0.60	0.95	0.60	0.91	0.61	0.94
	MRE (%)	-21.72	-15.55	-41.06	-21.62	-28.16	-17.57
	RMSE ($m^3 s^{-1}$)	30.74	5.90	25.59	6.78	29.13	6.21
Fish River	R^2	0.50	0.82	0.45	0.84	0.46	0.79
	NS	0.46	0.72	0.43	0.82	0.44	0.78
	MRE (%)	6.00	7.89	-17.16	-8.11	-1.72	2.56
	RMSE ($m^3 s^{-1}$)	0.95	0.37	2.47	0.44	1.62	0.39
Rio Caonillas	R^2	0.71	0.83	0.67	0.90	0.71	0.84
	NS	0.67	0.74	0.67	0.87	0.68	0.77
	MRE (%)	-3.27	4.78	2.42	11.35	-1.37	6.97
	RMSE ($m^3 s^{-1}$)	1.91	1.14	1.48	0.43	1.78	0.96

(2008b) obtained R^2 of 0.75 and NS of 0.74 for daily flows. For the verification period, the cited study obtained R^2 of 0.55 and NS of 0.54 for daily flows. In summary, daily calibration made by Diaz-Ramirez et al. (2008b) yielded higher R^2 and NS values than the current study results. However, current R^2 and NS values for the verification period were higher than the ones computed in the cited document.

In summary, among the three study areas evaluated in the current research, Rio Caonillas catchment model results showed the highest best-fit (R^2 and NS) for daily flows using HSPF followed by Luxapallila Creek basin and Fish River. The best monthly performance using the R^2 and NS values was by Luxapallila Creek basin model. Fish River and Rio Caonillas models performed similar monthly results (R^2 and NS).

Hydrograph comparisons between simulated and observed flows (figs. 6-8) showed similar temporal dynamics in both simulated and observed flows. In each application, many observed flow peaks were tracked by the model. However, some simulated peaks did not match observed ones, mainly because of uncertainty associated with the rainfall databases, effects of spatial discretization of rainfall stations, rainfall station density, and the effect of lumped parameter calculations.

Figures 9 through 11 depict scatterplots of daily flows for the entire evaluation period (01 Jan. 1999- 31 Dec. 2001). Streamflow datasets measured in this study ranged from 0.4 $m^3 s^{-1}$ (Rio Caonillas) to 541 $m^3 s^{-1}$ (Luxapallila Creek). It can be seen that the HSPF model was evaluated to a large range of streamflow regimes. High flow data showed more dispersion than low flow data. The linear regression of Rio Caonillas, Luxapallila Creek, and Fish River depicted a model tendency to underestimate high flows (slopes of linear equations less than 1). This study found a direct relation between the gradient of the linear regression and the R^2 value among the drainage areas. Rio Caonillas simulations showed the closest value to 1 of the gradient of the linear regression and the highest R^2 value. In contrast, Fish River results depicted the lowest slope of the linear regression (0.55) and R^2 (0.46). In the Fish River watershed, streamflow values higher than 25 $m^3 s^{-1}$ were consistently underestimated by

