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Impacts of Multiple Hurricanes and Tropical Storms on Watershed Hydrological Processes in the Florida Panhandle

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Abstract: Hurricanes and tropical storms (TS) are infrequent but disastrous events to human lives, social activities, and terrestrial ecosystems in coastal regions. Using the Environmental Protection Agency (US-EPA)'s Hydrologic and Water Quality System (HAWQS) model, principal component analysis (PCA), and principal factor analysis (PFA), we estimated impacts of multiple hurricanes and TS on hydrological processes in agricultural and forested watersheds. Five hurricanes and four TS that passed near or through the Apalachicola–Chattahoochee–Flint River basin (ACFRB) of the Florida panhandle from 1966 to 2018 were selected to estimate their impacts on rainfall, potential evapotranspiration (PET), evapotranspiration (ET), soil water percolation, surface runoff, stream discharge, groundwater recharge, and water yield (WYLD). Simulations showed that the category of hurricanes was not highly related to the amounts of rainfall, runoff, discharge, and WYLD. Based on PCA and PFA, PET and ET were highly and negatively, rainfall and discharge were highly and positively, and percolation, runoff, groundwater recharge and WYLD were moderately and positively affected by the hurricanes and TS at the ACFRB in the recent 50 years. This study provides water resource managers with critical insights into how multiple hurricanes and TS affected hydrological processes in agricultural and forested watersheds of the coastal region.

Keywords: Florida panhandle; hydrological processes; hurricane; tropical storm; HAWQS model; principal component analysis

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1. Introduction

Hurricanes and tropical storms are disastrous natural events to human lives, economical activities, and natural environments in coastal regions [1,2]. Natural hazardous disasters and human-made catastrophes have resulted in human deaths and more than 11,000 missing as well as economic losses greater than USD 337 billion in 2017 [3]. Hurricanes Harvey, Irma and Maria alone caused a loss of USD 217 billion in North America [4]. Impacts of hurricanes and tropical storms on hydrological processes in coastal agricultural and forested watersheds primarily include high peak discharge, reduced evapotranspiration, overbank flooding and groundwater table rise for weeks to month due to storm surges and heavy precipitation [5,6]. Jayakaran et al. [7] investigated the impact of Hurricane Hugo in 1989 on two paired coastal watersheds in South Carolina, United States of America (USA). They found a significant change in rainfall–runoff relationships, lower vegetative water use, and increased stream outflow due to hurricane damage to forests. Torres et al. [8] simulated the hydraulic interactions of hurricane storm surge and rainfall runoff at the Houston-Galveston region, USA and reported that the peak flows from storm surge dominate those from rainfall runoff although rainfall runoff can constitute more than half of the total flood volume. Brena-Naranjo et al. [9] assessed the contributions of tropical storms and hurricanes to rainfall in Mexico from 1998 to 2013 using the satellite-derived precipitation dataset. These authors observed that the southern regions of Mexico can receive more than 2400 mm of cyclonic rainfall during years with significant tropical cyclone activity. They also found that the number of tropical cyclones increased significantly from 1998, yet their rainfall contributions did not increase, and wind speed and rainfall intensity during cyclones were not highly correlated. Hou et al. [10] investigated hydrological responses to extreme weather-induced forest disturbances in a tropical experimental watershed of Hainan Province, China using the single watershed and paired-year approaches. They reported that typhoon and cold wave-induced forest disturbances have a positive effect on stream discharge. Vidon et al. [11] synthesized the impacts of Hurricane Irene in 2011 and Tropical Storm Lee in 2011 on riparian hydrology, biogeochemistry, and water quality from North Carolina to Maine, USA. They found that in almost all cases, these storms generated unprecedented changes in hydrology and water quality.

All the above and many other studies provide very useful insights into the impacts of hurricanes and tropical storms on some hydrological processes in agricultural and forest watersheds. However, a thorough literature review reveals that few studies have been devoted to scrutinizing the impacts of hurricanes and tropical storms on hydrological processes before and after the hurricanes and tropical storms, which are essential to water resource management. The goal of this study was to quantify the impacts of multiple hurricanes and tropical storms on hydrological processes in agricultural and forested watersheds, using the US-Environmental Protection Agency (EPA)'s Hydrologic and Water Quality System (HAWQS) model and multivariate statistics. The Apalachicola–Chattahoochee–Flint River basin (ACFRB), draining into the northern Gulf of Mexico (GOM) region, was selected because hurricanes and tropical storms occur in this forested and agricultural dominated region more frequently than most other regions in the world, making this basin an ideal location for the purpose of this study. Our specific objectives were to: (1) create, calibrate, and validate the HAWQS-based ACFRB model; (2) apply the model to assess hydrological processes in agricultural and forested watersheds before-during-after the hurricanes and tropical storms that had passed through the ACFRB from 1966 to 2018; and (3) identify the hydrological variables most affected by hurricanes and tropical storms using principal component and factor analyses. Hydrological processes of interest in this study include rainfall, surface runoff, evapotranspiration (ET), potential ET (PET), stream discharge, soil water percolation, groundwater recharge, and water yield (WYLD).

