PROBLEMS AND PROSPECTS OF SWAT MODEL APPLICATION ON AN ARID/SEMIARID WATERSHED IN ARIZONA

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Abstract: Hydrological characteristics in the arid/semiarid southwest create unique challenges to watershed modelers. Streamflow in these regions is largely dependent on seasonal, short term, and high intensity rainfall events. The objectives of this study are: 1) to analyze the unique hydrology of a watershed located in the southwestern USA; and 2) to evaluate the Soil and Water Assessment Tool (SWAT) applicability on this watershed. USGS historical precipitation and stream discharge patterns were analyzed to determine the hydrological characteristics of the upper San Pedro watershed. It was found that runoff was decreased in downstream gauging locations because of transmission loss due to low groundwater level. Based on this analysis, the SWAT model was calibrated to reflect the unique hydrological characteristics of the watershed. After calibration, the Nash-Sutcliff efficiency (NSE) coefficient and coefficient of determination (R^2) values were above 0.5 (except the NSE coefficient for annual calibration at Redington gauge), and percent bias (PBIAS) were in the range of ±25% (except annual calibration at Charleston gauge), suggesting satisfactory model performance. The SWAT model, set up with the optimal parameters, generally reflected the hydrological characteristics of this arid/semiarid watershed.

Keywords: Arid/semiarid watershed; hydrology; San Pedro River Watershed; SWAT model; transmission loss

INTRODUCTION

Given the growing demand for water due to urban growth and the likelihood of decreasing precipitation due to climate change, water sustainability has become a dominant issue in the arid/semiarid regions such as the Southwestern USA. To address a nation's or a region's water-related sustainability problems, one of the key elements is to characterize and quantify water resources for different future scenarios including different Landuse and Landcover (LULC) and climate in order to develop better management practices. In the arid/semiarid areas, it has been a great challenge to quantify the water resources due to limited access and monitoring systems on the land and limited capability of hydrological and water quality models to handle the unique hydrology associated with these regions (Baillie et al. 2007, Yu et al. 2011). To accurately model a watershed, the basic hydrology of the region must first be understood.

Streamflow formation after rainfall storm events and interactions with groundwater and vegetation must be properly represented in the model. In arid/semiarid regions, peak discharge and the overall flow regime are mostly produced by extremely variable, high intensity, 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). The processes of streamflow generation and interactions with groundwater and vegetation may be different from humid regions (Pilgrim et al. 2009). For example, transmission loss to the aquifer was found to be a major component of the hydrological processes in the arid/semiarid region.

Models, such as the Soil and Water Assessment Tool (SWAT), are commonly used for future projection and alternative scenario assessment. Using spatially variable data of elevation, soil, and LULC, the model is capable of simulating major hydrological processes including evapotranspiration (ET), surface runoff, percolation, lateral flow, groundwater flow (return flow), transmission losses, and ponds (Arnold et al. 1998) and keeping track of water balance components and crop yields of different land units at various temporal scales. Input data and model outputs are processed through a GIS interface. The model utilizes an interface that is very user friendly and allows users to develop modifications using model documentation and source code (Ouessar et al. 2009, Neitsch et al. 2005). Although SWAT was designed to evaluate the impact of LULC change on watershed hydrology and water quality and has been widely applied for watershed scenario analysis, its application in the arid/semiarid regions has been few but increasing in recent years (Ghaffari et al. 2010, Ouessar et al. 2009, Veith et al. 2010, Gassman PW 2007). Therefore, the objectives of this study are: 1) to analyze the unique hydrology of a watershed located in the southwest of the US, and 2) evaluate SWAT applicability on this arid/semiarid watershed.

METHODS AND PROCEDURES

Study Area and Its Background Information: The upper San Pedro Watershed originates in Sonora, Mexico near Cananea and flows north into southeastern Arizona, USA (Figure 1). In this study, the investigation area is composed of the upper San Pedro Basin and a part of the lower San Pedro Basin to the Redington USGS gauge (Figure 1). For convenience, the entire study area is referred as upper San Pedro in the text.

The upper San Pedro Watershed has a drainage area of about 7,400 km^2, and lies between latitude 30°54′ and 32°30′ N and longitude -110°48′ to -109°45′ W. Elevations in the watershed range from 900 to 2900 m, and annual rainfall ranges from 300 to 750 mm (Biggs 2009). As shown in Table 1, the LULC classes in the watershed mainly include woodland (oak and mesquite together make up 14%), desertscrub (32%), grassland (35%), agriculture crops (2%), urban (2%) (Saleh et al. 2009). Most soils in the San Pedro watershed are gravelly, medium and moderately coarse-textured (USDA). They are nearly level to very steep soils on dissected alluvial fan surfaces. Major soil series include Sierravista (Loamy-skeletal, mixed, superactive, thermic Petronodic Calciargids), Diaspar (Coarse-loamy, mixed, superactive, thermic Ustic Haplargids), Libby (Fine, mixed, superactive, thermic Petronodic Ustic Paleargids), and Forest (Fine, mixed, superactive, thermic Ustic Calciargids). These soils are characterized as well-drained soils with moderately high to high permeability. Major municipal areas along the San Pedro River from south to north are Cananea (Mexico), Hereford, Sierra Vista, Ft. Huachuca, Charleston, Tombstone, St. David, Benson, and Redington (Figure 1).

