2018-01-01

Assessing The Hydrologic Impacts Of Extreme Rainfall And Land Use Change On A Semiarid Watershed

Tahneen Jahan Neelam
University of Texas at El Paso, tjneelam.buet08@gmail.com

ASSESSING THE HYDROLOGIC IMPACTS OF EXTREME RAINFALL AND LAND USE CHANGE ON A SEMIARID WATERSHED

TAHNEEN JAHAN NEELAM

Master's Program in Civil Engineering

APPROVED:

Ali Mirchi, Ph.D., Chair

Saurav Kumar, Ph.D.

Stanley T. Mubako, Ph.D.

Charles Ambler, Ph.D.
Dean of the Graduate School

ASSESSING THE HYDROLOGIC IMPACTS OF EXTREME RAINFALL AND LAND USE CHANGE ON A SEMIARID WATERSHED

by

TAHNEEN JAHAN NEELAM

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Civil Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

August 2018

Acknowledgements

I would like to express my humble gratitude to my mentors, my funding source, colleagues, friends and family for helping me successfully finish my master's thesis. I would also like to profoundly acknowledge University of Texas at El Paso's (UTEP) support during the two years of my masters' study.

My sincere gratitude goes to my advisor Dr. Ali Mirchi for his incredible mentorship, motivation and most importantly, immense patience in shaping my academic life. This thesis work is an outcome of his expertise and thoughtful guidance. He has guided me throughout my entire graduate life with his valuable instructions, encouragement and provided me with various opportunities which helped me grow academically and professionally. I believe the training I have received from him will be a valuable asset for me in my future endeavors. I would also like to extend my gratitude to my thesis committee members Dr. Saurav Kumar and Dr. Stanley Mubako. I have worked with Dr. Kumar very closely and learned a lot from his technical expertise. His valuable comments on my work and constant motivation played an important role in my graduate education. Dr. Mubako has always shown interest in my work in various project meetings and symposiums and kept me motivated with his encouraging comments.

I thankfully acknowledge the funding source of my research US Department of Agriculture (USDA) Grant No: 2015-68007-23130 and Center for Environmental Resources Management (CERM) for granting me a research assistant position under this grant. I also acknowledge UTEP Graduate School Travel grant and Student Government Travel Grant for supporting my travels multiple times to present my work at international conferences.

I would like to thank my undergraduate mentor Dr. Adnan Rajib who has always been a phone call away with his valuable advice and motivation. I appreciate his time and effort in helping me with his knowledge and experience. I would also like to thank my undergraduate seniors Manashi Paul and my lab-mate Maryam Samimi for their suggestions and comments on my work which enriched my research in many ways.

My deepest gratitude goes to my parents. Not only for their unconditional love and support that made me come this far but also because of their invaluable life teaching that taught me to be always brave and kind. I have never felt the value of this schooling more than I did in last two years. My special thanks to my only younger sister for always having my back and to my husband for loving and supporting me defying all sorts of time-zonal and temperamental barriers.

Lastly, I would like to thank my amazing group of friends. Over the years, I was fortunate enough to make an incredibly capable band of female friends who go on to inspire and support me every day from every corner of the world. I would also like to thank the wonderful friends I have made here at El Paso who created a home away from home for me with their extraordinary love.

Assessing the Hydrologic Impacts of Extreme Rainfall and Land Use Change on a Semiarid Watershed

Tahneen Jahan Neelam

Department of Civil Engineering, The University of Texas at El Paso, 500 W University Ave., El Paso, TX 79968

Abstract: Intense precipitation events increase the risk of flash floods in the New Mexico-Texas-Mexico border region. Compounding effects of changing land use and precipitation pattern can influence rainfall-runoff processes that govern flash flooding. Paradoxically, this southwestern semiarid watershed has substantial water conflict that may get worse by 2025 due to changing climate and increasingly competitive demands for over-appropriated water resources. Using Soil and Water Assessment Tool (SWAT), we investigate the impact of changes in precipitation intensity and land use on runoff and arroyo flows in the dry, mountainous terrains. The baseline watershed simulation model shows that for a statistically insignificant change in the precipitation from 1996-2005 to 2006-2015, the water balance components (e.g. evapotranspiration, surface runoff, soil water content and water yield) showed a statistically significant decrease. Three extreme precipitation scenarios − largest 24-hr rainfall event in 1994-2015 period, 24-hr precipitation with 100-year and 200-year recurrence intervals−were modeled using NOAA precipitation frequency estimation data. The effect of these precipitation scenarios was also assessed under future land use/land cover scenarios using the USGS FOREcasting-SCEnarios (FORE-SCE) 2050 land use maps under A1B, A2 and B1 storylines developed by the Intergovernmental Panel on Climate Change (IPCC), representing different economic growth paths. The study identified the spatial location of sub-basins that are vulnerable to surface runoff and demonstrated that both extreme rainfall event and land use land cover change affect the hydrology of the watershed. Surface runoff is mostly governed by extreme rainfall events, but it shows spatial variability under future land use land cover scenarios. Results improve understanding of spatial and temporal variation of runoff associated with precipitation and land

use patterns, which has important implications for planning watershed management practices that mitigate flash flooding and sediment transport.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Background

Rainfall is a pivotal component in the hydrologic cycle as well as in watershed hydrology. Impacts of rainfall on the water cycle are generally reflected in the long-term spatial and temporal variation of water balance components such as surface runoff, soil moisture, evapotranspiration, groundwater and streamflow (Li et al., 2009; Fang et al., 2013; Memarian et al., 2014; Deng et al., 2015). In the last few decades, climate change has contributed to more frequent extreme events. Higher temperature induces more intense precipitation with higher amount which, in turn, affects various hydrological processes (Huntington, 2006; Melillo et al., 2014; Johnson et al., 2015; Pervez and Henebry, 2015; Paul et al., 2017). In the western U.S., future projections show an increasing pattern of very heavy precipitation events (Kharin et al. 2013, Polade et al. 2014, Walsh et al. 2014). Changes in precipitation pattern affects the magnitude and frequency of floods.

Another determinant factor in watershed hydrology is land use which occurs in response to evolving economic, social, and biophysical conditions (Lebow et al., 2012). In arid and semiarid southwestern U.S., exotic grasses with higher flammability are invading shrublands and deserts (Finch, Deborah M., 2012). Recent studies, evaluating impacts of intense land use changes, suggest that these changes affect local, regional, and global ecosystems and environmental processes (DeFries et al., 2004; Ellis and Pontius, 2007; Lambin and Meyfroidt, 2011; Sleeter et al., 2013; Turner et al., 2007). Examining the effects of both rainfall pattern and land use change on hydrological processes is important for making informed water resources management decision. In particular, it is necessary to develop a good understanding of the impacts of rainfall and land use change on regional water availability and water infrastructure in the southwestern U.S. where scarce water resources are managed to meet various demands.

1.2 Problem Statement

In the past few years, the world has experienced an increase in the number and intensity of extreme events including both droughts and floods. Although difficult to predict, very large precipitation events are projected to increase everywhere in the western U.S. (Kharin et al. 2013, Polade et al. 2014, Walsh et al. 2014). Heavy precipitation events that historically occurred once in 20 years are projected to occur as frequently as every 12 years by late this century in the southwestern U.S. (Wang and Zhang 2008). There are projections of prolonged droughts in the southern and northwestern parts of the contiguous U.S. (Walsh et al. 2014), especially the southwest and up the west coast, which are expected to have a larger number of dry days in the future (Polade et al. 2014). Wet and dry extremes are projected to increase in many areas across the conterminous U.S., although the changes in total average annual rainfall may be small.

The El Paso – Las Cruces watershed in the New Mexico – Texas border region is a semiarid hydrologic unit code 8 (HUC-8) watershed. With its highly managed surface water distribution system and varied land use, this desert river basin poses some challenges in water resources management. The watershed receives an average annual precipitation of approximately 250 mm and is heavily dependent on its only surface water source, the Rio Grande and groundwater sources the Hueco and Mesilla aquifers for all of the watershed's agricultural, urban and environmental water use. In the face of competing demands and changing climate, this watershed has a substantial water conflict potential by 2025 (Scruggs et al., 2017). Global or regional climate models (IPCC 2001s, NAST2000) project higher chances of more extreme events such as torrential rain and severe droughts in this region. Although very uncertain in nature, the weather pattern in southwestern region is also affected by El Nino-Southern Oscillation (ENSO) events. Moisture associated with the storm events during El Nino years, has the capacity to deliver above average precipitation to this region in winter and early spring. The El Nino influenced precipitation anomalies tend to show positive anomalies with more increase in precipitation in southern New Mexico than the northern regions (NOAA, 2015). The pattern is generally reversed in a La Nina year. These changing patterns affect the timing and magnitude of runoff peaks. Intense

precipitation in a brief period of time in this mountainous region increases the risk of flash flooding which already occur as a regular severe climatological event. The core of thunderstorm and subsequent flash flood season in this region is from July 20 to August 20. Figure 1.1 shows cumulative New Mexico flash flood events by month from 1993-2017. Among 33 counties in New Mexico, with 62 and 50 events Dona Ana and Sierra county of the study area ranks sixth and eighth, respectively. Flash floods with a peak discharge between 5 to 500 m^3/s cause arroyo erosion and subsequent sediment deposition in the main channel, reducing hydraulic conveyance capacity of water infrastructure (Dean et al., 2016). Alteration of land use and land cover in addition to changing climatic conditions should be investigated in terms of their implications for water availability and watershed management. Together, these changes affect the morphologic dynamics in the arroyos which are a significant topographic feature of the region.

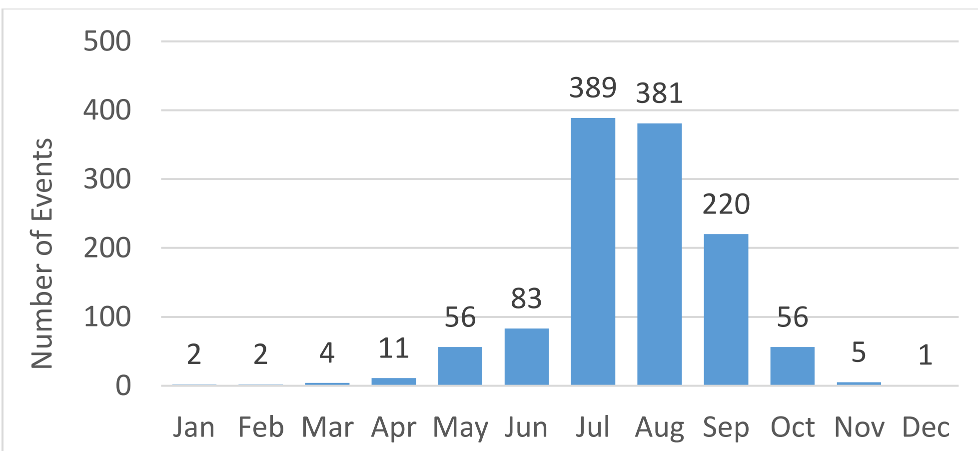


Fig 1.1: New Mexico flash flood events by month for the period 1993-2017

1.3 Objectives

This study provides insight into hydrologic processes taking place inside a highly managed southwestern semiarid watershed in two recent decades and its response to potential rainfall pattern and land use change. Understanding how rainfall pattern and land use changes affect hydrology in

on watershed scale would help watershed managers, agricultural producers, policy makers, and the public make informed assessments of water availability and potential vulnerabilities. This is an important step toward development of strategies for sustainable water resources and disaster management.

Objectives of this study are to

1. Characterize the change in water balance components in two recent decades in the watershed using a watershed simulation approach.
2. Assess the impact of extreme rainfall events and future land use change separately on the hydrologic components under current watershed conditions
3. Evaluate the compounding impacts of both the extreme rainfall event and land use change on the watershed

1.4 Thesis Organization

This thesis is organized in five chapters. Chapter 1 provides the background, problem statement and objectives of the study. Chapter 2 provides a literature review related to the effects of rainfall pattern and land use change on watershed hydrology in semiarid watersheds. This chapter also provides information on hydrologic modeling and future scenarios for extreme rainfall event and land use changes. Chapter 3 presents the methodology, results, and outcomes related to objective 1. Chapter 4 contains the methodology, results, and outcomes pertaining to objectives 2 and 3. Finally, conclusions of the study are summarized in Chapter 5.

Chapter 2: Literature Review

2.1 Rainfall in Semiarid Region

A semiarid region is an intermediate climate region between desert climate and humid climate which is characterized by very little annual rainfall. A semiarid region usually receives 200-500 mm rainfall annually. Across the world, streamflow trends in various regions are influenced by variation in rainfall (Changnon and Kunkel, 1995; Hall et al., 2006; Novotny and Stefan, 2007; Small et al., 2006). In particular, peak discharge and the overall flow regime in arid/semiarid regions are mostly produced by extremely variable but highly intense and short duration rainfall (Syed et al. 2003, Goodrich et al. 1997, Hernandez et al. 2000, Ouessar et al. 2009, Pilgrim et al. 2009, Ghaffari et al. 2010). In China, inside a typical continental arid and semiarid watershed in greater Hetao area, mean annual rainfall was found to be 188 mm and of which 80% occurs between June-August (Wu et al., 2014). In Walnut Gulch Experimental Watershed located in the southeastern Arizona, mean annual rainfall was found to be 324 mm with considerable seasonal and annual variation (Yuan et al., 2012). This testifies the short and intense pattern of rainfall in semiarid regions all over the world.

2.2 Impacts of Rainfall in Semiarid Region

2.2.1 Evapotranspiration

Evapotranspiration (ET) consists of two processes (e.g. evaporation and transpiration) that convert water at the earth's surface to water vapor (Allen et al.,1998; Aouissi et al., 2016). ET contains evaporation (*E*) from surface water bodies, land surfaces, soil, sublimation from snow and ice and plant transpiration or plant water consumption (Verstraeten et al., 2005). Evaporation rate depends on solar radiation, air temperature, humidity, and wind speed (Hanson, 1988) while transpiration depends on water availability in the soils and plants. These processes are among the most important in arid and semiarid regions which receive rainfall below potential evaporation (PET). As a result, annual rainfall is not sufficient to provide crop water requirements (Er-Raki et

al., 2007). Rainfall pattern and amount in these watersheds control the irrigation scheduling and amount which influences ET. In Tunisia, an irrigated watershed inside a semiarid region with 676 mm mean annual rainfall reports annual potential evapotranspiration of 1728 mm (Aouissi et al., 2016).

In an arid irrigated watershed inside the yellow river basin China, due to both potential higher temperature and precipitation, increased trends in ET were observed throughout the wet season from June to September (Zhang et al., 2016). Along with irrigated agriculture, a study in semiarid watershed in southeastern Arizona with grassland and shrubland cover reports a moderate correlation between precipitation and ET (Nagler et al., 2007).

2.2.2 Surface Runoff

Rainfall is the primary source of water in a watershed and contributes to surface runoff and streamflow after other losses have been considered. Under varying land use and soil types, increased rainfall leads to an increase in surface runoff after the initial abstraction and a decrease in rainfall results in the opposite (Rallison and Miller, 1981). More than 20 years of studies involving rainfall-runoff relationship across the U.S. suggests this positive correlation between precipitation and surface runoff is established in all kind of watersheds (USDA-SCS, 1972; Neitsch et al., 2011). In the semiarid Rio Grande river basin in southwestern U.S., runoff is predominantly generated by convective thunderstorms in summer and peak runoff volume also occurs during that period (Hall et al., 2007).

2.2.3 Streamflow and Flood

Historical fluctuations of streamflow have been dominated by precipitation variability as compared with temperature and this trend is likely to persist in the future (Karl and Riebsame 1989). Annual streamflow is projected to decline in the southwest in response to the combination of projected precipitation and temperature changes (Milly et al. 2008; USBR 2011; Dettinger et

al. 2014). Short duration rainfalls in the semiarid region increase the chance flash flooding (Villarini et al. 2009). Although floods have been decreasing in parts of the Southwest (Karl and Knight 1998, Gutowski et al. 2008, Villarini et al. 2009), with heavy rainfall events projected to increase the potential for flash flooding is expected to increase in many areas (Dettinger et al. 2014). Region-specific storm mechanisms and seasonality also affect flood peaks and high intensity.

2.2.4 Sediment Transport

Sediment transport occurs in large water bodies (e.g. river, lakes, sea, ocean, etc) due to currents and tides. This process is controlled by both flow strength and the type of bed materials (Dean et al., 2016). Monsoon events supply an excessive amount of sediment to the river systems (USBR, 2013). In the Rio Grande River, a large amount of sediment transport takes place during tributary-sourced flash floods occurring for short durations in summer months (Dean et al., 2016). These flash floods paired with upstream dam release can both erode and deposit sediments in Rio Grande river which is a huge management concern. As spatial and temporal patterns of sediment deficit and/or supply directly influence sediment transport processes, a comprehensive measurements of sediment transport can help make informed management decisions.

2.3 Land Use and Land Cover (LULC) in Semiarid Region

Semiarid climate give rise to a different set of biomes. In semi-arid and arid environments, plant species richness is positively correlated with higher water availability (Shmida, 1985; Ward & Olsvig-Whittaker, 1993; Kutiel et al., 2000; Hochstrasser et al., 2002). Studies show that, the dominant LULC in southwestern semiarid U.S. is sparsely vegetated grassland and shrubland (Nagler et al., 2006; Yuan et al., 2012; Niraula et al., 2012). But these lands have been extensively settled in last few decades and the most prominent LULC changes in this region was urban

expansion (Brown et al., 2014). A study by Steeler et. al 2013 shows that developed area in entire southwest has increased 0.61 percent between 1973 to 2000.

2.4 Impacts of LULC in Semiarid Region

Land use and land cover (LULC) change in a region alters soil water content, evapotranspiration (ET), infiltration, groundwater and interception rates. These changes lead to changes in surface runoff, streamflow and flood frequency (e.g., Li et al., 2009; Fang et al., 2013).

2.4.1 ET and Soil Moisture

LULC change contributes significantly to earth atmosphere interactions (Fu et al., 2000; Gashaw et al.,2017) and hydrological response of watersheds (Hurni et al., 2005; Girmay et al., 2009). As land-surface characteristics heavily influence the process of ET, it is highly susceptible to LULC change. Both ET and soil water content are affected by crop density, leaf area index, canopy resistance and plant-available water capacity (Zhang et al., 2001). As crop production is highly dependent on irrigation in a semiarid region, agricultural land cover and cropping pattern affects the ET and soil moisture of these watersheds. Studies show that in semiarid region, expansion of cultivated crop and urban area decreases ET (Rose and Peters, 2001; Liu et al., 2008; Gashaw et al., 2017).

