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Assessing impacts of Landuse and Landcover changes on hydrology for the upper San Pedro watershed

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SUMMARY

The assessment of Landuse and Landcover (LULC) changes on hydrology is essential for the development of sustainable water resource strategies. Specifically, understanding how change in each LULC class influences hydrological components will greatly improve predictability of hydrological consequences to LULC changes and thus can help stakeholders make better decisions. However, given the limited availability of digital LULC maps and simultaneous changes of multiple LULC classes, it is difficult to quantify impacts of change in individual LULC class on hydrology. In this study, an integrated approach of hydrological modeling and multiple regression analysis was applied to quantify contributions of changes for individual LULC classes on changes in hydrological components. As a case study, hydrological modeling was conducted for each of the LULC map in four time periods (1973, 1986, 1992, and 1997) in the upper San Pedro watershed using the Soil and Water Assessment Tool (SWAT). Changes in hydrological components between two simulations using LULC maps in 1997 and 1973, respectively, were related to changes of LULC in a multiple regression to quantify the effect of changes in LULC to that of hydrological components at the subbasinal scale. While urbanization was the strongest contributor to the increase of surface runoff and water yield from 1973 to 1997, replacement of desertscrub/grassland by mesquite was the strongest contributor to the decreased baseflow/percolation and contributed to the increased ET. Increased runoff, declined percolation, and increased ET have a negative impact on water resources in the upper San Pedro River Basin, thus urbanization and mesquite invasion seems to be major environmental stressors affecting local water resources. Our approach in quantifying the contributions of changes for individual LULC to hydrological components will provide quantitative information for stakeholders in planning and making decisions for land and water resource management. The approach to assess changes in surface hydrology could widely be applied to a variety of other watersheds, where time-sequenced digital LULC is available.

1. Introduction

Assessing impacts of Landuse and Landcover (LULC) changes on hydrology is the basis for watershed management and ecological restoration. The assessment usually includes evaluation of spatial patterns of hydrological consequences to different LULC maps, comparison of basinal values of simulated hydrological components to LULC changes at the basinal scale, and examination of temporal responses in channel discharge with changes in LULC (e.g. Miller et al., 2002; Liu et al., 2008a,b; Hernandez et al., 2000; Ghaffari et al., 2009; Franczyk and Changk, 2009; Mohammed et al., 2009). However, most studies do not quantify contributions of change for individual LULC to different hydrological responses. Without accurate quantification, the impacts of changes for some LULC classes on hydrologic components may be exaggerated or understated, or even misinterpreted. In this study, an integration approach of hydrological modeling and multiple regression analysis was applied in the upper San Pedro watershed (US/Mexico) to quantify contribution of changes for individual LULC on changes in hydrological components.

In the upper San Pedro watershed, major LULC changes in the period from 1973 to 1997 include declines of grassland and desertscrub, and major increases in mesquite woodland and urban area (Kepner et al., 2002). An increase of annual runoff, flashier flood response, and decreased water quality due to sediment loading simulated in the watershed was attributed to simultaneous changes of several LULC classes as described above (Miller et al., 2002). However, how changes in each LULC class influence changes of each hydrological component is still unknown. The answer to this question will improve predictability of hydrological consequences to LULC changes and thus is crucial for future LULC and/or water resource planning and management.

Objectives of this study include: (1) calibrate and validate the SWAT model in terms of streamflow for three USGS gages in the upper San Pedro watershed; (2) evaluate impacts of LULC changes

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on hydrology at the basinal scale; (3) quantify the contribution of changes in LULCs to changes of major hydrological components at the subbasinal scale.

2. Study site

The upper San Pedro Watershed originates in Sonora, Mexico and flows north into southeastern Arizona, USA (Fig. 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 gage (Fig. 1). For convenience, the entire study area is referred as "upper San Pedro" in the text.

The upper San Pedro Watershed has an area of about 7400 km^2, and lies between latitude 30°54′ and 32°30′N and longitude −110°48′ to −109°45′W. Elevations in the basin range from 900 to 2900 m, and annual rainfall from 300 to 750 mm. The LULC classes include woodland (oak and mesquite), desertscrub, grassland, forest, riparian, agriculture crops, urban, water, and barren (Kepner et al., 2000). 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 Forrest (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 (Fig. 1).

3. Methods

The method we used is divided into two parts: (1) hydrological modeling to simulate hydrological components for each of the LULC map in four time periods (1973, 1986, 1992, and 1997); (2) performing multiple regression analysis to determine the contribution of changes in LULC classes on change of hydrological components.

3.1. Hydrological modeling

3.1.1. Model description

The Soil and Water Assessment Tool (SWAT) 2005 (Neitsch et al., 2005) was applied in the upper San Pedro watershed to assess impacts of LULC changes on hydrological components. The SWAT model is a continuous, long-term, physically based distributed model developed to assess impacts of climate and land management on hydrological components, sediment loading, and pollution transport in watersheds (Arnold et al., 1998). In the SWAT model, a watershed is divided into subwatersheds or subba-