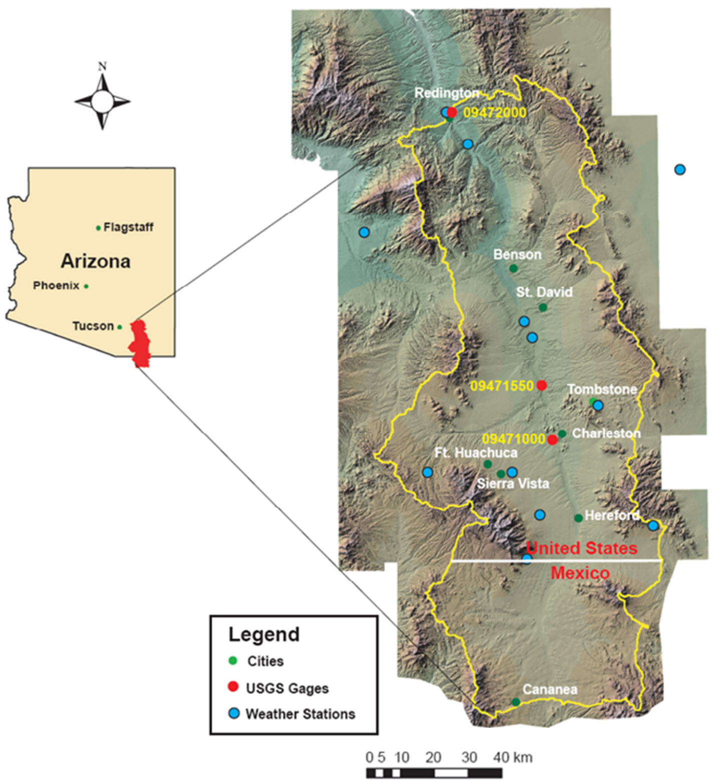


Figure 1 Locations of rural and municipal areas, USGS monitoring gauges, and weather stations in the upper San Pedro watershed (modified from (Kepner et al. 2000)).

The San Pedro River is the last remaining river in southern Arizona that has long perennial reaches (Kennedy and Gungle 2010). The San Pedro River headwaters flow north from Sonora, Mexico into Arizona where the river merges with the Gila River which flow into the Colorado River and finally empties into the Gulf of California. The Upper San Pedro River Basin is noted as a highly diverse ecosystem and important migratory bird habitat and is often studied for its vulnerability to landscape changes due to over development and lowering of the groundwater table (Steinitz 2003, Stromberg et al. 1996, Stromberg et al. 2005, Orr and Colby 2004, Arias 2000, Webb and Leake 2006, Steiner et al. 2000). Trend analysis of the San Pedro River at Charleston, Arizona shows a more than 50 percent decrease in annual streamflow during the 20th century (Thomas and Pool 2006). Efforts to conserve the Upper San Pedro basin are confounded by water rights, international mining operations, conservation of protected riparian zones, and economic considerations (Steiner et al. 2000, Steinitz 2003). Historical trends show decreases in riparian vegetation and baseflow and storm runoff volumes since the 1900s caused by human induced changes to the landscape and climate changes (Webb and Leake 2006).

Streamflow Data Collection and Analysis: Streamflow data from the USGS stream gauge stations 09471000 San Pedro River at Charleston (31º37′33″ N and 110º10′26″ W), 09471550 San Pedro River near Tombstone (31º45′03″ and 110º12′02″), and 09472000 San Pedro River at Redington (32º22′50″ N and 110º26′45″ W) were downloaded from the USGS website (http://waterdata.usgs.gov) for flow analysis, model calibration and validation.

Locations of those USGS gauges stations are displayed in Figure 1. The Redington gauge station (09472000) is located downstream (north) of the other stations and drains the entire watershed area, which is about 7493 square kilometers. The other two gauge stations Charleston (09471000) and Tombstone (09471550) drains approximately 3159 and 4454 square kilometers, respectively.

To effectively calibrate the model, streamflow trends at three stations were analyzed first to understand the hydrological characteristics of the watershed. Since concurrent streamflow data for all three stations were only available from 1967 to 1985, a streamflow hydrograph (Figure 2) was plotted for the year 1985 to analyze and compare daily discharge characteristics at the three gauge locations. Annual runoff (Figure 3), the sum of monthly runoff downloaded from the three USGS gauge stations, for each location was plotted from1967 to 1985 to analyze annual runoff differences at three sites. The Redington gauge station (09472000) has the largest drainage area (7493 square kilometres), followed by the Tombstone (09471550). The Charleston gauge station (09471000) has the least drainage area (3159 square kilometres).