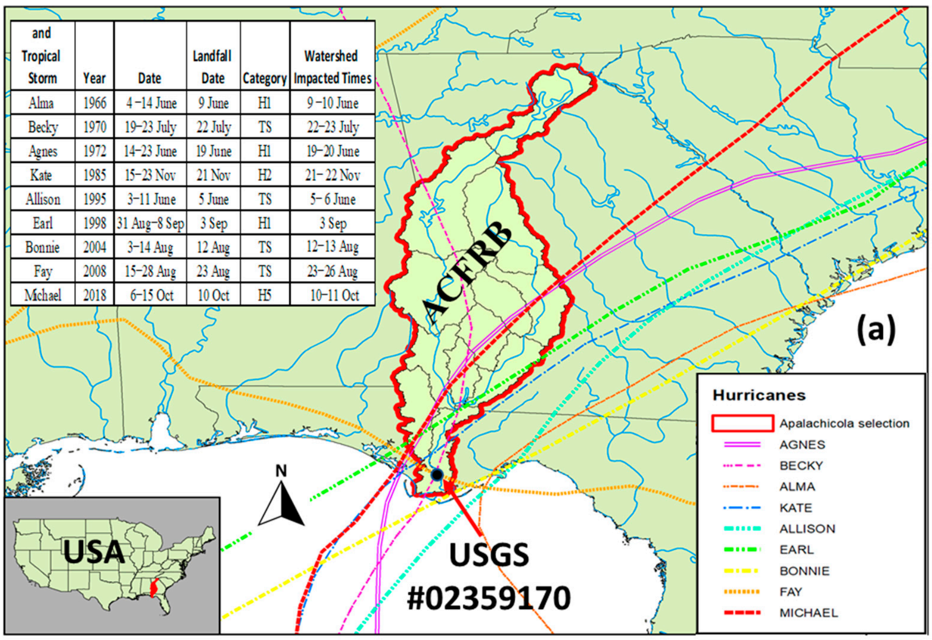
2. Materials and Methods

2.1. Study Site, Hurricanes, and Tropical Storms

The ACFRB consists of three river basins, namely the Chattahoochee River basin, Flint River basin and Apalachicola River basin (50,701 km^2), with headwaters initiating in tributaries feeding the upper reaches of the Chattahoochee River, Georgia, continuing southward through west Georgia and east Alabama, and ending at the coast of the Florida panhandle (Figure 1). The Apalachicola River in the Florida panhandle is the confluence of the Chattahoochee River (flows through Georgia and Alabama) and Flint River (flows through Georgia). The Chattahoochee River, with a drainage area of 22,714 km^2, arises as a cold-water mountain stream at altitudes above 914 m, flows 692 km to its confluence with the Flint River, and is a heavily used water resource in Georgia. The Flint River is approximately 563 km in length and drains an area of 21,911 km^2 prior to its confluence with the Chattahoochee River to form the Apalachicola River. The Apalachicola River flows 171 km from Jim Woodruff Lock and Dam to the GOM. The river drains approximately 6734 km^2 in the Florida panhandle with a shallow estuary of approximately 539 km^2 [12]. ACFRB is an important ecological and economic region of tri-states (i.e., Florida, Alabama, and Georgia) in the southeastern USA [13]. There are four major land-resource areas, namely the Southern Piedmont, Georgia Sand Hills, Southern Coastal Plain, and Eastern Gulf Coast

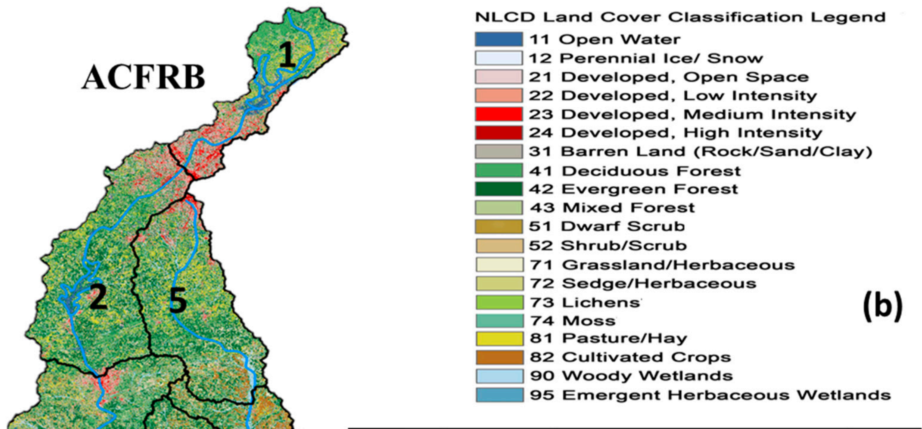
Flatwoods, in the ACFRB. The Southern Piedmont area is dominated by ultisols [14], while the Southern Coastal Plain and the Georgia Sand Hills areas are derived from marine and fluvial sediments eroded from the Appalachian and Piedmont Plateaus. Ultisols are found throughout these areas with an exception of some areas in the Georgia Sand Hills with entisols locally. The Eastern Gulf Coast Flatwoods area, which covers most of the Apalachicola River basin, is dominated by spodosols [12]. The ACFRB spans approximately 5 degrees of latitude, with average annual temperatures ranging from 16 °C in the north to 21 °C in the south. Average daily temperatures range from to 13 °C in January and from 24 to 27 °C in July. Precipitation is greatest either in the mountains because of orographic effect or near the GOM because of high air moisture. Average annual precipitation is approximately 1295 mm, with a range from 1143 mm in the east-central portion of the ACFRB to 1524 mm in the Florida panhandle portion of the basin [12]. There is a total of 12 8-digit Hydrologic Unit Code (HUC-8) watersheds in the ACFRB, with four in the Chattahoochee River basin, six in the Flint River basin, and two in the Apalachicola River basin. Land uses and area of each watershed are shown in Figure 1b.

Five hurricanes (i.e., Alma, Agnes, Kate, Earl, and Michael) and four tropical storms (i.e., Becky, Allison, Bonnie, and Fay) that occurred from 1966 to 2018 were used in this study. These hurricanes and tropical storms were selected simply because their central paths (or storm tracks) passed through or near the ACFRB (Figure 1a). Alma was a Category 1 hurricane, its central path passed through the ACFRB, which occurred from 4 to 14 June 1966, with watershed impact times on 9 to 10 June and landfall date on 9 June. Agnes was a Category 1 hurricane, its central path passed through the ACFRB, which occurred from 14 to 23 June 1972, with watershed impact times on 19 to 20 June and landfall date on 19 June. Kate was a Category 2 hurricane, its central path passed through the ACFRB, which occurred from 15 to 23 November 1985, with watershed impact times on 21 to 22 November and landfall date on 21 November. Earl was a Category 1 hurricane, its central path passed through the ACFRB, which occurred from 31 August to 8 September 1998, and its watershed impact time and landfall date were both on 3 September. Michael was a Category 5 hurricane, its central path passed through the ACFRB, which occurred from 6 to 15 October 2018, with its watershed impact times on 10 to 11 October and landfall date on 10 October. The table embedded in Figure 1a lists the dates, years, categories, and watershed impact times of the hurricanes and tropical storms used in this study.



and Tropical Storm	Year	Date	Landfall Date	Category	Watershed Impacted Times
Alma	1966	4–14 June	9 June	H1	9–10 June
Becky	1970	19–23 July	22 July	TS	22–23 July
Agnes	1972	14–23 June	19 June	H1	19–20 June
Kate	1985	15–23 Nov	21 Nov	H2	21–22 Nov
Allison	1995	3–11 June	5 June	TS	5–6 June
Earl	1998	31 Aug–8 Sep	3 Sep	H1	3 Sep
Bonnie	2004	3–14 Aug	12 Aug	TS	12–13 Aug
Fay	2008	15–28 Aug	23 Aug	TS	23–26 Aug
Mchael	2018	6–15 Oct	10 Oct	H5	10–11 Oct

Figure 1. *Cont.*



Watershed ID	HUC Number	Watershed Name	Area (km^2)
1	3130001	Upper Chattahoochee	4106.87
2	3130002	Middle Chattahoochee-Lake Harding	7875.21
3	3130003	Middle Chattahoochee-Walter F	7347.5
4	3130004	Lower Chattahoochee	3222.54
5	3130005	Upper Flint	6811.01
6	3130006	Middle Flint	4035.67
7	3130007	Kinchafoonee-Muckalee	2851.7
8	3130008	Lower Flint	3300.64
9	3130009	Ichawaynochaway	2859.48
10	3130010	Spring	2042.84
11	3130011	Apalachicola	2893.7
12	3130012	Chipola	3347.46

Figure 1. Location of the Apalachicola–Chattahoochee–Flint River basin (ACFRB) of the Florida panhandle, USA. (**a**) Hurricanes and tropical storms passed through or highly impacted the ACFRB from 1966 to 2018. (**b**) The name, area, and land use of the 12 watersheds at the ACFRB. USGS #02359170 is the US Geological Survey gage number.