2.4.2 Surface Runoff and Groundwater

Surface runoff is significantly controlled by LULC. In bare lands without any vegetation cover, surface runoff is relatively higher and groundwater flow is lower (Woldeamlak and Sterk, 2005; Gyamfi et al., 2016; Gashaw et al., 2017). By contrast, surface runoff is relatively lower and groundwater flow is higher in vegetative lands due to the greater infiltration of rainfall into both the shallow and deep aquifer. Therefore, changes in LULC alters the timing and magnitude of surface runoff and groundwater discharge (Niehoff et al., 2002; Jones and Post, 2004; Mao and

Cherkauer, 2009; Pai and Saraswat, 2011; Schilling et al., 2014). Urban expansion replacing forest land and vegetative cover increases impervious paved surface area which increases surface runoff and reduces the chance of infiltration of rainfall into the soil profile (Tu et al., 2009; Pai and Saraswat, 2011; Jacobson, 2011). Due to the expansion of cultivated lands and urban areas at the expense of rangelands in a semiarid watershed in South Africa, increase of surface runoff and reduction of groundwater flows were observed between 2000 and 2013 (Gyamfi et al., 2016).

2.4.3 Streamflow and Flood

Streamflow consists of stormflow and baseflow where the former is basically surface runoff from the watershed and the latter is groundwater discharge to a stream (Zhang and Schilling, 2006). Excessive surface runoff during storm events can exceed the flow carrying capacity of a stream within the watershed which may increase the risk of potential flooding (Paul, M., 2016). In semiarid watershed with high flash flooding potential, increasing land use conversion to urbanization and deforestation can potentially lead to an increase in flash flood frequency. Various studies have described the impacts of LULC changes on streamflow (Rientjes et al., 2011; Getachew and Melesse, 2012; Gebremicael et al., 2013; Gwate et al., 2015; Kidane and Bogale, 2017). Gebremicael et al. (2013) reported that the increase of peak flow (in wet season) and reduction of baseflow flow (in dry season) at El Diem station of Blue Nile Basin during 1970–2010 were attributed to the conversion of vegetation covers into agriculture and grasslands over large areas of the semiarid basin.

2.5 Future Scenarios for Extreme Rainfall Event and Land Use Changes

2.5.1 Future Extreme Rainfall Event Scenario

National Oceanic and Atmospheric Administration (NOAA) has been publishing updated precipitation frequency estimates and supplementary information for the United States (US) and affiliated territory since 2003. The NOAA atlas 14 estimates are published as volumes of the

NOAA atlas 14, precipitation frequency atlas of the US in the online Precipitation Frequency Data Server (PFDS). Figure 2.1 shows the server where upon clicking a state on the map online or selecting a state name from the drop-down menu, an interactive map of that state will be displayed. From there, a user can identify a location for which precipitation frequency estimates are needed. Estimates and their confidence intervals can be displayed directly as tables or graphs via separate tabs. Links to supplementary information (such as ASCII grids of estimates, associated temporal distributions of heavy rainfall, time series data at observation sites, cartographic maps, etc.) can also be found on the website https://hdsc.nws.noaa.gov/hdsc/pfds/index.html.

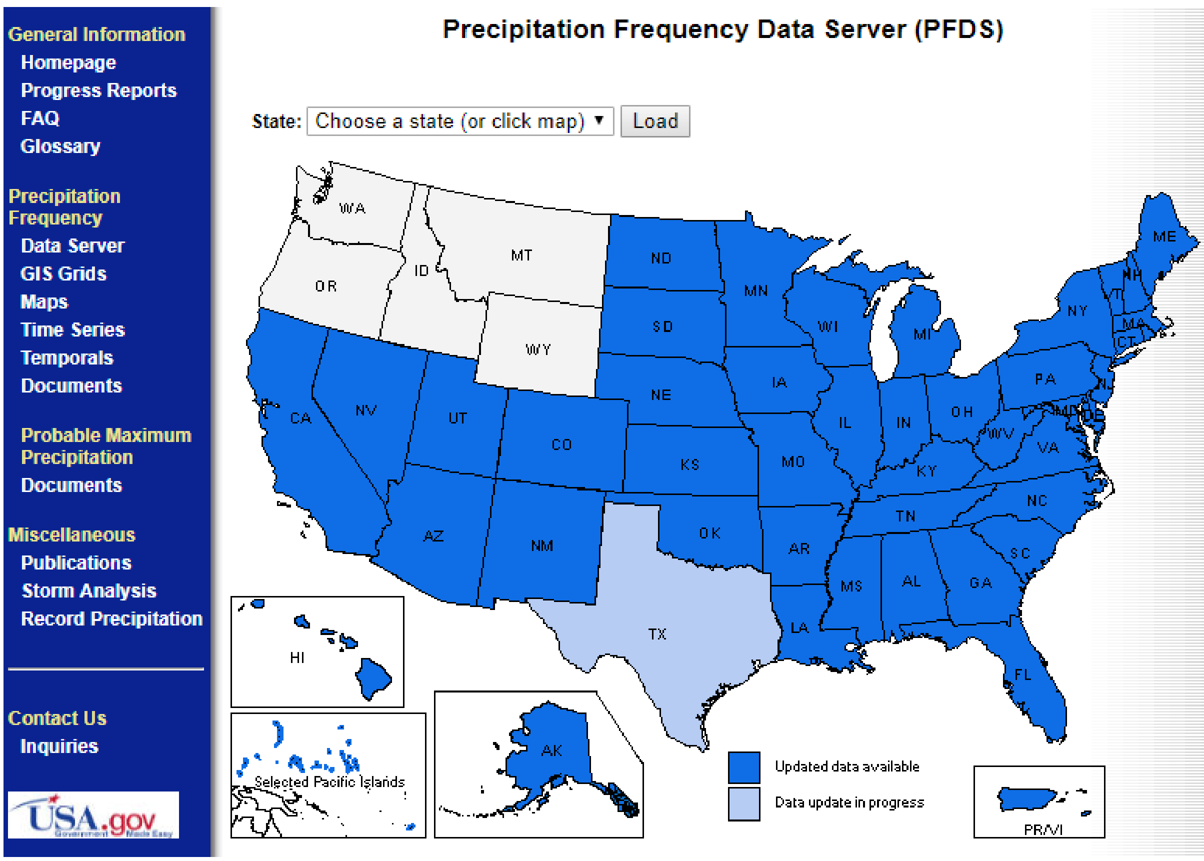


Fig 2.1: Web interface of NOAA's Precipitation Frequency Data Server (PFDS)

The Atlas provides precipitation frequency estimates for 5-minute through 60-day durations at average recurrence intervals of 1-yr through 1,000-yr (Bonnin et al., 2011). Daily

precipitation data from stations with at least 20 years of data were used. As the maximum 24-hr rainfall amount seldom falls under a single daily observation period, the daily observation data were converted to 24-hr rainfall data using ratios of the 2-yr quantiles computed from annual maxima series at the available stations with concurrent hourly and daily data in the project area. This way the time series for concurrent time periods were produced for 24-hour precipitation values summed from hourly observations and co-located daily precipitation observations. This series was then analyzed separately using L-moments. For precipitation frequency analysis, the data series were extracted based on both annual maximum series (AMS) method and partial duration series (PDS) method (Bonnin et al., 2011). The AMS method selected the largest single case that occurred in each calendar year of record and when the large case was not the largest in a year, it was not included in the series. The PDS method considered that more than one large case may happen during a single calendar year and a large case that is not the largest in a particular year could appear in the series. Frequency analysis is done for selected events with precipitation magnitudes exceeding 1000-yr average recurrence interval (ARI) (1/1000 annual exceedance probability) estimates over larger areas for at least one duration of interest (Bonnin et al., 2011). More about the data series, estimation method, calibration and validation of this process can be found at http://hdsc.nws.noaa.gov/hdsc and Bonnin et al. (2011).

2.5.2 Future Land Use Scenario

The United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center developed FOREcasting SCEnarios (FORE-SCE) model to provide spatially explicit detailed projections of plausible future land use and land cover (LULC) change for the conterminous United States (Sohl et al., 2016; Sohl et al., 2013). Four scenarios (A1B, A2, B1 and B2) of LULC were developed based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenario (SRES) (Sohl et al., 2016). The IPCC-SRES framework provides a set of four primary scenario families. They are:

A1B: This scenario is characterized by moderate population growth, very high economic growth, rapid technological innovation, strong bio-fuel demand including cellulosic based ethanol, grassland lost to food and biofuel crops and reduced regulation.

A2: This storyline is described by very high population growth, moderate economic growth, high demand for agricultural products, moderate biofuels demand, grassland lost to food crops and reduced regulation.

B1: This scenario will have a moderate population growth with compact urban development, high economic growth, low overall energy use, lower demands for biofuels, increased regulations and protection of natural land cover, restoration of natural land cover where possible.

B2: In this scenario, population growth will be low with compact urban development, moderate economic growth, moderate energy use and low biofuel use, regional development and reduction in agricultural exports, decrease in agricultural land extent and restoration of natural land cover where possible.

The FORE-SCE model produced projected land use maps for these four scenarios for each year from 1992 through 2100 using 1992 National Land Cover Dataset (NLCD) (Sohl et al., 2014; Vogelmann et al., 2001; Wu et al., 2013). Most classes modeled in FORE-SCE are the same as the 1992 NLCD but modeling detailed urban classes for the entire United States was impractical, so multiple NLCD urban classes were aggregated to one urban/developed class (Sohl et al, 2013). Local patterns of LULC change are generally determined by biophysical site information, while forces driving overall proportions of change come from larger-scale, outside drivers such as global trade or demographic change (Alcamo et al, 2006). To account for both bottom-up and top-down drivers of change, a non-spatial "demand' component was developed to produce future proportions of LULC change at an aggregated regional level (Sohl et. al, 2013). The demand component of the modeling framework was provided by (1) historical LULC proportions for the baseline 1992–2005 period, and (2) future scenarios for the 2006–2100 projection period (Sohl et. al, 2013). The FORE-SCE models are the first national-scale, moderate resolution and thematically detailed LULC

projections which are available for the conterminous United States (Sohl et al., 2014). The LULC maps are applicable to variety of ecological applications (Sohl et al., 2014).

2.6 Hydrologic Modeling

Watershed models are mathematical representations of hydrologic processes and affected socioeconomic and environmental systems (Mirchi et al., 2010). The purpose of a model is to simplify the actual watershed processes. A wide variety of models can be found to represent the complex hydrologic dynamics of the earth system. Singh (1988) classified various hydrologic models into different categories:

- Lumped hydrologic models – Lumped hydrologic models were developed in the late 60s or early 70s with the wide use of computers and are generally based on the concept of unit hydrograph. These models consider the complete basin as a homogenous system without accounting for the spatial distribution of processes (e.g. rainfall) (Xu, 2002). Stanford watershed model (Crawford and Linsley, 1966) was one of the first lumped hydrologic models to simulate watershed hydrology. Later, HBV model (Bergstrom, 1976) and Sacramento Soil Moisture Accounting (SAC-SMA) model (Burnash et al., 1973), among others, were developed as lumped hydrologic models.

- Semi-distributed hydrologic models – These models consider spatial heterogeneity of a watershed to a limited extent (Schumann, 1993). Semi-distributed hydrologic models sub-divide the watershed into separate sub-basins and calculate flow contribution from them considering that the sub-basins are homogenous (Xu, 2002). USDA developed physically based model Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012; Neitsch et al., 2011) is an example of semi-distributed hydrologic model.

- Distributed hydrologic models – Distributed hydrologic models were developed with the availability of hydrologic data and improvement of computer's computational capacity and precision. These models consider the entire watersheds spatial heterogeneity by dividing the

watershed area as a grid net where water flows from one grid point to another when water drains through the watershed (Xu, 2002). SHE (Abbott et al., 1986) and the Institute of Hydrology Distributed Model (IHDM) (Beven et al., 1987) are a few examples of distributed hydrologic models.

The Soil and Water Assessment Tool (SWAT) is a semi-distributed, continuous-time step, process-based river basin model (Arnold et al., 2012). SWAT has been widely used to analyze hydrological processes at watershed scales. This model was developed to evaluate the impact of climate and land management practices on water in large and complex watersheds with varying soils, land use, and management conditions over long periods of time (Arnold et al., 1998). The hydrological component of the model is based on a water balance equation with processes that include precipitation, surface runoff, water yield, ET, lateral flow, percolation and groundwater flow (Arnold et al., 1998; Neitsch et al., 2005). The water balance equation of the model (Neitsch et al., 2011) is as follows:

$$SW_t = SW_o + \sum_{n=i}^{t} P - Q_{surf} - ET - W_{seep} - Q_{gw}$$

where, SW is the change in soil water storage, P is the daily precipitation, ET is the Evapotranspiration, Q_{surf} is the surface runoff flow, Q_{gw} the groundwater flow and W_{seep} is the deep aquifer recharge. Surface runoff is determined through a modified Soil Conservation Service (SCS) curve number (CN) method (Arnold et al., 1998; Neitsch et al., 2011; Wu et al., 2012b). The SCS curve number equation is (SCS, 1972):

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{(R_{day} + 0.8S)}$$

where Q_{surf} is the accumulated runoff (mm H_2O), R_{day} is the rainfall depth for the day (mm H_2O) and S is the retention parameter. The retention parameter is defined as:

$$S = 25.4(\frac{1000}{CN} - 10)$$

where CN is the curve number for the day.

The Penman-Monteith method (Monteith, 1965) was used to estimate the potential ET in the current application of the SWAT model. For water budget, SWAT differentiates the solid and liquid precipitation based on near-surface air temperature. A more comprehensive description of the equations used in SWAT can be found in Neitsch et al. (2011).

2.7 Application of SWAT to a Semiarid Watershed

SWAT was initially designed to evaluate the impact of LULC change on watershed hydrology and water quality and has been widely applied for watershed scenario analysis but its application in the arid/semiarid regions has been few although increasing in recent years (Gassman PW 2007; Yuan, Y., 2009; Ouessar et al. 2009; Ghaffari et al. 2010; Veith et al. 2010). Arid/semiarid regions are characterized by short term, high intensity rainfall events during the summer monsoon season and discontinuous streamflow (Yuan, Y., 2009; Niraula et al., 2014). Moreover, in semiarid watersheds, soil moisture had little impact on stream flow because the watershed is almost always dry when it rains and soil moisture 'memory' is relatively short in semiarid conditions (Syed et al., 2003). For all these unique conditions, it is a little sensitive to model a semiarid watershed using SWAT. But some studies have shown that with adequate data and calibrated sensitive parameters, SWAT can satisfactorily reflect the hydrological characteristics of a semiarid watershed and then be used to evaluate alternative management scenarios (Yuan, Y., 2009; Ghaffari et al. 2010; Yuan et al., 2012; Niraula et al., 2014; Marek et al., 2017). A study in the semiarid Santa Cruz watershed in Arizona show that multi-gauge calibration can develop a reliable model with Nash-Sutcliffe Efficiency (NSE) as high as 0.8 (Niraula et al., 2014). Another study by Marek et al., 2016 suggested that with adequate management data, a calibrated SWAT model can simulate reasonable water use and crop yields for crops grown in the Texas High Plains. Various data scarce arid and semiarid region outside the U.S. also used SWAT to simulate watershed hydrology (Ouessar et al. 2009; Fadil et al. 2011). Ouessar et al. (2009) recommended installation of additional rainfall and runoff gauges with

continuous data logging and the collection of more field data to represent the soils and land use in a 270 km^2 watershed in southeastern Tunisia. But in another semiarid watershed in Morocco, with limited data SWAT simulated a dam inflow with a R^2 value of 0.9 (Fadil et al. 2011) which indicates proper calibration can enable SWAT to perform well in semiarid regions.

Chapter 3: Spatial and Temporal Characterization of Water Balance Components in New Mexico-Texas Border Region

3.1 Introduction

Watershed hydrology in the arid/semiarid southwest poses unique challenges. Streamflow in these watersheds is largely dependent on dam releases and seasonal, short term, and high intensity rainfall events. Water availability is quite inadequate in the New Mexico-Texas border region and changes in hydrological extremes and streamflow patterns can create social, economic, and environmental concerns. With increasing settlement and urban expansion, it is important to have a better understanding of potential changes in watershed hydrology in this region. The objectives of this chapter are to analyze the components of the water budget using Soil and Water Assessment Tool (SWAT) and evaluating SWAT model applicability to this watershed.

3.2 Study Area

The El Paso – Las Cruces HUC-08 scale watershed is located in the New Mexico – Texas -Mexico border region. At the heart of the watershed flows a portion of the Rio Grande River. Rio Grande originates in south-central Colorado and flows to the Gulf of Mexico through New Mexico and Texas before forming part of the US-Mexico border. Beginning at the downstream of Caballo Reservoir, this watershed covers an area of 6,331 sq. km before ending at El Paso where Rio Grande forms international boundary demarcation line between the US and Mexico. Dona Ana County, Sierra County and Grant County in New Mexico cover 74%, 22% and <1% of the watershed, respectively. El Paso County in Texas occupies 4% and the state of Chihuahua, Mexico, occupies <1% of the watershed. Elephant Butte Irrigation District (EBID) is located inside the watershed covering 6% of the entire watershed area with agricultural land use. Almost 83% of the watershed area is covered by shrubland. Approximately 6% of the watershed is classified as developed urban land. Most of the shrubland consists of hydrologic soil group B with an exception of a few parts, which have hydrologic soil group D. The agricultural land mostly has soil group B. Most of the river valley floor is compacted with sand and gravel of Santa Fe group.