SWAT Model Description: The Soil and Water Assessment Tool (SWAT) model is a continuous, long-term, physically based semi-distributed model developed to assess impacts of climate and land management on hydrological processes, sediment loading, and pollution transport in watersheds (Arnold et al. 1998). In the SWAT model, a watershed is divided into subwatersheds or subbasins, which are further partitioned into a series of hydrological response units (HRUs). HRUs are uniform units that share unique combinations of soil and land use. Hydrological components, sediment yield, and nutrient cycles are simulated for each HRU and then aggregated for the subbasins.

The hydrological cycle simulated in SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i-1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where, SW_t and SW_0 are the final and initial soil water content on day i (mm H_2O), t the time steps on day i, R_{day} the rainfall that reaches the soil surface on day i (mm), Q_{surf} the surface runoff on day i (mm), E_a the evapotranspiration on day i (mm), w_{seep} the interflow on day i (mm), and Q_{gw} is the baseflow on day i (mm) (Neitsch et al. 2005).

The simulated hydrological components include evapotranspiration (ET), surface runoff, percolation, lateral flow, groundwater flow (return flow), transmission losses, ponds, and water yield (Arnold et al. 1998). Evaporation and transpiration are simulated separately in SWAT: evaporation is computed using exponential functions of soil depth and water content and transpiration is estimated using a linear function of potential evapotranspiration (PET) and leaf area index. Three methods can be used to estimate PET: Hargreaves (Hargreaves et al. 1985), Priestley-Taylor (Priestley and Taylor 1972), and Penman-Monteith (Monteith 1965). The Pennman-Monteith method was used to calculate PET in this study. Surface runoff is simulated using a modification of the Soil Conservation Service (now the Natural Resources Conservation Service) Curve Number (SCS-CN) method (USDA, 2004) with daily rainfall. Curve number values used for runoff estimation are based on soil type, LULC, and land management conditions (Rallison and Miller 1981) and are adjusted according to soil moisture conditions (Arnold et al. 1993). Percolation is estimated using the combination of a storage routing technique and a crack-flow model (Arnold et al. 1998). The lateral flow is estimated simultaneously with percolation using a kinematic storage model (Solan et al. 1983). The groundwater flow (baseflow) into a channel is calculated based on the hydraulic conductivity of the shallow aquifer, distance from subbasin to main channel, and water table height (Hooghoudt 1940). Transmission loss, amount of water removed from tributary channels by transmission, is calculated using procedures described in the SCS Hydrology Handbook (USDA, 2007). The canopy interception is estimated based on the canopy storage which is a function of vegetation type.

Water yield, total amount of water leaving the HRU and entering main channel, is equal to surface runoff plus lateral flow and baseflow, and minus transmission loss and pond abstractions (Neitsch et al. 2005).

Model Input Preparation: The basic SWAT model inputs include a digital elevation model (DEM), soil data, LULC data, and meteorological data. The DEM was derived from the National Elevation Dataset (NED) of USGS with 1 arc-second resolution (Gesch et al. 2002), and the soil data was from the State Soil Geographic (STATSGO) database. The LULC data of 1992 and 1997 used for this study was from the NALC project (Landsat Multi-Spectral Scanner) and Landsat Thematic Mapper (Kepner et al. 2002, USEPA 1993). For climate information, daily maximum and minimum temperature, precipitation, solar radiation, relative humidity and wind speed are needed to account for temporal variations in weather. This data can be historically measured, generated using the SWAT built in WXGEN weather generator model (Sharpley and William 1990), or supplied to SWAT using a combination of the two methods. For this study, daily precipitation and minimum-maximum temperature from Jan. 1960 to Apr. 2008 were acquired from the National Climatic Data Center (NCDC). Twelve meteorological stations were found within or nearby the upper San Pedro watershed (Fig. 1). Missing records of daily observations of precipitation and minimum-maximum temperature were interpolated from weather data within a radius of 25 miles using the method developed by Di Luzio et al. (2008). The rest of the weather information (solar radiation, relative humidity and wind speed) used in SWAT simulation were generated by the WXGEN weather generator model (Sharpley and William 1990).

The area for stream definition was set as 3500 Ha, upon which the upper San Pedro River basin was divided into 116 subbasins. The divided subbasins matched 12-digit Hydrologic Unit Codes in the upper San Pedro watershed. The subbasins were further divided into HRUs based on the land use, soil, and slope types (0.1%, 1%, and 5%). The number of HRUs differs when using different LULC maps. As an example, the numbers of HRUs for 1992 and 1997 LULC are 2146 and 2225, respectively. There are 10 classes of LULC and 23 soil types in the upper San Pedro watershed. Watershed parameterization includes the calculation of subbasin geometry parameters from DEM and the assigning values to HRUs through inner database. The database of the SWAT model includes parameter values for crops, urban, and soils, such as CN2 values (SCS runoff curve number for moisture condition II), SOL_AWC (Available water capacity of the soil layer), LAI (leaf area index), and other soil physical and hydraulic properties. Values were assigned to each HRU based on its LULC class and soil type during the parameterization process. The simulation was initialized by setting default values of each parameter, a five year warm up period was applied to erase the impact of initial condition for the model calibration and validation.

