

## Article

# A Comparison of Streamflow and Baseflow Responses to Land-Use and Climate Change Using SWAT

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**Abstract:** Alteration of land use and climate change are among the main variables affecting watershed hydrology. Characterizing the impacts of climate variation and land use alteration on water resources is essential in managing watersheds. Thus, in this research, streamflow and baseflow responses to climate and land use variation were modeled in two watersheds, the Upper West Branch DuPage River (UWBDR) watershed in Illinois and Walzem Creek watershed in Texas. The variations in streamflow and baseflow were evaluated using the Soil and Water Assessment Tool (SWAT) hydrological model. The alteration in land use between 1992 and 2011 was evaluated using transition matrix analysis. The non-parametric Mann-Kendall test was adopted to investigate changes in meteorological data from 1980-2017. Our results indicated that the baseflow accounted for almost 55.3% and 33.3% of the annual streamflow in the UWBDR and Walzem Creek watersheds, respectively. The contribution of both land use alteration and climate variability on the flow variation is higher in the UWBDR watershed. In Walzem Creek, the alteration in streamflow and baseflow appears to be driven by the effect of urbanization more than that of climate variability. The results reported herein are compared with results reported in recent work by the authors in order to provide necessary information for water resources management planning, as well as soil and water conservation, and to broaden the current understanding of hydrological components variation in different climate regions.

**Keywords:** Streamflow, baseflow, SWAT, urbanization, climate alteration, Mann-Kendall.

## 1. Introduction

Ecosystems and humans are fundamentally dependent on different water resources. Thus, for the general development of any country, the quality and the quantity of these water resources flowing through rivers is of vital importance to socio-economic development [1]. Issues related to changes in water resources are commonly evaluated around the globe [2,3,4]. In the United States, evaluation of streamflow and baseflow have been documented [5,6,7]. However, the quantitative change in streamflow and baseflow has yet to be evaluated across different climatic conditions.

Climate alterations and human actions both act as stressors to place severe pressure on water resources [8,9]. The variations in climate and land use directly impact total streamflow, interflow, surface runoff and baseflow, causing events of droughts and floods that impact the sustainability of these resources and the social ecosystem [10]. Several studies have examined alterations in streamflow due to changes in temperature and precipitation [11,12,13], urbanization [14] and land use change [2,15]. Baseflow is the portion of streamflow sustained in a river by delayed pathways. Baseflow is often assumed to be equal to groundwater recharge [16]. It provides a relatively high water quality with a high clarity and stable temperature, and is considered indicative of sustained streamflow during dry periods of the season, which is important to stream biota and helps recreation based industries [17]. This low-flow data is essential in understanding the current and future changes

to watershed hydrology. Several reports have indicated that the change in baseflow over time is due to variations in agricultural management [18], climate change [8], urbanization [19], and land use alteration [20]. Therefore, in order to develop scenarios for water resources evaluation, land use change and climate variation are usually chosen as the main influencing factors. The impacts of climate variation and urbanization on streamflow and baseflow are reviewed in Aboelnour et al. [8] and Price [21].

Different methods have been used to evaluate the response of watershed streamflow and baseflow to human activities and climate change. These techniques include hydrologic similarities within the watersheds, paired catchments, statistical methods and hydrological modeling [22]. Since climate and land use change need to be investigated on a local scale and can vary from place to place [23], there is a need to use comprehensive and physical tools to evaluate as much information as possible from the limited existing data [24]. Hence, hydrological models are considered the most appealing approach to carry out impact assessment studies. They provide a conceptualized framework and are suitable for use as part of scenario studies on the relationship between hydrological components, climate variability, and land use change [25,26]. Among these models is the Soil and Water Assessment Tool (SWAT) model.

The SWAT model, developed by the United States Department of Agricultural (USDA) Agriculture Research Service, is designed to model hydrology at the scale of a watershed [27]. SWAT is widely used around the world to evaluate the influences of ecological and environmental alterations and for hydrological processes at different catchment scales, even with a limited amount of data [10,28]. In addition, it offers several software tools, and was therefore selected for this research. Each watershed was divided into smaller sub-basins in the SWAT model. These sub-basins were then divided into smaller HRUs that were fundamentally based on land use, soil type and slope [29]. Within each HRU, the Soil Conservation Service (SCS) curve number and Green-Ampt infiltration are adapted to compute surface runoff using daily precipitation. In addition, SWAT subdivides the groundwater system into deep confined aquifers that contribute to flow outside of the catchment, and shallow unconfined ones, in which the groundwater and baseflow return back to the stream [30]. The SWAT model has proven to perform well in streamflow and baseflow simulations around the world and in complex catchments with extreme events [31], since it allows the interconnections of different physical processes [32,33,34]. Therefore, in this research, the SWAT model was adopted to assess the impacts of land use and climate change.

Streamflow and baseflow responses to human activities, urbanization and climate variation are different in various basins with respect to climate regions, geographical variances, scale and urbanization levels [21,35]. However, the need to fully understand the streamflow and baseflow responses to external stimuli is of vital importance. Many studies in the last few years have been carried out to investigate the hydrological response to urbanization and climate change [36,13]. Outputs of these studies can help in understanding the cause of shifts in water resources. However, these studies mainly focus on the single impact of either land use change or climate variation, but neglect the combined effects of climate alteration and human activities and their contributions to the change. Thus, the combined effects are still not fully understood over different climatic conditions and geographical regions. For this reason, the responses of streamflow and baseflow to urbanization and climate variation will be evaluated for varying climate conditions with different urbanization levels. Two watersheds, the Upper West Branch DuPage River (UWBDR) watershed, Illinois, and Walzem Creek watershed, Texas, will be used as examples to quantify the changes in streamflow and baseflow as a response to climate and land use change.

As evidenced by the U.S. Census population data, the Upper West Branch DuPage River (UWBDR) watershed, Illinois, has undergone intense urbanization in the last four decades. In addition to this dramatic urbanization, the watershed has experienced major flood events, such as the floods of 1996 and 2008 [37]. Other incidences in the watershed have been identified as impactful on the development of the UWBDR. One of the main contributors is floodplain management that addressed overbank flooding of the main stream and its tributaries [37]. Hejazi and Markus [38] investigated the impacts of urbanization and climate variability on annual flooding in 12 urban

watersheds in Cook County, northeastern Illinois. They found that urbanization had a greater impact than climate on the increase in flood discharge, and due to increasing urbanization, discharge volume may become even higher in the future. In addition to floodplain management, wetland protection, bank stabilization, stream restoration, water quality, and groundwater recharge are also concerns within the catchments. Some sections of the stream are supplied with a substantial amount of their baseflow from local groundwater discharge, while other sections release baseflow to groundwater due to the presence of a large outwash plain at the base of West Chicago Moraine that creates conditions that promote rapid flooding and groundwater movement from the border of the moraine through the outwash [37].

The second watershed is the Walzem Creek, San Antonio, Texas. The city of San Antonio, Bexar County and other partners initiated a watershed protection plan in 2006 for the Upper San Antonio basin, including the Walzem Creek watershed, to track efforts that enhance urban outreach, and to bring the basin back into compliance with water resource and water quality recreation standards. In 2015, the Environmental Protection Agency (EPA) approved this protection plan, making the state eligible for project funding within the watershed to address nonpoint source runoff. The report can be viewed at <https://www.brwm-tx.org/>. A combination of rocky and clay soils contribute to larger runoff than groundwater flow in this watershed. Rock, clay, and slopes create nearly impervious conditions in the northern portion of the watershed and thus reduce the effect of development and its associated impervious cover on storm water flow [39].

The main target of this study is to evaluate the impact of separate and combined impacts of land use changes and climate alteration on streamflow and baseflow in two watersheds under different land use and climatic conditions. The specific goals of this research are: (1) identify the long term trend and the abrupt changes in hydrological and meteorological data; (2) determine the change in land use maps from 1992 to 2011; (3) use the new calibrated and validated SWAT model to assess the individual and combined impacts of land use change and climate variation on streamflow and baseflow; and (4) compare the outputs of this study with the findings of Aboelnour et al. [8]. Information gleaned from this study can be used to understand the variations in hydrological flow components, and are necessary for water resources management and planning, as well as water and soil conservation in geographically different watersheds.

## 2. Study areas

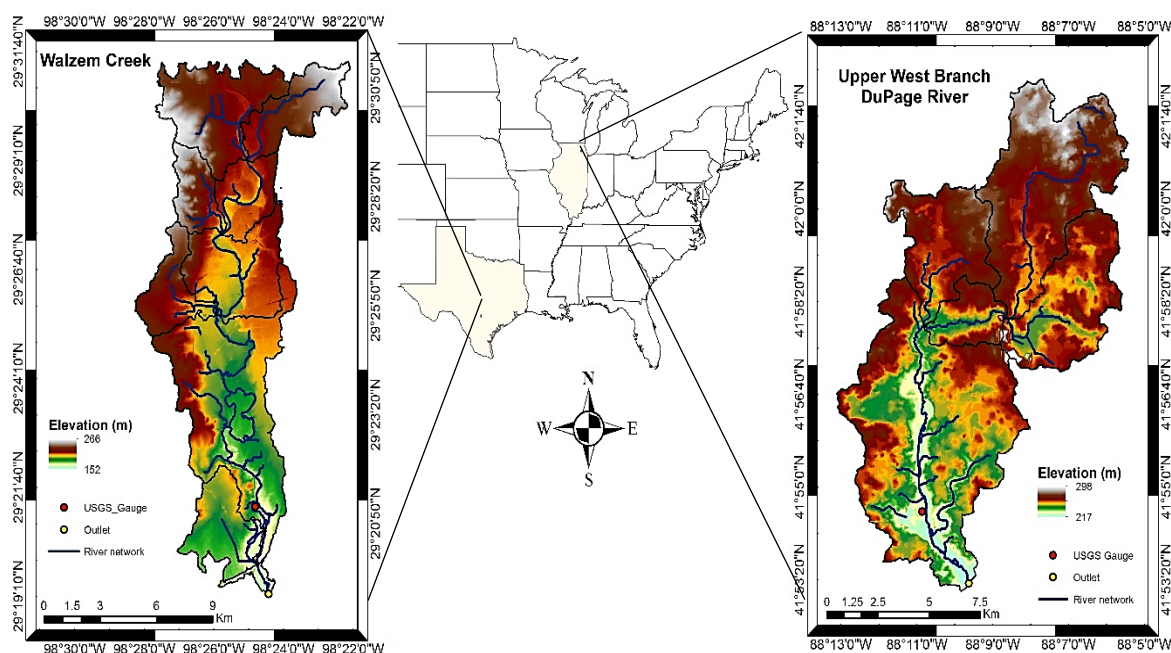
### 2.1 Upper West Branch DuPage River watershed

The Upper West Branch DuPage River watershed (UWBDR) is located in northeast Illinois, within the six-county Chicago metropolitan region. The watershed is located approximately in the western one third of DuPage County (Figure 1). The headwaters originate in the northwestern part of Cook County where the water flows generally to the south into and through DuPage County. The UWBDR is part of the West Branch DuPage River (WBDR) watershed that divides into upper, middle and lower branches within the DuPage catchment and belongs to the Des Plaines River basin. The UWBDR covers approximately 91.7 km<sup>2</sup> (USGS Gauge 05539900) with mean annual precipitation ranging from 612 to 1293 mm from 1980 to 2017, and average annual temperatures ranging from 8.4 to 12.5 °C. The minimum, maximum and mean elevations in the area are 217, 298 and 240 meters above sea level, respectively. Land use varies from residential (77.2%) to forest (4%), vacant (4.1%), and cultivated (2.4%). The river network in the watershed receives treated effluent and wastewater from the cities of West Chicago, Illinois [40].