Being situated in the semiarid region, this watershed receives approximately 250 mm average annual rainfall and 76.2 mm of annual average snowfall. Average daily temperature ranges between 58°F in January to 96°F in June. The National Hydrography Dataset classifies 8,953 km of water courses inside this watershed, majority of which flow intermittently during summer months due to high intensity convective thunderstorms as well as highly managed water distribution systems with dams and reservoirs. The main surface water source of this watershed is Caballo Dam located at the upstream of the watershed, which regulates releases from the Elephant Butte Reservoir which is the primary surface water source for this region. With 343,990 acre-feet capacity, Caballo Dam is located 25 km downstream of Elephant Butte Reservoir. According to Rio Grande compact, every year Elephant Butte reservoir supply water to EBID and El Paso County Water Improvement District No. 1 (EPCWID1) after delivering 60,000 acre-feet of water to Mexico. EBID and EPCWID1 share the water by 57% and 43% respectively according to their area in the watershed. A complex system of water rights allocates water resources among municipalities, Indian tribes, ecosystems, industrial users, and other groups in this watershed.

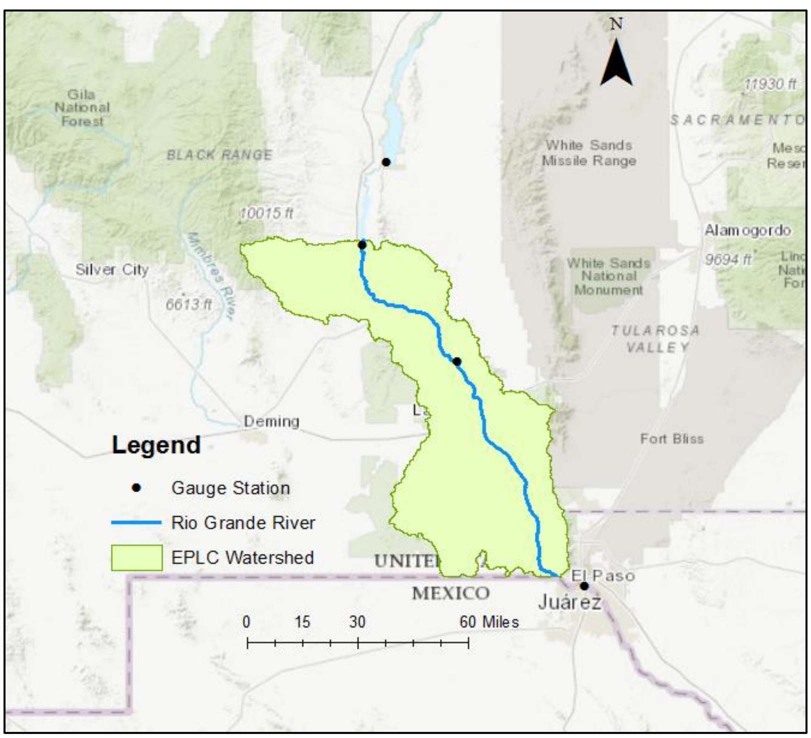


Fig 3.1: El Paso – Las Cruces Watershed

Table 3.1: Watershed characteristics represented in the developed SWAT model

Drainage Area, Km^2	6,331
No. of Sub-basins	37
No. of HRUs	1014
Main Stem Sub-basin	17
Non-Main Stem Sub-basin	20
Maximum Daily Streamflow (From 1990 - 2015) m^3/s	110
Minimum Daily Streamflow (From 1990 - 2015) m^3/s	0.37

3.3 Data and Methodology

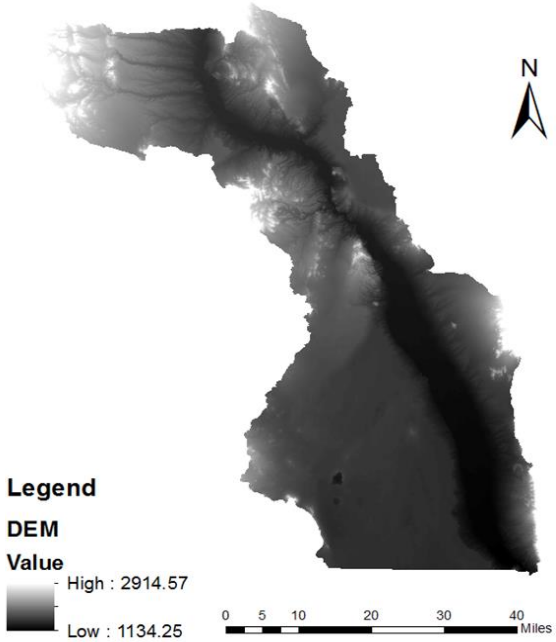
A SWAT model was created for the study watershed to characterize the hydrological processes and how it changed over two recent decades e.g. 1996-2005 and 2006-20015. ArcSWAT 10.2 was used to generate this baseline model.

3.3.1 SWAT Input Data

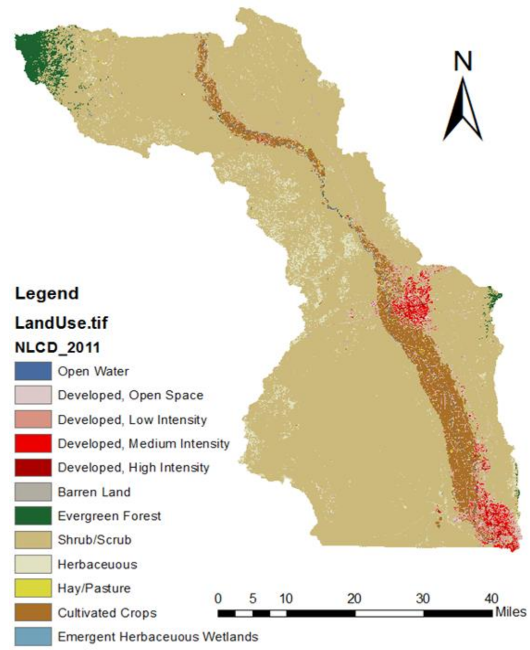
Setting up the SWAT model in ArcSWAT 2012 requires topography, land use land cover, soil texture (Figure 3.2). For this study, 1/3 arc second (10m * 10m) highest resolution DEM dataset was downloaded from the United States Geological Survey's (USGS) The National Map (TNM) download website. This DEM was used in the automatic watershed delineation feature of SWAT to sub-divide the watershed into sub-basins using 1.75% flow accumulation area threshold. A 30-m land use data from the National Land Cover Database (NLCD) 2011 and a 1:12,000 scale Soil Survey Geographic Database (SSURGO) included in SWAT 2012 database were used for the 1994-2015 period.

The model also requires climate data. Daily precipitation, maximum and minimum daily temperature data were collected from the National Climatic Data Center (NCDC) for the stations that fall inside or are adjacent to the study area. Other relevant climatic data (e.g. solar radiation, relative humidity and wind speed) were generated using the internal weather generator of ArcSWAT. Penman-Montieth equation was selected for estimating Potential Evapotranspiration

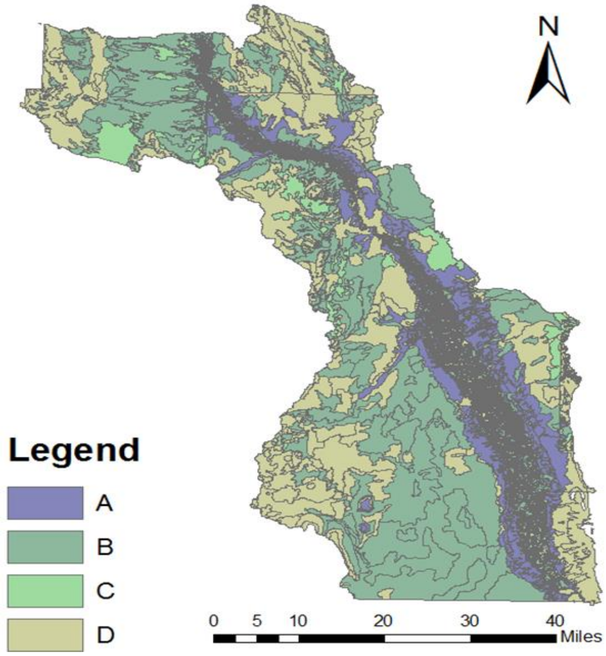
(PET). Curve number and variable storage methods (Neitsch et al., 2011) were used to calculate surface runoff generation and channel routing simulation, respectively.



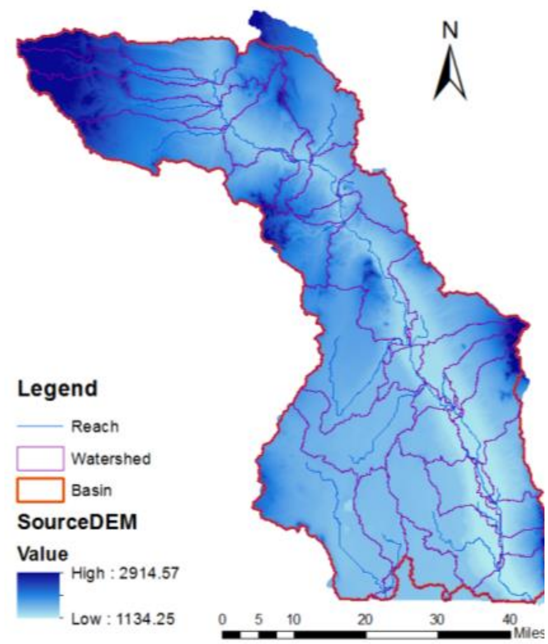
Digital Elevation Model (DEM)



Land Use Land Cover Map



Soil Map



Sub-basin

Fig 3.2: SWAT model inputs and result of sub-basing delineation

Three USGS gauging stations are located inside the watershed. USGS Site 08362500 is located in the middle of the upper boundary of the watershed on the Rio Grande below at Caballo Dam. Streamflow measured at this site was used as inflow to the watershed. The measured flow from other two stations USGS 08363510 Rio Grande below Leasburg and USGS 08364000 Rio Grande at El Paso were used to calibrate and validate the baseline model.

EBID uses both surface and groundwater irrigation during cropping season. SWAT plant database was used to model the crops growing in the irrigation district. Planting, irrigation and harvesting management operations were introduced with necessary data inputs (Table 3.2). The data were collected from literature (Kannan et al., 2010) and New Mexico Agriculture Statistics annual reports published by U.S. Department of Agriculture (USDA). SWAT irrigation schedule by date option was used to input the surface and groundwater irrigation that takes place inside the watershed.

Table 3.2: Management operations used for crop production

Crop	**Beginning of Planting Season**	**Irrigation amount (per application) (mm)**	**Harvesting Season**
Alfalfa	March	30	October
Cotton	February	70	July
Corn	April	70	Sep
Pecan	March	100	October
Pepper	May	80	September
Lettuce	April	80	September
Onion	April	65	October

3.3.2 Watershed Spatial Discretization and Modeling

To sub-divide the watershed into sub-basins 1.75% flow accumulation area threshold were used which resulted in 37 sub-basins. To further discretize the sub-basins into Hydrologic Response Units (HRUs) a 10% threshold for land use, soil and slope was used. The agricultural land use was divided up into 8 different crops according to their acreage collected from National Crop Data Layer. A 10% HRU aggregation was used to reduce the simulation time and to capture the temporal variability more accurately; a smaller (e.g. zero) threshold value leads to higher number of HRUs, therefore, demanding excessive computational time and space (Winchell et al., 2010). Land covers classified as agriculture (AGRR) and forest-evergreen (FRSE) were exempted from the aggregation to completely accommodate these land covers inside the model even if their extents are below the threshold (Winchell et al., 2010).

The baseline SWAT model (1994–2015; NLCD 2011) for El Paso – Las Cruces was run in both in daily and monthly time steps and, accordingly, calibrated against daily and average monthly streamflow observations obtained from 2 USGS gauge stations. As recommended by Daggupati et al. (2015), a 4-year period from 1990 to 1993 was used for "model warm-up" to initialize and then approach reasonable values of model parameters.

3.3.3 Calibration and Validation Methodology

The model was calibrated both manually and automatically. The manual calibration was performed by reviewing reports on groundwater by USGS due to the lack of continuous groundwater data (USGS, 1954). The GW_delay parameter was adjusted through manual calibration. The runoff curve number parameter for all the land use was also manually calibrated according to USDA report (USDA, 1986). For automatic calibration, the simultaneous multisite calibration is conducted by using the Sequential Uncertainty Fitting algorithm—version 2 (SUFI-2), which is a semi-automated inverse modeling procedure available inside SWAT-CUP platform (Abbaspour, 2015). SUFI-2 uses stochastic calibration method to capture the errors and uncertainties in the model. In SUFI-2, uncertainty in parameters considers uncertainty in driving variables (e.g. rainfall), conceptual model, parameters and measured data. Uncertainties in the

model output variables causes by the propagation of the uncertainties in the parameters, which are expressed as the 95% probability distributions and are calculated at the 2.5% and 97.5% levels of cumulative distribution of an output variable generated by the propagation of the parameter uncertainties using Latin Hyperbole sampling (Abbaspour, 2015). In a stochastic calibration approach, this 95% prediction uncertainties or 95PPUs are identified as model output.

Thirteen parameters related to surface, subsurface flow, and channel hydrologic responses were used for calibration (Table 3.3) after performing a parameter sensitivity analysis using SWAT-CUP. SWAT parameters and their initial value ranges were selected based on the review of existing literature (e.g., Jha et al., 2006; Van Griensven et al. 2006; Jin et al., 2015; Rajib et al., 2016) and suggestions from model developers (e.g. Neitsch et al., 2011).

Table 3.3: Parameters used in SWAT model calibration and their best estimates

No.	Parameters	Definition	Initial Range	Best Estimation
1	v_ALPHA_BF	Baseflow recession constant (days)	0-1	0.3
2	v_GWQMN	Threshold depth for return flow (mm H2O)	0.01-5000	2813.37
3	r_IRR_EFF	Irrigation efficiency	0.2-0.6	0.57
4	r_AUTO_WSTRS	Water stress to trigger irrigation	0.9-1	0.93
5	v_CANMX	Maximum Canopy Storage (mm H2O)	0.01-25	21.36
6	r_SOL_AWC	Available soil water capacity (mm/mm)	(-0.15)-0.15	0.023
7	v_SURLAG	Surface runoff lag coefficient (days)	0.05-24	22.5
8	v_CH_K2	Main channel hydraulic conductivity	5-100	24.5
9	v_CH_N2	Main channel Manning's N	0-0.3	0.13
10	v_EPCO	Plant uptake compensation factor	0-1	0.67
11	v_ESCO	Soil evaporation compensation factor	0-1	0.14
12	v_GW_REVAP	Groundwater "revap" coefficient	0.01-0.2	0.157
13	r_SOL_K	Soil saturated hydraulic conductivity	(-0.15)-0.15	-0.152

3.3.4 Statistical Analysis

A nonparametric Wilcoxon test was performed to determine any significant differences in the medians of precipitation, evapotranspiration, surface runoff, soil water content and water yield of the watershed over the two periods of time (1996-2005 & 2005-2015). The significance level was set at α=0.05 to compute the statistics.

3.4 Results and Discussion

3.4.1 Evaluation of SWAT Performance

A multi-site calibration was performed using streamflow data from two USGS gauging stations. A mid basin station's (USGS 08363510) streamflow data from 2011-2012 and the outlet gauging station's (USGS 08364000) data from 1999-2015 were used to calibrate the model. The validation was performed using USGS 08363510 station's streamflow data for 2013 and USGS 08364000 station's streamflow data from 1994-1998. In the outlet station, SWAT simulation matched well with the observations showing reasonably good performance scores. Average monthly streamflow simulation at the basin outlet (USGS 08364000) during 1999–2015 produces only 0.9% percent bias with R^2 and NSE respectively being 0.83 and 0.7. In the mid-basin location (USGS 08363510), although calibrated for a shorter period (2011-2013) SWAT shows similar high-performance with R^2 and NSE ranging between 0.82-0.86. The model performs even better during the validation period in the basin outlet. The R^2 value is 0.9 and NSE is 0.83 here. However, the performance scores of model calibration and validation shown in Table 3.4 can overall be considered satisfactory according to the evaluation recommendations by Moriasi et al. (2007), Moriasi, Gitau, Pai, and Daggupati (2015), and Moriasi et al. (2015). The model performance shown here is comparable to various other large- scale SWAT applications as well (e.g., Abbaspour et al., 2015; Daggupati et al., 2015; Daggupati et al., 2016). The ET and groundwater recharge of the calibrated model also reasonably characterizes the ET and GW recharge of the watershed. Although SWAT input can take a specific amount of ground water to irrigate every year and cannot adjust between the conjunctive use of surface and ground water if need be.