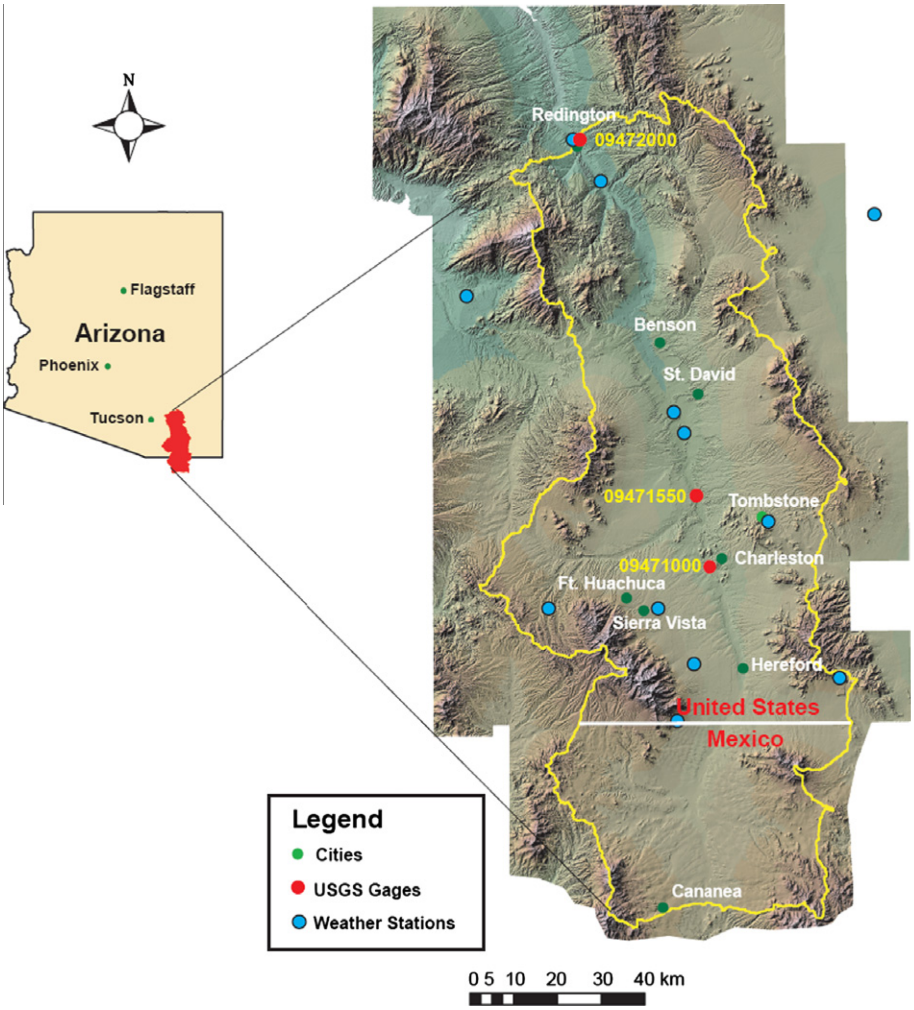

Fig. 1. Locations of municipal areas, USGS monitoring gages, and weather stations and cities in the upper San Pedro watershed (modified from Kepner et al., 2002).

sins. Subbasins are further divided into a series of uniform hydrological response units (HRUs) based on soil and LULC. Hydrological components, sediment yield, and nutrient cycles are simulated for each HRU and then aggregated for the subbasins.

Hydrological components simulated in the SWAT model include evapotranspiration (ET), surface runoff, percolation, lateral flow, groundwater flow (return flow), transmission losses, and ponds (Arnold et al., 1998). Evaporation and transpiration are simulated separately: 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 used to estimate PET include: Hargreaves et al. (1985), Priestlr and Taylor (1972), and Monteith (1965). The Pennman–Monteith method was used to calculate PET in this study. The surface runoff is estimated using a modification of the SCS (Soil Conservation Service, now the Natural Resources Conservation Resource) curve number method (USDA, 1972) with daily rainfall amounts. The curve number values 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 calculated 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 the channel is calculated based on hydraulic conductivity of shallow aquifer, distance from subbasin to main channel, and water table height (Hooghoudt, 1940).

3.1.2. Model inputs

The input data used in the SWAT model includes a digital elevation model (DEM), soil data, digital Landuse and Landcover (LULC) maps, and climate data. The DEM was derived from the USGS National Elevation Dataset (NED, Gesch et al., 2002; Gesch, 2007) with a resolution of 1 arc-second (about 30 m), and the soil data was from the State Soil Geographic (STATSGO) Database (NRCS). The LULC data for four time periods (1973, 1986, 1992, and 1997) used to assess the impact of LULC change on hydrology, was from the North American Landscape Characterization (NALC) project (Landsat Multi-Spectral Scanner) and Landsat Thematic Mapper (USEPA, 1993; Kepner et al., 2003; Skirvin et al., 2004). The LULC maps in years1992 and 1997 were covered by 1.4% and 2.2% clouds, respectively (Kepner et al., 2002). Clouds in of 1992 LULC map were overlain by LULC in 1986, and clouds in 1997 were replaced by 1992. The impact of this replacement on hydrological simulation could be ignored because clouds were mainly distributed in non-urban areas where vegetation changes were not significant from 1986 to 1997. The climate data, including daily values of precipitation and minimum–maximum temperature in the period from January 1960 to April 2008, were derived from 12 meteorological stations located in the upper San Pedro watershed. The missing records of precipitation and temperature were interpolated by the method proposed by Di Luzio et al. (2008).

3.1.3. Model calibration and validation

Simulations set up using 1992 LULC map were used to calibrate annual streamflow from 1991 to 1995 at two USGS gages (Redington and Charleston, Fig. 1). After model calibration, simulations set up using 1997 LULC map were used to validate annual streamflow from 1996 to 2000 at two stations (Charleston and Tombstone, Fig. 1).The model was calibrated manually and three criteria were used to evaluate performance of model calibration/validation.

3.1.3.1. Manual calibration processes. Surface runoff and baseflow were calibrated separately. The simulated and observed streamflow in three observation gages was separated into surface runoff and baseflow by Baseflow Filter (Arnold and Allen, 1999). Simulations were calibrated to match with observations for: (1) proportional extent of baseflow, and (2) annual streamflow.