### 2.2 Walzem Creek

Walzem Creek is located in Bexar County in the state of Texas and in the San Antonio East USGS quad (Figure 1). Currently, except for the lower most portion of the watershed, the majority of Walzem Creek is characterized by dense, urban development. The lower portion of the watershed is characterized by a mix of vegetation and forests and normally dry except during rain events. The Walzem Creek is a part of Upper San Antonio Watershed and covers approximately 109 km<sup>2</sup> (USGS

Gauge 08178800), with a mean annual precipitation ranging from 320 to 1200 mm and average annual temperatures ranging 19.3 to 22.3 °C. Mean elevation in the area is 204 meters, with a minimum and maximum of 152 and 266 meters above sea level, respectively. Similar to the UWBDWR watershed, most of Walzem Creek is covered with developed areas (92.5%); however, other land uses varies from wetlands (7.8%), shrublands (4.5%) and forests (2.8%). This area is a large portion of the Upper San Antonio Watershed, hence, it contributes a large amount of total streamflow. According to the main Koppen-Geiger climate classes for US counties, the San Antonio, Bexar County area lies at the border between warm, humid, equatorial zone and fully hot arid and steppe zone [41]. Therefore, this watershed will be representative of semi-arid regions.



**Figure 1:** Index map showing location of the study watersheds: Upper West Branch DuPage River in Illinois (right) and Walzem Creek in Texas (left)

### 3. Materials and Methods

The data described herein includes spatial topography, Digital Elevation Model (DEM), land use and soil data, and hydro-meteorological data. Data analysis procedures and methods used are detailed extensively in Aboelnour et al. [8]. A flow chart depicting procedures used in this study is summarized in Figure 2.

#### 3.1 Data development

##### 3.1.1 Spatial data

Two raster land use maps for the years 1992 and 2011 were obtained from the National Map Viewer (NMV). Digital Elevation Model (DEM) data were acquired from the Geospatial Data Gateway (GDG) with a resolution of 10 m. Soil Survey Geographic Data (SSURGO) data were used in this research with a resolution ranging from 1:12,000 to 1:63,630. Land use, soil type and slope were then used to divide the delineated sub-basins into a small series of uniform Hydrologic Response Units (HRUs) that represent the smallest representative units within the watershed [42].

##### 3.1.2 Hydro-meteorological data

The required datasets used include daily observed streamflow data at gauged USGS stations for the period 1980 to 2017. The streamflow data were used to separate baseflow from surface runoff, and for the SWAT model calibration and validation. In addition, long-term daily meteorological datasets for the same period (1980-2017) were collected from the National Climate Data Center



(NCDC). The meteorological weather stations were 12 kilometers and 0.8 kilometer away from the borders of the UWBD and Walzem Creek watersheds, respectively.

### 3.2 Methodology

#### 3.2.1 Baseflow separation

Baseflow measurements were separated from daily streamflow data acquired from USGS gauged stations using the automatic baseflow digital filter method (Bflow). The Bflow filter separates streamflow data into baseflow and surface runoff by passing the observed streamflow through the filtering equation three times [43,44]:

$$BF_t = \alpha \times BF_{t-1} + \frac{1 - \alpha}{2} \times (Q_t + Q_{t-1}) \quad (1)$$

where  $BF$  is the baseflow,  $\alpha$  is the filter parameter (0.925),  $Q$  is the total streamflow, and  $t$  is the time step. Equation 1 is applied only when  $BF \leq Q_t$  [45].

#### 3.2.2 Soil and Water Assessment Tool (SWAT) model calibration and validation

The monotonic trends in the historical meteorological data were evaluated using the modified Mann-Kendall (MK) test developed by Hamed and Rao [46]. Based on the abrupt change in the trends in precipitation and temperature using the MK test, the study period from 1980 to 2017 was split into two time spans, 1980 to 1998 and 1999 to 2017, with a breakpoint in 1998. The period 1980–1998 was assigned as a baseline for model calibration and validation. The model simulation time was segmented into a warm up period (1980–1983), calibration period (1984–1993), and validation period (1994–1998). The SWAT model calibration and validation were performed using the land use map of 1992 and streamflow data from 1980 to 1998 for each of the selected watersheds. Model optimization, sensitivity analysis, calibration, validation and uncertainty analysis of parameters were carried out using the Sequential Uncertainty Fitting program algorithm (SUFI-2) approach within the SWAT-CUP interface developed by Abbaspour et al. [47]. Based on Aboelnour et al. [8], the twenty hydrologic parameters listed in Table 1 were used in this study for the UWBD and Walzem Creek watersheds calibration of streamflow and baseflow. However, sensitivity analysis using the SUFI-2 global sensitivity analysis was carried out in the first stage due to the presence of a large number of parameters within the SWAT model [44]. Only parameters sensitive for the watersheds were then used in the calibration process and optimized based on monthly values [48]. Both automatic and manual calibration were carried out to allow qualitative and quantitative comparisons of the values, to fine tune the values of the auto-calibrated parameters, as well as to decrease the differences between the observed and simulated outputs [49].

#### 3.2.3 Model sensitivity analysis

The global sensitivity analysis procedures showed that the sensitive parameters obtained from the LEC in Aboelnour et al. [8] were critical in the case of the UWBD watershed, but with a different rank order. It was also found that these rankings were impacted by the selected objective function in the model. For example, curve number (CN2), soil evaporation compensation factor (ESCO), snowfall temperature (SFTMP), melt factor for snow (SMFMN), baseflow recession constant (ALPHA\_BF), and deep aquifer percolation fraction (RCHRG\_DP) were the most critical parameters in UWBD when KGE was selected to be the objective function incorporated in the model (Table 2). These parameters characterize surface runoff, soil properties and groundwater.

In the case of Walzem Creek, the parameters in Table 2 were consistent with other SWAT parameter sensitivity analyses completed for semi-arid regions. The SWAT model is highly sensitive to surface runoff and basin parameters when the watershed is characterized by inconsistent rainfall events [50,51]. ALPHA\_BF followed by CN2 were the most sensitive parameters in Walzem Creek. In contrast to the other watersheds, snowfall and snow melt parameters were not sensitive in Walzem Creek since there was no persistent snowpack. The high ALPHA\_BF constant in Walzem Creek

indicated a rapid response to groundwater recharge. However, the lower baseflow recession constant in the UWBDR indicated large storage discharge and slow drainage in the shallow aquifer, which might be attributed to the complex geological structure of the watershed such as the presence of folds and faults [36]. The high deep aquifer percolation parameter (RCHRG\_DP) in Walzem Creek indicated the increase of water movement to the deep aquifer. SOL\_AWC represented the soil moisture content and hence played a role in surface runoff and was considered to be directly proportional to the soil's ability to hold water, affecting streamflow.

**Table 1.** SWAT input parameters used for the UWBDR and Walzem Creek watersheds calibration of streamflow and baseflow [8]

Parameter	<sup>1</sup> Ext.	Description	Adjustment	<sup>1</sup> IV	<sup>1</sup> LB	<sup>1</sup> UB
<b>Parameters controlling water balance</b>						
ESCO	hru	Soil evaporation compensation factor	R	0.95	0.01	1
EPCO	hru	Plant uptake compensation factor	R	1	0.01	1
CANMX	hru	Max canopy storage	R	0	0	25
SFTMP	bsn	Snowfall temp	R	1	-5	5
SMTMP	bsn	Snowmelt base temp	R	0.5	-5	5
TIMP	bsn	Snow back temp lag factor	R	1	0.01	1
SMFMX	bsn	Melt factor for snow on June 21	R	4.5	0.01	10
SMFMN	bsn	Melt factor for snow on Dec. 21	R	4.5	0.01	10
<b>Parameters controlling surface water response</b>						
CN2	mgt	Initial SCS Curve number	V	--	-0.25	0.25
SURLAG	bsn	Surface runoff lag coefficient	R	4	0.1	10
<b>Parameters controlling sub-surface water response</b>						
ALPHA_BF	gw	Baseflow alpha factor	R	0.048	0.01	1
GWQMN	gw	Depth of water for return flow	R	1000	0.01	5000
GW_DELAY	gw	Groundwater delay time	R	31	0.1	50
REVAPMN	gw	Depth of water for evaporation	R	750	0.01	250
GW_REVAP	gw	Groundwater evaporation coefficient	R	0.02	0.02	0.2
RCHRG_DP	gw	Deep aquifer percolation fraction	R	0.05	0.01	1
<b>Parameters controlling soil's physical properties</b>						
SOL_AWC	sol	Available water capacity of the soil water	V	--	-0.25	0.25
SOL_K	sol	Saturated hydraulic conductivity	V	--	-0.15	0.15
<b>Parameters controlling channel's physical properties</b>						
CH_K2	rte	Effective hydraulic conductivity	R	0	5	300
CH_N2	rte	Main channel Manning's "n"	R	0.014	0.01	0.15

<sup>1</sup>Ext: Extension, R: Replace by value, V: Multiply by value, IV: Initial values, LB: Lower bound, UB: Upper bound

### 3.2.4 Statistical criteria and model evaluation performance

The performance of the SWAT model can be computed using statistical indices and graphical comparisons [52]. For the simulated streamflow and baseflow, the coefficient of determination ( $R^2$ ), Nash–Sutcliffe model efficiency (ENS), PBIAS and modified Kling–Gupta Efficiency (KGE) were adopted to evaluate the model performance [53,54]. The monthly statistical streamflow and baseflow values for the calibrated models were adopted to evaluate the model performance. The performance of the SWAT model is considered good on a monthly basis when  $R^2 > 0.75$ ; ENS and KGE  $> 0.7$ ; and PBIAS  $\leq 15$  according to Moriasi et al. [55] and Thirel et al. [56].

**Table 2.** Top 10 optimized SWAT sensitive parameter values in the UWBDP watershed and Walzem Creek watershed

UWBDP Watershed					Walzem Creek Watershed				
Rank	Parameter	Fitted	t-stat	p value	Rank	Parameter	Fitted	t-stat	p value
1	ALPHA_BF	0.81	44.71	0	1	CN2	-0.10	-24.87	0.00
2	CN2	0.02	18.47	0	2	ESCO	0.99	5.78	0.00
3	CH_K2	28.39	-13.34	0	3	SFTMP	0.31	-3.12	0.00
4	CH_N2	0.08	-4.72	0	4	SMFMN	0.86	-2.79	0.01
5	SOL_AWC	-0.17	-4.13	0	5	ALPHA_BF	0.23	-2.51	0.01
6	RCHRG_DP	0.01	-3.16	0	6	RCHRG_DP	0.01	2.47	0.01
7	EPCO	0.16	-2.99	0	7	SOL_AWC	0.03	-2.07	0.04
8	SMTMP	-1.51	2.48	0.01	8	GW_DELAY	32.14	-0.78	0.44
9	SFTMP	4.90	-2.24	0.03	9	SURLAG	0.92	0.75	0.45
10	CANMX	23.27	1.95	0.05	10	CANMX	0.31	-0.74	0.46