2.2. The HAWQS Model and Statistical Analysis

Using the Soil and Water Assessment Tool (SWAT) model as the core simulation engine, the HAWQS is a web-based modeling system applied to simulate water quantity and quality in watersheds of continental USA (https://hawqs.tamu.edu/, accessed on 6 March 2022). The SWAT model is a small watershed to river basin-scale model used to simulate the quality and quantity of surface and ground water and predict the environmental impact of land use, land management practices, and climate change. The SWAT model is widely used in assessing soil erosion prevention and control, non-point source pollution control and regional management in watersheds (https://swat.tamu.edu/, accessed on 6 March 2022). The HAWQS is a customized version of the SWAT model, which has interactive web interfaces and maps; online watershed-specific model development and execution; pre-loaded input data; and output data in tabulate and chart formats. Additionally, the past and future climate datasets are pre-loaded into the model for users to develop their own modeling projects [15]. Overall, the HAWQS is a time-saving and cost-effective modeling system for predicting water quantity and quality in complex watersheds.

The ACFRB model was developed with the HAWQS through the web interface at https://hawqs.tamu.edu/#/projects/ (accessed on 6 March 2022), using the following three major procedures: (1) Create a project. The ACFRB model was created at the data resolution of HUC-8 for the downstream HUC #03130011 (or Apalachicola River basin). After entering this HUC number into the Map Options of the HAWQS, the additional 11 upstream watersheds contributing to the Apalachicola River watershed were delineated. This generated the entire ACFRB model (Figure 1). (2) Set the Hydrologic Response Unit (HRU). A threshold level of 1% for HRUs was used to eliminate the effects of minor land uses, soils, and slopes in each watershed. (3) Create a scenario. Detailed procedures on how to develop a modeling project with the HAWQS can be found in the US-EPA's website (https://hawqs.tamu.edu/#/, accessed on 6 March 2022), whereas elaborated definitions of input parameters in the HAWQS are provided in the SWAT model user manual (https://swat.tamu.edu/docs/, accessed on 6 March 2022). After calibration and validation of the ACFRB model, a simulating scenario was created to assess hydrological processes under the stresses of nine hurricanes and tropical storms. The paths, durations and categories of the hurricanes and tropical storms are shown in Figure 1a.

Principal component analysis (PCA) and principal factor analysis (PFA) are multivariate statistics for identifying important components or factors that describe most of the variances in a system. They can be used to reduce explanatory variables to a small number of principal (or key) variables while preserving the relationship present in the original data [16,17]. PCA was first coined by Pearson (1901), who believed that this was the correct solution to some of the problems that were of interest to biometricians at that time, although he did not propose a practical method of calculation for more than two or three variables [16]. PFA seeks the fewest factors that can account for common variance in a set of variables. The major difference between the two methods is that PFA analyzes only the reliable common variance of data, while PCA analyzes all the variance of data. PCA is a linear combination of variables and PFA is a measurement model of a latent variable [18]. In recent decades, PCA and PFA techniques have widely been used in hydrology and water quality analysis [17,19–22]. In this study, PCA and PFA were applied to identify the hydrological variables affected most by the hurricanes and tropical storms in the R-statistics platform.

2.3. Model Calibration and Validation

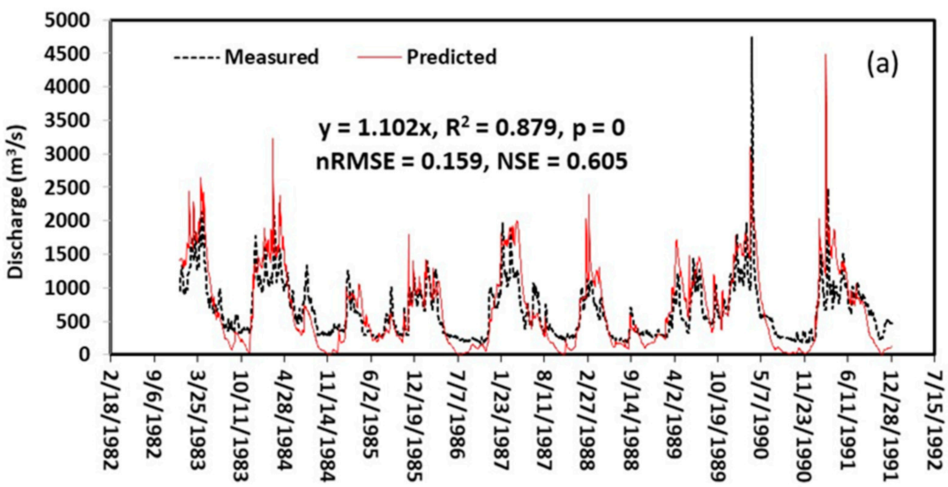
The ACFRB model was manually calibrated by changing input parameter values within an acceptable range to match predicted discharges with observed discharges in the HAWQS. The discharge dataset was downloaded from the USGS Station #02359170 (Figure 1a) in Apalachicola River near Sumatra, FL. The input parameter values used for model calibration are given in Table 1. Figure 2a shows the predicted (Y) and observed (X) daily stream discharges for the near 10-year simulation period from 1 January 1983 to 31 December 1991. The values of R^2, the normalized root mean square error (nRMSE), the Nash–Sutcliffe Efficiency (NSE), and *p*-value were, respectively, 0.879, 0.159, 0.605, and 0, suggesting good agreement was obtained between the predicted and observed daily discharges during model calibration.

Table 1. Major input parameter values used for the ACFRB-HAWQS model.