Different parameter values were applied for the upper- and down-stream reaches of the San Pedro watershed in model calibration and validation, because the proportional extent of baseflow in upperstream (i.e. Gages Charleston and Tombstone) was much higher than that of downstream (i.e. Gage Redington). The upperstream (subbasin 48–116) is from Mexico to Tombstone and the downstream (subbasin 1–47) is from Tombstone to Redington. The areas for the upper and lower streams are 4311 and 3093 km^2, respectively.

The model was calibrated by manually editing sensitive parameters for hydrological components (surface runoff, baseflow, lateral flow, and ET). In this study, we assume that lateral flow is equal to zero, because no obviously impervious layers in soil profiles (prerequirement for the generation of lateral flow, such as shales) were identified in the upper San Pedro watershed. The lateral flow was erased by setting the adjust factor for later flow into 0.02 in SWAT source code. The surface runoff was calibrated by editing CN2 (SCS runoff curve number for moisture condition II). The baseflow was calibrated by enhancing ET and Revap, the water removed from capillary fringe by evaporation or from shallow aquifer by deep-root uptake (Neitsch et al., 2005). The sensitive parameters for ET were ESCO (soil evaporation compensation factor) and SOL_AWC (available water capacity of the soil layer) and sensitive parameters for Revap and baseflow were GW_REVAP (re-evaporation coefficient), REVAPMN (threshold water level in shallow aquifer for revap), GWQMN (threshold water level in shallow aquifer for baseflow) and ALPHA_BF (baseflow recession constant). The ALPHA_BF values were estimated by Baseflow Filter for the upper and down streams (Arnold and Allen 1999). The rest of parameters were manually estimated. The optimal values for SWAT calibration were listed in Table 1.

3.1.3.2. Performance evaluation criteria. Three criteria were used to evaluate the model's performance on calibration and validation:

Table 1
Description, default and optimal values that used in the model calibration/validation (∗, the multiple sign, means the default values of parameter are multiplied by the number following the "∗").

Parameter	Default	Description	Optimal value	
			Subbasin 1–47	48–116
Adjf_latq	1	Adjust factor for lateral flow	0.02	0.02
CN2	30–92	SCS runoff curve number for moisture condition II	∗0.87	∗0.83
ESCO	0.950	Soil evaporation compensation factor	0.050	0.050
SOL_AWC	0.01–0.19	Available water capacity of the soil layer	∗1.4	∗1.4
Alpha_BF	0.048	Baseflow recession constant	0.0852	0.0167
GW_Revap	0.02	Revaporation coefficient	0.20	0.20
Revapmn	1.0	Threshold water level in shallow aquifer for revap	0.0	0.0
GWQMN	0.0	Threshold water level in shallow aquifer for baseflow	20.0	25.0

Nash-Sutcliff (NS) coefficient, coefficient of determination (R^2), and percent bias (PBIAS). The R^2 was estimated as:

$$R^2 = \left\{ \frac{\sum_{i=1}^{n} (Q_{obsi} - Q_{obsave})(Q_{simi} - Q_{simave})}{\left[\sum_{i=1}^{n} (Q_{obsi} - Q_{obsave})^2 \sum_{i=1}^{n} (Q_{simi} - Q_{simave})^2\right]^{0.5}} \right\}^2 \tag{1}$$

where n is the number of number of events, Q_{simi} and Q_{obsi} the simulated and observed runoff at event i, Q_{simavg} and Q_{obsavg} the average simulated and observed runoff over the validation period. The NS coefficient was calculated following Nash and Sutcliffe, (1970) and Gupta et al., (1999) as:

$$NS = 1 - \left[\frac{\sum_{i}^{n} (Q_{simi} - Q_{obsi})^2}{\sum_{i}^{n} (Q_{obsi} - Q_{avg})^2} \right] \tag{2}$$

where n is the number of time steps, Q_{simi} and Q_{obsi} the simulated and observed streamflow at time step i, and Q_{avg} the average observed streamflow over the simulation period. PBIAS was calculated based on equation 3:

$$\text{PBIAS} = \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim}) \times (100)}{\sum_{i=1}^{n} (Y_i^{obs})} \right] \tag{3}$$

where Y_i^{obs} and Y_i^{sim} are observed and simulated streamflow at time step i.

The calibration/validation performance for SWAT model is considered acceptable when R^2 and NS are greater than 0.5 (Moriasi et al., 2007). The SWAT model performance is satisfied when NS is larger than 0.5, adequate when NS ranges from 0.54 to 0.65, and very good when NS is larger than 0.65 (Moriasi et al., 2007). When the absolute value of PBIAS ranges from 15 to 25, the SWAT model is rated as satisfactory, rated good when from 10 to 15, and very good when smaller than 10 (Moriasi et al., 2007).

3.1.4. Model application

To assess the impacts of LULC changes on surface water availability, the calibrated model was run for each of the LULC maps (1973, 1986, 1992, and 1997) with constant DEM and soil data from January 1960 to April 2008 (48.3 years). The simulated results were used to evaluate impacts of LULC changes on change in surface water hydrology at the basinal scale and to quantify contribution of changes for individual LULC classes on changes of hydrological components at the subbasinal scale.

3.2. Multiple regression analysis

Before regression analyses, pair-wise correlations between variables were computed (Proc Corr, SAS® 9.2) to assess the relationship between variables. Changes in hydrological components between two simulations using LULC maps in 1997 and 1973, respectively, were related to changes of LULC in a multiple regression to quantify the effect of changes in LULC to that of hydrological components at the subbasinal scale. Independent variables are the changes for five LULC classes (i.e. Urban, Mesquite, Grassland, Desertscrub, and Agriculture). Dependent variables (responses) are changes for five hydrological components (i.e. Surface Runoff, Baseflow, Water Yield, Percolation, and Evapotranspiration). Multiple regression analyses with stepwise selection (Proc Reg, SAS® 9.2) were carried on. Initially one global regression line was fit to the data where all sites (subbasins) are included. Diagnostic checking of the residuals using the qq plot indicated that the model was not linear and two regression lines seem to fit the data better than one global regression line. Hence, sites were grouped into two and a regression model was fit to each group. Diagnostic checking of residuals was carried on each of ten models to observe normality, outliers, clustering and trend before finalizing models. Residuals were randomly fluctuated around the horizontal "0" value and with Shapiro–Wilk normality test larger than 0.974 and p larger than 0.052. Pair-wise correlation values for the retained variables in the stepwise regression model were all below the cutoff value (<0.5) based on sample size (Nash and Bradford, 2001, pg 8). This grouping stems from the combined effects of many LULC classes on hydrological components, which are explained in the following results section.