### 3.2.5 Scenarios separating the impact of land use change and climate change

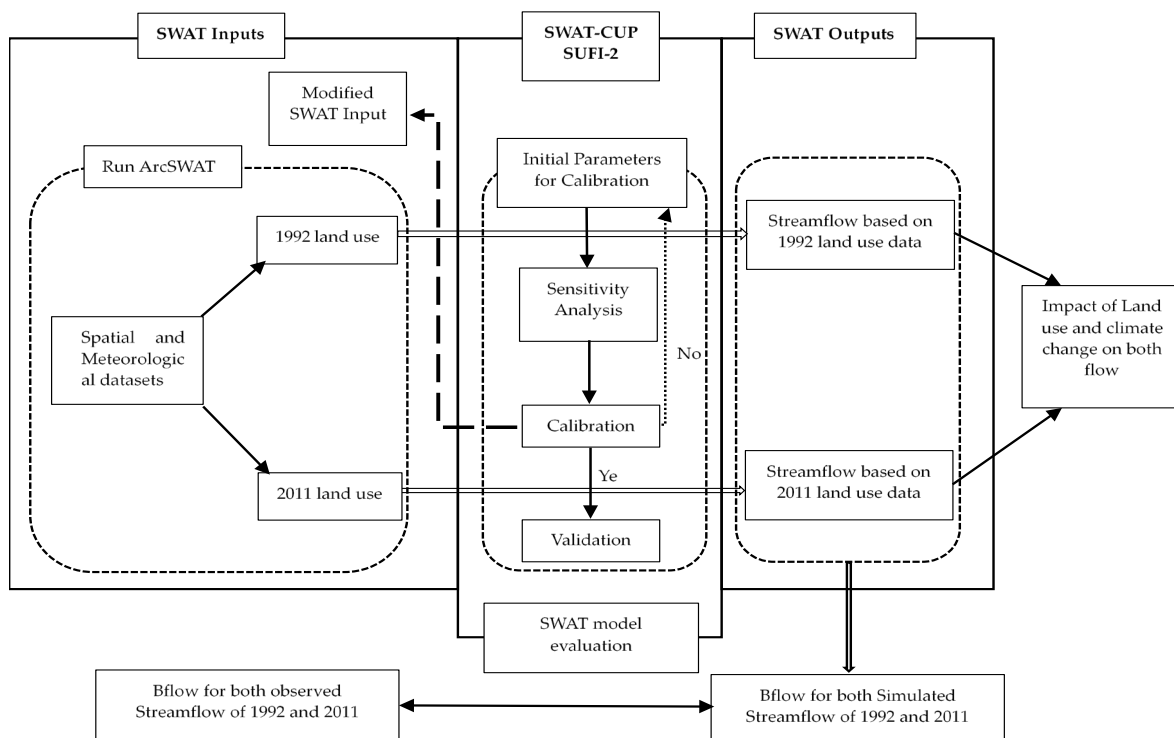
In this research, the “change-fix” approach used in Aboelnour et al. [8] was applied in order to evaluate the streamflow and baseflow as a response to separate and combined impacts of urbanization and climate alteration. Land use maps of 1992 and 2011 were used to represent the two time periods. The land use map of 1992 was adopted to represent the patterns in the first period (1980–1998), herein called TS1. On the other hand, the 2011 land use map was used to represent the second time span (1999–2017), herein called TS2.

A combination of four simulations were developed to evaluate the natural and human impacts on hydrology: (1) 1992 land use and TS1 climate data of 1980–1998 (X1); (2) 2011 land use and TS1 climate data of 1980–1998 (X2); (3) 1992 land use and TS2 climate data of 1999–2017 (X3); and (4) 2011 land use and TS2 climate data of 1999–2017 (X4). The well-calibrated SWAT model, using the land use data of 1992 and first climate period, was used to run the other four scenarios (X1 to X4). The simulated output values obtained from these scenarios were compared to the corresponding baseline model. X1 represents the baseline scenario with the corresponding circumstances, while the difference between X4 and X1 simulation describes the combined effects of land use change and climate variation. The comparison between X1 and X2 attempts to depict the separate impact of land use change. Finally, the differences between X3 and X1 outputs emphasize the individual impact of climate alteration.

## 3. Results and discussion

### 3.1. Trends in hydrologic components

Statistical analyses were performed on climatological variables using the modified non-parametric Mann–Kendall (MK) test [46] to evaluate possible transition points, trends and their significance in the time series from 1980 to 2017. The modified MK test statistic,  $\tau$ , is standardized and can be used in comparing variables that experience differences in their magnitude [57]. A positive slope magnitude indicates an upward trend and vice versa [58]. As shown in Table 3, the slope and the  $\tau$ -statistics for annual streamflow and baseflow were all positive, except for the baseflow trend in Walzem Creek which showed a significant decrease in monotonic trend. However, the null hypothesis was accepted in the case of annual streamflow, as it showed an insignificant increasing trend (Figure 3). Results also showed that the annual baseflow increased at a significance level greater than 0.1 for the UWBDP watershed, which indicates a slightly increasing trend. However, a significant increasing trend in streamflow during 1980–2017 was detected for the UWBDP watershed (Figure 3).



**Figure 2:** Flow chart showing the methodology used in this study (modified from Aboelnour et al. [8])

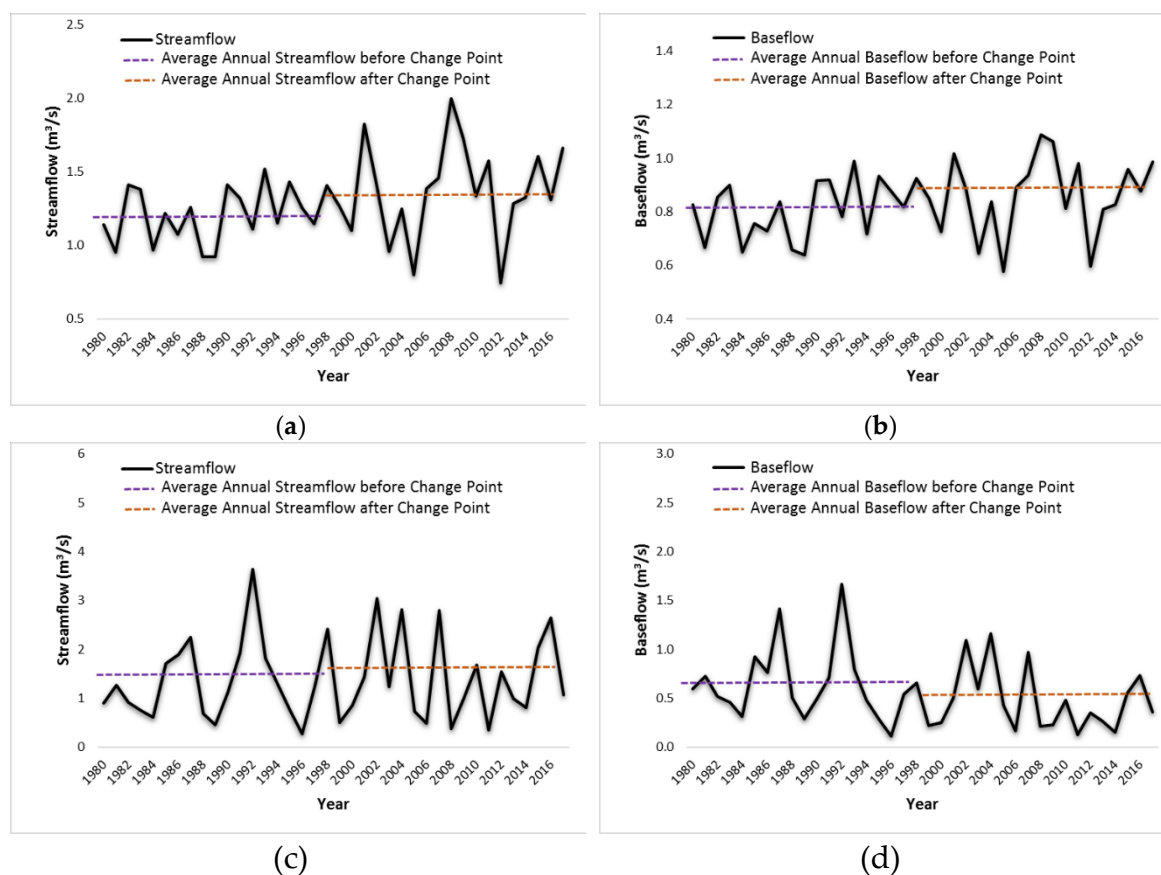
**Table 3.** Temporal trends in annual streamflow and baseflow in the study areas

		Streamflow	Baseflow
<b>UWBDR watershed</b>	$\tau$ -Stat	2.238	1.848
	Slope	3.195	1.301
	$\alpha$	<b>0.001</b>	> 0.1
<b>Walzem Creek</b>	$\tau$ -Stat	0.277	-1.961
	Slope	2.043	-3.335
	$\alpha$	> 0.1	<b>0.001</b>

The increase in average precipitation played an important role in the increasing trend of streamflow for the UWBDR watershed, while the slight increase in streamflow at Walzem Creek was accompanied by decreased precipitation. Moreover, human activity, such as construction of urban areas on agricultural areas, played a vital role in the amount of streamflow and baseflow.

The relationship between baseflow and human impacts and climate change varied. Results here showed similar trends with the findings of Ficklin et al. [1], indicating that baseflow exhibits a negative trend over time in the southern part of the US, while having a positive one in the central US. The reduction of annual baseflow in the Walzem Creek watershed may be attributed to the reduction of cultivated area and implementation of imperviousness, which in turn has a negative impact on the infiltration rate by increasing the surface runoff, specifically during the wet season of the year [49]. On the other hand, the increasing trend in the annual baseflow in the UWBDR was similar to the trend of the Little Eagle Creek (LEC) watershed mentioned in Aboelnour et al. [8]. It might be attributed to the influx of water from outside the watershed during the process of urban development and infrastructure, leakage from water supply pipes, detention basins, in addition to physiological features including topography, geology and soil type which can play a significant role in increasing infiltration [59].



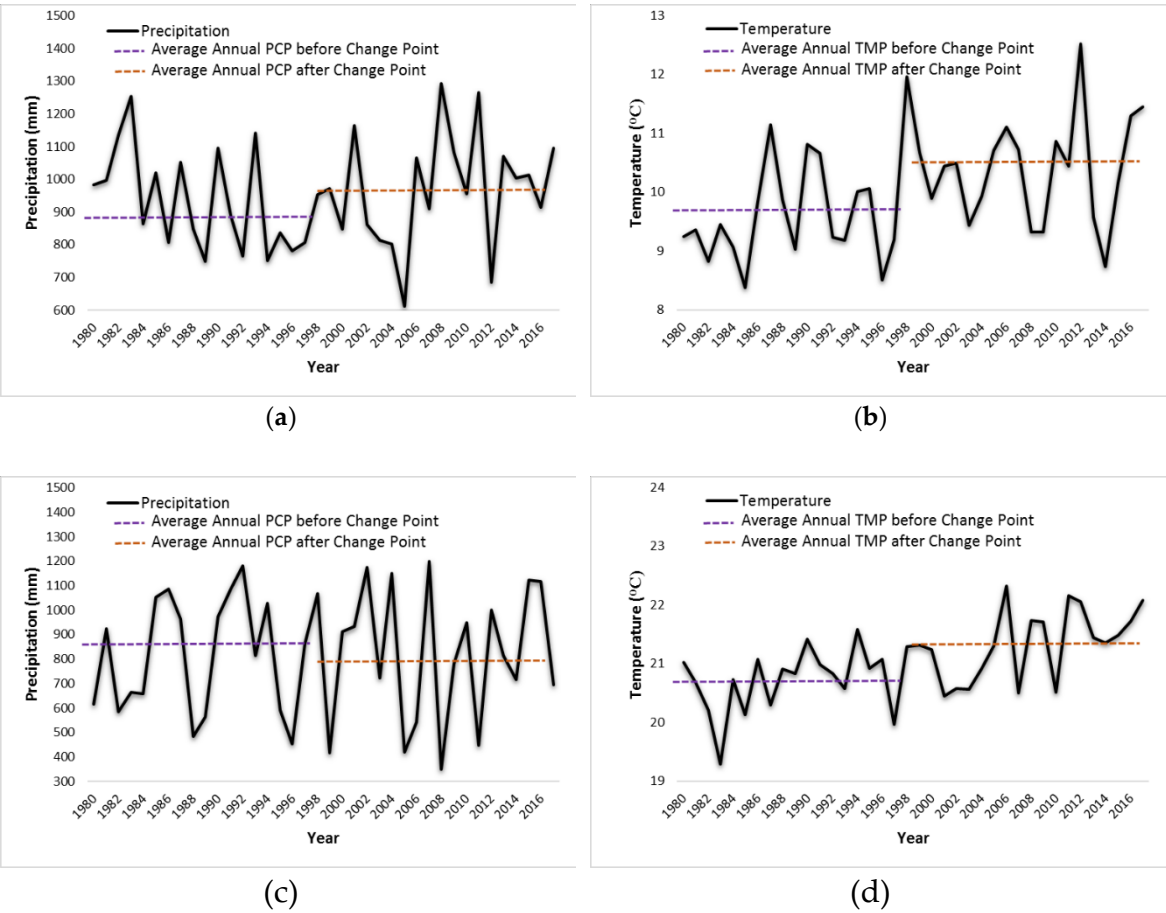


**Figure 3.** The MK trends for average daily streamflow (a) and baseflow (b) in the UWBD watershed; average daily streamflow (c) and baseflow (d) in the Walzem Creek watershed

### 3.2. Trends in climatic components

The MK test was furthermore employed to quantify the monotonic trends of precipitation and temperature in the selected watersheds. Compared to the first climate period (1980–1998), statistical results indicated that the mean air temperature increased by 0.7 °C (from 9.7 °C to 10.4 °C) and 0.6 °C (from 20.7 °C to 21.3 °C) during TS2 at the UWBD and Walzem Creek watersheds, respectively. Average annual precipitation increased by 9.1% (82 mm, from 890 mm to 972 mm) during TS2 in the UWBD, while decreasing by 6.5% (56 mm, from 858 mm to 802 mm) in Walzem Creek (Figure 4).