Parameter	Definition	Value	Unit/Method/Explanation	Reference
SFTMP	Snowfall temperature	1	°C	Local observation
SMTMP	Snow melt base temperature	0.5	°C	Local observation
SMFMX	Melt factor for snow on 21 June	4.5	mm H_2O/°C-day	Local observation
SMFMN	Melt factor for snow on 21 December	4.5	mm H_2O/°C-day	Local observation
TIMP	TIMP: Snow pack temperature lag factor	1		Local observation
IPET	Potential evapotranspiration (PET) method	0	Priestley-Taylor method	
ESCO	Soil evaporation compensation factor	1		Calibrated
EPCO	EPCO: Plant uptake compensation factor	1		Calibrated

Table 1. *Cont.*

Parameter	Definition	Value	Unit/Method/Explanation	Reference
ICN	Daily curve number calculation method	0	Calculate daily CN value as a function of soil moisture	Calibrated
CNCOEF	Plant ET curve number coefficient	2		
ICRK	Crack flow code	0	Do not model crack flow in soil	Local observation
SURLAG	Surface runoff lag time	4	days	Calibrated
CN2	Subbasins curve number	−10%	CN2 decreased 10% for all subbasins	Calibrated
IRTE	Channel water routing method	0	Variable Storage Method	Calibrated
MSK_COL1	Calibration coefficient used to control impact of the storage time constant for normal flow	0		Calibrated
MSK_COL2	Calibration coefficient used to control impact of the storage time constant for low flow	3.5		Calibrated
MSK_X	Weighting factor controlling relative importance of inflow rate and outflow rate in determining water storage in reach segment	0.2		Calibrated
TRNSRCH	Fraction of transmission losses from main channel that enter deep aquifer	0		Calibrated
EVRCH	Reach evaporation adjustment factor	1		
IDEG	Channel degradation code	0	Channel dimension is not updated as a result of degradation	Local observation
Dataset 1	NCDC NWS/NOAA	Measured	Base scenario	Downloaded from HAWQS



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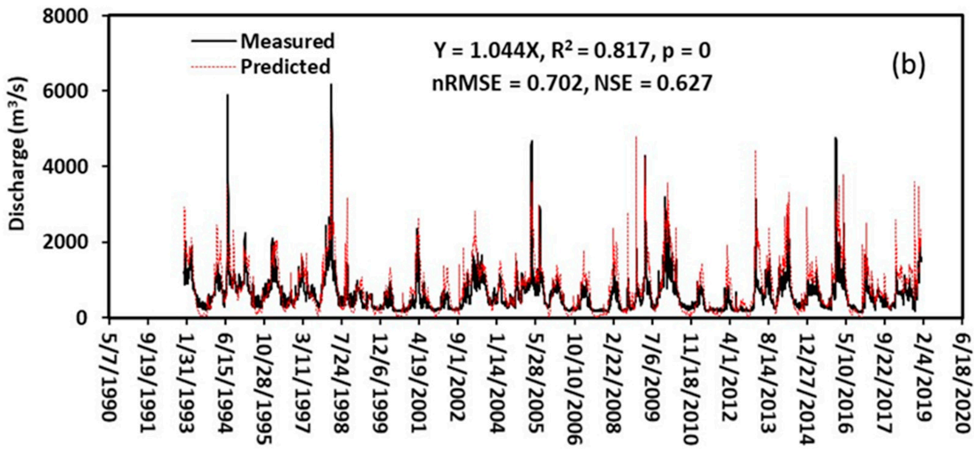


Figure 2. Comparison of the observed and predicted daily discharges during model calibration (**a**) and validation (**b**).

The ACFRB model was validated by comparing the daily stream discharges between model predictions and field observations for a 16-year simulation period from 1 January 1993 to 31 December 2016 (Figure 2b). During model validation, the input parameter values were the same as those used during model calibration. With values of R^2, nRMSE, NSE, and p of 0.817, 0.702, 0.627, and 0, respectively (Figure 2b) that were comparable to those of model calibration, we demonstrated that very good agreement was achieved between the predicted and observed daily discharges during model validation.

3. Results and Discussion

3.1. Impact of Hurricane

Changes in daily observed rainfall and predicted stream discharge one month before, during, and one month after the hurricanes at the outlet of ACFRB are shown in Figure 3. In general, daily stream discharge increased with daily rainfall. For example, the average daily stream discharge was 787 m^3/s (Figure 3g) during Agnes (watershed impact times or WIT: 19–20 June 1972) when the average daily rainfall was 48.9 mm (Figure 3b), while the average daily stream discharge was 2557 m^3/s (Figure 3i) during Earl (WIT: 3 September 1993) when the average daily rainfall was 92.1 mm (Figure 3d). A 1.9-fold increase in daily rainfall increased the daily stream discharge by more than 3.2 folds. This occurred because rainfall is a major driving force for stream discharge. However, the amount of rainfall was not necessarily proportional to the amount of stream discharge during the hurricanes. For instance, the amounts of rainfall and stream discharge were, respectively, 60.7 mm (Figure 3b) and 1220 m^3/s (Figure 3g) on 20 June 1972 for Agnes, whereas the amounts of rainfall and stream discharge were, respectively, 42.3 mm (Figure 3c) and 1943 m^3/s (Figure 3h) on 22 November 1985 for Kate. Apparently, Kate had a higher stream discharge than that of Agnes although the opposite was true for the amount of rainfall. This occurred because there was a much higher amount of rainfall one month before Kate than before Agnes (Figure 3b,c), which resulted in a higher daily average soil water content (SWC) before Kate (SWC = 222 mm on 21 November 1985) than before Agnes (SWC = 110 mm on 18 June 1972). The higher antecedent SWC produced more stream discharge during the hurricanes. The results indicate that rainfall conditions preceding the event also played a role in stream discharge during the hurricanes. Figure 3 further reveals that the category of hurricane was not highly related to the amounts of rainfall and discharge during the hurricanes. The amounts of rainfall and discharge were, respectively, 42.3 mm and 1943 m^3/s during Kate (Category 2) but were, respectively, 92.1 mm and 2461 m^3/s during Earl (Category 1). Although Earl was of a weaker category than Kate, the amounts of rainfall and stream discharge during Earl were much higher than during Kate.