4. Results and discussion

The calibration/validation and simulation results are presented in this section. Impacts of LULC changes on change of surface water hydrology at the basinal scale are discussed and quantification results of contributions of changes in five LULCs on change of hydrological components at the subbasinal scale are reported.

4.1. Calibration results

The proportional extent of baseflow (ratio of total base flow over total streamflow) for the simulated and observed streamflow are 26% and 25% at the Charleston gage, and are 17% and 18% at the Redington gage in the period from 1991 to 1995 (estimated in the second pass by Baseflow Filter, Arnold and Allen, 1999). The good match indicates that the partitioning between surface runoff and baseflow can be represented by the calibrated model.

The comparison between simulated and observed annual streamflow values in the periods of calibration (1991/01–1995/12) and validation (1996/01–2000/12) is shown in Fig. 2. A good match can be seen between simulated and observed values. The NS and R^2 values for the annual calibration and validation are listed in Table 2. All NS and R^2 values are above 0.5, and PBIAS are in the range of ±15% (most PBIAS are in the range of ±10%), suggesting satisfactory model performance (Moriasi et al., 2007). Although the overall performance of the model is satisfactory as shown in Table 2, a large difference was observed for the year of 1992 at Redington and 1999 at both Redington and Charleston. Intuitively, the simulated values seem more reasonable for the year of 1992 at Redington and 1999 at both Redington and Charleston because of the rainfall patterns as shown in Fig. 2. Other possible reasons are due to the limitation of curve number method. For example, the SCS-curve number method used in SWAT model does not consider the duration and intensity of precipitation. In the upper San Pedro Watershed, rainfall events were mainly composed of high-intensity, short-duration, limited-areal extent summer thunderstorms (Simanton et al., 1996). Using averaged daily rainfall depths as SWAT inputs will lead to uncertainty in streamflow simulation. In addition, study shows that curve number method overestimates runoff for large rainfall events and underestimates runoff small rainfall events for watersheds with retention being a large fraction of the rainfall, such as arid and semiarid watersheds in Arizona (Hjelmfelt, 1980). The limitation of curve number method in this area is addressed more by another ongoing study, results of which are going to be submitted to a journal article. Overall, the good match between simulation and observation, as well as high NS, R^2, and low absolute values for PBIAS indicates that yearly streamflow can be described by the calibrated model. Thus, the SWAT models set up by the optimal parameters were applied to evaluate hydrological consequences to LULC changes.

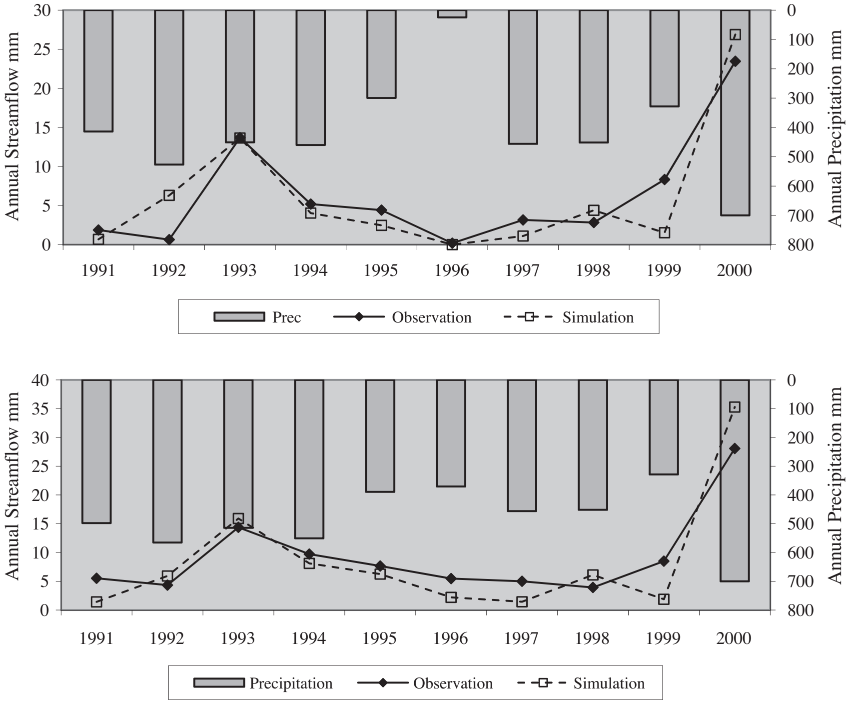

Fig. 2. Annual precipitation and simulated and observed streamflow in the upper San Pedro watershed. Upper: Redington (1991–1995) and Tombstone (1996–2000) gages; Lower: Charleston gage (1991–2000).

Table 2
Criteria for examing the accuracy of the model calibration and validation.