Table 3.4: Model performance statistics

Stations	R^2	NSE	PBIAS
Calibration (USGS 08364000)	0.83	0.7	0.9%
Calibration (USGS 08363510)	0.86	0.82	16%
Validation (USGS 08364000)	0.9	0.83	2.2%
Validation (USGS 08363510)	0.81	0.8	3.6%

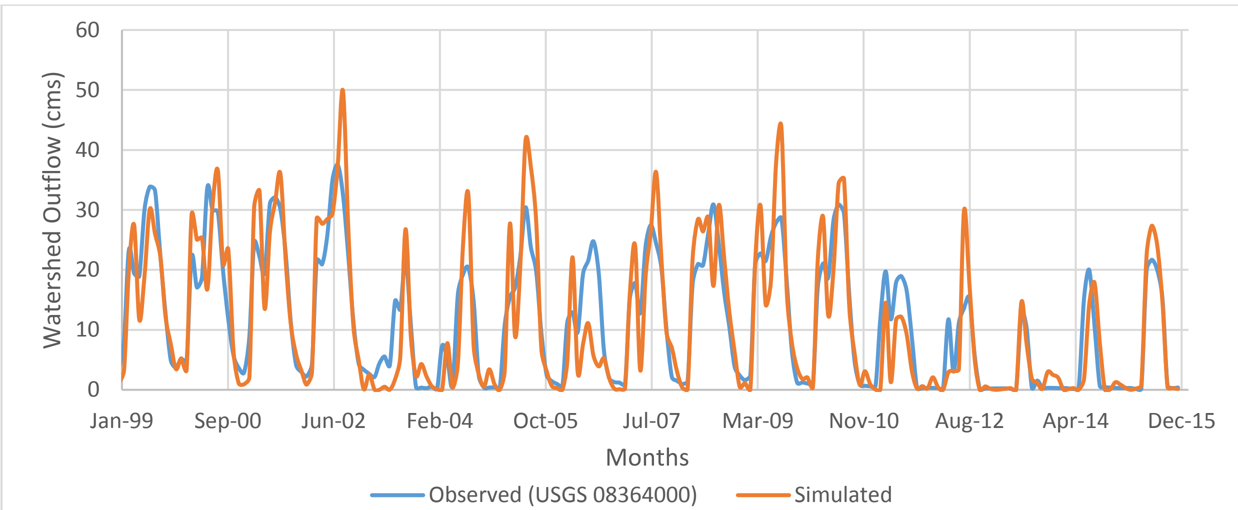


Fig 3.3: Comparison of observed and simulated streamflow at the basin outlet (USGS 0836400) during the calibration period (1999-2015)

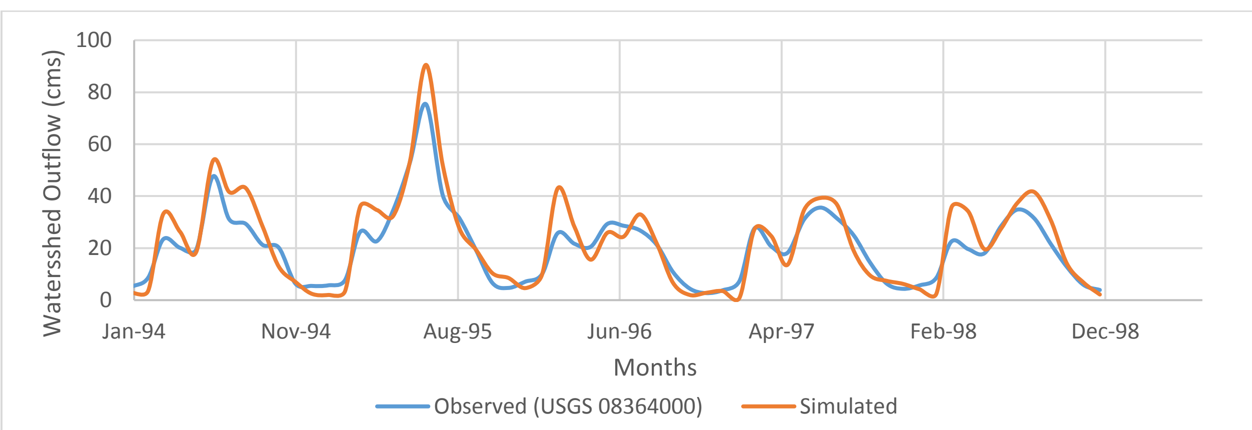
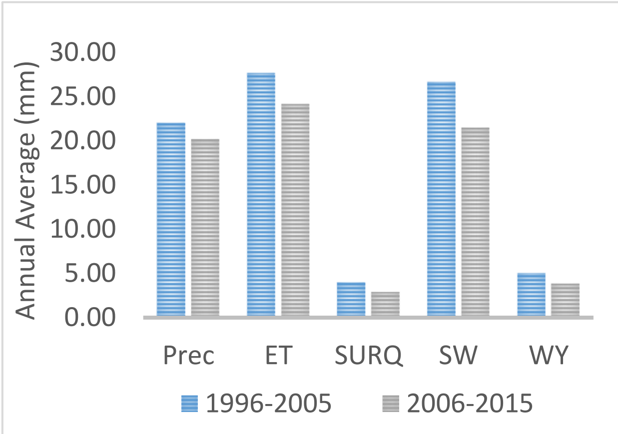


Fig 3.4: Comparison of observed and simulated streamflow at the basin outlet (USGS 0836400) during the validation period (1994-1998)

3.4.2 Assessment of Annual Water Balance

The average annual water balance components and their relative change over two time periods (1996-2005 and 2006-2015) for the watershed are shown in figures 3.5 and 3.6. The magnitude of water balance components such as lateral flow, percolation and groundwater flow were found to be relatively small in the current SWAT model application and are, thus, not discussed herein. The p-value from the nonparametric Wilcoxon test shows that there was a non-significant decrease in rainfall from the period 1996-2005 to 2006-2015. But other water balance components in the watershed had a significant decrease for the same period. According to Whitfield and Cannon (2000), statistically insignificant climate variations can trigger statistically significant changes in seasonal streamflow patterns. In mountainous regions, substantial changes in fresh water supply might be observed in area far from the mountain due to small shifts in the amount and form of mountain precipitation (Beniston et al., 1997). Moreover, this highly managed semiarid watershed depends heavily on irrigation. The Caballo Dam release which is the only surface water source for irrigation had a significant decrease in its annual flowrate during the 2006-2015 period as compared with the 1996-2005 period (Figure 3.7). According to previous research, ET is correlated with precipitation (R^2 = 0.66 and p=0.001) in semiarid rangelands (Nagler et al., 2007; Wu et al., 2012). This explains the 12.7% decrease in ET in this rangeland dominated watershed. Although surface runoff shows an overall significant decrease of 26.81%, the annual average change is just 1.06 mm which is not a large amount. The 19.35% decrease in soil water content can be attributed to the drought years in the 2006-2015 period. But this needs more intensive spatial and temporal investigation. Water yield is defined as the amount of water that becomes available to stream after leaving the landscape (Water yield = Surface runoff + baseflow + lateral flow – losses; Neitsch et al. 2011). This can be considered as a combined indicator of net water gain of water in a sub-basin. Decrease in all other water balance components explain the 23.34% decrease in water yield, too, but like surface runoff the overall annual average change of 1.17 mm is not substantial.



	Diff (mm)	%-change	p-value
PREC	1.84	8.36	0.14
ET	3.51	12.69	0.03
SURQ	1.06	26.81	0.03
SW	5.15	19.35	0.02
WY	1.17	23.34	0.05

Fig 3.5: Average annual values and percent change of precipitation (prec), evapotranspiration (ET), surface runoff (SR), soil water content (SW) and water yield (WY) for two study periods (1996-2005 & 2006-2015) in El Paso-Las Cruces watershed

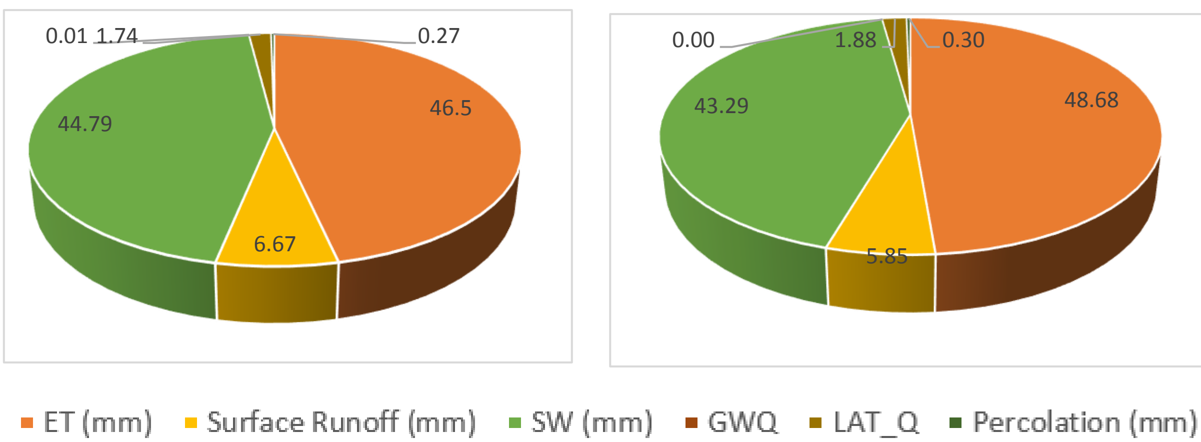


Fig 3.6: Average annual water budget for the two study periods (i.e., 1996-2005 & 2006-2015) in El Paso – Las Cruces Watershed

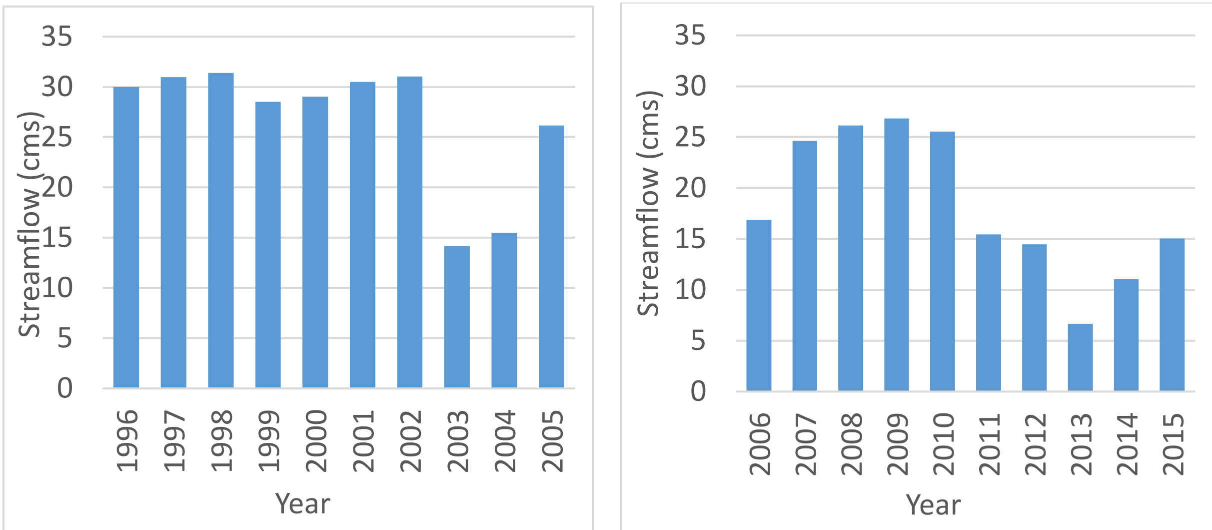


Fig 3.7: Average annual Caballo Dam release into El Paso-Las Cruces watershed during the 1996-2005 and 2006-2015 periods

3.4.3 Seasonal Variation in Water Balance Components

Figure 3.8 shows seasonal variation in hydrologic water balance components over 1996-2005 and 2006-2015 period. The values presented here are respective monthly averages for the two time periods, calculated over the entire watershed. Rainfall peaks in July and August due to North American Monsoon System (NAMS). Seasonal variation in surface runoff and especially ET follows the variation in precipitation. Runoff increased from April to August (i.e. warmer months) and decreased in the winter months. Soil water content decreased in the spring and summer months which is the plant growing season and this decline in soil water content can be explained by high plant canopy activities. Increase of ET in summer months (May to August) can be also be explained by this phenomenon and increased temperature. Comparison between the two time periods show that all the hydrologic components follow the same pattern in these two periods. There was no major shift in pattern between the 1996-2005 and 2006-2015 periods.

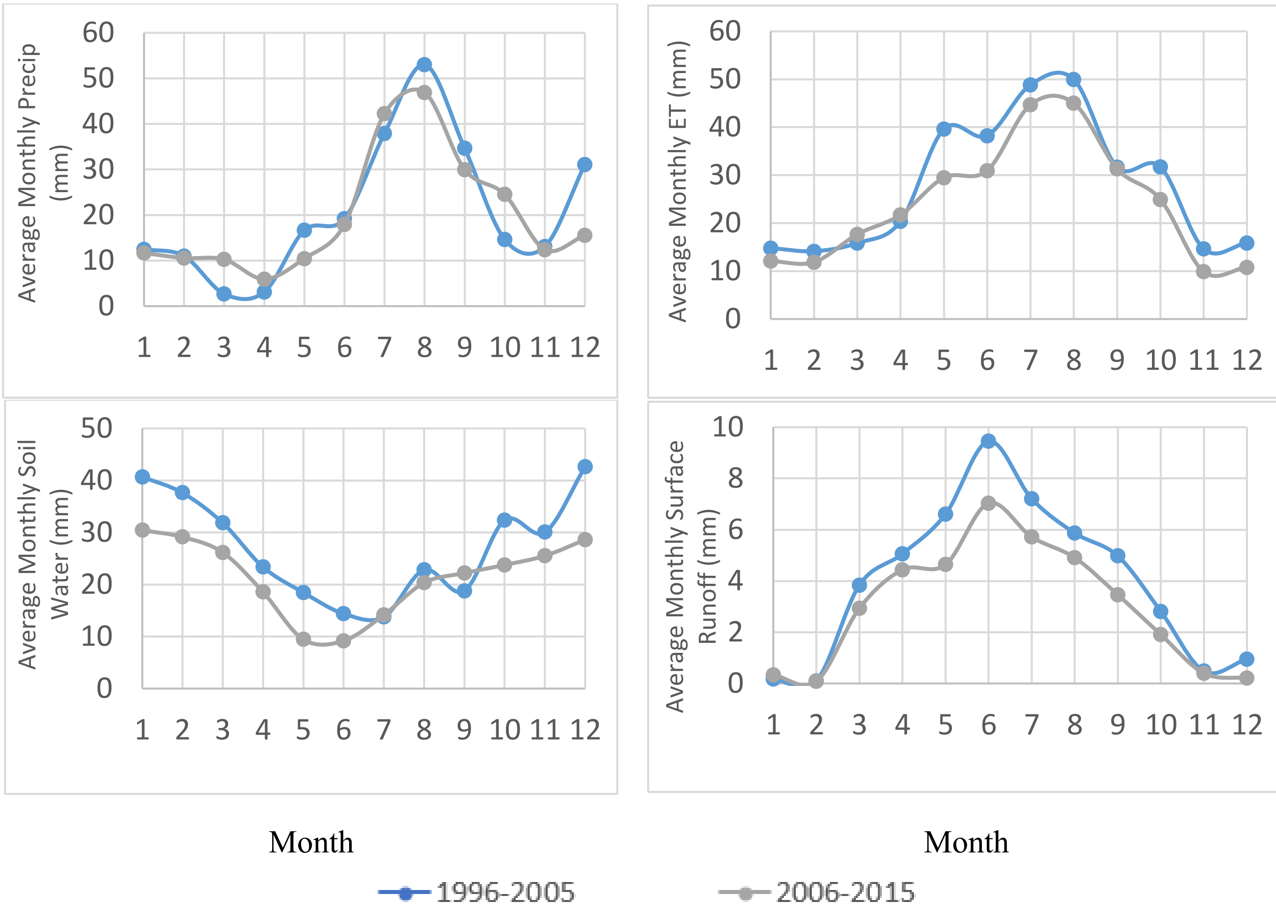
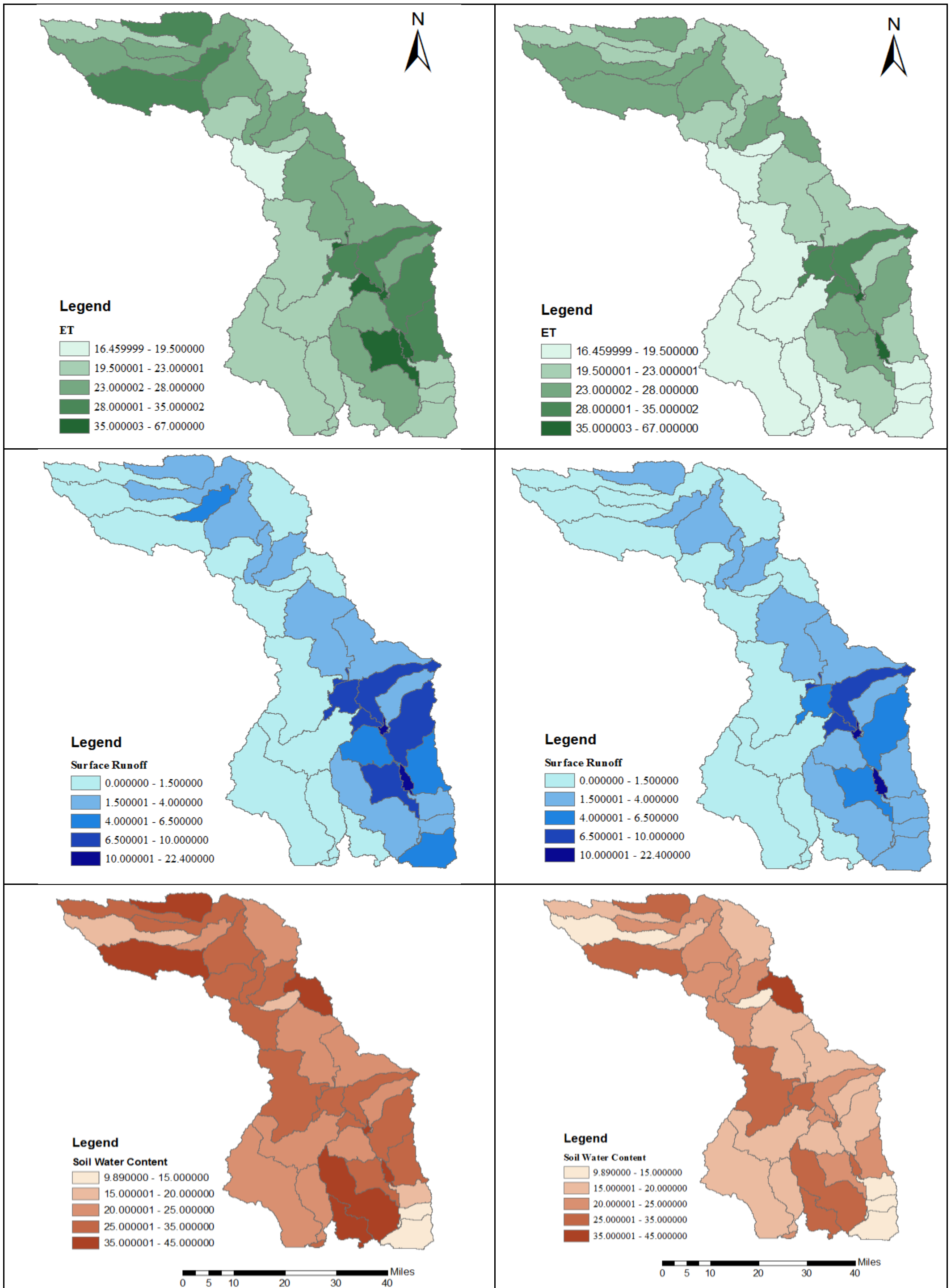


Fig 3.8: Seasonal variation in precipitation, ET, surface runoff and soil water content over 1996-2005 and 2006-2015 period of time in El Paso-Las Cruces watershed

3.4.4 Hydrological Responses at Sub-basin Scale

Sub-basin scale average outputs of ET, surface runoff and soil water content for the two time periods are shown in Fig 3.9. The spatial variation in ET indicates that sub-basins with rangeland/shrubland and urban development get lower ET than sub-basins with agricultural land. This can be explained by the irrigation activity taking place in these sub-basins. ET is an important hydrologic component in semiarid region. Sub-basins with higher soil water content also has higher ET in this watershed. The surface runoff is highest in the sub-basins with developed areas. The agricultural sub-basins also get relatively higher surface runoff due to the higher soil water content in these sub-basins during irrigation period.