In the case of UWBD, the trend of  $\tau$ -test statistics and the slope of precipitation and temperature were positive and are provided in Table 4. The results show a difference in the monotonic trends of annual temperature and precipitation. For the time series from 1980 to 2017, the annual air temperature increased at a significance level greater than 0.001, which indicates that the long-term trend of temperature is statistically significant. The annual precipitation increased only at a significance level greater than 0.1, indicating a minor increase of precipitation over time and that the trend is statistically insignificant at the 95% confidence level. On the other hand, the average annual precipitation after the change point in Walzem Creek exhibited a slight decrease from the average before the change point. However, the temperature at Walzem Creek showed an increasing trend at the 0.001 significance level, which indicates that the climate at Walzem Creek became warmer and drier during the study period. While the average annual precipitation and temperatures shifted over time, these trends may not reflect the true picture as the change displayed in both may have been seasonally influenced [60]. Therefore, the MK test was further performed at a monthly scale for time series data from 1980 to 2017 (Table 5).



**Figure 4.** The MK trends for annual precipitation (a) and temperature (b) in the UWBDP watershed; and annual precipitation (c) and temperature (d) in the Walzem Creek watershed

**Table 4.** Temporal trends in annual precipitation and temperature in the study areas

		Precipitation	Temperature
UWBDR	$\tau$ -Stat	0.503	2.709
	Slope	0.821	0.037
	$\alpha$	> 0.1	<b>0.001</b>
Walzem	$\tau$ -Stat	0.327	3.640
	Slope	1.179	0.036
	$\alpha$	> 0.1	<b>0.001</b>

**Table 5.** Summary of significance test and trend analysis for monthly precipitation and temperature in the UWBDR and Walzem Creek watersheds

		UWBDR				Walzem Creek			
		$\tau$ -Stat	Slope	Sig	<i>p</i> -value	$\tau$ -Stat	Slope	Sig	<i>p</i> -value
Jan	PRCP	1.245	0.551	NS	0.106	0.704	0.564	NS	0.240
	TEMP	0.805	0.045	NS	0.210	1.722	0.051	NS	0.042
Feb	PRCP	0.905	0.409	NS	0.183	-0.905	-0.142	NS	0.183
	TEMP	0.339	0.005	NS	0.367	2.351	0.071	S	0.009
Mar	PRCP	0.126	0.035	NS	0.450	0.855	0.248	NS	0.196
	TEMP	0.729	0.043	NS	0.233	1.685	0.048	NS	0.046
Apr	PRCP	0.805	0.425	NS	0.211	0.629	0.992	NS	0.265
	TEMP	1.383	0.036	NS	0.083	1.722	0.038	NS	0.043
May	PRCP	1.584	0.988	NS	0.057	-0.704	-0.268	NS	0.241
	TEMP	0.981	0.024	NS	0.163	0.893	0.017	NS	0.186
Jun	PRCP	1.534	1.364	NS	0.061	-1.282	-1.678	NS	0.100
	TEMP	2.012	0.051	S	0.022	1.798	0.03	NS	0.036
Jul	PRCP	-0.427	0.581	NS	0.335	0.729	0.741	NS	0.233
	TEMP	0.465	0.014	NS	0.321	1.031	0.013	NS	0.151
Aug	PRCP	-0.805	-1.349	NS	0.210	-0.641	0.493	NS	0.261
	TEMP	1.358	0.021	NS	0.087	1.585	0.025	NS	0.056
Sep	PRCP	-0.855	-0.442	NS	0.196	1.383	1.52	NS	0.083
	TEMP	2.364	0.054	S	0.009	1.245	0.019	NS	0.107
Oct	PRCP	0.151	0.25	NS	0.440	-0.930	-0.547	NS	0.176
	TEMP	2.087	0.058	S	0.018	1.207	0.031	NS	0.114
Nov	PRCP	-2.024	-1.669	S	0.021	-1.471	-0.504	NS	0.071
	TEMP	1.320	0.043	NS	0.093	1.886	0.042	NS	0.030
Dec	PRCP	-0.226	-0.324	NS	0.411	0.176	-0.238	NS	0.430
	TEMP	0.566	0.051	NS	0.286	1.119	0.04	NS	0.132

<sup>1</sup> Significant level ( $\alpha$ ) = 0.05. S: Significant. NS: Not significant

### 3.3. Changes in land use characteristics

Cross tabulation analysis and post classification comparison were applied to evaluate the quantity of temporal conversions and nature of changes from one land cover category to another in land use maps of 1992 and 2011 [61,62]. In the UWBDR, a comparison of land use maps for the years 1992 and 2011 indicated that the most significant changes occurred in three classes: developed urban, planted and forest (Figure 5). In 1992, the main land use types were planted and developed areas, which occupied 76.1% of the total watershed area. However, owing to urban expansion, the proportional extent of developed areas increased from 44% to 77% from 1992 to 2011. Conversely, the proportional extent of planted and forest decreased from 35.8% to 2.7% and from 8.1% to 4.4%, respectively. The transition matrix of UWBDR land use in Table 6 explains these changes in detail. 43.6% or 39.9 km<sup>2</sup> of the developed area in 1992 remained unchanged, whereas 27.7 km<sup>2</sup> (30.2%) and 5.38 km<sup>2</sup> (5.9%) of the planted and forest areas, respectively, were primarily converted to developed urban areas from 1992 to 2011. In hydrological modeling, uncertainties in land use data is determined by the sensitivity of the model output to different land use data inputs. Some uncertainties might be associated with different classification algorithms used in both 1992 and 2011 NLCD land use data.

Therefore, the presence of low percentages of land use changes between 1992 and 2011 will be omitted. Uncertainties and accuracies in NLCD data are also dependent on the interpretation of the person(s) collecting the information and therefore may be assessed differently depending on how it was analyzed. Some uncertainties, therefore, might be applicable to the intended application, while others may have no effects [63].

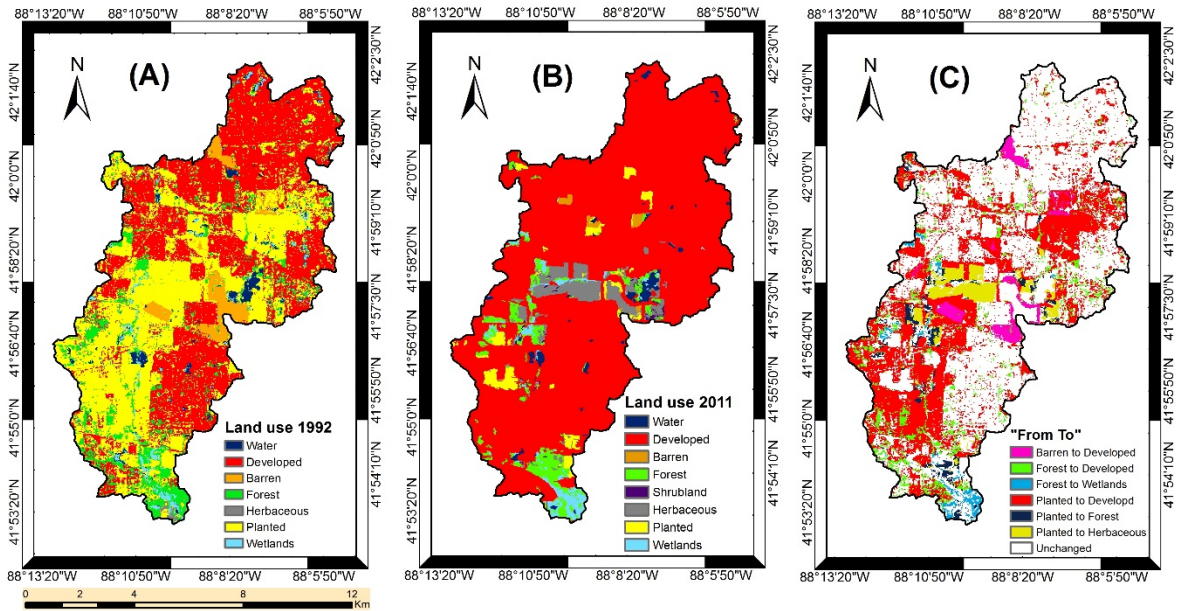


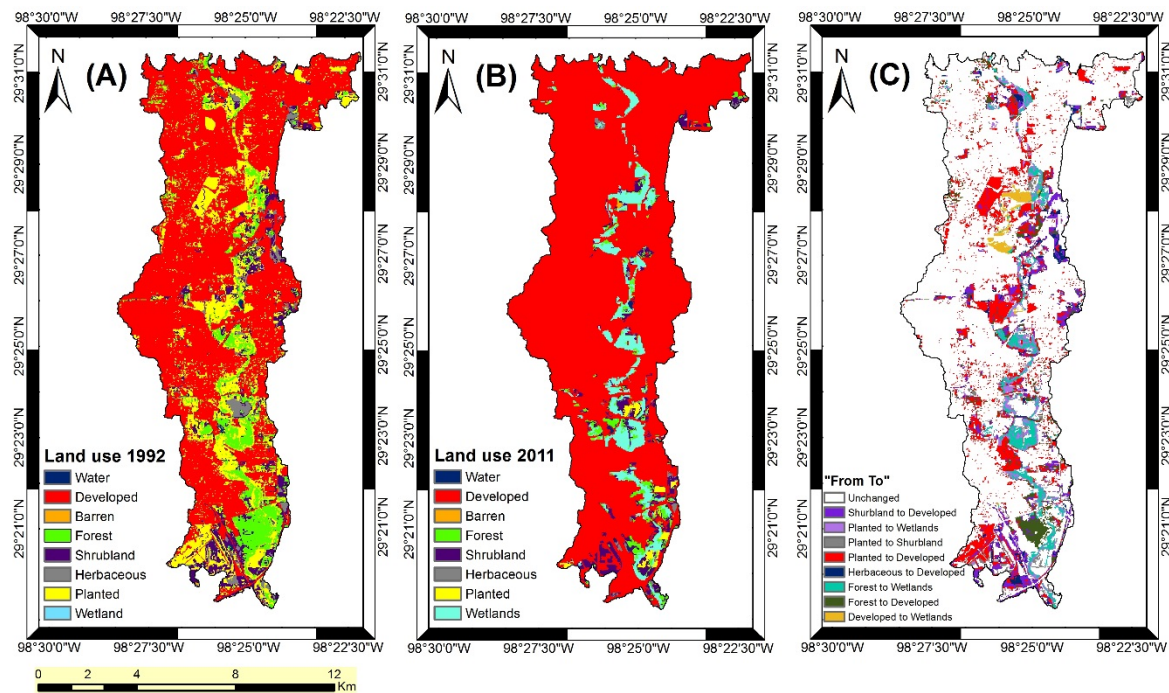
Figure 5. Land use types in the UWBD watershed in (A) 1992; (B) 2011 and (C) the transition between 1992 and 2011

Table 6. Transition matrix (in percentages) of land use change in UWBD from 1992 to 2011

1992	2011								
	Water	Developed	Barren	Forest	Shrubland	Herbs	Planted	Wetlands	Total
Water	0.77	0.82	0.01	0.08	0.00	0.07	0.14	0.11	2.00
Developed	0.04	43.56	0.00	0.22	0.00	0.08	0.14	0.01	44.06
Barren	0.01	2.59	0.07	0.03	0.01	0.65	0.21	0.02	3.59
Forest	0.07	5.87	0.00	1.52	0.01	0.11	0.16	1.09	8.82
Herbs	0.01	0.39	0.00	0.16	0.00	0.02	0.00	0.10	0.69
Planted	0.20	30.25	0.47	2.03	0.23	3.52	1.96	0.35	39.01
Wetlands	0.24	0.76	0.01	0.36	0.01	0.07	0.03	0.36	1.84
Total	1.34	84.24	0.56	4.40	0.26	4.52	2.65	2.04	

The Walzem Creek watershed also underwent some land use changes over the past few decades (Figure 6). During the 20-year period, developed and planted areas were the two largest land use types, and they accounted for approximately 64% and 17% of the total area, respectively. The planted areas shrunk from 1992 to 2011 by 18.3 km<sup>2</sup>. Developed and wetland areas had the greatest increase from 64% to 92% and from approximately 0% to 7.8%, respectively. These increases were due to a large scale, continuous decrease in planted areas (19.2% to 0.8% of the watershed area) and a gradual decrease in forests (9.5% to 2.5%). The increase in wetland areas mostly occurred after 2006 (from 0.06 km<sup>2</sup> to 7.82 km<sup>2</sup>) due to the ecological restoration program for watershed protection that enhanced the urban reaches, bringing the basin back into compliance with water resources and water quality recreation standards. On the other hand, developed areas increased to the detriment of planted and cultivated areas due to the rapid urban development and expansion in the city of San Antonio (Table 7).