Index	Calibration (1991–1995)		Validation (1996–2001)	
	Redington	Charleston	Tombstone	Charleston
NS Coefficient	0.63	0.58	0.81	0.70
R^2	0.66	0.82	0.90	0.93
PBIAS	−5.1	9.6	10.7	7.9

4.2. Impacts of LULC changes on hydrology at the basinal scale

A comparison of LULC maps for the years 1973, 1986, 1992, and 1997 indicates that the most significant changes occurred in five LULC classes: Mesquite, Grassland, Desertscrub, Urban, and Agriculture during 1973–1986 (Table 3 and Fig. 3). The proportional extent of mesquite increased from 2.8% to 14.3%, (relative expansion is 410%) from 1973 to 1986, and mesquite invasion stopped after 1986 (14.0–14.3%). Conversely, from 1973 to 1986, the proportional extent of grassland and desertscrub decreased from 41.1% to 35.0%, and from 39.7% to 32.7%, respectively. After 1986, the grassland extent was relatively stable (34.6–35.0%) and the desertscrub decreased from 32.7% to 31.8%. The urban region was

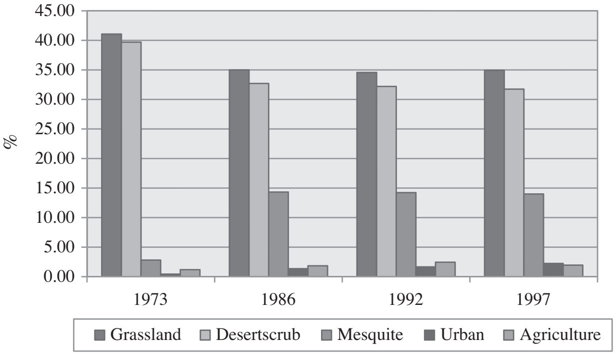

Fig. 3. Changes in proportional extent for four LULC classes in the upper San Pedro watershed (1973–1997).

Table 3
Proportional LULC extent, changes of LULCs (from Kepner et al., 2002), average annual basinal values of hydrological components, and changes in hydrological components, for the upper San Pedro watershed in the period from 1973 to 1997.

Time period	Mesquite (%)	Grassland (%)	Desertscrub (%)	Agriculture (%)	Urban (%)	Water yield (mm)	Surface runoff (mm)	Baseflow (mm)	Percolation (mm)	ET (mm)
1973	2.8	41.1	39.7	1.2	0.4	3.67	2.61	1.13	13.14	385.30
1986	14.3	35.0	32.7	1.8	1.4	3.74	2.74	1.09	12.85	385.10
1992	14.2	34.6	32.2	2.5	1.7	3.80	2.80	1.08	12.84	385.50
1997	14.0	34.9	31.8	2.0	2.2	3.92	2.93	1.09	12.86	385.70
1986–1973	11.5	−6.1	−7.0	0.7	0.9	0.07	0.13	−0.04	−0.29	−0.20
1992–1986	−0.1	−0.4	−0.5	0.6	0.3	0.06	0.06	−0.01	−0.01	0.40
1997–1992	−0.2	0.4	−0.5	−0.5	0.6	0.12	0.13	0.01	0.02	0.20
1997–1973	11.2	−6.1	−8.0	0.8	1.8	0.25	0.32	−0.04	−0.28	0.40

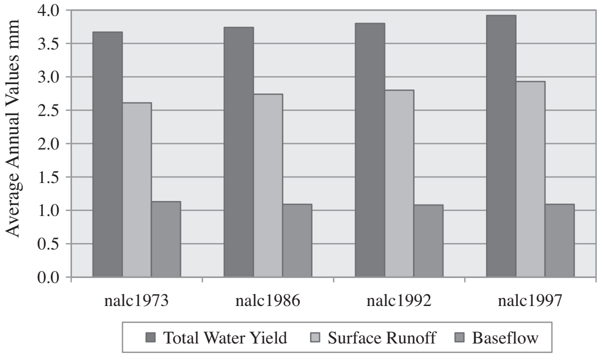

Fig. 4. Average annual basin values of water yield (total flow), surface runoff, and baseflow for four past LULC maps in the upper San Pedro watershed.

gradually expanded from 0.4% to 2.2% (relative expansion is over 400%) between 1973 and 1997. The agriculture region gradually increased from 1.2% to 2.5% from 1973 to 1992 and then decreased to 2.0% in 1997.

The average annual basin values of total water yield, surface runoff, and baseflow simulated from each LULC maps are shown in Table 3 and Fig. 4. Compared to the LULC baseline in year 1973, the average annual water yield over the watershed is 0.07 mm higher in 1986, 0.13 mm higher in 1992, and 0.25 mm higher in 1997(increasing 1.9%, 3.5%, and 6.8%, respectively). Similar to water yield, average annual surface runoff with LULC in 1973 was 2.61 mm; it gradually increased to 2.93 mm with LULC in 1997 (increasing 12.3%). On the contrary, the average annual baseflow for LULC in 1986 was 0.04 mm lower than that in 1973(decreased 3.5%); but baseflow for LULC in 1992 or 1997 was similar with that in 1986. Similar to baseflow, average annual basin percolation decreased from 13.14 mm for LULC in year 1973 to 12.85 mm for LULC in 1986 and percolation values for the other two LULC maps were similar to that in 1986. Consequences of ET to LULC changes, however, are more complicated than other hydrological components. The average annual basin ET decreased from 385.3 mm for LULC in 1973 to 385.1 mm for LULC in 1986 and then increased to 385.7 mm for LULC in 1997.

The comparison of variations of surface runoff and changes in LULCs suggests that the increase of average annual basin surface runoff could be mainly attributed to the urban expansion from 1973 to 1997. As shown in Table 3, the gradual increase of surface runoff from 1973 to 1997 matches the trend of urban expansion. In addition, a very strong positive correlation was observed between surface runoff and proportional urban area (R^2 is 0.9825). Increased average annual basin runoff associated with urbanization should be due to the increase of impervious surfaces (Franczyk and Changk, 2009).