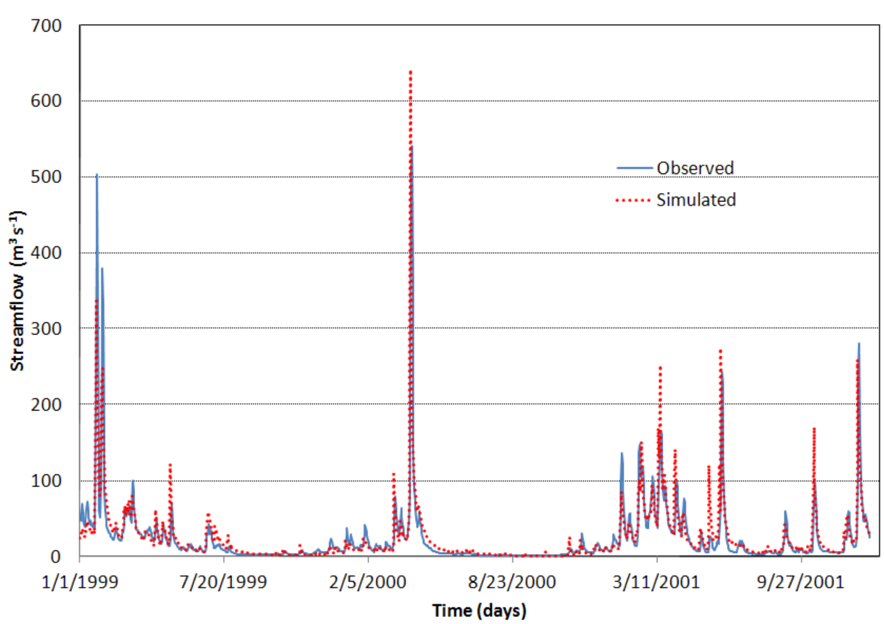

Figure 6. Observed and simulated daily streamflows at Luxapallila Creek outlet.

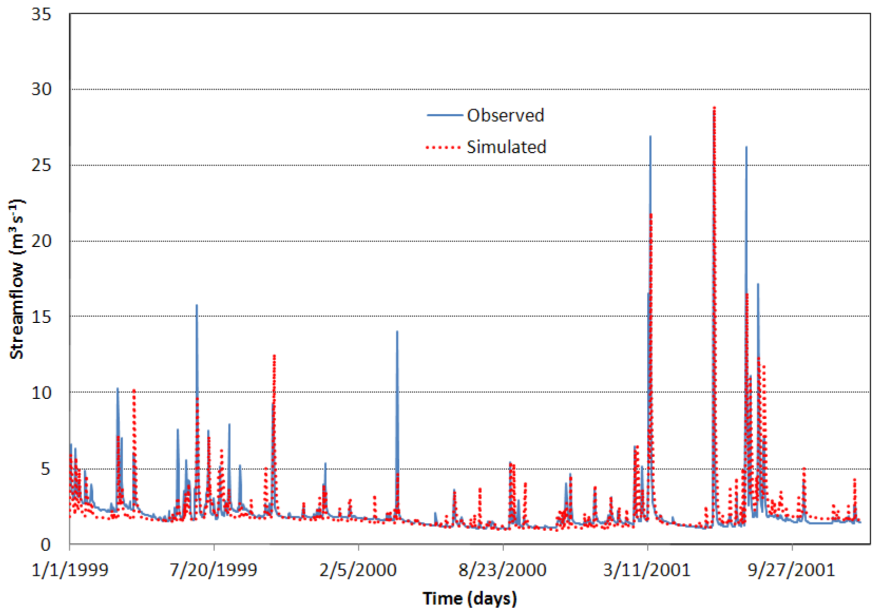

Figure 7. Observed and simulated daily streamflows at Fish River outlet.

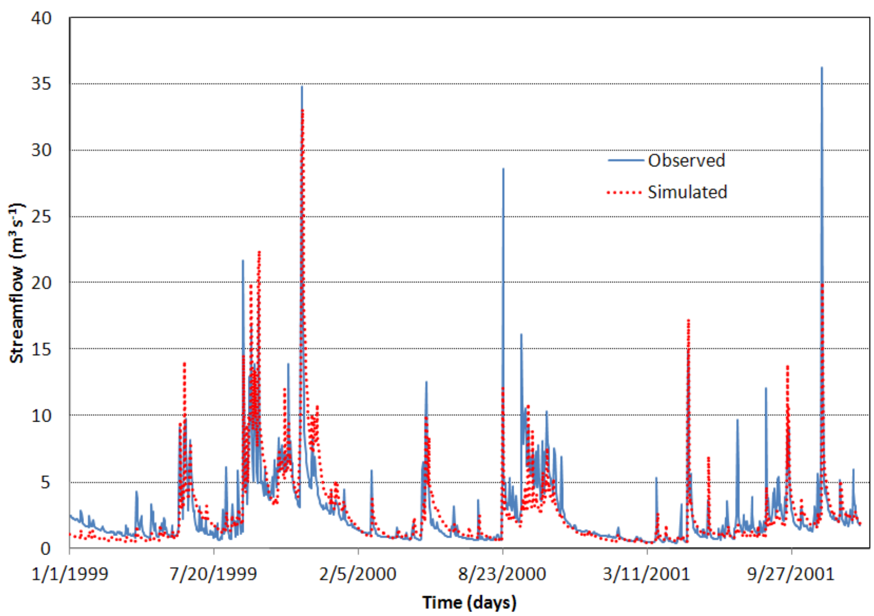

Figure 8. Observed and simulated daily streamflows at Rio Caonillas outlet.