SWAT Model Sensitivity Analysis, Calibration and Validation: A sensitivity analysis was first performed on parameters affecting streamflow using Latin hypercube (10 intervals) and one at a time (OAT) analysis with a ±5% parameter change (van Griensven et al., 2006). The analysis was done using the model set up with 1992 NALC LULC data and average streamflow response at the watershed outlet (subbasin 1) for five years from 1990 to 1994.

After sensitivity analysis, the model was calibrated by manually editing sensitive parameters for hydrological components (surface runoff, baseflow, lateral flow, ET, and channel transmission loss). Sensitive parameters on hydrological components were also reviewed from past sensitive studies of the model (Veith et al. 2010) and hydrological studies of the arid/semiarid areas (Hernandez et al. 2000, Goodrich et al. 1997). In this study, the lateral flow was assumed to be zero, because no obviously impervious layers in soil profiles, such as black shales, which were pre-required for the lateral flow to be generated, were observed in the watershed. The lateral flow was reduced to a very low level (close to zero) by changing the adjust factor for lateral flow (Adjf_latq) from the default value of 1 into 0.02 during SWAT simulations. Baseflow should be a very small portion recharging back to the stream because very large portions of the upper San Pedro River are ephemeral. At the Redington gauge (down- stream), the river only contains water during and immediately after a storm event and is dry the rest of the year. At the Tombstone and Charleston gauges (upper-stream), although the river flows intermittently, the water supply may not be from baseflow for the relatively higher elevation (corresponding to deeper groundwater table level values) than down-stream. Thus the baseflow was eliminated from simulations by reducing threshold water level in shallow aquifer for re-evaporation (REVAPMN) and enhancing the re-evaporation coefficient and threshold water level in shallow aquifer for baseflow (GWQMN).

Due to the availability of LULC (1992 and 1997) and the USGS data, simulations for model calibration were performed using the model set up of 1992 NALC LULC data which was also used for the sensitivity analysis. Annual (water year) and monthly streamflow from Oct. 1986 to Sept. 1995 at two USGS gauges (Redington and Charleston, Fig. 1) were used for model calibration. After model calibration, simulations for model validation were set up using 1997 Landsat Thematic Mapper LULC data; and annual (water year) and monthly streamflow at Tombstone (10/1996 – 09/2005) and Charleston (10/1995 – 09/2005) were used for model validation. Validation was not performed at the Redington gauge station because monitoring data were not available after 1995. Three commonly used criteria were used to evaluate the model's performance on calibration and validation: Nash-Sutcliff efficiency (NSE) coefficient, coefficient of determination (R^2), and percent bias (PBIAS).

RESULTS AND DISCUSSION

Unique Hydrological Characteristics of the San Pedro River Watershed: Precipitation within the San Pedro Basin is generally characterized by a bimodal trend with a majority (about 70%) of the rainfall falling during the summer monsoon season (approximately mid-June to mid-October) and a minority (about 20%) during the winter wet season (early December to April) with the remaining throughout the rest of the year (Baillie et al. 2007). The Upper San Pedro watershed is characterized as semiarid conditions, and the sources of flow are attributed to intermittent precipitation governed by monsoon type rainfall events. As shown in Figure 2, the bimodal precipitation trend is reflected by the daily discharge data for 1985 plotted for each gaging station (Charleston, Tombstone, and Redington). In most channel locations (Figure 2) in the San Pedro River, low or intermittent baseflow with ephemeral peak discharge occuring during sporadic storm events was observed.