An association between the decrease of baseflow/percolation and mesquite invasion from 1973 to 1986 can be indicated from the comparison between variations of average annual basinal baseflow/percolation and changes in LULC from 1973 to 1997. As shown in Table 3, baseflow and percolation decreased from 1973 to 1986 and then approximately remain unchanged until 1997. An opposite change of mesquite extent was observed from 1973 to 1997, indicating negative correlation between variation of baseflow/percolation and invasion of mesquite woodland. In the upper San Pedro watershed, the invasion of mesquite woodland occurred by replacing grassland or desertscrub.. Invasion of mesquite by replacing grassland destroyed the complete grassland canopy cover, which was a favored landscape for infiltration through lowering the effective energy of raindrops (Schlesinger et al., 1990). Depletion of canopy cover results in declines of percolation and baseflow. Invasion of mesquite by replacing grassland can also change local water balance and reduce percolation/baseflow through increasing ET. The quantification of ET for different riparian species in the upper San Pedro River Basin suggested that mesquite woodlands have much higher annual ET rates than grasslands (Scott et al., 2006). Unlike the shallow rooted grassland, mesquite has a shallow lateral root system and a deep vertical root system, which enables it to use water in the shallow and deep soil, as well as in the groundwater system (Heitschmidt et al., 1988; Scott et al., 2006). This ability enhances the capacity of mesquite to compete for water with grassland and other shallow-rooted vegetations, especially during dry periods. Consequently, less water will be infiltrated into deep soil and percolation/baseflow will be reduced with invasion of mesquite into grassland.

Further comparison between changes in water yield and changes of LULCs (Table 3) indicated that increase of water yield from 1973 to 1997 is due to gradual increase of urban and this effect is reduced by invasion of mesquite woodland. Table 3 shows that the increases of water yield are comparable with those of surface runoff from 1986 to 1992 or from 1992 to 1997, but the increased water yield is smaller than the increased surface runoff from 1973 to 1986. Water yield is mainly composed of surface runoff and baseflow. Thus, the decrease of baseflow from 1973 to 1986 due to invasion of mesquite woodland reduced the total increase of water yield resulted from urban expansion.

One may argue that the changes in average basinal hydrological components could be caused by simulation errors. As an example, the changes in average basinal hydrological components from 1992 to 1997, as shown in Table 3 (some less than 1%), could be less than the simulation error because the percent of bias in model calibration are from −5.1% to 9.6% and from 7.9% to 10.7% in the validation period (Table 2). However, much higher variations in hydrological components at subbasin scale exist. The increase of urban area at subbasinal scale is up to 9.0%, much higher than the average increase of 0.6% in the watershed scale (Table 3). Similarly, increases of surface runoff in subbasins are up to 1.48 mm, much higher than 0.13 mm increase in the whole watershed (Table 3). The relative changes of 1997 in surface runoff with respect to 1992 values of each subbasin are from −52.7% to 527.0%. The high coefficient of determination between deviation of urban area and surface runoff at subbasinal scale ($R^2 = 0.975$) indicated that the increases of runoff in subbasins are mainly derived from increase of urban area, rather than from simulation errors. In addition, relative changes of ET, Percolation, Baseflow, and Water Yield in 1997 with respect to 1992 values range from −6.1% to 29.7%, −73.3% to 6.8%, −40.4% to 40.5%, and −52.7% to 527.0%, respectively. The high variations of hydrological components on local scale (subbasins) indicate that changes in hydrological components with respect to LULC changes are much higher than the level of model accuracy, even for very small LULC changes during 1992 and 1997. Thus, simulation results from the calibrated model were used to evaluate impacts of LULC changes on hydrological components.

4.3. Contribution of changes for individual LULCs on hydrological components

The spatial distribution of changes for five LULCs (i.e. urban, mesquite, grassland, desertscrub, and agriculture) and five simulated hydrological components (i.e. surface runoff, baseflow, water yield, percolation, and evapotranspiration) between LULC maps in 1973 and 1997 are shown in Fig. 5. Urban expansion mainly occurred at the middle-stream reaches along the upper San Pedro River Basin, near Hereford, Sierra Vista, Tombstone, and Benson, and also occurred for the city of Cananea (Mexico) in the upperstream. Mesquite invasion occurred across almost the entire