1996-2005	2006-2015

Fig 3.9: Spatial variation in ET, surface runoff and soil water content over 1996-2005 and 2006-2015 period of time in El Paso-Las Cruces watershed

All the water balance components presented in this section have decreased in the 2006-2005 period in comparison to the 1996-2005 period. Especially, the soil water content in almost all sub-basins decreased substantially, likely due to the drought condition during this period.

3.5 Conclusion

This chapter reported the watershed hydrology analysis of a semiarid watershed using SWAT and evaluated the applicability of SWAT on this watershed. The results show that SWAT can be applied satisfactorily in a highly managed semiarid watershed with adequately available data. But there was one limitation of applying SWAT in an irrigated watershed where both surface and ground water were used conjunctively as SWAT could not adjust between the sources by itself. This study also evaluated the changes in the average annual water budget components and found out for a non-significant decrease in precipitation from 1996-2005 period to 2006-2015. ET, surface runoff, soil water content and overall water yield faced a significant decrease. Previous studies confirm the pattern, and this might also happen due to less dam release from the Caballo Reservoir. Seasonal variation in the water balance components follow the rainfall pattern. The comparison between change in water balance component based on the spatial pattern of the watershed indicates that most of the changes in ET and soil water content happen in the sub-basins containing the irrigation district. Other parts of the watershed containing mostly rangeland/shrubland experience less change in the hydrologic components.

Chapter 4: Hydrological Impacts of Extreme Rainfall and Land Use Changes

4.1 Introduction

Hydrologic models are used to analyze the impacts of changes in various factors that govern the water balance components on watershed scale. Semiarid watersheds are characterized by relatively larger extreme hydrologic event. The hydrologic extremes include low annual precipitation but high intensity storms, high evaporation, low base flows but high flash floods, and runoff loss through stream beds (Niraula et al., 2012; Hernandez et al., 2000). Rainfall is one of the main factors that govern the water balance components like ET, surface runoff, timing and magnitude of streamflow and flood events in a watershed. Evaluation of the impacts of high intensity, extreme rainfall and land use change is important in water resources management, flood inundation mapping, soil degradation, nutrient losses and biodiversity conservation practices (e.g., Heller and Zavaleta, 2009; Morton and Olson, 2014; Principe and Blanco, 2012; Schilling et al., 2014). The objectives of this chapter were to 1) evaluate the effects of extreme rainfall event with existing land use condition, 2) evaluate the effects of projected land use change scenarios with existing rainfall condition, and 3) assess the combined effects of extreme rainfall event and future land use on hydrological processes in a semiarid watershed.

4.2 Data and Methodology

4.2.1 Extreme Rainfall Events

A high intensity daily rainfall event in semiarid mountainous region can cause flash floods. Three high intensity 24-hr rainfall events were simulated to assess the potential effects of these events on the hydrological processes of El Paso – Las Cruces watershed in a recent year (2015). The calibrated model (1994-2015) was used to generate the baseline scenario. The largest 24-hr rainfall events recorded in each of the weather stations inside the watershed during the 22-year simulation period was used for the first scenario. The 100-yr 24-hr and 200-yr 24-hr rainfall for each of the weather stations inside the watershed were collected from National Oceanic and Atmospheric Administration (NOAA) Atlas 14’s precipitation frequency estimates. NOAA atlas

14 precipitation frequency estimates are delivered entirely in digital format through NOAA Precipitation Frequency Data Server (PDFS). The largest rainfall event in the simulating years, 100-yr 24-hr rainfall event and 200-yr 24-hr rainfall event were used to replace the largest 24-hr rainfall event in 2015 in three different models. The largest 24-hr rainfall event in 2015 was used as the baseline scenario. Table 4.1 lists the weather stations and 24-hr rainfall amount used for all these three models.

Table 4.1: 24-hr rainfall amount used for the three extreme rainfall events scenarios

Rainfall Event	Largest Rainfall in the Simulated Period (mm)	100 -yrs 24-hr Rainfall (mm)	200-yrs 24-hr Rainfall (mm)
Caballo Dam (Lat-32.90°, Lon- -107.30°)	64.8	86.9	96.8
Hatch 5 NW (Lat-32.74°, Lon- -107.25°)	52.2	81.3	89.9
State University (Lat-32.28°, Lon- -106.76°)	68.5	95.8	112.8
Afton 8 NE (Lat-32.17°, Lon- -106.83°)	77	92.2	103.1
El Paso International Airport (Lat-31.81°, Lon- -106.38°)	99	101.6	120

4.2.1 USGS Land Use Model

Projected LULC for 2050 from the FORE-SCE model was used to assess potential hydrologic impacts of LULC change by mid-century under the IPCC-SRES A1B, A2, and B1 scenarios. Table 4.1 shows the absolute area (km^2) and the percentage of watershed area occupied by different land use classes in the baseline model. The predominant LULC class for this watershed is shrubland covering 82% of the watershed area. Developed area (8.62%) and agricultural lands

(6.42%) area are the two other major land uses. The percentage of watershed area occupied by different land use classes for 2050 in A1B, A2, B1 and baseline condition are shown in Figure 4.1. The figure shows that the major LULC conversion happens between shrubland and grassland in all the projected future scenarios. The relative change (% change from the baseline condition) is shown in Table 4.3. Under the A1B scenario, which represents strong biofuel demand and high technological innovation, the agricultural land use decreased 45.5%. A2 and B1 scenario also showed a decreasing trend in agricultural land use in this region by 47.4% and 50.2%, respectively. In contrast to baseline watershed's 3.75%, grassland in A1B scenario occupies 27.2% which is relatively 625.33% more than the corresponding value in the baseline land use class. On the other hand, shrubland, the major land use class in baseline is decreased by around 29% in all three scenarios. Urban area expanded in all the future emission scenarios and the greater expansion was clearly visible in the highly populated A2 scenario with a relative increase of 24.3%. The A1B and B1 emission scenarios also indicated an increase of 8.4% and 9.1% in urban areas, respectively.

4.2.3 Scenario Simulation

The calibrated and validated baseline SWAT model was used to simulate the scenarios. For the rainfall scenarios, three different pcp.dat files were prepared with the new rainfall data and used as the model input in three separate models. For the future land use scenarios, the HRUs were defined again with 2050's land use maps for A1B, A2 and B1 emission scenarios in another three separate models. The calibrated parameters from the baseline model were transferred to the new model by rewriting the project database. To assess the combined effects of both extreme rainfall and land use change, the three pcp.dat files were used as the model weather data input into the models with new land use maps. There were nine new models for the assessment of compounding effects of extreme rainfall event and land use change on the hydrological processes on this semiarid watershed. Altogether, 15 scenario models were simulated and analyzed for this study.

Table 4.2: Land use classes in the El Paso-Las Cruces watershed based on NLCD 2011 (Baseline Scenario)

Land Use	Area (Sq. Km)	% of Watershed Area
Open Water	12.02	0.2
Cultivated Crop	385.82	6.42
Developed High Intensity	316.11	5.26
Developed Low Intensity	15.02	0.25
Developed Medium Intensity	126.81	2.11
Developed Open Space	60.1	1.00
Evergreen Forest	105.17	1.75
Grassland	225.36	3.75
Hay/Pasture	9.015	0.15
Herbaceous Wetland	1.2	0.02
Barren Land	15.02	0.25
Shrubland	4928	82
Woody Wetland	3	0.05

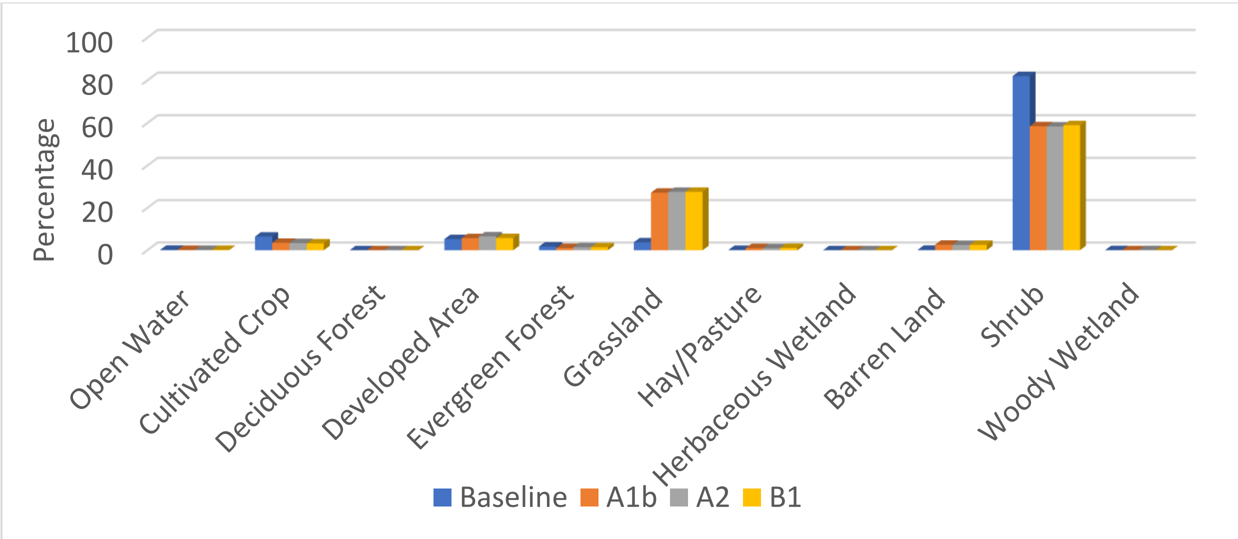


Fig 4.1: Percentage of area occupied by land use classes in Baseline (NLCD 2011) and A1B, A2 and B1 condition in 2050

Table 4.3: Percentage of area under different thematic classes in baseline and 3 FORE-SCE Models

Thematic Class	A1B (% of Area)	A2 (% of Area)	B1 (% of Area)
Open Water	-25%	-25%	-25%
Cultivated Crop	-45.5%	-47.4%	-50.2%
Deciduous Forest	0%	1%	1%
Developed High Intensity			
Developed Low Intensity	8.4%	24.3%	9.1%
Developed Medium Intensity			
Evergreen Forest	-37.14%	-18.87%	-18.2%
Grassland	625.33%	636%	636%
Hay/Pasture	586.67%	553.33%	613.33%
Herbaceous Wetland	-100%	-50%	-100%
Barren Land	940%	900%	920%
Shrub	-28.65%	-28.8%	-28.04%
Woody Wetland	-100%	0	-100%

4.3 Result and Discussion

4.3.1 Sub-Basin Scale Surface Runoff Response to Extreme Rainfall

The SWAT model used SCS curve number method to estimate the surface runoff. This method considers rainfall amount, infiltration prior to surface runoff, land use, land management practices, slope of the land, soil type and soil water content for calculating the accumulated surface runoff in a sub-basin. Given all these parameters, a sub-basin scale investigation was performed to assess the spatial response of surface runoff due to extreme rainfall events. Figure 4.2 (a) shows, in a typical rainfall year, the daily surface runoff is quite insignificant in this watershed. The sub-basin with the outlet of the watershed gets the highest daily runoff of 8.1 mm. This can be attributed to presence of urban land use. In Figure 4.2 (b), when the largest rainfall in the simulated years (1994-2015) was used as a model input, the surface runoff all over the watershed increased and showed almost the same pattern as the baseline model. Correspondingly, the models with (c) 100-yrs 24-hrs rainfall event and (d) 200-yrs 24-hrs rainfall event show an increasing pattern in surface runoff as well. Although heavy rainfall is usually a factor in causing flash floods, it results when some specific meteorological and hydrological conditions occur simultaneously. The most important conditions are magnitude, efficiency and direction of runoff, size of the drainage basin, antecedent condition of the basin and streamflow, precipitation intensity and duration, storm location, movement and evolution with respect to the basin location, soil type and soil moisture condition, land use and land cover (NOAA, 2010). As SWAT model cannot be run on a sub-daily timescale, it is hard to analyze the flash flooding potential that these surface runoffs might have on the sub-basins without all these specific data needs, particularly hourly information on rainfall-runoff processes inside the watershed. For this study, considering the area of the sub-basins, LULC and soil types, the sub-basins with daily surface runoff that exceeded 25% of the daily rainfall amount were considered vulnerable sub-basins. Several specific sub-basins fall under this category in all three scenarios. Spatial variation of rainfall from table 4.1 shows downstream stations of the watershed recorded larger rainfall events than the upstream ones and this might be one of the

reasons for the greater surface runoff of the downstream sub-basins. Sub-basin 6, 19 and 37 were identified as example vulnerable sub-basins in terms of large surface runoff potential.

4.3.2 Sub-basin Scale Response to Extreme Rainfall Event on Sediment Yield

Extreme rainfall and consequent flash flooding have significant effects on the sediment yield in the streams. Flash floods might have peak discharge between 5 to 500 m^3/s which causes arroyo erosion and subsequent sediment deposition in the main channel (Dean et al., 2016). Although due to lack of continuous historic sediment data, the baseline SWAT model has not been calibrated for the total sediment yield, an annual sediment load estimation using remote sensing data showed similarity between the observed and simulated sediment yield. The simulated value was found to be 34.2 kilo tons of annual average sediment yield in the watershed in year 2007 in comparison to 35.74 kilo tons of observed annual average sediment yield according to 'Channel Maintenance Alternatives and Sediment-transport Studies for the Rio Grande Canalization Project: Final Report'. As suggested by the study 'Preliminary Gradation Analysis of Rio Grande River Sediment Samples Collected between Leasburg and American Diversion Dams', the bed materials in this portion of the Rio Grande river bed can be categorized as sand. So, the density of beach sand was used for the conversion of volumetric sediment measurement of the observed data to match with the mass of the sediment yield estimated by the baseline SWAT model. Fig 4.3 shows the effect of all four rainfall scenarios including baseline condition on the sediment yield of the three vulnerable sub-basins those were identified in section 4.3.1. In the baseline scenario, the stream in sub-basin 6 shows a daily total sediment erosion of 0.106 tons during the largest rainfall event of 2015. Although very small in amount, both the streams in sub-basin 19 (1.317 tons) and 37 (0.135 tons) experienced a deposition of sediment during their respective largest rainfall events. In sub-basin 6, there was a substantial increase in sediment erosion during all three extreme rainfall events. The steep slope of this sub-basin might be a reason behind it being erosion-prone during extreme rainfall events. Also, a part of sub-basin 6 consists of hydrologic soil group D which has a very high runoff potential and might cause subsequent erosion.

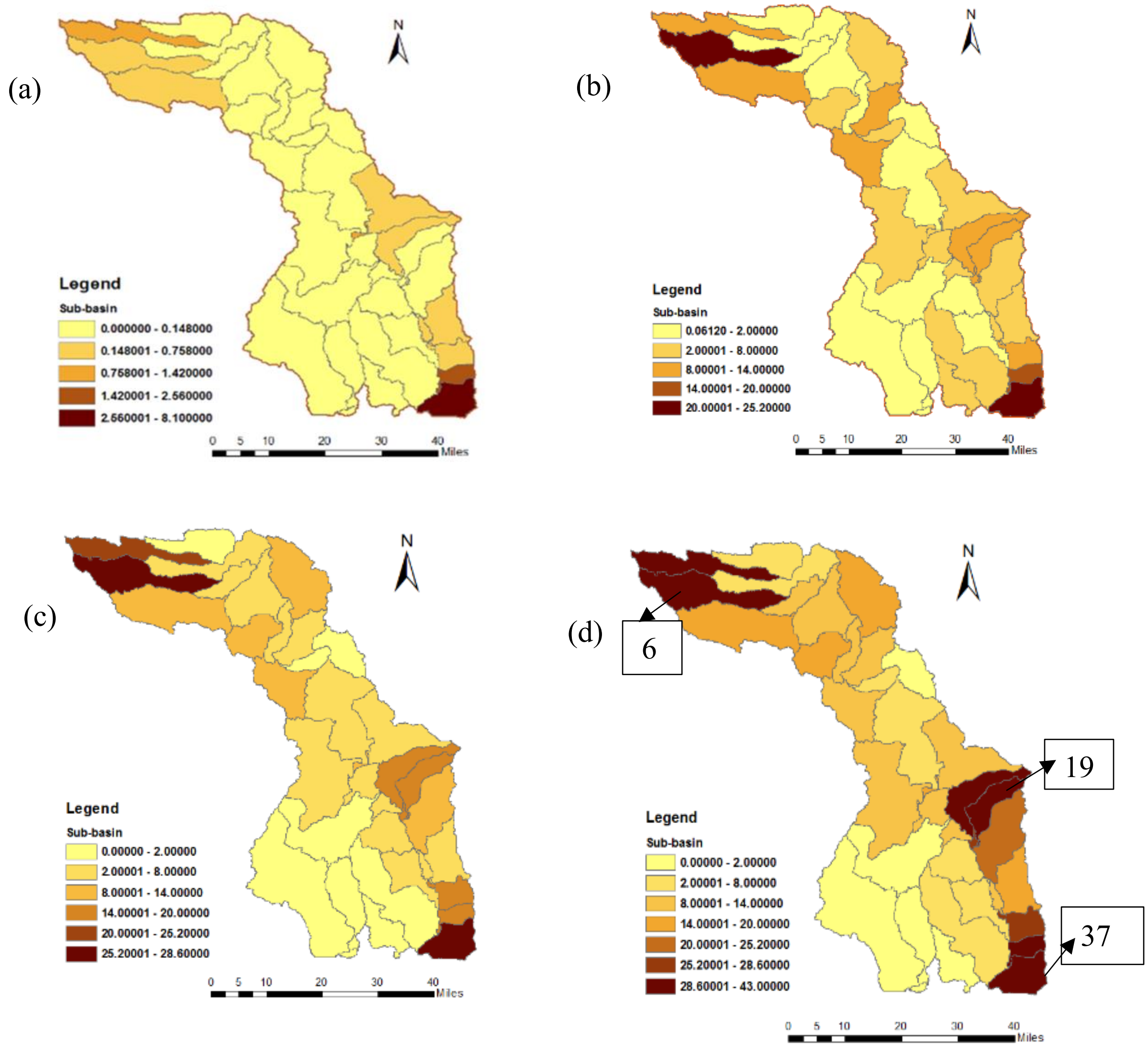


Fig 4.2: Spatial variation of surface runoff due to (a) baseline rainfall, (b) largest rainfall event in simulated years, (c) 100-yr 24-hrs rainfall, (d) 200-yr 24-hrs rainfall in El Paso-Las Cruces Watershed

Although sediment was deposited in the stream in sub-basin 19 during the baseline rainfall event, it showed an eroding trend under three extreme rainfall events. But even under the 200-yr 24-hr rainfall event, sub-basin 19 had a sediment erosion of 61.9 tons which is significantly less than sub-basin 6 which had an erosion amounting to 197.5 tons under the same rainfall scenario. Being two non-main stem streams, the difference in stream size, soil type and slopes between these two

sub-basins contributes to this difference. Sub-basin 37 contains a main channel that receive sediment depositions during heavy rainfall. Fig 4.3 illustrates that the largest rainfall event in the simulated period and the 100-yr 24-hr rainfall events deposit 9.74 tons and 6.5 tons of sediment in the stream, but the stream is more severely eroded under a 200-yr 24-hr rainfall event. The spatial variation of rainfall reported in Table 4.1 confirms the downstream station records the highest 200-yr 24-hr rainfall which is a potential reason behind severe erosion in the stream.