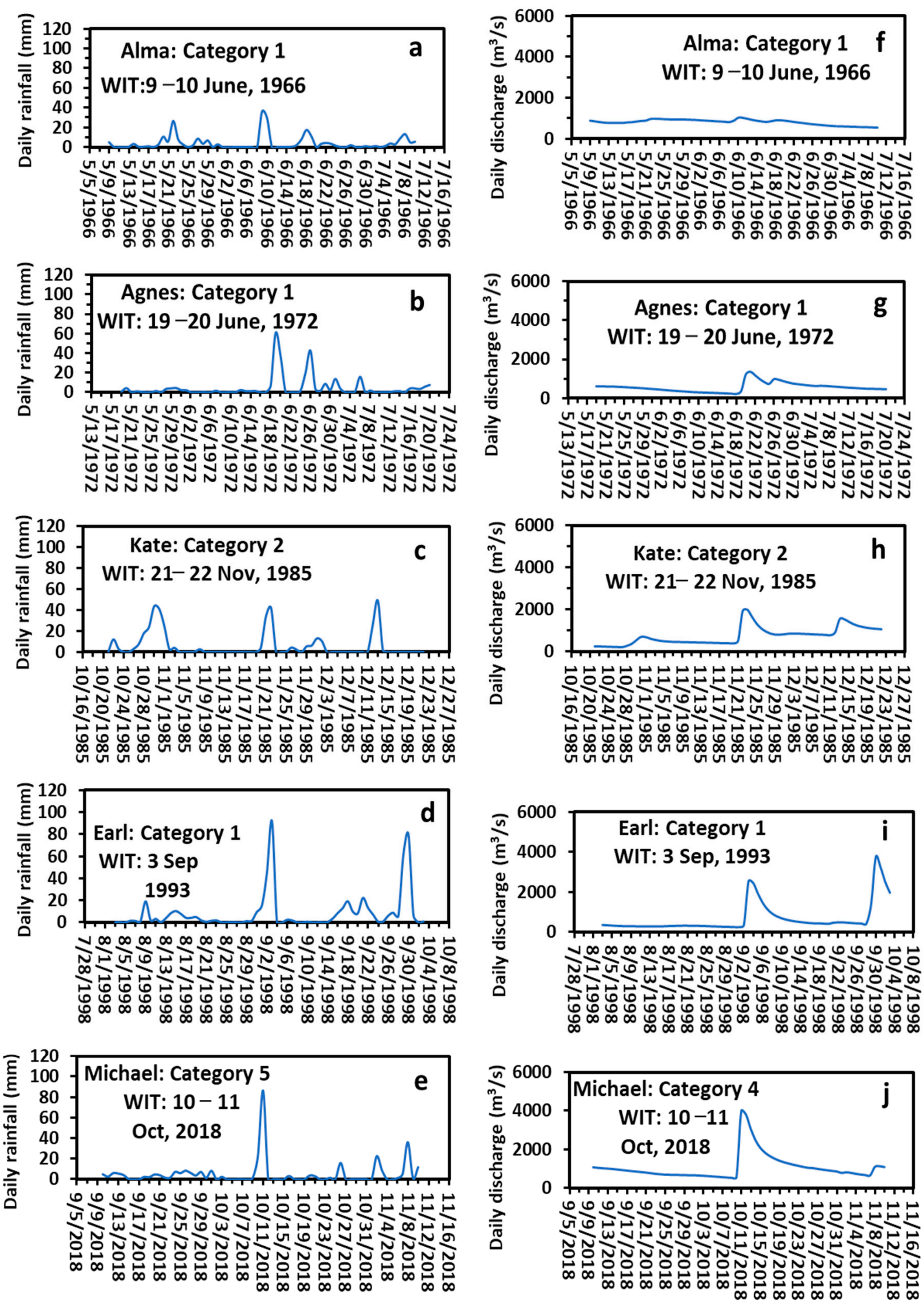


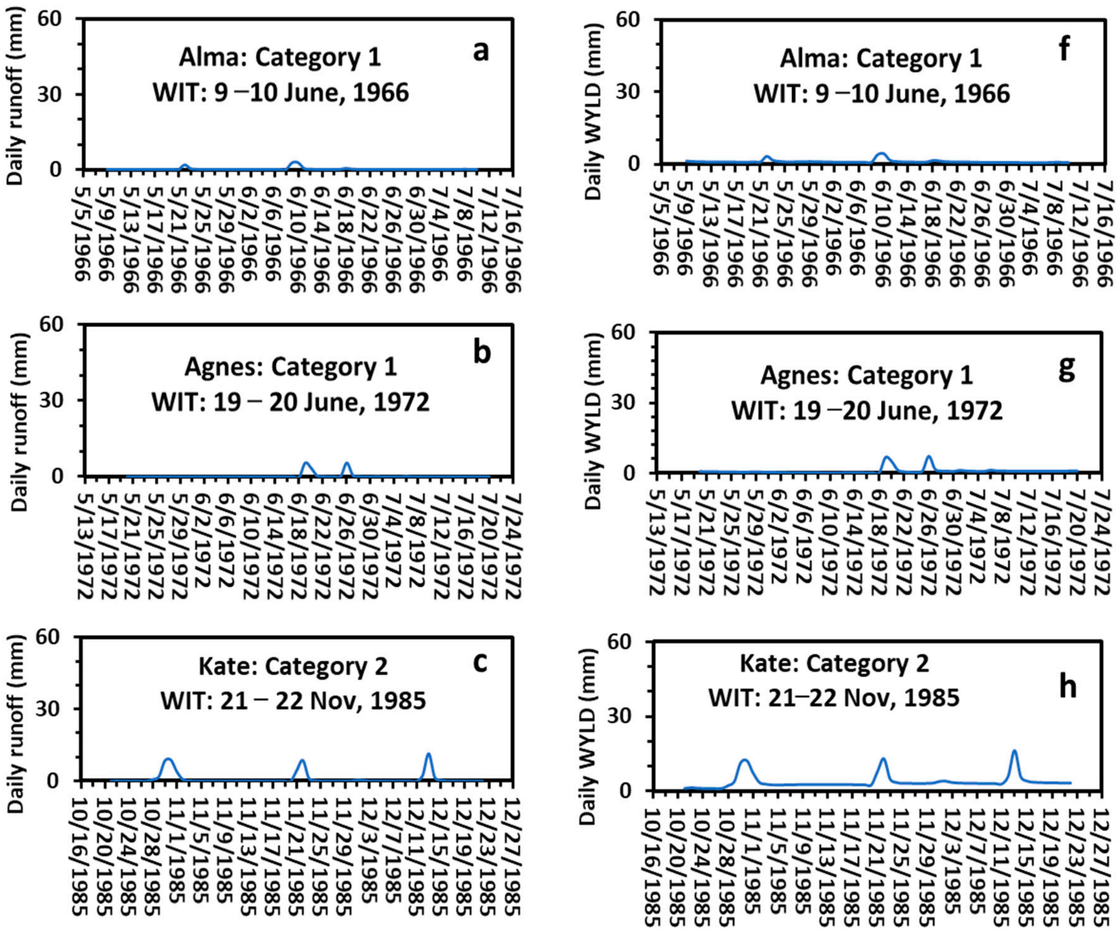
Figure 3. Daily rainfall and stream discharge under five hurricanes from 1966 to 2018. WIT is the watershed impact times.

In most cases, the rate of stream discharge was higher one month after the hurricanes than before the hurricanes. For Agnes, the rate of stream discharge was 206.2 m^3/s on

18 June (just before the hurricane) and 450.1 m^3/s on 20 July 1972 one month after the hurricane (Figure 3g)—approximately 2.18-fold (450.1 ÷ 206.2 = 2.18) higher. Similar results were also observed for Kate, Earl, and Michael (Figure 3h–j). That is, the rates of stream discharge were 2.14-, 5.48-, and 1.97-fold higher one month after Kate, Earl, and Michael than one month before. This occurred because more rainfall events were observed on the watersheds within one month after the hurricanes than before the hurricanes (Figure 3b–e). This also explained why much higher discharge was obtained almost one month after Earl (3751 m^3/s) than during Earl (2461 m^3/s), as shown in Figure 3i.