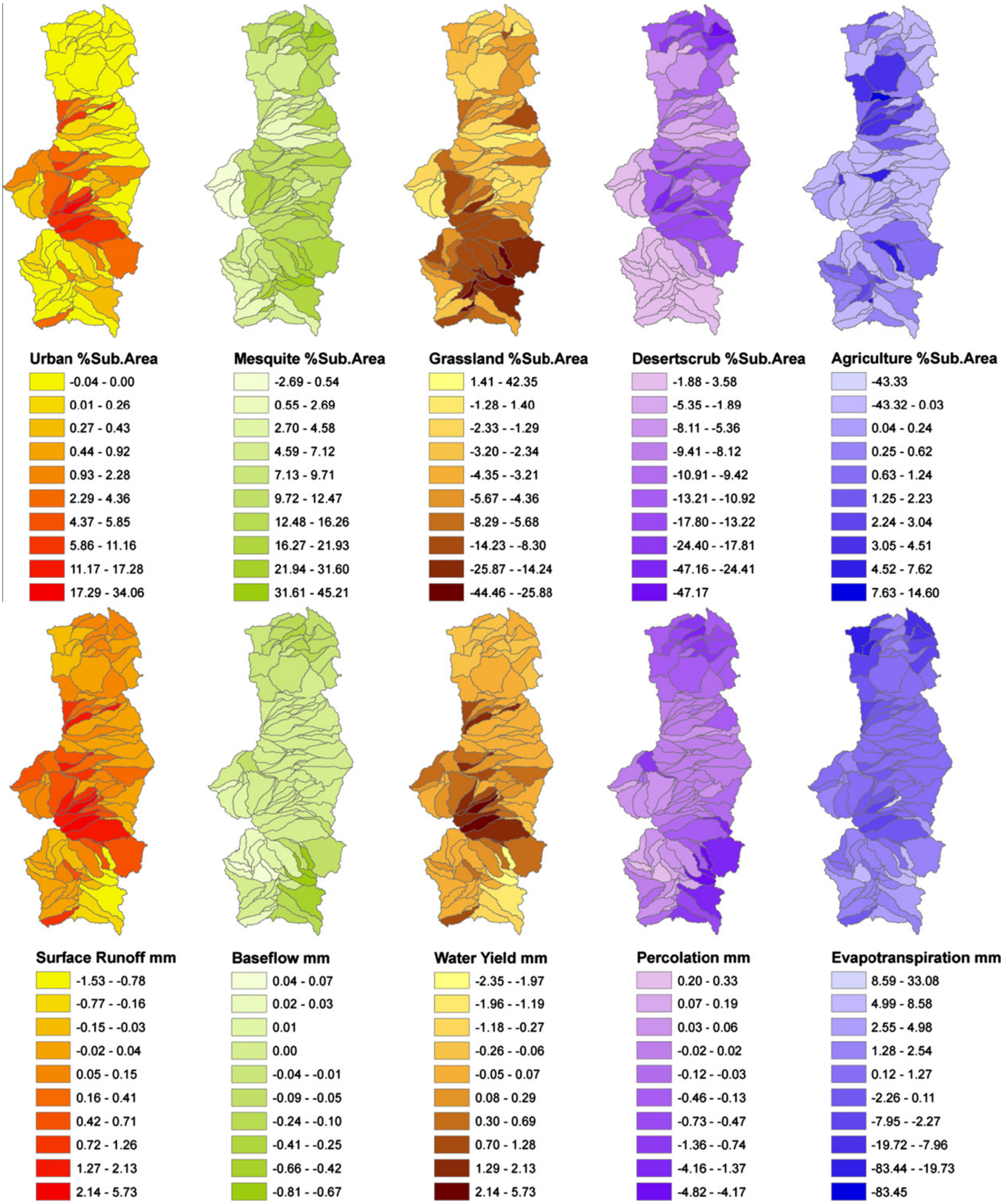

Fig. 5. Spatial distribution of deviation of five LULC classes and hydrological components between LULC maps in year 1997 and 1973.

watershed by replacing grassland and desertscrub. The conversion between grassland and mesquite can be distinguished in the upper-stream (Mexico) where no apparent decrease of desertscrub was observed (Fig. 5). The increased agriculture area was mainly distributed in the upper and down-stream of the basin.

The most significant increases of surface runoff and water yield also mainly occurred in the middle-stream, largely matching the spatial distribution pattern of urban expansion, which was confirmed by the positive high correlation between urban expansion and an increase of runoff/water yield (Table 4). The decrease of surface runoff and water yield in the southeast of the watershed spatially corresponds to subbasins where the majority of grassland was replaced by mesquite (Fig. 5). Spatial patterns of baseflow and percolation are almost the same, with an apparent decrease in the southeastern and northern part of the watershed (Fig. 5). This pattern partially matches the spatial distribution of mesquite invasion. In Table 4, negative medium correlations were seen between mesquite with each of baseflow and percolation, indicating an association of mesquite invasion and decrease of baseflow/percolation. The spatial pattern of ET did not correspond to any class

Table 4
Pair-wise Pearson correlation for the changes of five LULC classes and five hydrological components between LULC maps in 1997 and 1973; ET: evapotranspiration.

	Surface runoff	Baseflow	Water yield	ET	Percolation	Urban	Mesquite	Agriculture	Grassland	Desertscrub
Surface Runoff	1.00									
Baseflow	**0.35**	1.00								
Water Yield	**0.99**	**0.48**	1.00							
ET	−0.04	−0.13	−0.06	1.00						
Percolation	**0.34**	**0.98**	**0.47**	−0.13	1.00					
Urban	**0.95**	0.09	**0.90**	0.01	0.09	1.00				
Mesquite	−0.12	**−0.47**	−0.18	0.08	**−0.48**	−0.01	1.00			
Agriculture	0.03	0.03	0.03	0.01	0.03	0.01	0.01	1.00		
Grassland	0.04	**0.50**	0.11	−0.18	**0.47**	−0.13	**−0.54**	−0.09	1.00	
Desertscrub	**−0.38**	0.00	**−0.35**	0.08	0.04	**−0.36**	**−0.54**	−0.07	**−0.23**	1.00

$n = 116$, bold numbers are for $p < 0.05$.

Table 5
Summary of multiple regression analyses of five LULC (predictors) with each hydrological component (responses), partial R^2 are listed with direction of influence (negative or positive). Bold numbers are for the strongest predictor.

Responses	Group	Number of Subbasins	Predictors					R^2
			Urban	Mesquite	Agriculture	Grassland	Desertscrub	
Surface runoff	1	85	**0.9991(+)**				0.0001(+)	0.9992
	2	31	**0.7928(+)**			0.1251(+)		0.9179
Baseflow	1	89	0.1477(+)				**0.3793(+)**	0.5271
	2	26	0.0388(+)		0.1641(+)	**0.6791(+)**		0.8820
Water yield	1	91	**0.9973(+)**	0.0006(−)				0.9978
	2	25	**0.6944(+)**		0.0274(+)	0.1505(+)		0.8724
Percolation	1	96	0.0841(+)				**0.3184(+)**	0.4025
	2	20			0.3053(+)	**0.5074(+)**		0.8127
ET	1	82	**0.9098(−)**	0.020(+)			0.0136(+)	0.9484
	2	30				**0.4436(−)**	0.1674(+)	0.6110

$p < 0.05$ for all F tests.