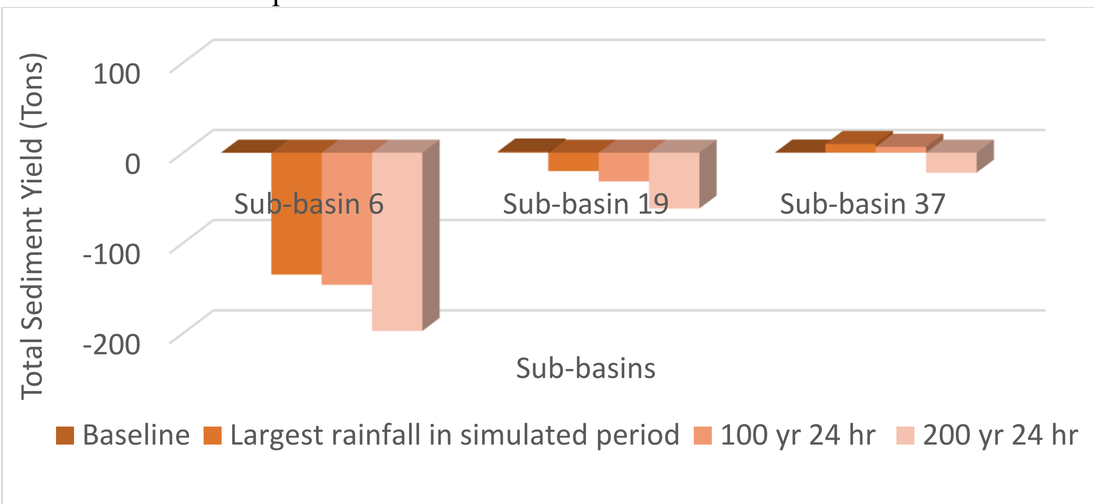


Fig 4.3: Effect of extreme rainfall on sediment yield

4.3.3 Hydrologic Response to Land Use Change

Fig 4.4 displays annual averages of major water balance components (e.g., ET, surface runoff and soil water content) under different land use scenarios and its percent changes in comparison to the baseline land use scenario. The results show ET decreases in every land use scenario, likely due to around 45-50% decrease in agricultural land in all the three scenarios.

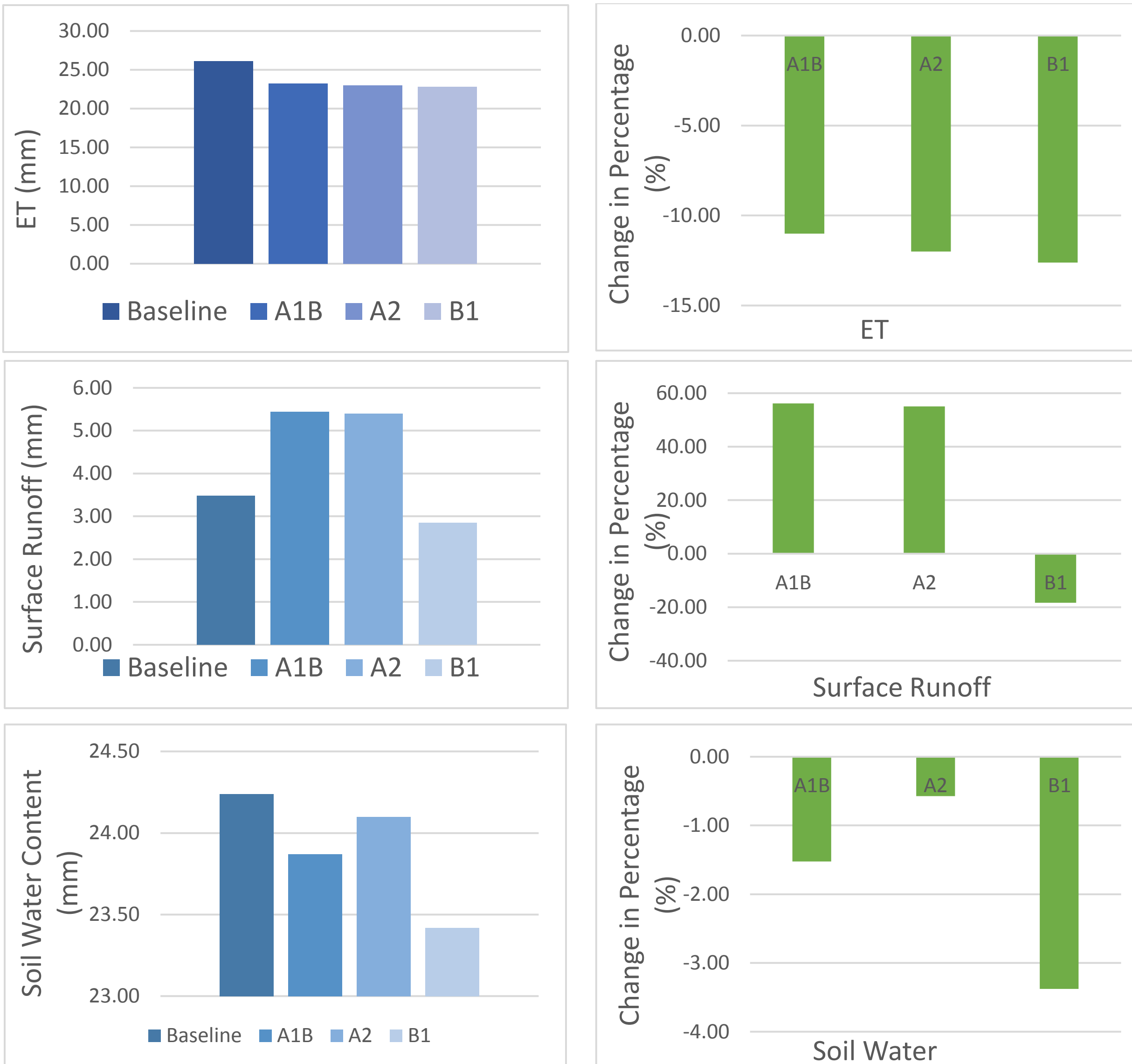


Fig 4.4: Annual average ET, surface runoff and soil water content under baseline (NLCD 2011), A1B, B1 and A2 land use scenarios over 1994-2015 in El Paso-Las Cruces watershed

In a semiarid watershed, agricultural activities depend largely on irrigation, which contributes to the overall ET in the watershed. Decreased cultivated crop land needs less irrigation and hence explains the 10-12% decrease in ET in all the three scenarios. The surface runoff in A1B and A2 scenario showed an increase of 55-56% but this amounts to about 2 mm annual increase over the watershed. Expansion of developed area under the A1B and A2 growth scenarios might cause this

increase in runoff. Thirty percent decrease in shrubland and its conversion to desert brush/grassland can also be a reason of this increased surface runoff as desert shrubland has a slightly higher curve number than the grassland. Scenario B1 with a lesser increased developed area has a slightly decreased surface runoff. With a decreased cropland and irrigation, soil water content also decreased to some extent under all the scenarios.

4.3.4 Compounding Impacts of Extreme Rainfall Event and Land Use Change on Surface Runoff

The compounding impact of both extreme rainfall event and land use change on surface runoff was studied in the example vulnerable sub-basins. Sub-basin 6 gets more than 30% of its rainfall as daily surface runoff in all the extreme rainfall event scenarios whereas sub-basin 19 receives more than 25% in just the 200-yr 24-hrs rainfall event. Sub-basin 37 gets more than 25% of its rainfall as daily surface runoff in both the 100-yrs and 200-yrs 24-hrs rainfall event (Figure 4.5).

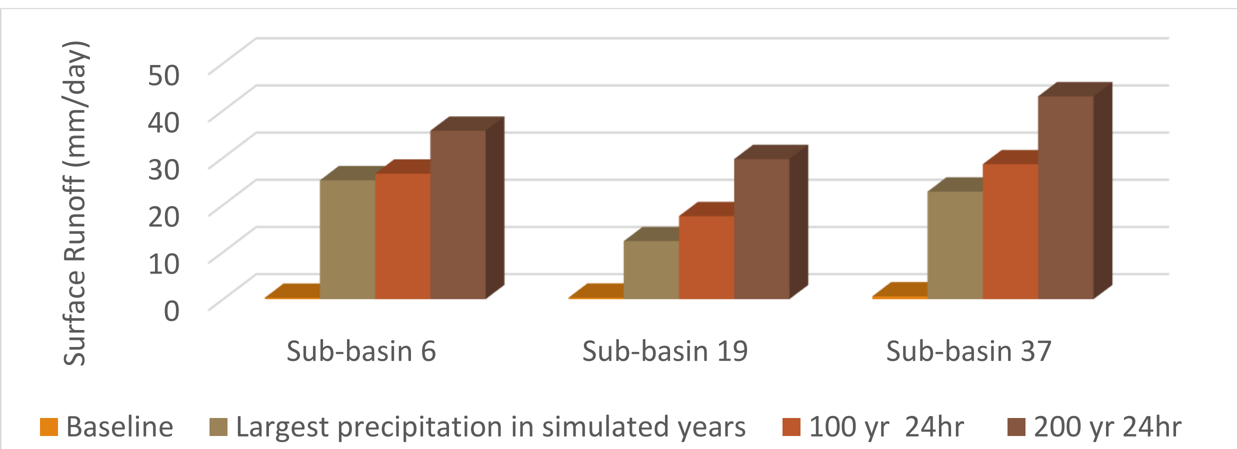


Fig 4.5: Surface runoff under different extreme rainfall events in vulnerable sub-basin

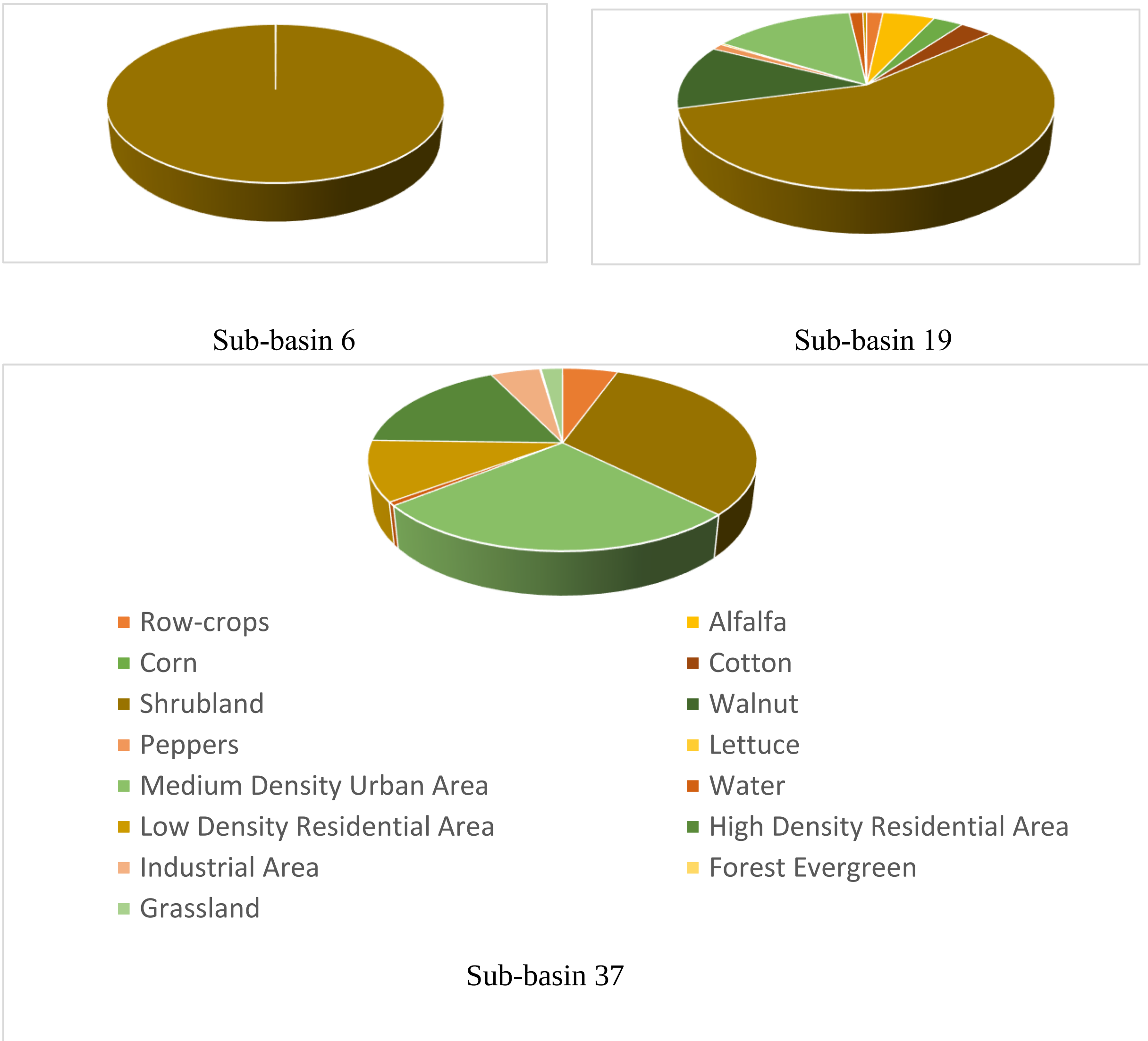


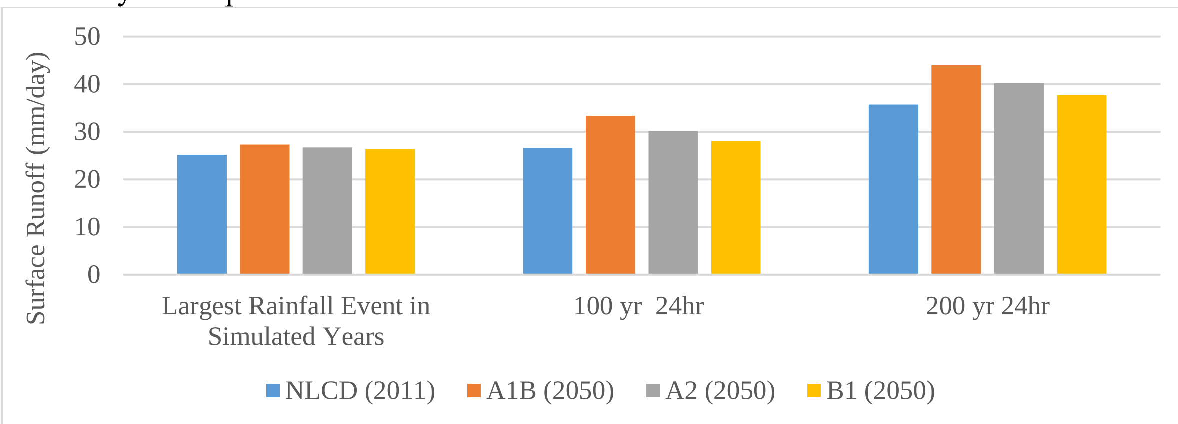
Fig 4.6: Land use land cover of the vulnerable sub-basins

These sub-basins were examined thoroughly for their land use, soil type, slope and other factors that affects surface runoff. Sub-basin 6 has a predominantly shrubland land cover (99.91%) with mostly B and D hydrologic soil groups. While soil group B has a moderate infiltration and surface runoff potential, soil group D has the highest surface runoff potential. In an arid and semiarid region, desert shrubland with soil group D can have a curve number between 84-88 which is quite high and might be the reason behind the high surface runoff in sub-basin 6. Moreover, this sub-basin has the steepest slope in the entire watershed. This also explains its vulnerability to large

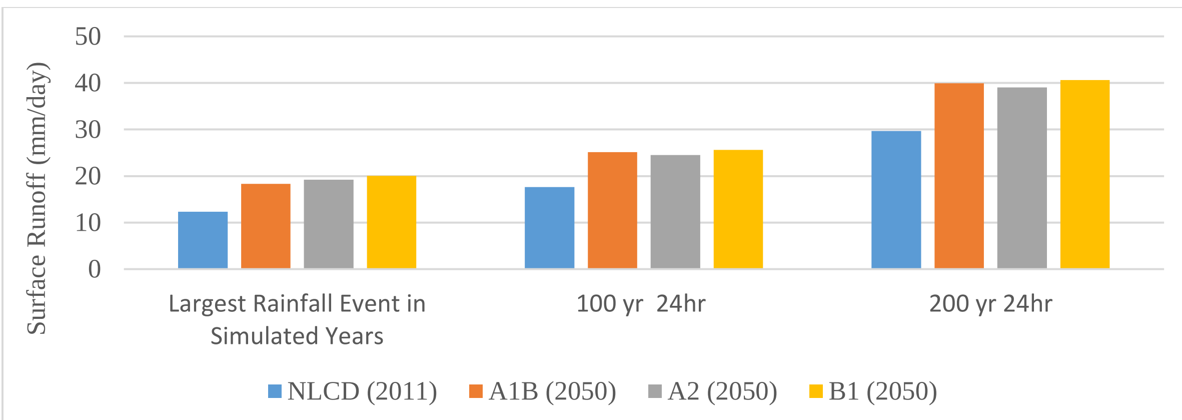
surface runoff. Sub-basin 19 has almost 25% urban developed area and 28% agricultural area. Both residential and industrial urban land cover have higher curve numbers between 84-98. Agricultural land in this sub-basin has hydrologic soil group A which has very high infiltration rate and low surface runoff potential. But the soil water content in agricultural land is usually higher in irrigation season than other land use classes, which causes a slightly increased surface runoff. Sub-basin 37 is a pre-dominantly urban area with around 60% developed land cover and mostly with hydrologic soil group D, which make this sub-basin the most vulnerable in the watershed. This analysis shows that land use land cover plays a secondary runoff-increasing role as compared with extreme rainfall event in the vulnerable sub-basins. Although hydrologic soil group played a role, but it was observed that sub-basins with higher surface runoff potential (sub-basin 32) with shrubland cover did not show the risk of higher surface runoff. For this reason, future land use land cover (2050) under different emission scenarios were modeled with extreme rainfall event and the result for the vulnerable sub-basins were presented in figure 4.7.