HSPF. In the Luxapallila Creek basin, streamflow values higher than 250 m^3 s^{-1}were constantly underestimated by the model. Model correlations will increase by taking out those mentioned high flows for Fish River and Luxapallila Creek. Large discrepancies at high flows can be mainly explained by uncertainties related to rainfall databases (missing data, malfunction of equipment, equipment setup, data processing), rainfall station density (area/gauge), distribution of precipitation gauges (within or out of watershed boundaries). In addition, uncertainties in model setup (watershed discretization of land surface and channel network), model parameters, model equations, and model solver could affect model results.

An analysis of high-flow volumes (with roughly 10% probability of exceedance) is shown in table 9 for all events exceeding 70 m^3 s^{-1} in Luxapallila Creek, 6 m^3 s^{-1} in Fish River, and 5 m^3 s^{-1} in Rio Caonillas. Storm flow volumes were computed by integrating streamflows per storm duration (days). Rio Caonillas catchment showed the highest number of events (24) among the study areas due to the combine of high annual precipitation values and long rainy season (table 2). The size and duration ranges of storm events were high in Rio Caonillas and Luxapallila Creek but short in Fish River. Discrepancies between observed and simulated storm-runoff volumes were only 6.33% for Rio Caonillas and 8.58% for Luxapallila. In contrast, Fish River discrepancies were 35.00%, indicating that the Fish River model underpredicted storm flows.

Positive discrepancies (MRE) at storm events suggest that rainfall data were missed, in particular at the Fish River

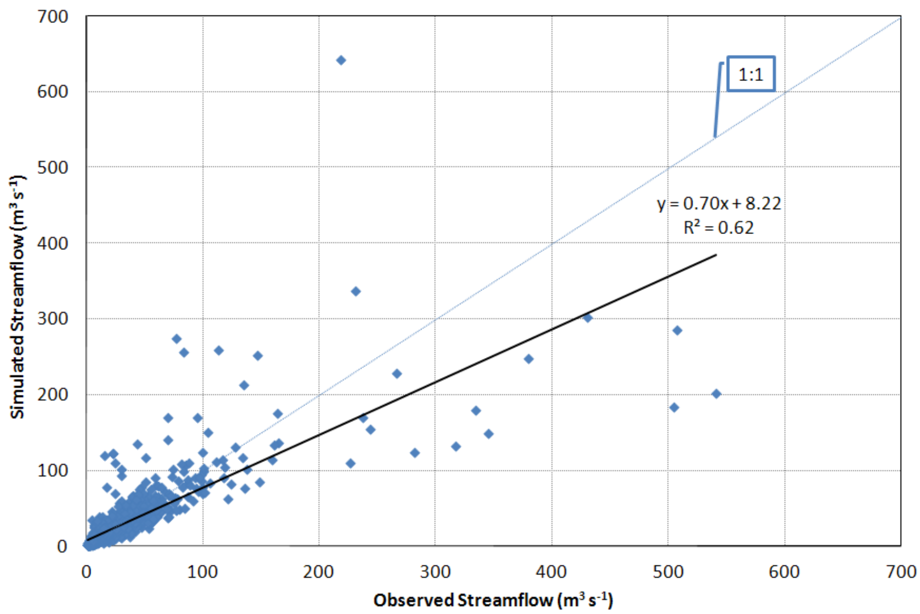

Figure 9. Scatterplot of observed versus simulated daily streamflows at Luxapallila Creek outlet (01 Jan. 1999 - 31 Dec. 2001).

watershed where no rainfall gauges were located within the watershed boundaries (~9 km away from the watershed outlet). In addition to uncertainties in rainfall time series, physical representation of the channel network can affect storm-runoff model results. This study used data from the USGS National Hydrography Dataset to develop the hydraulic reach characteristics (FTABLE). The FTABLE can be improved using field data (cross section data, reach length, and flow). Diaz-Ramirez (2007) evaluated the impact of streamflow simulations using two different FTABLE scenarios in Luxapallila Creek watershed. He found substantial differences in the time to peak flow and recessing limbs of storm events.