**Figure 6.** Land use types in the Walzem Creek watershed in (A) 1992; (B) 2011 and (C) the transition between 1992 and 2011

**Table 7.** Transition matrix (in percentages) of land use change in Walzem Creek from 1992 to 2011

1992	2011								
	Water	Developed	Barren	Forest	Shrubland	Herbs	Planted	Wetlands	Total
Water	0.09	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.18
Developed	0.00	62.63	0.05	0.26	0.38	0.05	0.09	0.95	64.40
Barren	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.09
Forest	0.00	3.42	0.00	1.15	0.61	0.05	0.11	3.32	8.66
Herbs	0.00	1.32	0.00	0.05	0.43	0.12	0.21	0.00	2.13
Shrubland	0.00	4.79	0.00	0.23	1.47	0.09	0.12	0.26	6.95
Planted	0.00	12.15	0.00	0.87	1.26	0.29	0.29	2.64	17.50
Wetlands	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.09
Total	0.09	84.57	0.05	2.55	4.16	0.59	0.82	7.17	

3.4. SWAT Model calibration and validation results

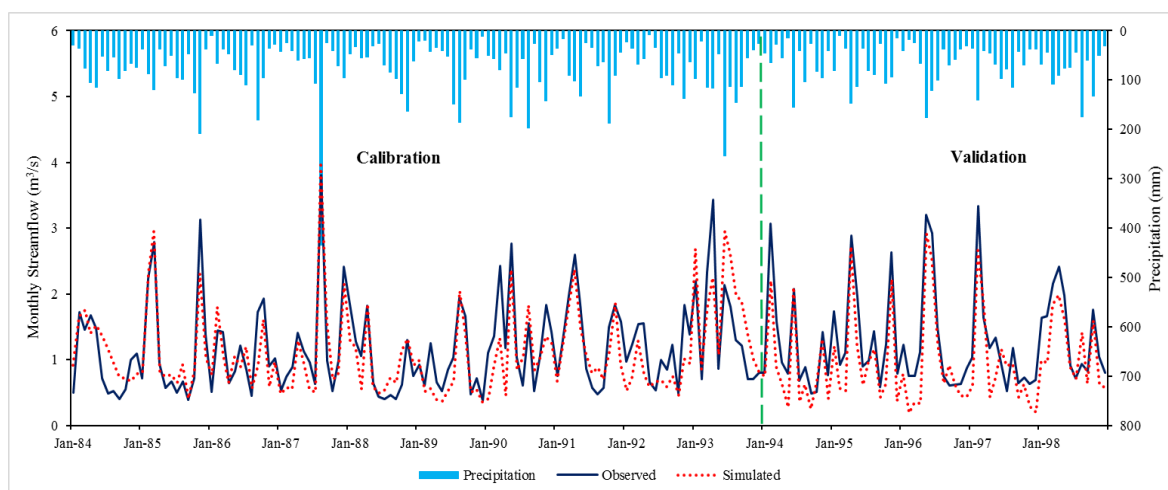
At the UWBDR, the total observed and simulated streamflow during the calibration period were 7.52 m<sup>3</sup>/s and 7.60 m<sup>3</sup>/s, respectively. The resulting hydrograph from SWAT streamflow in the UWBDR also showed agreement in trends between the two (Figure 7). The best calibration achieved was an R<sup>2</sup> of 0.69, PBIAS of 4.86, ENS of 0.67 and KGE of 0.82. Note that KGE was used as an objective function type in the SUFI-2 calibration and validation because it could be decomposed into three terms that represented the correlation, bias and relative variability between the measured and simulated values [64]. Hence, it allowed the simultaneous use of baseflow and streamflow in calibration and enabled comparison between different strategies. The summed observed and simulated streamflow during the validation period were 9.03 m<sup>3</sup>/s and 8.27 m<sup>3</sup>/s, respectively. Streamflow validation showed a higher performance than the calibration with an R<sup>2</sup> of 0.84, PBIAS of 23.1, ENS of 0.68 and KGE of 0.67 (Table 8).

On the other hand, the total annual baseflow during the calibration and validation periods for both measured and simulated data were 8.02 m<sup>3</sup>/s and 7.82 m<sup>3</sup>/s, respectively. Goodness-of-fit

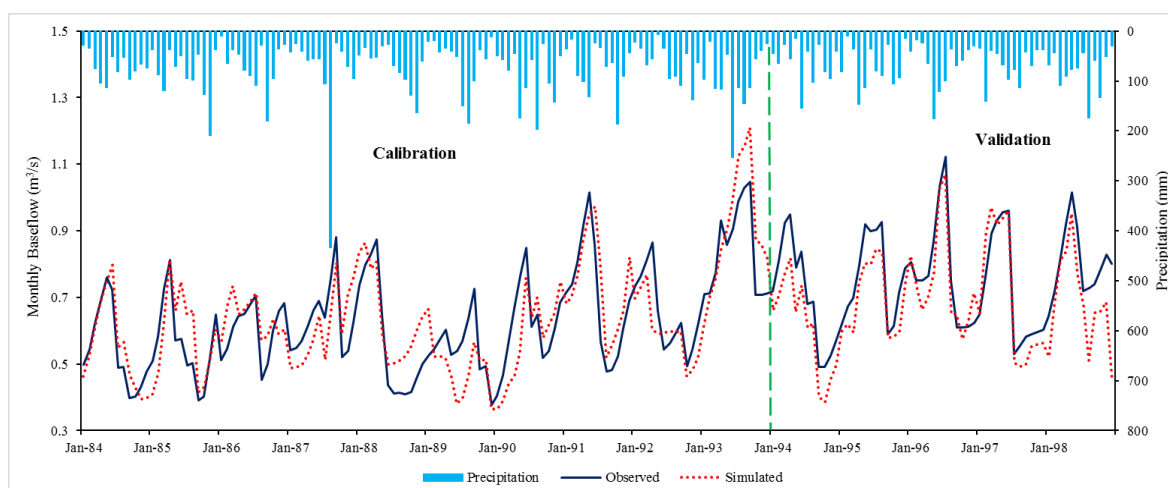


measures were evaluated to test the performance of baseflow predictions. The  $R^2$  for the calibration period was 0.67, with a PBIAS of -1.08, ENS of 0.60 and KGE of 0.80 (Table 8). Figure 8 shows the results of model calibration and validation of baseflow at the UWBDR. Overall, there was reasonably good agreement between computed and simulated baseflow. Further, the model performance was validated using data for the subsequent time period. It was observed that the computed baseflow from the USGS streamflow values were reasonably close to the simulated ones. The evaluation indices  $R^2$ , PBIAS, ENS and KGE were 0.79, 8.43, 0.58 and 0.79 for the baseflow of the validation period, respectively.

In general, the results suggested that the SWAT model performed satisfactorily in the UWBDR watershed according to the criteria set by Moriasi et al. [52]. However, the model underestimated the simulated streamflow for the validation period at a monthly time step during low streamflow, which indicates that there may be uncertainty in the results of SWAT simulations for urban watersheds. The lower performance of the SWAT model in the UWBDR may be attributed to the fact that the climate data obtained from the main weather station were located outside the basin, and the distribution of the climate stations with a complete record was sparse. In addition, the overestimation of some peaks in baseflow could be related to the existence of the West Chicago Moraine outwash plain, creating circumstances that promote fast groundwater movement from the moraine through the outwash. Ratios of baseflow to the total annual streamflow were 55.3% and 60.8% for both measured and simulated streamflow, respectively. This discrepancy is acceptable because all of the separation methods of baseflow using different filters are subject to uncertainties [36].



**Figure 7.** Observed and simulated time series streamflow for the UWBDR watershed during calibration and validation periods



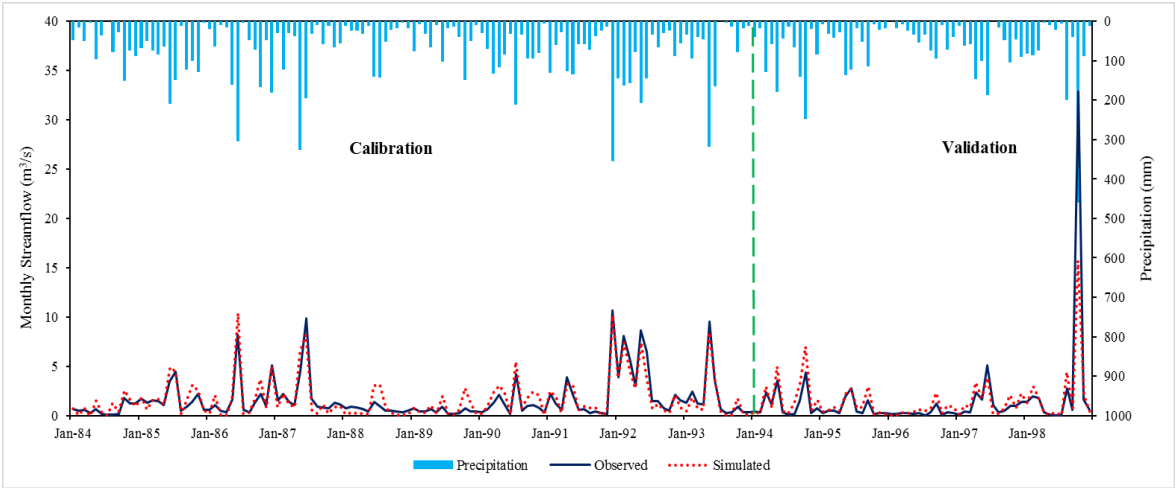
**Figure 8.** Observed and simulated time series baseflow for the UWBDR watershed during calibration and validation periods

Unlike the UWBD and the LEC watersheds in Aboelnour et al. [8], the baseflow proportion of the observed and simulated streamflow at the Walzem Creek watershed were 33.3% and 26.8%, respectively, which indicated that surface runoff was a major supply component for the stream. Figure 9 shows the comparison between the simulated and observed monthly streamflow for the calibration and validation periods. USGS records show that the total monthly streamflow for Walzem Creek was 18.7 m<sup>3</sup>/s, while the simulated one was 19.5 m<sup>3</sup>/s. However, streamflow was overestimated for most of the light rainfall events (dry climate periods) and showed very good agreement with the large rainfall events (wet periods). Previous studies have shown that SWAT performed better under more humid climatic conditions [65,66]. In addition, SWAT has some problems with precisely accounting for water loss through infiltration and evapotranspiration, especially during dry climate seasons, and evaluating the soil moisture storage [67,68].