In sub-basin 6, the compounding impact of A1B land use scenario and largest extreme rainfall event in simulated years shows just 8.3% increase in runoff as compared with the baseline land use. A2 and B1 land use show a slightly decreased runoff than the A1B scenario. During the 100-yr and 200-yr 24-hrs rainfall events, the surface runoff increases to 25.6% and 23.25%, respectively, from the baseline to A1B land use scenario. But in both rainfall events, A2 scenario has 13.5% and 12.6% more surface runoff than the NLCD 2011 land use scenario, which is less than what it received under A1B scenario. The same pattern is shown by B1 land use scenario. The major land use conversion in this sub-basin occurs between desert shrubland and grassland. Around 3% of evergreen forest is also changed to grassland with high curve number in A1B scenario, which also contributes to the high surface runoff. But both A2 and B1 scenarios indicate less conversion of shrubland into grassland and consequently get less runoff than the A1B scenario. Sub-basin 19 shows more than 30% surface runoff increase from baseline to A1B land use scenario in all the three rainfall events. But A2 and B1 show a reverse pattern of increasing runoff than sub-

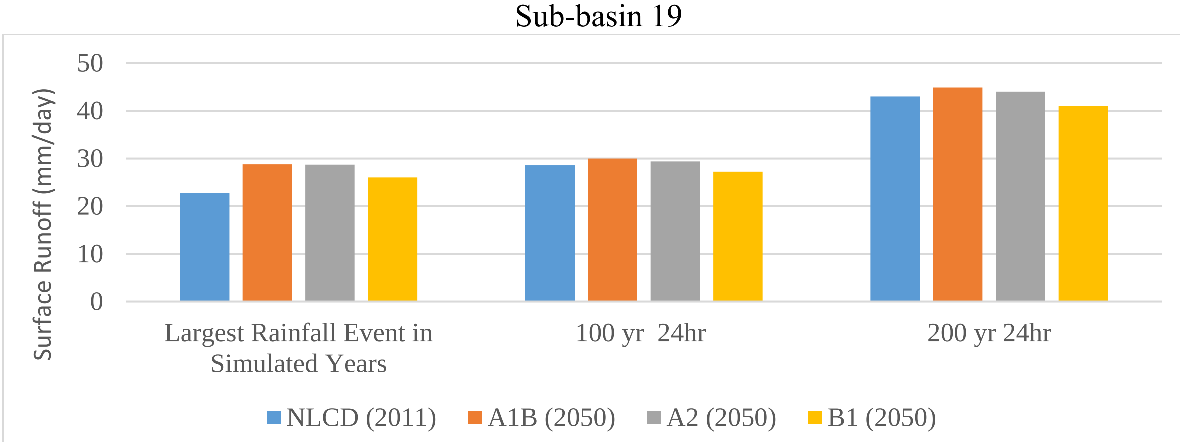
basin 6. Sub-basin 37 does not get affected much due to land use change as it was already a pre-dominantly developed area.



Sub-basin 6



Sub-basin 19



Sub-basin 37

Fig 4.7: Compounding impacts of extreme rainfall and land use change on surface runoff in vulnerable sub-basin

4.4 Conclusion

The hydrologic impacts of extreme rainfall events and land use changes in El Paso – Las Cruces watershed were examined using SWAT. The impacts of largest daily rainfall event in 1994-2015 period, 100-yr 24-hr rainfall event and 200-yr 24-hr rainfall event on the watershed in a recent year were evaluated. For land use scenario, future land use map of 2050 under A1B, A2 and B1 emission scenarios were simulated. The land use maps were derived from USGS FORE-SCE model. The compounding impacts of both the extreme rainfall scenario and land use land cover change scenario were also evaluated.

In the baseline condition, which was defined by the largest rainfall event in a recent year (2015), the sub-basins do not receive a significant amount of surface runoff. Under the extreme rainfall events scenario, vulnerable sub-basins were selected by identifying sub-basins where more than 25% of the rainfall amount produced surface runoff. The sub-basins were spatially scattered including one upstream (6), one downstream (37) and one mid-basin sub-basins (19). Further study involved investigation of the characteristics of these sub-basins and evaluation of their performance under different land use scenarios.

Evaluation of sediment transport characteristics of the vulnerable sub-basins revealed that they are also very erosion prone under extreme rainfall scenarios. The stream in sub-basin 6 was found to be the most susceptible to erosion possibly because of its steep slope. Both the streams in sub-basins 6 and 19 show erosion prone nature under all extreme rainfall scenarios but the stream in sub-basin 37 was eroded only under a 200-yr 24-hr rainfall event as it contains a main channel of the Rio Grande River.

Under different future land use scenarios, the entire watershed experiences a decrease in annual average ET and an increase in annual average surface runoff except in B1 scenario. This decrease in ET can be attributed to 45-50% decrease in cropland. The increase in surface runoff can be a contribution of both the increase in developed urban area and conversion of desert shrubland to grassland as desert grassland has a slightly higher curve number. Soil water content also shows a decreasing pattern except under A2 scenario, which also might be due to the decrease in cropland.

The compounding impacts of both extreme rainfall events and land use changes on the vulnerable sub-basins shows a deteriorated condition with surface runoff further increasing under all land use scenarios. However, extreme rainfall had the dominant impact on surface runoff as compared with land use change. Sub-basin 19 experienced the highest increase in runoff under a compounding condition due to its greater urban expansion.

Chapter 5. Conclusions

To better understand the regional hydrology of a southwestern semiarid watershed, a baseline SWAT model was developed for the 6331 sq. km El Paso – Las Cruces watershed. With available datasets and calibration, the model satisfactorily represented the hydrological processes of the watershed. At the outlet of the watershed, the simulated streamflow had a R^2 value of 0.83 and 0.9 and NSE of 0.7 and 0.82, respectively, during the calibration and validation period. The results indicate SWAT can be applied to a highly managed semiarid watershed with proper hydrologic and management data to analyze various climate and policy scenarios. Although SWAT input can take a specific amount of ground water to irrigate every year and cannot adjust between the conjunctive use of surface and ground water if need be. This should be taken into consideration while applying SWAT to an irrigated basin.

The baseline model was simulated for 22 years from 1994-2015. The hydrological processes occurring inside the watershed were investigated for two recent decades (e.g. 1996-2005 and 2006-2015) to examine any significant change in pattern. The study showed that for a statistically insignificant change in the precipitation from 1996-2005 to 2006-2015, the water balance components (e.g. ET, surface runoff, soil water content and water yield) showed a statistically significant decrease. The dam release for these two periods showed a substantial decrease causing the water balance components to decrease, too.

The temporal and spatial variation of the water balance components inside the watershed were also evaluated. The temporal variation of ET, surface runoff and soil water content follow the precipitation and dam release pattern throughout the year. The spatial variation indicates the hydrological processes mostly change in the agricultural cropland and urban sub-basins. The rest of the watershed containing desert shrubland/rangeland does not experience a significant hydrological change.

The baseline model was used to assess the impact of 15 scenarios including three extreme rainfall event scenarios, three land use land cover change scenarios and nine scenarios combining both these extreme rainfall events and land use land cover scenarios. The extreme rainfall event scenarios were the largest daily rainfall event in 1994-2015 period, 100-yr 24-hr rainfall event and

200-yr 24-hr rainfall event according to NOAA PFDS. The land use land cover change scenarios were derived from USGS FORE-SCE model for A1B, A2 and B1 emission scenarios in 2050.

Spatial attributes of the most vulnerable sub-basins to surface runoff under extreme rainfall event scenarios were evaluated. Land use land cover, soil type and slope contributed to these sub-basins' surface runoff susceptibility along with the spatial variation in rainfall amount. These vulnerable sub-basins are also sediment erosion prone under extreme rainfall events.

Under mid-century future land use for A1B, A2 and B1 scenarios the entire watershed experiences decreases in ET and soil water content due to urban expansion, cropland reduction and conversion of shrubland to grassland. But the surface runoff increases especially in the vulnerable sub-basins.

The compounding impact of both extreme rainfall events and land use changes on the vulnerable sub-basins shows a deteriorated condition with surface runoff further increasing under all land use scenarios. While no significant difference was discerned among the land use scenarios themselves, sub-basin 19 experienced the highest increase in runoff under a compounding impact scenario due to greater urban expansion. By contrast, sub-basin 37 was not significantly affected as it was already an entirely developed area.

In summary, both extreme rainfall event and land use land cover change affect the hydrology of the watershed. Surface runoff is mostly governed by extreme rainfall events, but it shows spatial variability under future land use land cover scenarios. Further investigations involving both rainfall events and land use land cover change are needed to inform future water resources and disaster management in this region.

References

Abbott, M. B., J. C. Bathurst, J. A. Cunge, P. E. O'Connell, and J. Rasmussen. 1986. An introduction to the European Hydrological System—Systeme Hydrologique Europeen,"SHE", 1: History and philosophy of a physically based, distributed modelling system. *Journal of Hydrology* 87(1):45-59.

Alcamo, J. and Schaldach, R., 2006. LandShift: global modelling to assess land use change. *EnviroInfo*, *2006*, p.20th.

Aouissi, J., Benabdallah, S., Chabaane, Z.L. and Cudennec, C., 2016. Evaluation of potential evapotranspiration assessment methods for hydrological modelling with SWAT—Application in data-scarce rural Tunisia. Agricultural Water Management, 174, pp.39-51.

Arnell, N. W. 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global environmental change* 14(1):31-52.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large area hydrologic modeling and assessment part I: Model development1. Wiley Online Library.

Arnold, J., D. Moriasi, P. Gassman, K. Abbaspour, M. White, R. Srinivasan, C. Santhi, R. Harmel, A. Van Griensven, and M. Van Liew. 2012. SWAT: Model use, calibration, and validation. *Transactions of the ASABE* 55(4):1491-1508.

Beven, K., A. Calver, and E. Morris. 1987. *The Institute of Hydrology distributed model.*

Bonnin, G., D. Martin, T. Parzybok, B. Lin, D. Riley, and M. Yekta, 2006: Precipitation frequency atlas of the United States. *NOAA Atlas 14 Volume 2, Version 3.0, National Weather Service, Silver Spring, Maryland.*

Bergstrom, S. 1976. Development and application of a conceptual runoff model for Scandinavian catchments. Report No. RHO 7, *Hydrologi och Oceanografl*, Swedish Meteorological and Hydrological. p. 44.

Brown, D. G., C. Polsky, P. Bolstad, S. D. Brody, D. Hulse, R. Kroh, T. R. Loveland, and A. Thomson, 2014: Ch. 13: Land Use and Land Cover Change. *Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 318-332. doi:10.7930/ J05Q4T1Q*

Burnash, R., R. Ferral, and R. McGuire. 1973. A generalised streamflow simulation system–conceptual modelling for digital computers. *Joint Federal and State River Forecast Center. Sacramento, Technical Report.*

Changnon, S. A., and K. E. Kunkel. 1995. Climate-related fluctuations in midwestern floods during 1921-1985. *Journal of Water Resources Planning and Management* 121(4):326-334.

Crawford, N. H., and R. K. Linsley. 1966. Digital Simulation in Hydrology *Stanford Watershed Model 4.*

Dean, D.J., Topping, D.J., Schmidt, J.C., Griffiths, R.E. and Sabol, T.A., 2016. Sediment supply versus local hydraulic controls on sediment transport and storage in a river with large sediment loads. *Journal of Geophysical Research: Earth Surface*, *121*(1), pp.82-110.

DeFries, R. S., J. A. Foley, and G. P. Asner. 2004. Land-use choices: balancing human needs and ecosystem function. *Frontiers in Ecology and the Environment* 2(5):249-257

Deng, Zhimin, Xiang Zhang, Dan Li, and Guoyan Pan. "Simulation of land use/land cover change and its effects on the hydrological characteristics of the upper reaches of the Hanjiang Basin." *Environmental Earth Sciences* 73, no. 3 (2015): 1119-1132.

Dettinger, M., Udall, B. and Georgakakos, A., 2015. Western water and clima**te** change. *Ecological Applications*, *25*(8), pp.2069-2093.

Ellis, E., and R. Pontius. 2007. Land-use and land-cover change. *Encyclopedia of earth*.

Elsner, M. M., L. Cuo, N. Voisin, J. S. Deems, A. F. Hamlet, J. A. Vano, K. E. B. Mickelson, S. Y. Lee, and D. P. Lettenmaier. 2010. Implications of 21st century climate December 2015 *ESA CENTENNIAL PAPER 2089 change for the hydrology of Washington State. Climatic Change 102:225–260.*

Er-Raki, S., Chehbouni, A., Guemouria, N., Duchemin, B., Ezzahar, J., Hadria, R.,2007. Combining FAO-56 model and ground-based remote sensing to estimatewater consumptions of wheat crops in a semi-arid region. Agric. WaterManage. 87, 41–54.

Fadil, A., Rhinane, H., Kaoukaya, A., Kharchaf, Y. and Bachir, O.A., 2011. Hydrologic modeling of the Bouregreg watershed (Morocco) using GIS and SWAT model. Journal of Geographic Information System, 3(04), p.279.

Fang, X., Ren, L., Li, Q., Zhu, Q., Shi, P. and Zhu, Y., 2013. Hydrologic response to land use and land cover changes within the context of catchment-scale spatial information. *Journal of Hydrologic Engineering*, *18*(11), pp.1539-1548.

Ficklin, D.L., Luo, Y., Luedeling, E. and Zhang, M., 2009. Climate change sensitivity assessment of a highly agricultural watershed using SWAT. *Journal of Hydrology, 374(1-2), pp.16-29.*

Finch, D.M., 2012. Climate change in grasslands, shrublands, and deserts of the interior American West: a review and needs assessment. *Gen. Tech. Rep. RMRS-GTR-285. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 139 p., 285.*

Fu, B., Chen, L., Ma, K., Zhou, H., Wang, J., 2000. The relationships between land use and soil conditions in the hilly area of the Loess Plateau in northern Shaanxi, China. *Catena 36, 69–78.*

Gashaw, T., Tulu, T., Argaw, M. and Worqlul, A.W., 2018. Modeling the hydrological impacts of land use/land cover changes in the Andassa watershed, Blue Nile Basin, Ethiopia. *Science of The Total Environment, 619, pp.1394-1408.*

Gassman P.W, Reyes, R.M., Green C.H., and Arnold J.G. 2007. The soil and water assessment tool: Historical development, applications, and future research directions. *Transactions of the Asabe,* 50, 1211-1250.

Gebremicael, T.,Mohamed, Y., Betrie, G., van der Zaag, P., Teferi, E., 2013. Trend analysis of runoff and sediment fluxes in the Upper Blue Nile basin: a combined analysis of statistical tests, physically-based models and land use maps. *J. Hydrol. 482, 57–68.*

Getachew, H., Melesse, A., 2012. The impact of land use change on the hydrology of the Angereb watershed, Ethiopia. *Int. J. Water Sci. 1 (4), 1–7.*

Ghaffari, G., Keesstra, S., Ghodousi, J., and Ahmadi, H. 2010. SWAT-simulated hydrological impact of land-use change in the Zanjanrood Basin, Northwest Iran. *Hydrological Processes,* 24(7), 892-903.

Girmay, G., Singh, B., Nyssen, J., Borrosen, T., 2009. Runoff and sediment-associated nutrient losses under different land uses in Tigray, Northern Ethiopia. *J. Hydrol. 376, 70–80.*

Goodrich, D.C., Lane, L.J., Shillito, R.M., Miller, S.N., Syed, K.H., Woolhiser, D.A.1997. Linearity of basin response as a function of scale in a semiarid watershed. *Water Resources Research,* 33, 2951-2965.

Gutowski, J., Hegerl, C., Holland, J., Knutson, R., Mearns, O., Stouffer, J., Webster, J., Wehner, F. and Zwiers, W., 2008. Causes of observed changes in extremes and projections of future changes. *Weather and climate extremes in a changing climate, CCSP synthesis and assessment product 3.3*, *3*, pp.81-116.

Gwate, O., Woyessa, Y., Wiberg, D., 2015. Dynamics of land cover and impact on streamflow in the Modder River Basin of South Africa: case study of a Quaternary catchment. *Int. J. Environ. Prot. Pol. 3 (2), 31–38.*

Gyamfi, C., Ndambuki, J., Salim, R., 2016. Hydrological responses to land use/cover changes in the Olifants basin, South Africa. *Water 8:588.* *https://doi.org/10.3390/ w8120588*.

Hall, A. W., P. H. Whitfield, and A. J. Cannon. 2006. Recent variations in temperature, precipitation, and streamflow in the Rio Grande and Pecos River Basins of New Mexico and Colorado. *Reviews in fisheries science* 14(1-2):51-78.

Hanson, R. L. 1988. Evapotranspiration and droughts. *Paulson, RW, Chase, EB, Roberts, RS, and Moody, DW, Compilers, National Water Summary*:99-104.