Conclusion

The Hydrological Simulation Program - FORTRAN (HSPF) interfaced with Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) was used to study hydrologic processes in the Luxapallila Creek basin (Alabama and Mississippi), Fish River watershed (Alabama), and Rio Caonillas catchment (Puerto Rico). Hydrology simulations ranged from 1999 to 2001. In each drainage area, daily streamflow data recorded at USGS gauging stations were compared to HSPF simulated streamflows. In this study, evaluation of HSPF outputs was accomplished using hydrographs, scatterplots, and numerical criteria (R^2, NS, MRE, and RMSE). A manual

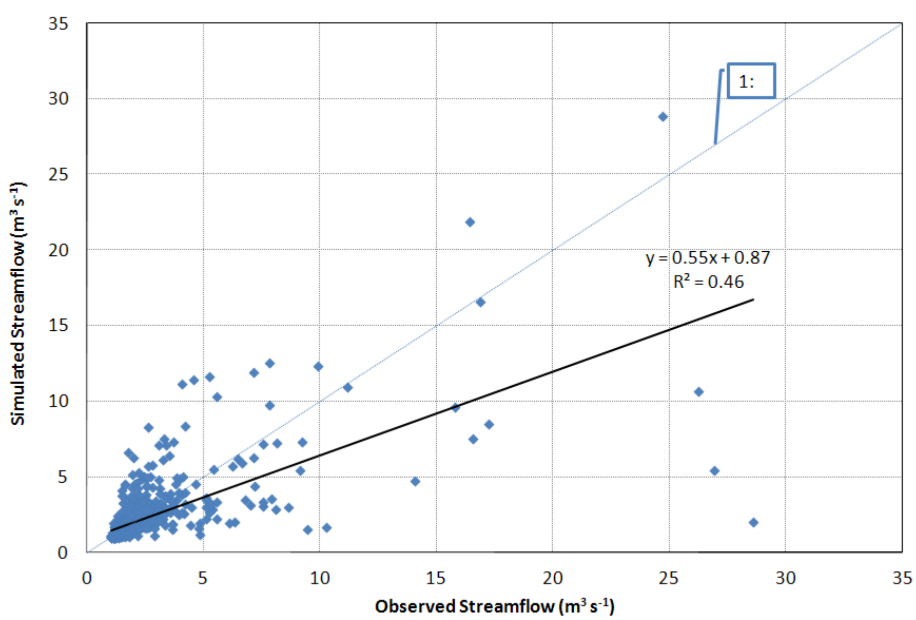

Figure 10. Scatterplot of observed versus simulated daily streamflows at Fish River outlet (01 Jan. 1999 - 31 Dec. 2001).

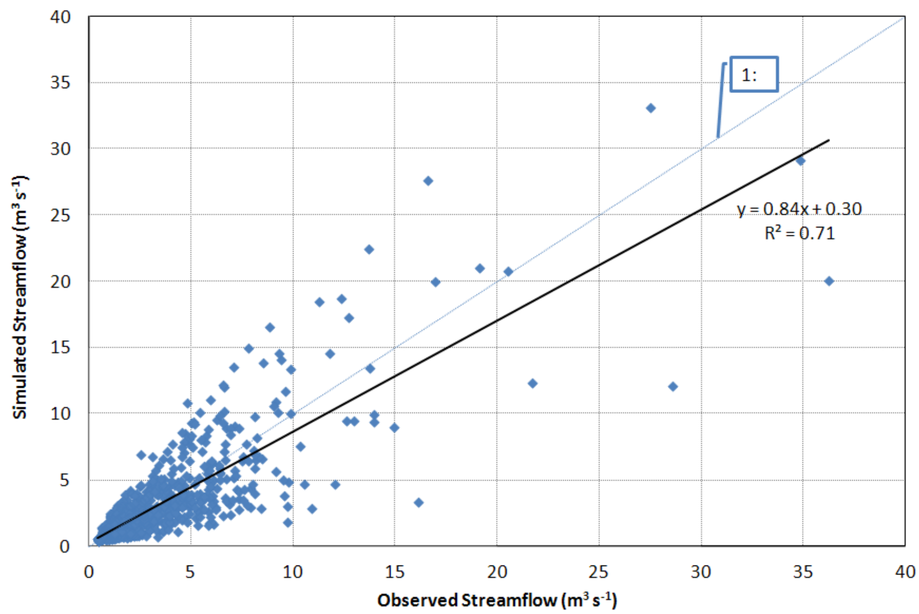

Figure 11. Scatterplot of observed versus simulated daily streamflows at Rio Caonillas outlet (01 Jan. 1999 – 31 Dec. 2001).