Similar variation patterns were observed between daily surface runoff and daily water yield (WYLD) one month before, during, and one month after the hurricanes (Figure 4). That is, an increase in surface runoff increased WYLD except that the amount of surface runoff was always lower than that of WYLD. For example, the amount of surface runoff was 8.75 mm on 22 November 1985 during Kate (Figure 4c) when the amount of WYLD was 13 mm (Figure 4h). The former was 48.57% lower than the latter. This occurred because WYLD includes not only surface runoff but also lateral flow and shallow groundwater discharge to reach.

Analogous to the case of stream discharge, the category of hurricane was not related to the amounts of runoff and WYLD during the hurricane. The amounts of runoff and WYLD were, respectively, 8.75 and 13 mm during Kate, which was a Category 2 hurricane (Figure 4c–h), but were, respectively, 29.7 and 32.5 mm during Earl, which was a Category 1 hurricane (Figure 4d–i). Although Earl was a lower category hurricane than Kate, the amounts of runoff and WYLD for Earl were higher than for Kate. It is apparent that the amount of rainfall rather than the category of hurricane was a controlling factor for changes in runoff and WYLD.



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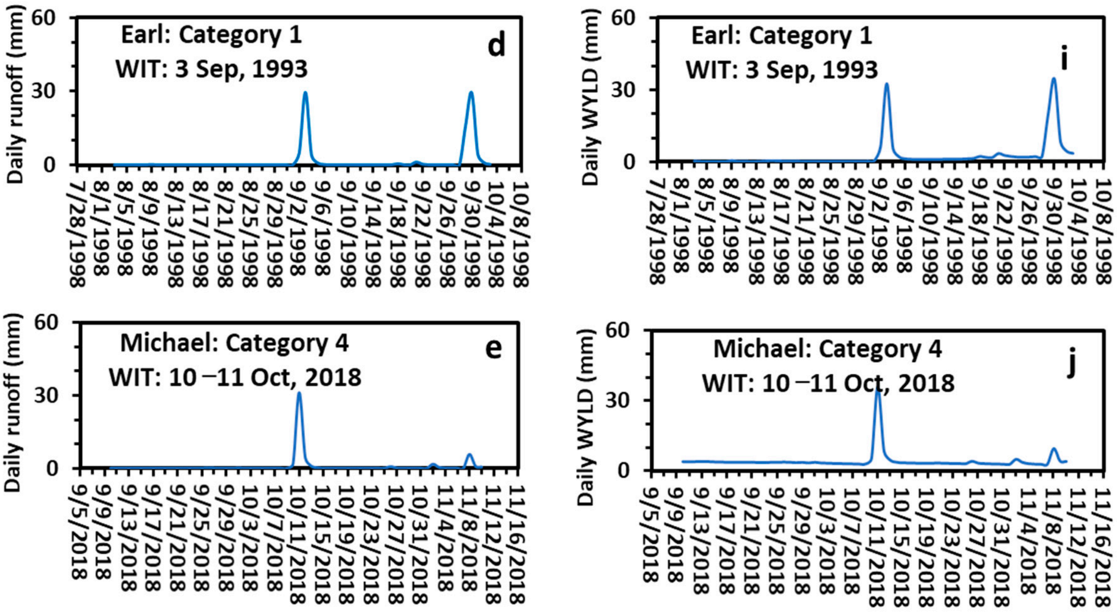

Figure 4. Simulated daily runoff and water yield (WYLD) under five hurricanes from 1966 to 2018. WIT is the watershed impact times.

3.2. Impact of Tropical Storm

Impacts of tropical storms on daily rainfall, stream discharge, runoff, and WYLD one month before, during, and one month after Barry and Fay are shown in Figure 5. Analogous to the impacts of the hurricanes, daily discharge, runoff, and WYLD increased with daily rainfall during tropical storms. Daily discharge was 899.2 m^3/s on 6 August 2001 during Barry (Figure 5b) when the daily rainfall was 53.5 mm (Figure 5a), while daily discharge was 2956 m^3/s on 23 August 2008 during Fay (Figure 5f) when the daily rainfall was 92.6 mm (Figure 5e). A 73% increase in rainfall resulted in a 2.3-fold increase in daily discharge. Comparable results were obtained for runoff and WYLD. That is, daily runoff and WYLD were, respectively, 13.8 mm and 18.3 mm on 6 August 2001 during Barry (Figure 5c,d) when the daily rainfall was 53.5 mm (Figure 5a), while daily runoff and WYLD were, respectively, 33.1 mm and 36.2 mm on 23 August 2008 during Fay (Figure 5g,h) when the daily rainfall was 92.6 mm (Figure 5e). A 73% increase in rainfall resulted in a 2.4- and 2.0-fold increase in daily runoff and WYLD, respectively. Similar results were also obtained for Becky and Bonnie (figures not shown). The results indicate that rainfall was a major driving force for stream discharge, runoff, and WYLD during tropical storms.

Average daily rainfall, runoff, WYLD, and stream discharge one month after the hurricanes compared with one month after the tropical storms are given in Figure 6. Overall, the average amounts of rainfall, runoff, WYLD, and stream discharge one month after the hurricanes were always higher than one month after the tropical storms. However, a Kolmogorov–Smirnov test revealed that the differences were not statistically significant at $\alpha = 0.05$. The results demonstrate that the hurricanes and tropical storms had similar impacts on daily rainfall, runoff, WYLD, and stream discharge.