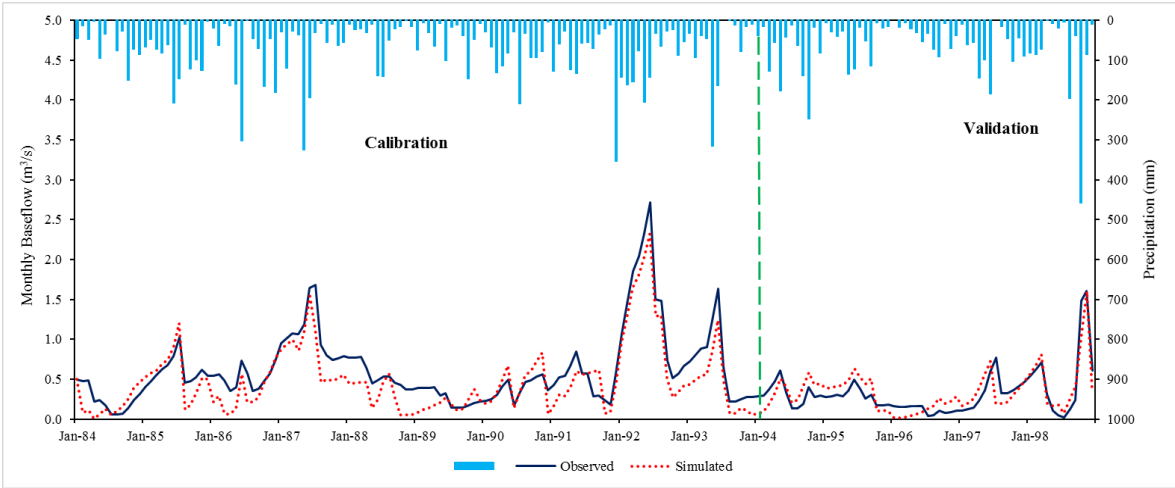
During the streamflow calibration period, the R<sup>2</sup>, ENS, PBIAS and KGE were 0.87, 0.87, -4.31 and 0.91, respectively, while they were 0.83, -3.83, 0.70 and 0.52 during the validation period (Table 8). The SWAT performance for the monthly streamflow during both the calibration and validation periods was very good [52]. Moreover, the high values of R<sup>2</sup> and ENS in the calibration and validation periods indicated that, with calibrated parameters, the SWAT model was useful to simulate streamflow in semi-arid regions and to further quantify the hydrological impacts of climate variation and land use change over water balance components. Although the SWAT performance for the streamflow validation period was not as good as the calibration period, results showed that its performance was still good, implying that SWAT is applicable to Walzem Creek. The reason that SWAT validation performance was less than the calibration performance is most likely due to the occurrence of an extreme flooding event in October 1998, in which a strong flood killed at least 25 people and caused hundreds of millions of dollars in damages across counties in the southern and eastern regions of San Antonio. The SWAT model poorly matched the peak flow of this large event.

Results also indicated that the simulated values of baseflow were slightly lower than those of the computed ones from observed USGS records. The computed monthly baseflow from USGS records and the simulated one were 6.23 m<sup>3</sup>/s and 5.22 m<sup>3</sup>/s, respectively, during the whole calibration and validation periods. Figure 10 shows the comparison between the simulated and the computed monthly baseflow values at the Walzem Creek watershed in the calibration and validation periods. In the calibration period, the baseflow of the computed and simulated results had a similar trend. Meanwhile, the values of R<sup>2</sup>, ENS, PBIAS and KGE were 0.85, 21.65, 0.76 and 0.70, respectively, with a P-factor of 70% and R-factor of 0.62. In the validation period, these measures were 0.70, -5.12, 0.68 and 0.79, respectively. The statistical measure results indicated a 'very good' to 'good' match between the simulated baseflow in the calibration and validation periods and the computed records [52]. However, SWAT overestimated the computed baseflow during the validation period, which was exemplified in the negative values of PBIAS. The statistical indicator and the similar trend between the computed and simulated results showed that the SWAT model was adequate in the semi-arid region of Walzem Creek, and confirmed that the optimized and calibrated model can be applied to evaluate the responses of the basin's hydrology to land use and climate change.

However, considering the study area was in a semi-arid region and only one meteorological station within the catchment was used, it was hard to detect whether the climatic conditions in the entire watershed were precisely captured. In addition, the design of the SWAT model may not fully capture the groundwater flow characteristics. However, the outputs are expected to be accurate and reliable since the model was calibrated and validated using observed streamflow.



**Figure 9.** Observed and simulated time series streamflow for the Walzem Creek watershed during calibration and validation periods



**Figure 10.** Observed and simulated time series baseflow for the Walzem Creek watershed during calibration and validation periods

**Table 8.** Statistical indicators for calibration and validation periods for streamflow and baseflow in the UWBDR watershed and Walzem Creek watershed

Period			Streamflow (m³/s)				Baseflow (m³/s)			
			R²	ENS	PBIAS	KGE	R²	ENS	PBIAS	KGE
UWBDR	Calibration	(1984-1993)	0.69	0.67	4.9	0.82	0.67	0.60	-1.1	0.80
	Validation	(1994-1998)	0.84	23.09	0.7	0.67	0.79	0.58	8.4	0.79
Walzem	Calibration	(1984-1993)	0.87	0.87	-4.3	0.91	0.85	0.76	21.6	0.70
	Validation	(1994-1998)	0.83	0.70	-3.8	0.54	0.70	0.68	-5.12	0.79

3.5. Impacts of land use change

The SWAT simulation suggested that the conversion of the existing planted land cover to urban areas in the UWBDR watershed caused a minor increase in the annual mean water yield by 0.5% (Table 9). The variation could be explained by the reduction in the extent of forests and planted areas and implementation of imperviousness, leading to the reduction of evapotranspiration and infiltration, and increase in surface runoff. However, the reduction of evapotranspiration and the increase in surface runoff considered not significant at the UWBDR watershed. This could explain the minor increase in the annual mean water yield at the area. Other than the total water yield, the SWAT simulation also suggested a considerable change in baseflow due to the effect of urbanization.

It was observed that baseflow increased by 2 mm (accounting for 3.0%) when only the effect of land use dynamics between the two different periods was considered.

Figures 11 and 12 show the distribution of the monthly average water yield and baseflow simulated by SWAT, respectively, for the four scenarios for the UWBD. We observed that the average monthly water yield was concentrated in the late fall/spring seasons and accounted for 29% in the land use change scenario (X2). The change in water yield tended to be positive under the X2 scenario except for the winter season. On the other hand, land use change had minimal effect on baseflow, with no obvious change between X1 and X2. Baseflow variation showed increasing trends in warm months from May to September, then decreased from October to April. Such increase may be attributed to leakage from an outwash plain at the base of West Chicago Moraine and the increased precipitation during the wet season.

The results in Table 10 show that the average annual water yield increased by 15.5% due to the urbanization effect in Walzem Creek (X2-X1). Meanwhile, urbanization caused the baseflow to experience a dramatic increase by 186.8%. Based on the proposed approach, the average annual evapotranspiration and surface runoff variability during the three scenarios were further analyzed to provide deeper insight into how climate and land use dynamics interacted with hydrologic systems in Walzem Creek watershed. In semi-arid regions, hydrologic systems could be very sensitive to climate variability. Evapotranspiration was an important component of the hydrologic process, often nearly equaling precipitation in the catchment water balance, and under given climate conditions, it was mainly affected by vegetation cover [69]. Under the same precipitation conditions, decreased evapotranspiration brought an increase in baseflow and streamflow, while increased evapotranspiration led to the reduction in both [70]. This is illustrated in our finding shown in Table 12, in which evapotranspiration experienced a reduction by 2.4% due to the land use alteration.

Figure 13 illustrates the monthly impacts of land use change, climate and their joint effect on Walzem Creek's water yield. Land use change had a more pronounced effect for all months in conjunction with a higher monthly average of rainfall in the first period of time (TS1). For example, the monthly average precipitation in June was 120.2 mm in TS1, and decreased to 75.0 mm in TS2. The contribution of land use impacts on monthly water yield were the highest in February, June, October, and December. Conversely, deforestation and urban expansion resulted in a major increase in monthly baseflow in all months from January to July with a total of 68.8% (Figure 14).

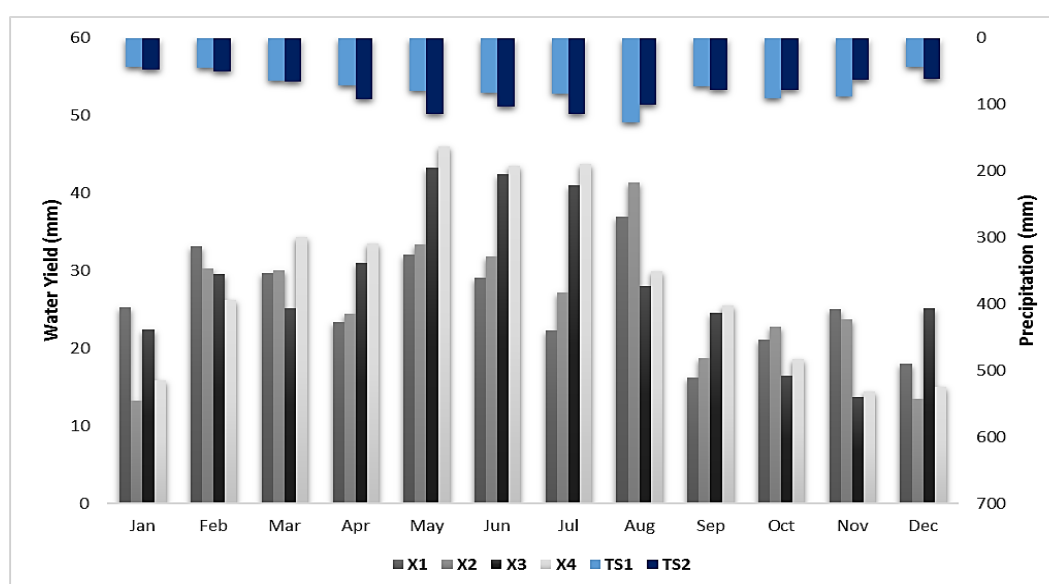
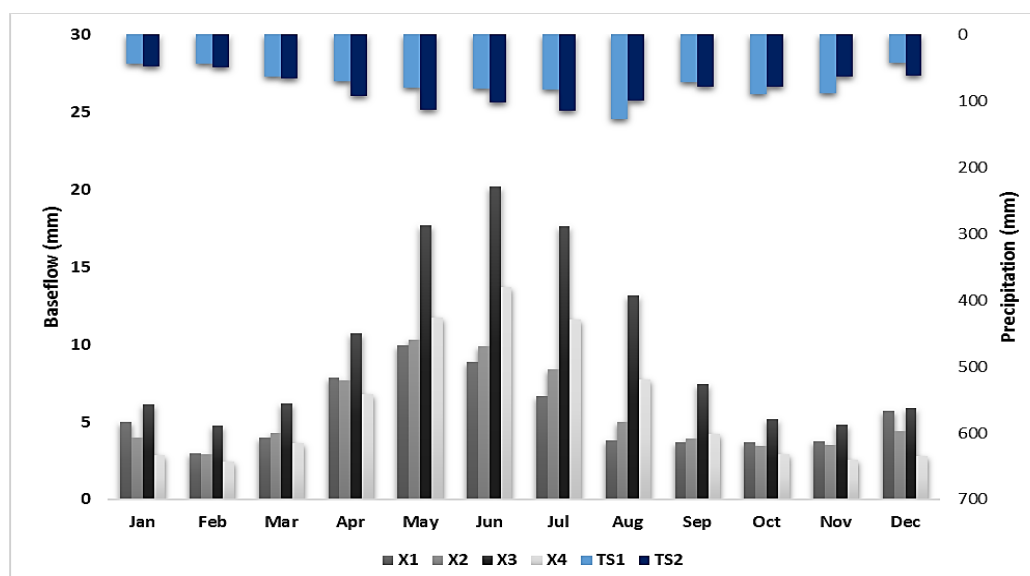
The streamflow changes in the UWBD watershed appeared to occur in the same manner as changes for the LEC watershed discussed in Aboelnour et al. [8], with some minor differences (Figure 15). For instance, under X2, streamflow was reduced in winter months by 5.4% to 35.8%. In addition, the average annual water year experienced an increase of 6.7% in the LEC watershed, while it was simulated to be only 0.5% and 15.5% in the UWBD watershed and Walzem Creek watershed, respectively. In contrast to the LEC watershed which showed a reduction in average annual baseflow due to urbanization by 28.8%, both the UWBD watershed and Walzem Creek watershed experienced an average increase in baseflow regardless of the urbanization trend, especially in the semi-arid Walzem Creek watershed. The reduction in baseflow in the LEC watershed could be caused by over-exploitation, and excessive pumping of groundwater used in industry and production [7], while the minor increase in average annual baseflow in the UWBD might be attributed to flooding of underground structure and the leakage of the groundwater into wastewater systems. While the significant increase in average annual baseflow at Walzem Creek might be due to clearing vegetation or planting non-native vegetation which in turn led to the reduction of evapotranspiration. In addition, construction of practices such as rain gardens, swales, piping of roof runoff to underground layers and irrigation from water tanks can mimic natural infiltration and thereby increase groundwater discharge [59].