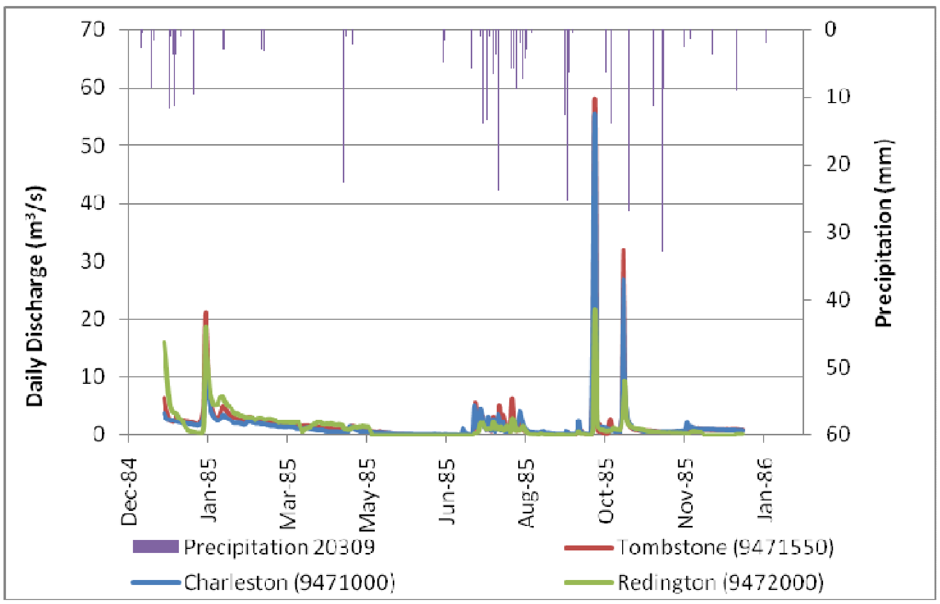


Figure 2 Daily Discharge (m^3/s) for from Jan. 1985 to Dec. 1985

Streamflow in gaining portions of the river is generally perennial; however, several sections of the upper San Pedro River can be classified as both gaining and losing reaches where streamflow is intermittent and associated with a mixture of monsoon water sources and aquifer sources stored in the alluvial groundwater. According to a USGS report released in 2010 (USGS, 2010), both gaining and losing reaches exist upstream from the gaging station near Tombstone. At the Tombstone gaging station, upstream groundwater flow to the vicinity of the stream is less than the volume of water removed by ET during the growing season; therefore, during the summer there is generally no base flow. The reach between the Charleston gauge and the Tombstone gauge is primarily losing (Kennedy and Gungle 2010). Following the summer monsoon, the water stored in near stream sediments must remain saturated for perennial flow to exist; however as shown in Figure 2 (1985 hydrograph), the summer flow is often insufficient to maintain flow in the fall, and thus, the upstream influent flow must re-saturate these sediments resulting in increased transmission loss and decreased to nonexistent streamflow conditions. The Redington station is the furthest downstream from the San Pedro River headwaters yet overall has the smallest response to rainfall events compared to the upstream stations. Transmission losses in the stream channel are likely responsible for this trend and must be considered accordingly when using a distributed model to simulate hydrologic conditions in this watershed. This trend is also noted in Figure 3 which depicts the annual runoff at each station from 1967 to 1985 (streamflow data is only available during 1967 to 1985 for all three gauge stations). Though the Redington station is hydrologically a larger stream order than the upstream gauge station locations, flow at Redington is characterized by containing the least amount of storm runoff and little baseflow conditions. Larger order streams typically have greater baseflow and steadier flow conditions; however, this phenomena is not observed in this semiarid stream systems due to transmission losses and other factors, such as increased ET. Goodrich et al. (1997) found that the role of channel processes in semiarid watersheds becomes more critical in describing the peak runoff response as the size of drainage area increases. Transmission loss due to channel infiltration, evapotranspiration processes, and limited spatial uniformity of rainfall become dominant factors which limit the linearity of basin response to storm events in semiarid regions. Therefore, the accuracy of using a unit hydrograph, which assumes linearity in the response, in determining watershed runoff response in semiarid watersheds is not reliable due to the nonlinearity of the system.

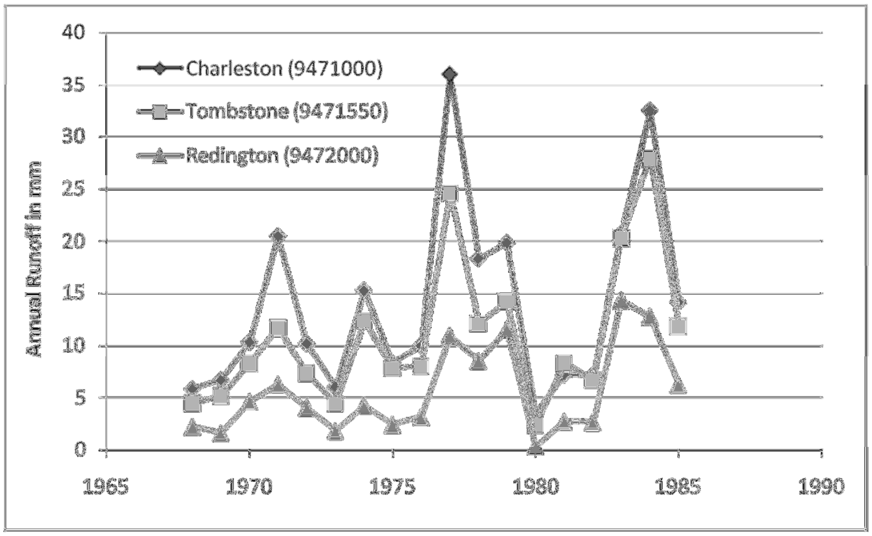


Figure 3 Annual Runoff at three gauges stations from 1967 to 1985

A recent USGS study statistically accounted for streamflow variations due to fluctuations in precipitation and found that predominant factors for the decrease in annual streamflow beyond fluctuations in precipitation and air temperature include changes in watershed characteristics, human activities, or changes in seasonal distribution of bank storage (Thomas and Pool 2006). Possible changes in watershed characteristics that may have influenced streamflow trends are changes in riparian vegetation, changes in landcover (mesquite invasion), and changes in stream-channel geomorphology. Human activities that may have influenced streamflow trends are ground-water pumping, construction of runoff-detention structures, urbanization, and cattle grazing. Seasonal pumping from wells near the river for irrigation in the spring and summer were a significant factor affecting streamflow; however, year-round pumping from wells in the regional aquifer away from the river did not significantly impact streamflow in the river (Thomas and Pool 2006).