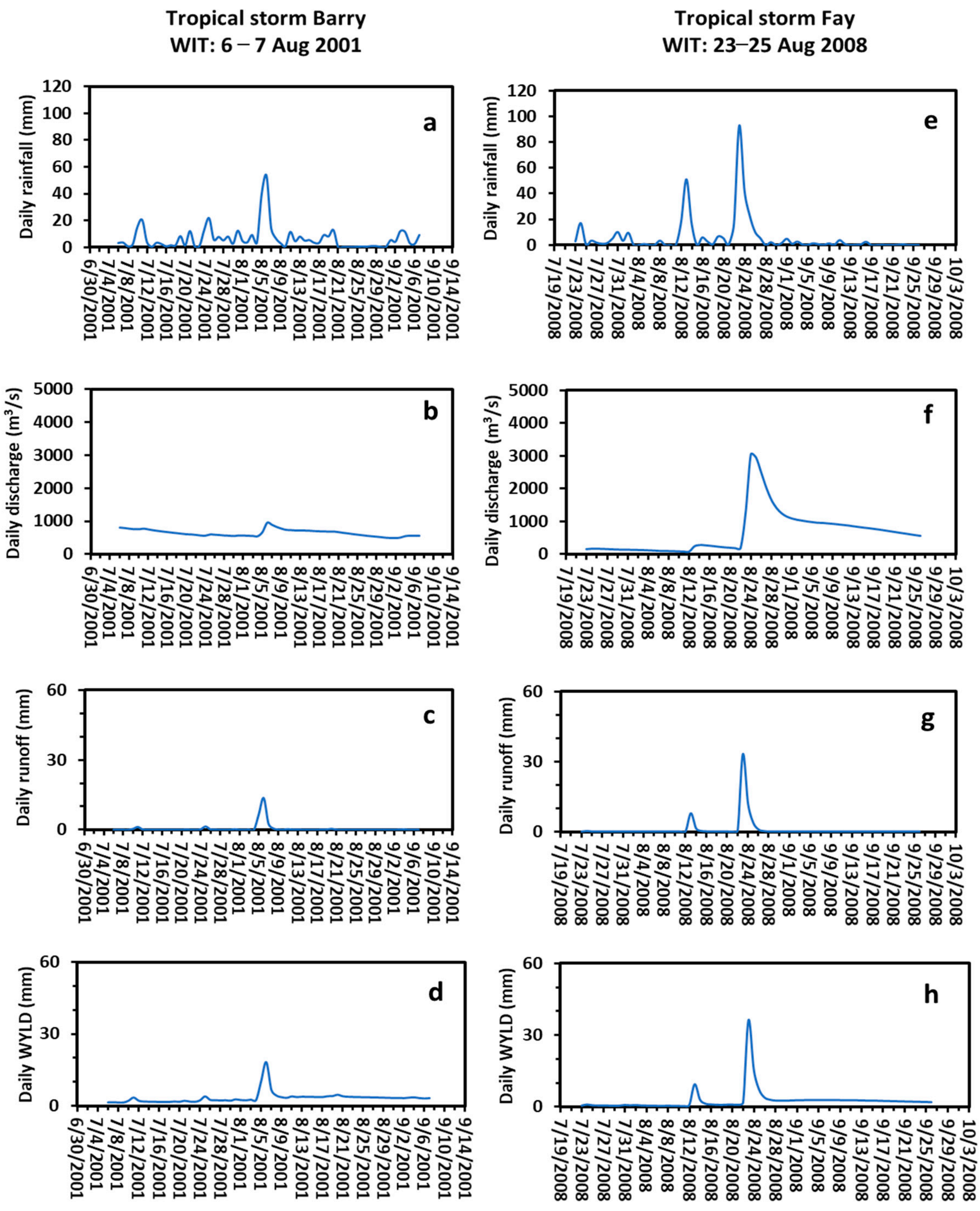

Figure 5. Daily rainfall, stream discharge, surface runoff and water yield (WYLD) under tropical storms Barry and Fay. WIT is the watershed impact times.

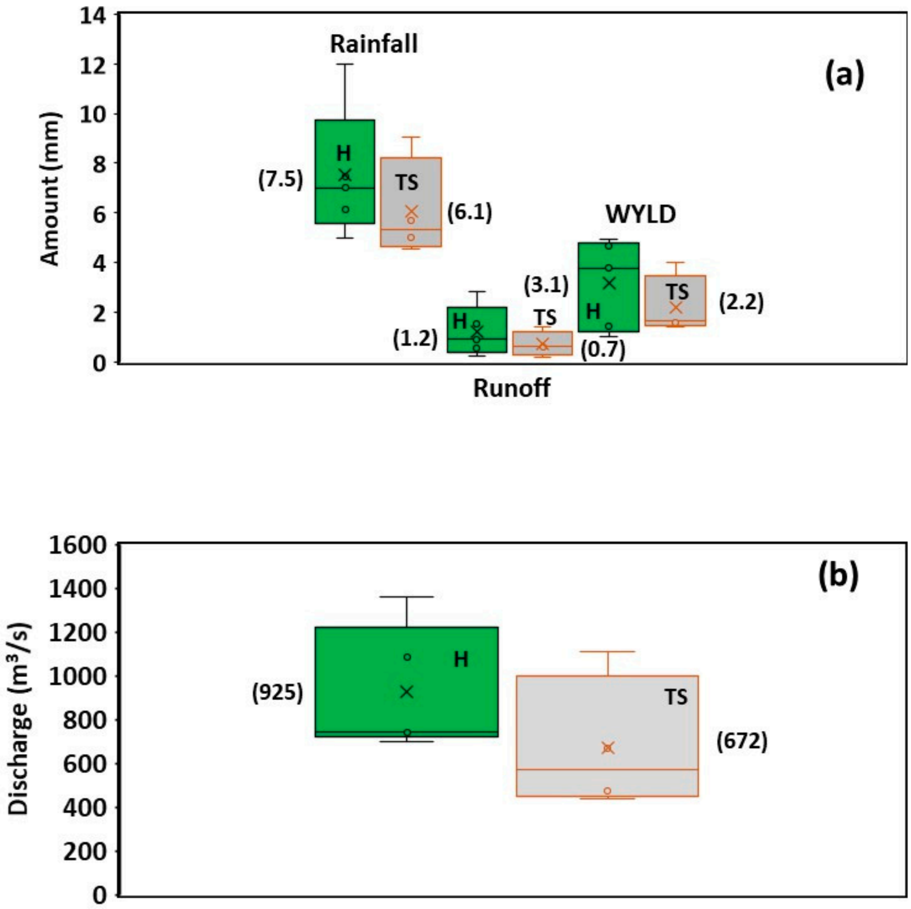

Figure 6. Comparison of (**a**) average daily rainfall, surface runoff and water yield (WYLD) and (**b**) stream discharge between the hurricanes (H) and the tropical storms (TS). The numbers in parentheses are the average values.

3.3. Identification of Most-Impacted Hydrological Variables

Very few studies have been conducted to identify which hydrologic variables are affected most by hurricanes and tropical storms in the literature, which is critical for sustainable water resource and ecosystem management. In this study, eight hydrological variables, namely rainfall, PET, ET, percolation, runoff, groundwater discharge, WYLD and stream discharge, were analyzed with PCA and PFA to identify which hydrological variables were affected most during and one month after the hurricanes and tropical storms. In a PCA, the number of components is equal to the number of variables (or eight components in this case). However, a component is comprised of more than a single variable in a study [15]. Table 2 shows the component loadings of the hydrological variables during and one month after the hurricanes and tropical storms, which were obtained by PCA. Of the 8 components, the first component (PC1) accounted for 68% and the second component (PC2) accounted for 21.1% of the total variance in the dataset. These two components together accounted for 89% of the total variance and the rest of the components accounted for 11% of the total variance. Thus, we should focus on the first two components. For PC1, the component loadings of rainfall, percolation, runoff, groundwater recharge, WYLD, and stream discharge were positive (Table 2), indicating that the hurricanes and tropical storms resulted in increased amounts of these variables, whereas the component loadings of PET and ET were negative (Table 2), specifying that the hurricanes and tropical storms resulted in decreased amounts of these two variables. Apparently, PC1 represents changes in the hydrological variables. For PC2, the component loadings of rainfall, PET, ET, percolation, runoff, and WYLD were negative, while the component loadings of groundwater recharge and stream discharge were positive. This component seemed to measure the effects of the hurricanes and tropical storms on the hydrological variables. In other words, during and one month after the hurricanes and tropical storms, rainfall, PET, ET, percolation, runoff, and WYLD decreased but groundwater discharge and stream discharge increased.