**Table 9.** Average annual change in water yield and baseflow in the UWBDR watershed.

Scenario	Land Use	Climate	Water Yield (mm)			Baseflow (mm)			Evapotranspiration (mm)			Surface Runoff (mm)		
			Av.	Ch. Δ	(%)	Av.	Ch. Δ	(%)	Av.	Ch. Δ	(%)	Av.	Ch. Δ	(%)
X1	1992	TS1	312.6	-	-	65.9	-	-	568.6	-	-	238.3	-	-
X2	2011	TS1	314.1	1.5	0.5	67.9	2.0	3.0	567.8	-0.8	-0.1	240.86	2.59	1.1
X3	1992	TS2	343.4	30.8	9.9	119.7	53.8	81.6	608.6	40	7.0	265.24	26.97	11.3
X4	2011	TS2	347.1	34.6	11.1	73.0	7.1	10.8	605.2	36.6	6.4	268.38	30.11	12.6

**Table 10.** Average annual change in water yield and baseflow in Walzem Creek watershed.

Scenario	Land Use	Climate	Water Yield (mm)			Baseflow (mm)			Evapotranspiration (mm)			Surface Runoff (mm)		
			Av.	Ch. Δ	(%)	Av.	Ch. Δ	(%)	Av.	Ch. Δ	(%)	Av.	Ch. Δ	(%)
X1	1992	TS1	289.2	-	-	30.5	-	-	541.3	-	-	252.2	-	-
X2	2011	TS1	334.1	44.9	15.5	87.3	56.9	186.8	520	-21.3	-3.9	239.5	-12.7	-5.0
X3	1992	TS2	291.8	2.70	0.9	82.2	51.7	169.9	514.9	-26.4	-4.9	202.6	-49.6	-19.7
X4	2011	TS2	300.5	11.3	3.9	74.6	44.1	144.9	505.1	-36.2	-6.7	219.1	-33.0	-13.1

**Figure 11.** Monthly water yield change for the UWBDR watershed under different scenarios**Figure 12.** Monthly baseflow change for the UWBDR watershed under different scenarios



### 3.6. Impacts of climate variation

In comparison to the land use change scenario, the climate variation scenario caused the average annual water yield to increase by 9.9% as a result of a prominent increase in precipitation. Baseflow also showed an increase when only climate variation was considered (X3), however this increase was much more pronounced than the change in water yield, with an amount of 53.8 mm (81.6%) (Table 9). These results indicate that both land use change and climate variability played a role in increasing baseflow. However, climate change played a more pronounced role than land use change in impacting the hydrologic regime of the UWBDR during the recent past, due mainly to the increase in precipitation. This can also be seen in Table 9, in which the surface runoff and evapotranspiration increased by 11.3% and 7.0%, respectively. Together, these results indicate that the climate alteration contributes more substantially to the effects observed on hydrological components compared to urbanization.

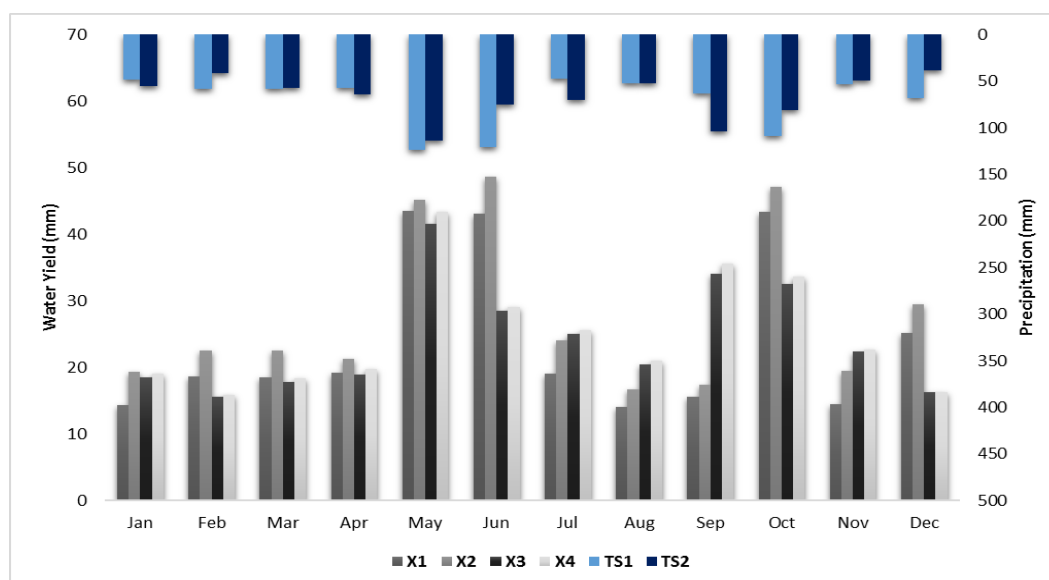
Similar to the land use change scenario, the average monthly water yield was predominantly observed in late fall/spring. Of note, the highest change in monthly water yield is observed in July (39%) due to the X3 (climate change) scenario. The change in water yield tended to be positive in months that experienced a significant increase in precipitation in the second period (TS2) compared to the first one (TS1) (Figure 11). On the other hand, results showed an increase in average monthly baseflow under the effect of climate change only, impacts of S3 in all months, though the highest growth was detected in the warmest months of the year (May to September) (Figure 12).

The climate change scenario had a minimal impact on the average annual water yield, causing it to increase by only 0.9% at Walzem Creek, while it caused the average annual baseflow to increase by 169.9% (51.7 mm) compared to the baseline scenario (X1) (Table 10). This may be attributed to the significant reduction in the precipitation pattern and the increase in temperature in TS2 as compared to TS1, where the climate became warmer and drier. Therefore, these likely played an important role in the contribution to the total streamflow for Walzem Creek. Climatic variables, specifically precipitation, largely determined the runoff hydrograph. Precipitation reduction in the second climatic period (TS2) resulted in the significant decline of surface runoff by 49.6 mm (19.7%), and a reduction in evapotranspiration by 4.9%, within the X3 scenario (Table 10).

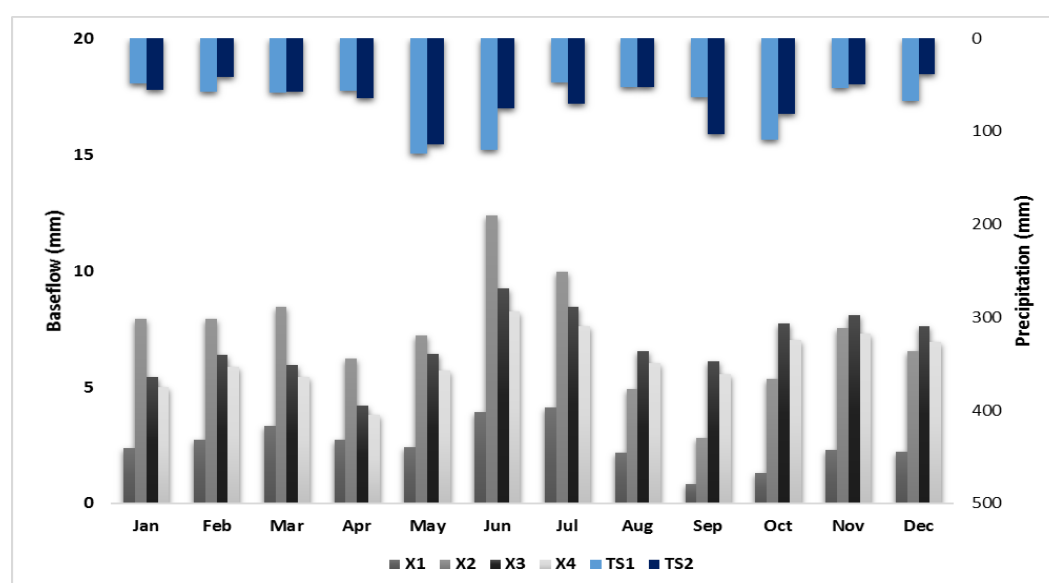
On a monthly basis, the highest impacts of climate change were detected in July, August and September, where the average monthly precipitation was higher in TS2 as compared to TS1. It could be inferred that climate variation had a lasting negative effect on water yield (Figure 13). However, the climate change scenario (X3) caused an increase in monthly baseflow from August to December by an amount of 43.9%. The increase of baseflow in the second half of the year was mainly due to changes in precipitation and temperature patterns from TS1 to TS2. For example, TS2 experienced less precipitation as compared to TS1, while the temperature was higher in TS2 compared to TS1. Hence, baseflow played a role in water contribution to total streamflow when the weather got warmer and drier in the semi-arid watershed (Figure 14).

The streamflow changes under the X3 scenario, which was considered the climate change scenario, were remarkably similar to those at the LEC watershed, in which all months exhibited an increase of 12.2% to 34.5% (Figure 15). In addition, the relative change in streamflow percentage in the UWBDR watershed was higher than the change in the LEC watershed, suggesting that streamflow change is more sensitive to climate change than to land use dynamics. Climate change had a similar impact on the average annual water yield in both the UWBDR and the LEC watersheds, in which it increased by 17.9% and 9.9% in the LEC and UWBDR watersheds, respectively. However, minimal impacts due to the X3 scenario occurred in Walzem Creek, indicating that the land use change and urbanization had the predominate impact in the semi-arid region at Walzem Creek. On the other hand, the climate change caused the average annual baseflow to increase in the three watersheds, with the most significant detected at Walzem Creek, then UWBDR and finally the LEC watersheds by an amount of 169.9%, 81.6% and 15.2%, respectively. In addition, the average annual surface runoff exhibited an increase in the LEC watershed due to the impact of climate change by an amount of 22.7%, but decreased in Walzem Creek by 19.7%. These findings imply that baseflow is

the main contributor to the total streamflow considering the sole effect of climate variation at the Walzem Creek watershed.



**Figure 13.** Monthly water yield change for the Walzem Creek watershed under different scenarios



**Figure 14.** Monthly baseflow change for the Walzem Creek watershed under different scenarios

### 3.7. Combined impacts of both land use change and climate variations

To evaluate the combined impacts of land use and climate change, the simulated results under the X4 scenario were compared to the baseline scenario. The annual mean water yield increased by 11.1% as a response to the X4 scenario at Walzem Creek (Table 9). These changes, compared to X2 and X3 scenarios, emphasize that the joint effects of land use change and climate variability led to consistent growth in water yield in the UWBDW watershed. Furthermore, the effect of climate variation was larger than that of the land use dynamic on the total water yield. This can be clearly seen by the X3 and X4 scenarios, in which the mean annual precipitation showed an increase of 82 mm, resulting in an increase in the mean annual water yield. These changes are similar to the changes reported in the LEC watershed discussed in Aboelnour et al. [8], resulting from the combined impacts of land use and climate change. In contrast to the LEC watershed, where baseflow decreased, the X4 scenario for the UWBDW watershed led to an increase in the average annual baseflow to 7.1 mm (10.8%) (Table 9). This difference might be attributed to the prevalence of negative urbanization

impacts for the LEC watershed, in contrast to the significant positive effects of climate variation for the UWBDW watershed.