Table 9. Summary of high flow volume performance by study area.

Statistic	Luxapallila Creek	Fish River	Rio Caonillas
No. of events	13	9	24
Range of events (days)	2-12	2-4	2-22
Mean observed (m^3)	5.01E+08	1.04E+07	4.42E+07
Mean simulated (m^3)	4.58E+08	6.76E+06	4.14E+07
R^2	0.96	0.97	0.89
NS	0.95	0.51	0.88
MRE (%)	16.88	28.39	18.05
RMSE (m^3)	1.06E+08	4.84E+06	2.65E+07

technique was used to optimize selected HSPF hydrology parameters.

The results of this study are representative of drainage areas in Mississippi, Alabama, and Puerto Rico. HSPF parameter values were calibrated for each land use, soil type, topographic, channel, and aquifer characteristics found in each drainage area to account for different hydrological processes within each simulated watershed. The HSPF infiltration parameter (INFILT) was related to *in situ* soil hydrologic conditions giving it a physical representation of the flow partition between infiltration and surface runoff in simulated areas. Spatial and temporal rainfall data were characterized using gauge networks from NOAA and USGS agencies. Differences in rainfall interception capacity and evapotranspiration rates were associated to land cover parameters for each drainage area.

In general, Rio Caonillas showed the highest annual precipitation rate followed by Fish River and Luxapallila Creek. In each study area, simulated actual evapotranspiration was the main mechanism of water loss followed by river discharge. Mechanisms generating discharge (surface runoff, interflow, and baseflow) were different among the study areas and represent physical characteristics of each drainage area. Annual baseflow values ranged from 57.9% of total discharge in the Luxapallila Creek basin to 84.0% of total discharge in the Fish River watershed. In the Rio Caonillas catchment, the surface runoff to interflow ratio was greater than 1, indicating that surface runoff was the primary mechanism of direct runoff. This catchment has low soil infiltration rates and steep topography (38%) that produces rapid storm runoff. In Luxapallila Creek and Fish River, the surface runoff to interflow ratio was lower than 1, indicating that interflow was the primary mechanism of direct runoff. These two watersheds present low slopes (less than 3%) and high HSPF interflow parameter (INTFW) values. Deep groundwater losses through the aquifer ranged from 1% of the total input rainfall in Rio Caonillas to 7.3% of the total input rainfall in Fish River. Small changes in annual water storage occurred among the study areas.

The HSPF model simulated the different hydrologic characteristics of the Luxapallila Creek basin, Fish River watershed, and Rio Caonillas catchment within an acceptable margin of error. Daily hydrographs depicted simulated streamflow and corresponding observed streamflow were close. Marked differences in observed flow values for the calibration (1999-2000) and verification (2001) periods were found in Rio Caonillas and Luxapallila Creek. Daily R^2 and NS statistics were good in the Rio Caonillas catchment, fair in the Luxapallila Creek basin, and poor in the Fish River watershed. The statistics showed that the models performed better during calibration compared to the verification period. On a monthly streamflow basis, R^2 and NS criteria were very good in the Luxapallila Creek basin and the Rio Caonillas catchment, and good in the Fish River watershed. Storm flow volume performance was very good represented by Rio Caonillas and Luxapallila Creek models with R^2 and NS values between 0.88 and 0.96. In this regard, the HSPF model for the Fish River watershed performed poorly due to low NS (0.51) and high MRE (28.39%). This is likely due to the lack of detailed spatial and temporal rainfall data available to the Fish River model. NOAA rainfall gauges for the Fish River are located out of the watershed boundaries. Overall, this study showed the robustness of the HSPF rainfall-runoff model under different environments (coastal vs. upland watersheds, subtropical vs. tropical climates, flat vs. steep mountain catchments, low vs. moderate/high runoff potential, small catchments vs. big basins).

It is generally concluded that the modeling approach used in this study increased the understanding of hydrological processes in representative drainage areas in Mississippi, Alabama, and Puerto Rico. The hydroenvironmental data with the modeling framework approach and results presented in this research are very useful to get increasing knowledge on pollutant fate and transport processes, climate and land cover variability, and water resources management for stakeholders and researchers.

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