Sensitivity Analysis and Calibration/Validation Results: The most sensitive input parameters are shown in Table 1. Those parameters are consistent with other SWAT parameter uncertainty and sensitivity analysis done for arid/semiarid conditions. The SWAT model is highly sensitive to surface runoff parameters (CN2, ESCO, SOL_AWC) and basin parameters (CH-K2) when the watershed is characterized by the intense and inconsistent precipitation events (Veith et al. 2010). High ratios of evaporation to precipitation may overwhelm the SWAT subsurface parameters (Veith et al. 2010); as does increased transmission loss due to stream bed geology and channel condition (gaining or losing) (Cataldo et al. 2010, Baillie et al. 2007). Since there is no persistent snowpack in the mountains of the San Pedro River Watershed, snowmelt and snowfall parameters were not shown to be sensitive for this watershed.

Surface runoff is the major water supply for the stream. Whereas, we noticed that streamflows were often under-estimated for light rainfall events and over-estimated for large rainfall events. Woodward et al. (2002) found that runoff estimates could be enhanced for relatively light rainfalls and be reduced for relative large rainfalls by changing the initial abstraction ratio to be 0.05 from its originally defined value of 0.2. Thus, to calibrate surface runoff, we set the initial abstraction ratio to be 0.05 and edited the CN2 (SCS runoff curve number) to a relatively low value to match the change of initial abstraction ratio. Channel transmission loss is a large portion (4% - 100%) of the water balance in the Walnut Gulch Experimental Watershed, a sub-watershed of the upper San Pedro River basin (Cataldo et al. 2010). USGS records show that monthly streamflow (in volume) at downstream locations (Redington gauge) is not always larger than in upperstream (Tombstone and Charleston gauges), indicating that transmission loss exists for the major channel (stream order 4 and 5). However, it's hard to quantify the ratio of channel transmission loss to total water recharge. To calibrate the transmission loss, we set the TRNSRCH (Fraction of transmission loss partitioned into deep aquifer) to be 1 and manually edited the effective hydraulic conductivity of channel (CH_K2). The optimal values for SWAT calibration were listed in Table 1.

Table 1 Top ranking sensitive parameters (in the order of ranking) and their description, default and calibrated values that were used in the model calibration/validation (*, the multiple sign, indicates that default parameter values are multiplied by the number shown).

Parameter	Default	Description	Calibrated Value
Adjf_latq	1	Adjust factor for lateral flow	0.02
λ	0.2	Initial Abstraction Ratio	0.05
CN2	30-92	SCS runoff curve number for moisture condition II	*0.58
ESCO	0.95	Soil evaporation compensation factor	0.05
Revapmn	1	Threshold water level in shallow aquifer for revap	0
SOL_AWC	0.01-0.19	Available water capacity of the soil layer	*1.4
Sol_K		Saturated hydraulic conductivity of first layer	
CH_K2	0	Effective hydraulic conductivity of channel	0.6
GW_Revap	0.02	Revaporation coefficient	0.2
GWQMN	0	Threshold water level in shallow aquifer for baseflow	100
TRNSRCH	0	Fraction of transmission loss partitioned into deep aquifer	1

The comparison between simulated and observed annual (in water year) and monthly streamflow for the periods of calibration (Oct. 1986 – Sept. 1995) and validation (Oct. 1996 – Sept. 2005) are shown in Figures 4 and 5, respectively. Overall, a good match can be seen between simulated and observed values. The NS and R^2 values for the annual (in water year) and monthly calibration and validation are listed in Table 2. All NS and R^2 values are above 0.5 (except NS coefficient for annual calibration at the Redington gauge), and PBIAS are in the range of ± 25% (except annual calibration at the Charleston gauge), suggesting satisfactory model performance (Moriasi et al. 2007). Although the overall performance of the model is satisfactory as shown in Figures 4 and 5, and Table 2, a large difference was observed for the water year of 1992 at the Redington gauge and in 1993 at both the Redington and Charleston gauges. Intuitively, the simulated values seem more reasonable because they match the rainfall patterns as shown in Figure 4. Possible reasons for the discrepancies are the limitation of the curve number method. First, high uncertainties could be generated by using daily total rainfall depth as SWAT input. As an example, a large amount of streamflow (4.21 mm) at the Redington gauge on Aug. 1992 simulated in the SWAT model was mainly attributed to a daily rainfall of 127.8 mm on Aug. 24, 1992 in the downstream of the watershed close to the Redington gauge. Whereas, the rainfall depth at that day could be the combination of several relatively small rainfall events, which may not be able to generate significant runoff (recorded streamflow in Aug. 1992 is 0.58 mm). Second, the curve number method fails to consider the effects of duration and intensity of precipitation. For instance, runoff could be generated by some high-intensity, short-duration, limited areal extent summer thunderstorms (Simanton et al. 1996) near the observation gauges. Whereas, those limited areal extent summer thunderstorms may not be simulated by the SWAT model for a large extent.