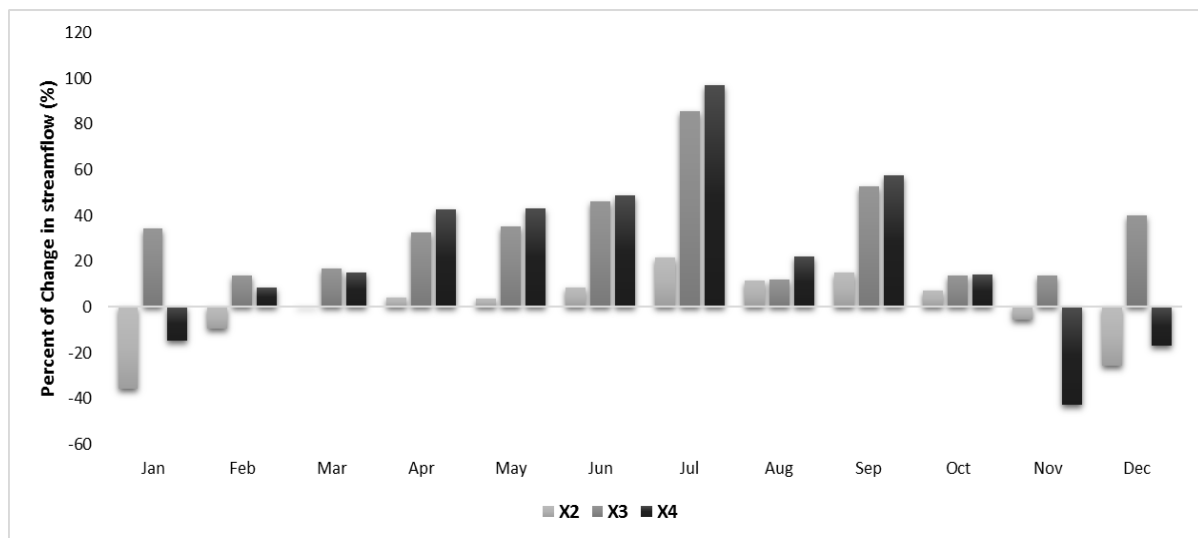
Similar to the climate scenario, we observed that the average monthly water yield was concentrated in the late fall and early spring in the X4 scenario, totaling 39% of the annual yield. In general, positive changes were detected in all months under different scenarios except for November, January and February. However, the variation due to the joint effects tended to be higher in all months with a higher precipitation pattern in the second period of time (TS2) than in TS1 (Figure 11). For instance, the effect of land use scenario (X2) was higher than those of X3 and X4 in August, as the average monthly rainfall was 127.2 mm in TS1, while it was only 99.8 mm in TS2. Meanwhile, the combined effect of land use change and climate variability and the sole effect of climate change had greater impacts on water yield in July, as the average monthly precipitation was 83.7 in TS1, increasing to 114.8 mm in TS2. Baseflow variations showed increasing trends in warm months from May to September, then decreased from October to April in conjunction with the joint effect of climate variation and land use change (Figure 12). The increase in baseflow may be mostly due to an increase in rainfall, and could be explained by fluctuations in both precipitation and temperature between TS1 and TS2. The freeze-thaw processes of the active layer could have changed the soil infiltration capacity and the volume of subsurface water storage, thus impacting baseflow as well [71].

Results from the X4 scenario in the Walzem Creek watershed indicate that the average annual water yield increased by only 3.9%, while the average annual baseflow showed a significant increase of 144.9% (Table 10). Additionally, the annual evapotranspiration was negatively impacted by the joint effect of climate variation and land use change, decreasing by 6.7%. The decline in evapotranspiration is mainly caused by reduction in green cover (Table 7). Compared to X1, the combined effects of land use change and climate variability under X4 decreased surface runoff by 33.0 mm (13.1%). Therefore, with the decline in precipitation and increase in water yield, baseflow was the predominant contributor to the total streamflow in Walzem Creek. These findings indicate that, with the concurrent reduction in evapotranspiration, average annual water yield and baseflow had a remarkable increase under the X4 scenario. However, the joint effect of climate variability and land use change on water yield and baseflow was lower than the sole impact of the land use change scenario. On the other hand, X4 had the greatest negative impact on evapotranspiration. Furthermore, on a monthly basis, the contribution of the joint effect of both climate variability and land use change tended to be similar to the contribution of climate change impacts. Therefore, it should be noted that the impact of land use change was the dominant contributor to both water yield and baseflow expansion for Walzem Creek, and was greater than the sole effects of climate change and the combined effects of land use and climate change.

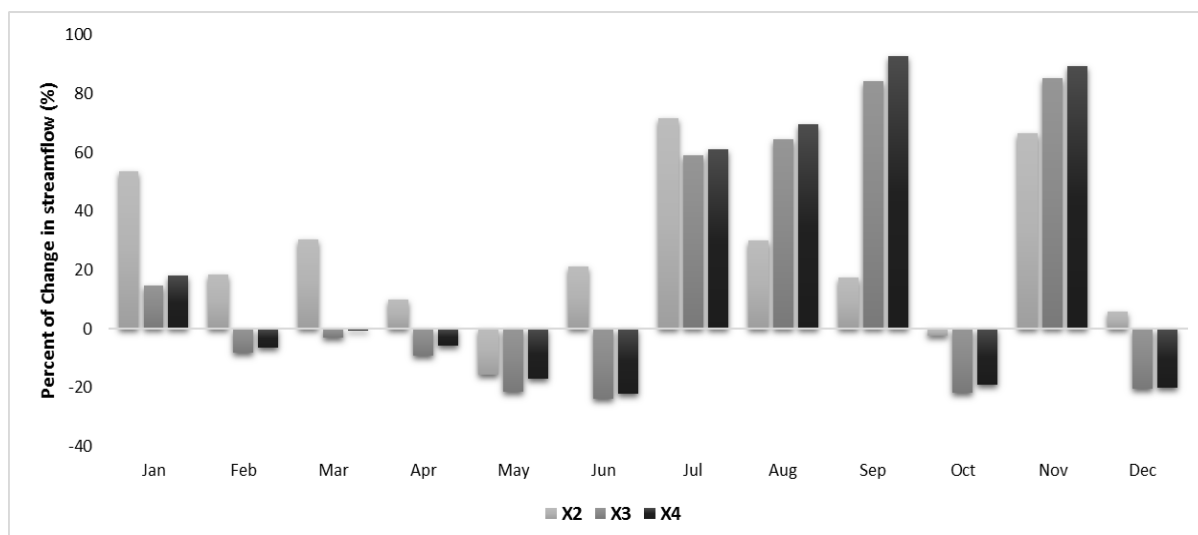
At a monthly timescale, the streamflow increased in January, July, August, September and November for all three scenarios, with the highest increase in November by 66.5% (X2), 85.13% (X3), and 89.4% (X4). Note that streamflow in Walzem Creek showed a significant increase in all months when considering the impacts of land use change (X2), except for May and a minor reduction in October (Figure 16), which was caused by the reduction in rainfall and the insignificant increase of temperature for these months. Moreover, the streamflow rate tended to decrease when considering scenarios X3 and X4, except in January, July, August, September and November, due to the increase in precipitation during these months. The impact of the combined effect of land use change and climate variability showed the same behaviors as the sole impact of climate variability in the Walzem Creek watershed. This situation is well demonstrated by the monthly streamflow variation in the watershed (Figure 16), with the greatest streamflow increase estimated in September by 92.8%. Meanwhile, the highest reduction in monthly streamflow when considering the combined impacts was estimated in June by 22.35%. These changes were mainly the result of incremental, dynamic precipitation patterns between the two periods, TS1 and TS2. For instance, September experienced the highest increase in rainfall with an amount of 40.4 mm, while June showed the highest reduction in monthly precipitation with an amount of 45.2 mm in TS2 as compared to TS1.

Compared to the LEC watershed, in which the urbanization had the prevailing negative effect on baseflow while climate changes caused increases in both flows, in Walzem Creek watershed, both

land use change and climate change had an impact on streamflow and baseflow. However, our study showed that land use dynamics and urban expansion played a more important role on streamflow and baseflow in semi-arid regions than solely climate change impacts.



**Figure 15.** Absolute change in mean monthly streamflow for the UWBDP watershed under different scenarios.



**Figure 16.** Absolute change in mean monthly streamflow for the Walzem Creek watershed under different scenarios.

#### 4. Summary and Conclusions

Urbanization and climate change play an important role in altering the spatiotemporal distribution of water resources and hydrologic components. Streamflow and baseflow are two critically important components of hydrology that are essential to sustain water demands by various sectors, such as agriculture and industry, and are vulnerable to these changes. Therefore, it is of vital significance to understand the behaviors of these components under the separate and combined impacts of climate variation and land use dynamics in different climate regions. In this research, we followed the methodology discussed by Aboelnour et al. [8] for computing streamflow and baseflow for diverse watersheds.

The SWAT model was used to calibrate and validate streamflow and baseflow over the time-span of 1980 to 1988 to determine the separate impact of urbanization and climate variability at the UWBDP watershed in Illinois, and the semi-arid Walzem Creek watershed in Texas. In addition to the hydrologic model, the non-parametric Mann-Kendall statistical test was used to evaluate the

break point and the trends in hydrological and meteorological components. The SWAT model exhibited high-quality results for calibrating and validating models in the selected watersheds as indicated by evaluation criteria, and proved versatile in modeling the effects of environmental change in complex catchments. In addition, the automated SUFI-2 approach helped in minimizing the discrepancies between the observed and simulated data.

Findings of this research indicated that the climate became warmer and wetter for both the UWBD and LEC watersheds evaluated in Aboelnour et al. [8] but warmer and drier at the Walzem Creek watershed. The combined effect of these changes showed nonlinear responses to the water balance component. Changes at the UWBD watershed were remarkably similar to those for the LEC watershed, with the exception that the climate variation was shown to have the greater impact on both streamflow and baseflow, while land use change exerted a relatively small influence on either flow. On the other hand, urbanization influenced streamflow and baseflow in the semi-arid Walzem Creek watershed, possibly because of the change in rainfall pattern between the two climate periods. The small reduction in mean annual precipitation in the TS2 produced a considerable reduction in runoff.

Generally, with the variation in spatio-temporal properties of precipitation, and increasing hazardous events associated with water, such as droughts and floods, stress on water resources will increase and will further encourage the development of mitigation approaches. Based on this research, findings will provide practical suggestions for policy makers on how to sustain water resources more efficiently in relation to its variability as a response to urbanization, land use and climate change. These changes can be problematic and incur great cost to establish new infrastructure, especially in undeveloped nations. Therefore, policy makers need to develop policies to address these types of changes, taking into account the individual influences of human activities and climate variation, for instance, improving infrastructure to be more resilient to human activities, constructing dams following proper regulations on water resources, and limiting the amount of deforestation, which threatens some hydrological components. In addition, outcomes of this study can be used in quantifying the potential impacts of future projected climate change and land use change. Nevertheless, it might be found that the driving factors interact to impact streamflow and baseflow through chain effects, in which one factor is trying to increase/decrease the magnitude of the other. Hence, more studies are crucial to evaluate this potential future impact on the hydrological system, with the emphasis on the interactive effect of environmental change drivers when predicting future change.

While this research showed the separate and combined impacts of human activity and climate alteration using the SWAT model, modelers should be aware that other types of uncertainties associated with the model exist that may result from observed data, the parameterization process, or from the conceptual model itself. One of the potential shortcomings of this study is that the urbanization processes is an integrated part of the watershed, along with climate alteration. Therefore, it is difficult to discern whether the separate effects of human action and climate change were able to be truly simulated and this issue might therefore create a biased condition. Thus, a suggestion to avoid this limitation in future research is to hypothesize an extreme land use/land cover change that is sensitive to the change instead of a natural system simulated by the model.

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