Hernandez-Guzman, R., Ruiz-Luna, A. and Berlanga-Robles, C. A. 2008. Assessment of runoff response to landscape changes in the San Pedro sub-basin (Nayarit, Mexico) using remote sensing data and GIS. *Journal of Environmental Science and Health Part a-Toxic/Hazardous Substances & Environmental Engineering,* 43(12), 1471-1482.

Hochstrasser, T., Kröel-Dulay, G., Peters, D.P.C. and Gosz, J.R., 2002. Vegetation and climate characteristics of arid and semi-arid grasslands in North America and their biome transition zone. *Journal of arid environments*, *51*(1), pp.55-78.

Hosking, J.R.M. and J.R. Wallis, 1997: Regional frequency analysis, an approach based on L-moments. Cambridge University Press, 224 pp.

Huntington, T.G., 2006. Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology*, *319*(1), pp.83-95.

Hurni, H., Kebede, T., Gete, Z., 2005. The implications of changes in population, land use, and land management for surface runoff in the Upper Nile Basin area of Ethiopia. *Mt. Res. Dev. 25 (2), 147–154.*

Intergovernmental Panel on Climate Change (IPCC) (2001a), Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)], *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

Intergovernmental Panel on Climate Change (IPCC) (2013), The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press, Cambridge, United Kingdom*

Jacobson, C. R. 2011. Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review. *Journal of Environmental Management* 92(6):1438-1448.

Jha, M. K., and P. W. Gassman. 2014. Changes in hydrology and streamflow as predicted by a modelling experiment forced with climate models. *Hydrological Processes* 28(5):2772-2781.

Johnson, T., J. Butcher, D. Deb, M. Faizullabhoy, P. Hummel, J. Kittle, S. McGinnis, L. Mearns, D. Nover, and A. Parker. 2015. Modeling Streamflow and Water Quality Sensitivity to Climate Change and Urban Development in 20 US Watersheds. *JAWRA Journal of the American Water Resources Association*

Jones, J. A., and D. A. Post. 2004. Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States. *Water Resources Research* 40(5).

Karl, T.R. and Knight, R.W., 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. *Bulletin of the American Meteorological society*, *79*(2), pp.231-242.

Karl, T. R., and W. Riebsame. 1989. The impact of decadal fluctuations in mean precipitation and temperature on runoff: a sensitivity study over the United States. *Climatic Change 15:423–447.*

Kharin, V.V., Zwiers, F.W., Zhang, X. and Wehner, M., 2013. Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Climatic change*, *119*(2), pp.345-357.

Kidane, W., Bogale, G., 2017. Effect of land use land cover dynamics on hydrological response of watershed: case study of Tekeze Dam watershed, northern Ethiopia. *Int. Soil Water Conserv. Res. 5, 1–6.*

Kim, H. K., P. B. Parajuli, and S. D. Filip To. 2013a. Assessing impacts of bioenergy crops and climate change on hydrometeorology in the Yazoo River Basin, Mississippi. *Agricultural and Forest Meteorology* 169:61-73.

Kutiel, P., Kutiel, H. & Lavee, H. (2000). Vegetation response to possible scenarios of rainfall variations along a Mediterranean-extreme arid climatic transect. *Journal of Arid Environments*, **44**: 277–290.

LaFontaine, J. H., L. E. Hay, R. J. Viger, R. S. Regan, and S. L. Markstrom. 2015. Effects of Climate and Land Cover on Hydrology in the Southeastern US: Potential Impacts on Watershed Planning. *JAWRA Journal of the American Water Resources Association* 51(5):1235-1261.

Lambin, E. F., and P. Meyfroidt. 2011. Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences* 108(9):3465-3472.

Lebow, B., Patel-Weynand, T., Loveland, T. and Cantral, R., 2013. Land use and land cover national stakeholder workshop technical report. *Report prepared for*, p.73.

Li, Z., Liu, W.Z., Zhang, X.C. and Zheng, F.L., 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of hydrology*, *377*(1-2), pp.35-42.

Lirong, S., and Z. Jianyun. 2012. Hydrological Response to Climate Change in Beijiang River Basin Based on the SWAT Model. *Procedia Engineering* 28(0):241-245.

Liu, M., H. Tian, G. Chen, W. Ren, C. Zhang, and J. Liu. 2008. Effects of Land- Use and Land-Cover Change on Evapotranspiration and Water Yield in China During 1900- 20001. *JAWRA Journal of the American Water Resources Association* 44(5):1193-1207.

Mao, D., and K. A. Cherkauer. 2009. Impacts of land-use change on hydrologic responses in the Great Lakes region. *Journal of Hydrology* 374(1–2):71-82.

Marek, G.W., Gowda, P.H., Marek, T.H., Porter, D.O., Baumhardt, R.L. and Brauer, D.K., 2017. Modeling long-term water use of irrigated cropping rotations in the Texas High Plains using SWAT. Irrigation Science, 35(2), pp.111-123.

Melillo, Jerry M. Climate change impacts in the United States, highlights: US national climate assessment. *Government Printing Office, 2014.*

Memarian, H., Balasundram, S.K., Abbaspour, K.C., Talib, J.B., Boon Sung, C.T. and Sood, A.M., 2014. SWAT-based hydrological modelling of tropical land-use scenarios. *Hydrological sciences journal*, *59*(10), pp.1808-1829.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. Stationarity is dead—whither water management. Science 319:573–574.

Mirchi, A., Watkins Jr, D. and Madani, K., 2010. Modeling for watershed planning, management, and decision making. *Watersheds: management, restoration and environmental impact (Vaughn JC ed). Nova Science Publishers, Hauppauge, NY, USA*.

Monteith, J.L., 1965, July. Evaporation and environment. In *Symp. Soc. Exp. Biol* (Vol. 19, No. 205-23, p. 4).

Nagler, P.L., Glenn, E.P., Kim, H., Emmerich, W., Scott, R.L., Huxman, T.E. and Huete, A.R., 2007. Relationship between evapotranspiration and precipitation pulses in a semiarid rangeland estimated by moisture flux towers and MODIS vegetation indices. *Journal of Arid Environments*, *70*(3), pp.443-462.

National Assessment Synthesis Team (NAST) (2000), Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change, US Global Change Research Program (URL: www.usgcrp.gov/usgcrp/Library/nationalassessment/overview.htm)

Neitsch, S.L., Arnold, J.G., Kiniry, J.R. and Williams, J.R., 2011. *Soil and water assessment tool theoretical documentation version 2009*. Texas Water Resources Institute.

Neupane, R. P., and S. Kumar. 2015. Estimating the effects of potential climate and land us changes on hydrologic processes of a large agriculture dominated watershed. *Journal of Hydrology* 529:418-429.

Niehoff, D., U. Fritsch, and A. Bronstert. 2002. Land-use impacts on storm-runoff generation scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. *Journal of Hydrology* 267(1):80-93.

Niraula, R., Norman, L.M., Meixner, T. and Callegary, J.B., 2012. Multi-gauge calibration for modeling the semi-arid Santa Cruz Watershed in Arizona-Mexico border area using SWAT. Air, Soil and Water Research, 5, pp. ASWR-S9410.

NOAA National Centers for Environmental Information, State of the Climate: Synoptic Discussion for October 2015, *published online November 2015, retrieved on July 14, 2018 from https://www.ncdc.noaa.gov/sotc/synoptic/201510*.

Novotny, E. V., and H. G. Stefan. 2007. Stream flow in Minnesota: Indicator of climate change. *Journal of Hydrology* 334(3–4):319-333.

Oki, T., and S. Kanae. 2006. Global hydrological cycles and world water resources. *Science* 313(5790):1068-1072.

Ouessar, M., Bruggeman, A., Abdelli, F., Mohtar, R.H., Gabriels, D., and Cornelis, W.M. 2009. Modelling water-harvesting systems in the arid south of Tunisia using SWAT. *Hydrology and Earth System Sciences,* 13(10), 2003-2021.

Pai, N., and D. Saraswat. 2011. SWAT 2009 _LUC: A Tool to Activate the Land Use Change Module in SWAT 2009. *Transactions of the ASABE* 54(5):1649-1658.

Paul, Manashi, "Impacts of Land Use and Climate Changes on Hydrological Processes in South Dakota Watersheds" (2016). *Theses and Dissertations.* Paper 1018.

Paul, M., Rajib, M.A. and Ahiablame, L., 2017. Spatial and temporal evaluation of hydrological response to climate and land use change in three South Dakota watersheds. *JAWRA Journal of the American Water Resources Association*, *53*(1), pp.69-88.

Pervez, M. S., and G. M. Henebry. 2015. Assessing the impacts of climate and land use and land cover change on the freshwater availability in the Brahmaputra River basin. *Journal of Hydrology: Regional Studies* 3:285-311.

Pilgrim, D.H., Chapman, T.G., and Doran, D.G. 2009. Problems of rainfall-runoff modelling in arid and semiarid regions. *Hydrological Sciences Journal*, 33(4), 379-400.

Polade, S.D., Pierce, D.W., Cayan, D.R., Gershunov, A. and Dettinger, M.D., 2014. The key role of dry days in changing regional climate and precipitation regimes. *Scientific reports*, *4*, p.4364.

Rallison, R.E. and Miller, N., 1982. Past, present, and future SCS runoff procedure. In *Rainfall-runoff relationship/proceedings, International Symposium on Rainfall-Runoff Modeling held May 18-21, 1981 at Mississippi State University, Mississippi State, Mississippi, USA/edited by VP Singh*. Littleton, Colo.: Water Resources Publications, c1982.

Rientjes, T., Haile, A., Kebede, E., Mannaerts, C., Habib, E., Steenhuis, T., 2011. Changes in land cover, rainfall and streamflow in Upper Gilgel Abbay catchment, Blue Nile basin — Ethiopia. *Hydrol. Earth Syst. Sci. 15, 1979–1989.*

Rose, S., and N. E. Peters. 2001. Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. *Hydrological Processes* 15(8):1441-1457.

Schilling, K. E., P. W. Gassman, C. L. Kling, T. Campbell, M. K. Jha, C. F. Wolter, and J. G. Arnold. 2014. The potential for agricultural land use change to reduce flood risk in a large watershed. *Hydrological Processes* 28(8):3314- 3325.

Scruggs, C.E. and Thomson, B.M., 2017. Opportunities and challenges for direct potable water reuse in arid inland communities. *Journal of Water Resources Planning and Management*, *143*(10), p.04017064.

Schumann, A.H., 1993. Development of conceptual semi-distributed hydrological models and estimation of their parameters with the aid of GIS. *Hydrological Sciences Journal*, *38*(6), pp.519-528.

Shmida, A. (1985). Biogeography of the desert flora. In: Evenari, M., Noy-Meir, I. & Goodall, D.W. (Eds), *Hot Deserts and Arid Shrublands. Ecosystems of the World*, Vol. 12A, pp. 23–77. Amsterdam: Elsevier, 365 pp.

Singh, V.P., 1988. *Hydrologic systems: Rainfall-runoff modeling* (No. 551.49 S5).

Sleeter, B. M., T. L. Sohl, T. R. Loveland, R. F. Auch, W. Acevedo, M. A. Drummond, K. L. Sayler, and S. V. Stehman. 2013. Land-cover change in the conterminous United States from 1973 to 2000. *Global Environmental Change* 23(4):733-748.

Small, D., S. Islam, and R. M. Vogel. 2006. Trends in precipitation and streamflow in the eastern US: Paradox or perception? *Geophysical research letters*. VOL. 33, L03403

Sohl, T.L. and Claggett, P.R., 2013. Clarity versus complexity: Land-use modeling as a practical tool for decision-makers. *Journal of Environmental Management*, *129*, pp.235-243.

Sohl, T.L., Sayler, K.L., Bouchard, M.A., Reker, R.R., Friesz, A.M., Bennett, S.L., Sleeter, B.M., Sleeter, R.R., Wilson, T., Soulard, C. and Knuppe, M., 2014. Spatially explicit modeling of 1992–2100 land cover and forest stand age for the conterminous United States. *Ecological applications*, *24*(5), pp.1015-1036.

Sohl, T.L., Wimberly, M.C., Radeloff, V.C., Theobald, D.M. and Sleeter, B.M., 2016. Divergent projections of future land use in the United States arising from different models and scenarios. *Ecological modelling*, *337*, pp.281-297.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. 2007. Summary for policymakers. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change. *Cambridge University Press, Cambridge, UK.*

Syed K.H., Goodrich, D.C., Myers, D.E., and Sorooshian, S. 2003. Spatial characteristics of thunderstorm rainfall fields and their relation to runoff. *Journal of Hydrology* 271: 1-21.

Tu, J. 2009. Combined impact of climate and land use changes on streamflow and water quality in eastern Massachusetts, USA. *Journal of Hydrology* 379(3–4):268-283.

Turner, B. L., E. F. Lambin, and A. Reenberg. 2007. The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences* 104(52):20666-20671.

USBR. 2011. Reclamation managing water in the West: Interim Report No. 1, Colorado River Basin water supply and demand study, *status report. U.S Department of the Interior, U.S. Bureau of Reclamation, Denver, Colorado, USA.*

USBR. 2013. Geomorphic Assessment of the Rio Grande Upstream of Elephant Butte Reservoir, *U.S Department of the Interior, U.S. Bureau of Reclamation, Albuquerque, New Mexico, USA.*

USDA, S., 1972. Section 4: Hydrology. *National Engineering Handbook, Washington, DC, Soil Conservation Service*.

Veith, T.L., Van Liew, M.W., Bosch, D.D., and Arnold, J.G. 2010. Parameter Sensitivity and Uncertainty in SWAT: A Comparison Across Five USDA-ARS Watersheds. *Transactions of the Asabe,* 53(5), 1477-1486.

Verstraeten, W.V., Veroustraeten, F., Feyen, J., 2005. Estimating evapotranspiration of European forests from NOAA-imagery at satellite overpass time: towards anoperational processing chain for integrated optical and thermal sensor dataproducts. Remote Sens. Environ. 96, 256–276.

Villarini, G., Serinaldi, F., Smith, J.A. and Krajewski, W.F., 2009. On the stationarity of annual flood peaks in the continental United States during the 20th century. *Water Resources Research*, *45*(8).

Vogelmann, J. E., S. M. Howard, L. Yang, C. R. Larson, B. K. Wylie, and N. Van Driel. 2001. Completion of the 1990s National Land Cover Data Set for the conterminous United States from Landsat Thematic Mapper data and ancillary data sources. *Photogrammetric Engineering and Remote Sensing* 67(6).

Walsh, J., Wuebbles, D., Hayhoe, K., Kossin, J., Kunkel, K., Stephens, G., Thorne, P., Vose, R., Wehner, M., Willis, J. and Anderson, D., 2014. Our changing climate. *Climate change impacts in the United States: The third national climate assessment*, pp.19-67.

Wang, J., and X. Zhang. 2008. Downscaling and projection of winter extreme daily precipitation over North America. *Journal of Climate 21:923–937.*

Ward, D. & Olsvig-Whittaker, L. (1993). Plant species diversity at the junction of two desert biogeographic zones. *Biodiversity Letters*, **1**: 172–185.

Woldeamlak, B., Sterk, G., 2005. Dynamics in land cover and its effect on streamflow in the Chemoga watershed, Blue Nile basin, Ethiopia. *Hydrol. Process. 19, 445–458.*

Wu, Y., S. Liu, T. L. Sohl, and C. J. Young. 2013. Projecting the land cover change and its environmental impacts in the Cedar River Basin in the Midwestern United States. *Environmental Research Letters* 8(2):024025.

Wu, Y., Li, C., Zhang, C., Shi, X., Bourque, C.P.A. and Zhao, S., 2016. Evaluation of the applicability of the SWAT model in an arid piedmont plain oasis. *Water Science and Technology*, *73*(6), pp.1341-1348.

Xu, C.-y. 2002. Hydrologic models. *Uppsala University Department of Earth Sciences Hydrology*.

Yuan, Y., 2010. Problems and Prospects of Swat Model Application on an Arid/semiarid Watershed in Arizona.

Yuan, Y., Nie, W., McCutcheon, S.C. and Taguas, E.V., 2014. Initial abstraction and curve numbers for semiarid watersheds in Southeastern Arizona. *Hydrological Processes*, *28*(3), pp.774-783.

Zhang, Y. K., and K. E. Schilling. 2006. Increasing streamflow and baseflow in Mississippi River since the 1940s: Effect of land use change. *Journal of Hydrology* 324(1–4):412-422.

Zhang, L., W. Dawes, and G. Walker. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* 37(3):701-708.

Zhang, L., Z. Nan, W. Yu, and Y. Ge. 2016. Hydrological Responses to Land-Use Change Scenarios under Constant and Changed Climatic Conditions. *Environmental Management* 57(2):412-431.

Vita

Tahneen Jahan Neelam holds a B.Sc in Civil Engineering from Bangladesh University of Engineering and Technology (BUET). Prior to joining UTEP as a graduate student, she worked in the diverse water resources sector in Bangladesh. Her first employment was at Center for Environmental and Geographic Information Services as a junior specialist in water resources and management division. She was involved in the environmental impact assessment of coastal embankment improvement project and in preparing reports for the Bangladesh Delta Plan 2100 project. Later she joined International Finance Corporation's (IFC) 2030 Water Resources Group as a short-term consultant.

She started her M.S. in Civil Engineering at UTEP from Fall 2016 and worked as a research assistant in the project named "Sustainable Water Resources for Irrigated Agriculture in a Desert River Basin Facing Climate Change and Competing Demands: From Characterization to Solutions" at the Center for Environmental Resources Management (CERM). During her graduate study, she has presented her works "Modeling Water and Land Management Adaptation in New Mexico–Texas-Mexico Border Region Using SWAT" and "Assessing the Compounding Impact of Precipitation and Land Use Change on Runoff in a Semiarid Watershed" at the World Environmental and Water Resources Congress in 2017 and 2018, respectively. She has also attended CUAHSI-NWC summer institute 2017 and presented her summer work "Framework for Statistical Analysis and Visualization of the National Water Model Streamflow Product" at CUAHSI conference on Hydroinformatics.

Permanent address: 781 Anowar Ali Chowdhury Lane

Bogura, Bangladesh, 5800

Email: tneelam@miners.utep.edu

This thesis was typed by Tahneen Jahan Neelam.