Table 2. Component loading coefficients from principal component analysis. PC denotes principal component and the number refers to the number of components. For example, PC1 is principal component 1.

Parameter	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Precipitation	0.2069	−0.6412	−0.2687	0.4357	−0.1773	0.4809	−0.1419	0.0334
PET	−0.3386	−0.3881	0.4167	−0.0570	−0.0406	−0.3055	−0.6789	0.0437
ET	−0.3712	−0.3020	0.2830	0.0231	0.6968	0.2615	0.3684	−0.0268
Percolation	0.3835	−0.2590	−0.2982	0.1910	0.4423	−0.6787	0.0400	0.0514
Runoff	0.3535	−0.3865	0.1826	−0.6682	−0.1501	0.0260	0.2363	0.4084
Groundwater discharge	0.3724	0.3561	0.1336	0.0644	0.4328	0.3242	−0.4548	0.4618
Water yield (WYLD)	0.4227	−0.0482	0.1373	−0.2963	0.1780	0.1581	−0.2063	−0.7830
Stream discharge	0.3396	0.0380	0.7177	0.4812	−0.2101	−0.1248	0.2765	−0.0210
Proportion of variance	68.0%	21.1%	8.3%	1.2%	1.1%	0.2%	0.1%	0.0%
Cumulative proportion	68.0%	89.0%	97.4%	98.6%	99.6%	99.9%	100.0%	100.0%

While PCA identified that the first two components accounted for 89% of the total variance in the dataset, it did not determine which hydrological variables explained most of the variance. Therefore, PFA was employed to meet this need. Analogous to PCA, the number of factors is equal to the number of variables in PFA. Since there were eight hydrological variables in this study, there were eight factors. Principal factors with an eigenvalue above or close to one [17], a total of three factors, are discussed in our analysis. Table 3 shows the rotated factor correlation coefficients for all eight hydrological variables. The results show that factor 1 accounted for 38.8%, Factor 2 for 31.7%, and Factor 3 for 25.3% of the total variance in the dataset. These three factors together accounted for 95.8% of the total variance. In this study, the factor correlation coefficient is considered significant when it is greater than 0.85 (or 85%). This conservative criterion was used because the ACRFB is a complex river basin. Based on this criterion, rainfall, PET, ET, and stream discharge had coefficient values greater than 0.85 at least from one of the three factors. These hydrological variables were very important in explaining the total variance of the dataset, and were thereby highly affected by the hurricanes and tropical storms. In contrast, percolation, runoff, groundwater discharge and WYLD scored lower than 0.85 for all three factors and were considered less important in explaining the total variance of the dataset and were thereby relatively less affected by hurricanes and tropical storms.

Table 3. Rotated factor correlation coefficients from principal factor analysis.

Parameter	Factor1	Factor2	Factor3	Factor4
Rainfall	−0.0561	0.9664	0.0332	0.0099
PET	−0.9780	−0.0910	−0.1721	−0.0288
ET	−0.9094	−0.1860	−0.2789	0.0953
Percolation	0.5042	0.8049	0.2816	0.1173
Runoff	0.1895	0.7785	0.5517	−0.2223
Groundwater discharge	0.7893	0.0360	0.6029	0.0913

Table 3. *Cont.*

Parameter	Factor1	Factor2	Factor3	Factor4
Water yield	0.5637	0.5173	0.6398	−0.0590
Stream discharge	0.2959	0.1973	0.8702	0.0044
Proportion of variance	38.8%	31.7%	25.3%	1.1%
Cumulative proportion	38.8%	70.5%	95.8%	96.9%

4. Conclusions

The US-EPA's HAWQS model system was applied to develop a model for the Apalachicola–Chattahoochee–Flint River basin (ACFRB) of the Florida panhandle. There was good agreement between model predictions and field measurements during model calibration and validation. A simulation scenario was chosen to estimate the impact of hurricanes and tropical storms on hydrological processes in the last 52 years (from 1966 to 2018).

In general, daily stream discharge increased with daily rainfall and occurred because rainfall is a major driving force for stream discharge. However, the amount of rainfall was not necessarily proportional to the amount of stream discharge during the hurricanes and tropical storms. Rainfall conditions preceding the hurricanes also played a role in stream discharge during the events. The category of hurricane was not highly related to the amounts of daily rainfall, surface runoff, water yield (WYLD), and stream discharge during the hurricanes.

In most cases, the amounts of stream discharge, surface runoff, and WYLD were higher one month after the hurricanes and tropical storms than before the events at the ACFRB and occurred because more rainfall fell on the basin within one month after the events than before the events. It should be noted that there are no scientific reasons for more rainfall events after the hurricanes than before the hurricanes although this finding was observed in the Florida panhandle. Further study is therefore delineate the reasons for this.

The amount of surface runoff was always lower than that of WYLD during the hurricanes and tropical storms because WYLD includes not only surface runoff but also lateral flow and shallow groundwater discharge to reach.

The average amounts of rainfall, runoff, WYLD, and stream discharge one month after the hurricanes were higher than one month after the tropical storms. However, a Kolmogorov–Smirnov test revealed that the differences were not statistically significant at $\alpha = 0.05$. The results demonstrate that the hurricanes and tropical storms had similar impacts on daily rainfall, runoff, WYLD, and stream discharge.

Our PCA showed that rainfall, PET, ET, and stream discharge were highly influenced by the hurricanes and tropical storms, but percolation, runoff, groundwater discharge and WYLD were relatively less influenced by the hurricanes and tropical storms.

It should be noted that only one USGS gage station at the basin outlet and one hydrological variable (i.e., stream discharge) were used for model calibration and validation in this study. Further study is, therefore, warranted to include more gage stations and hydrological variables for such a purpose.

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List of Acronyms

ACFRB	Apalachicola–Chattahoochee–Flint River basin
ET	evapotranspiration
HAWQS	Hydrologic and Water Quality System
PCA	principal component analysis
PET	potential evapotranspiration
PFA	principal factor analysis
TS	tropical storm
WYLD	water yield

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