Another reason for simulated streamflow peaks not fully matching with observations is due to the high heterogeneity of rainfall across the watershed. Rainfall events in the upper San Pedro watershed were mainly composed of high-intensity, short-duration, limited areal extent summer thunderstorms (Thomas and Pool 2006, Kennedy and Gungle 2010). The high heterogeneity of rainfall may not be fully represented by weather stations used in SWAT simulations in this study. Syed et al. (2003) used interpolated values from raingauges and found that the storm event's areal coverage, location within the watershed, and intensity are factors that impact runoff generation, which vary greatly as catchment size increases. SWAT has been shown to adequately simulate streamflow using sparse raingauge data over large arid basin areas, especially when combined with precipitation data estimated from radar predictions (Yu et al. 2011).

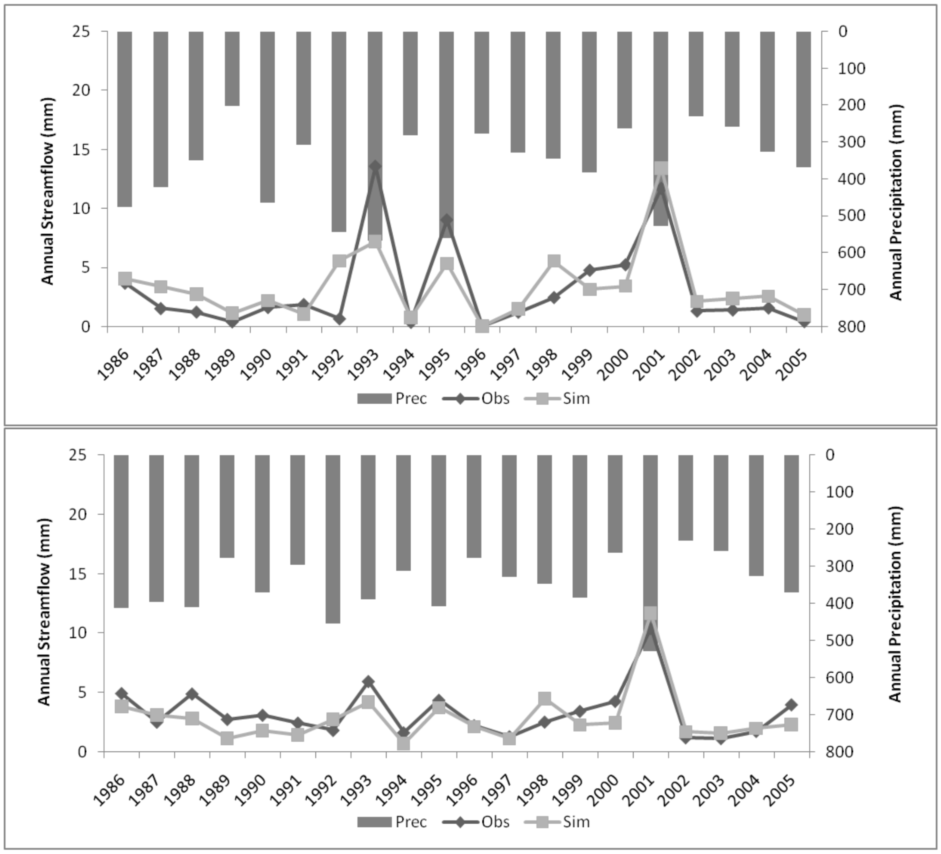


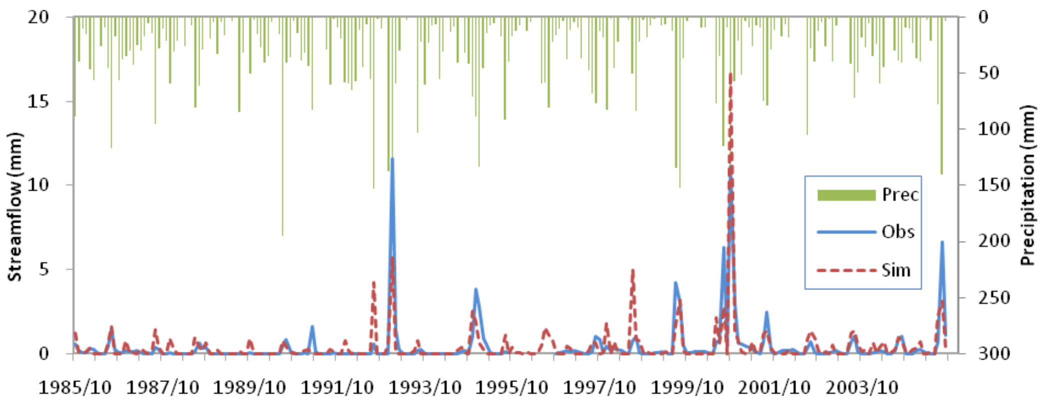
Figure 4 Annual (in water year) precipitation and simulated and observed streamflow in the upper San Pedro Watershed. Upper: Redington (1986 – 1995) and Tombstone (1997 – 2005) gauges; Lower: Charleston gauge (1986 – 2005).

A calibrated and validated SWAT model can be used to assess current conditions in the watershed, and then be used to evaluate alternative management scenarios. SWAT provided good correlation of simulated streamflow conditions, which have been applied to scenario analysis of management practices aimed to evaluate the effects of landuse changes on hydrological response (Ouessar et al. 2009, Ghaffari et al. 2010, Hernandez et al. 2000). Arid/semiarid watersheds are often coupled with issues of data availability. SWAT simulations using remote sensing input data have adequately simulated overland flow, channel flow, and transmission losses in watersheds where streamflow and climatic data are lacking (Al-Dousari et al. 2010, Hernandez-Guzman et al. 2008). The SWAT model has been found useful in arid/semiarid watershed analysis of the effect of landuse changes on hydrological properties and changes of water balance components due to crop management (Ghaffari et al. 2010, Hernandez et al. 2000).

Table 2 Criteria for examining the accuracy of calibration and validation (the validation period at Tombstone gauge is from Oct. 1996 to Sept. 2005).

Index	Calibration (10/1985 - 09/1995)				Validation (10/1995 - 09/2005)			
	Redington		Charleston		Tombstone		Charleston	
	Yearly	Monthly	Yearly	Monthly	Yearly	Monthly	Yearly	Monthly
NS Coefficient	0.45	0.56	0.82	0.52	0.94	0.57	0.93	0.55

R^2	0.66	0.57	0.66	0.55	0.84	0.70	0.82	0.70
PBIAS	1.94	-1.29	25.46	24.63	-16.27	-9.23	1.38	3.00



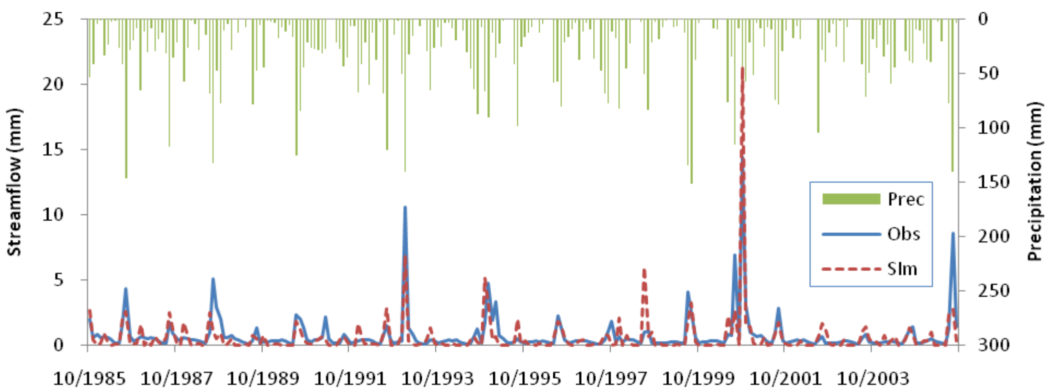


Figure 5 Monthly precipitation and simulated and observed streamflow in the upper San Pedro watershed. Upper: Redington (10/1985-09/1995) and Tombstone (10/1996-09/2005) gauges; Lower: Charleston gauge (10/1985-09/2005).

CONCLUSIONS

Identifying the impacts of LULC changes on hydrologic processes is the basis for watershed management and ecological restoration efforts. Semiarid regions of the southwest United States have unique hydrologic characteristics that create challenges for watershed modelers. Streamflow in these regions is largely dependent on short term, high intensity rainfall events during the summer monsoon season. In this study, the hydrology of the upper San Pedro watershed was assessed based on review of USGS trend analysis reports, historical precipitation and stream discharge patterns. Based on the hydrological characteristics of the region, SWAT sensitivity analysis for this watershed and findings from other studies performed under similar watershed conditions, sensitive SWAT model parameters were determined and calibrated to achieve suitable simulations of the watershed hydrologic processes. The SWAT model input parameters were modified to simulate the limited baseflow conditions, increased ET and transmission loss, and decreased runoff in downstream gauge stations observed in the watershed. All NS and R2 values were above 0.5 (except NS coefficient for annual calibration at the Redington gauge), and PBIAS were in the range of ± 25% (except annual calibration at the Charleston gauge), suggesting satisfactory model performance. Thus, the SWAT model, set up with the optimal parameters obtained through model calibration, generally reflects the hydrological characteristics of this arid/semiarid watershed. A calibrated and validated SWAT model can assess current conditions in the watershed, and then be used to evaluate alternative management scenarios.

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