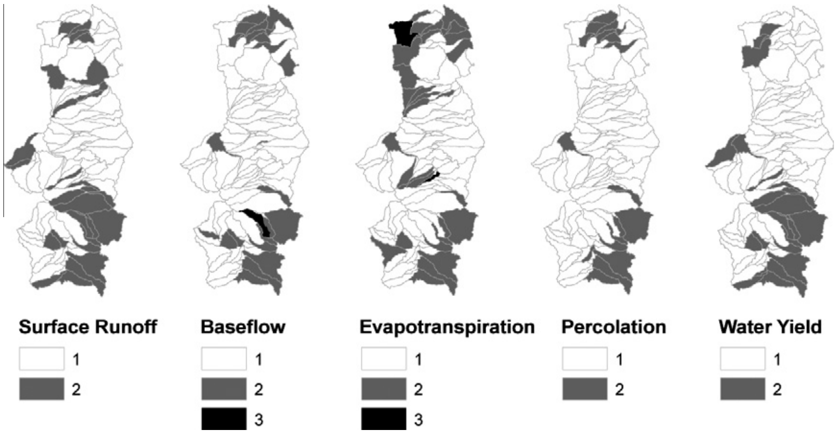

Fig. 6. Two groups divided for multiple regression analyses (Group 3 is outliers).

of LULC change and no significant correlation between ET and other variables were examined (Table 4), suggesting a more complicated mechanism controlling the change of ET.

Results of multiple regression analyses are given in Table 5. The 116 subbasins were divided into two groups (Fig. 6) to meet normality of residuals (Group 3 are outliers). Changes in surface runoff in both groups were highly influenced by urban changes from 1973 to 1997. While change in the urban area was the highest contributor (partial $R^2 > 0.79$, positive) in both groups, the second contributor was changes in desertscrub (partial $R^2 = 0.0001$, positive) in Group 1 and grassland (partial $R^2 = 0.1251$, positive) in Group 2. Similar to the surface runoff, the highest contributor for water yield in both groups is change of urban (positive) and the second highest contributor for Group 2 is change of grassland (positive). In addition, the change of mesquite (negative) and change of agriculture (positive) are also contributors to the changes of water yield (Table 5). For percolation and baseflow, the highest contributor for Group 1 is change of desertscrub (positive) followed by urban (positive) and the highest contributor for Group 2 is change of grassland (positive) followed by change of agriculture (positive). Both desertscrub and grassland were predominantly replaced by mesquite woodland in the upper San Pedro watershed from 1973 to 1997 (Kepner et al., 2002), indicating that any decrease of percolation/baseflow can be attributed to mesquite invasion. For the ET, the highest contributor in Group 1 is change of urban area (partial $R^2 = 0.9098$, negative) followed by change of mesquite (positive) and change of desertscrub (positive); and the highest contributor in Group 2 is grassland (partial $R^2 = 0.4436$, negative) followed by desertscrub (partial $R^2 = 0.1674$, positive).

The overall increase of runoff simulated in the Sierra Vista subbasin of the upper San Pedro Watershed from LULC in 1973 to 1997 reported by Miller et al. (2002) was attributed to the simultaneous increase of urban, agriculture and woody mesquite, and decrease of grassland and desertscrub. In our current study, urbanization was identified as the strongest contributor of change in surface runoff, suggesting that the simulated increase of runoff from 1973 to 1997 can be mainly attributed to the expansion of urban area, although mesquite invasion was the dominant LULC changes from 1973 to 1997. Surface runoff is the most significant component of water yield (more than 70%), thus the most significant contributor for changes of water yield is also the urbanization. Changes of desertscrub and grassland were the strongest contributor (positive) to the changes of percolation and baseflow, suggesting the primary decrease of percolation/baseflow was attributed to the decrease of grassland/desertscrub from 1973 to 1997. In the upper San Pedro watershed, the decreased grassland and desertscrub was replaced by mesquite. The decline of percolation and baseflow after mesquite invasion can be attributed to the decrease of available water due to increasing ET (Schlesinger et al., 1990).

Changes of urban and grassland were identified as the strongest contributors (negative) for the change of ET from 1973 to 1997. The negative influence of urbanization on ET can be attributed to the increase of impervious area, less of vegetation cover implies less water that recycle to the atmosphere by plant transpiration. The negative impact of grassland on ET is due to its relatively low transpiration demand compared to that of shrubs and woodland (desertscrub and mesquite). Mesquite and desertscrub have a shallow lateral root system and a deep vertical root system, which enables them to use water in the shallow and deep soil, as well as in the groundwater system (Heitschmidt et al., 1988; Scott et al., 2006). In the upper San Pedro watershed, the replacement of grassland by mesquite from 1973 to 1997 enhanced the transpiration demand, and thus resulted in the increase of ET.

5. Summary and conclusions

Contributions of changes of LULCs to that of major hydrological components in the upper San Pedro watershed were evaluated using a combination of hydrological modeling and multiple regression analyses. The impacts of LULC change on changes in hydrology were evaluated; associations and contributions of LULC changes to changes in hydrological components were identified and quantified. We summarize our conclusions as follows:

1 Although mesquite invasion (2.8–14.3% from 1973 to 1986) was the most significant LULC change in the upper San Pedro watershed from 1973 to 1997, increased surface runoff and total water yield were mainly attributed to urban expansion (0.4–2.2% from 1973 to 1997).
2 The replacement of grassland by mesquite also contributed to the decrease of surface runoff and water yield.
3 The replacement of desertscrub or grassland by mesquite from 1973 to 1997 was identified as the strongest contributor for the declines of baseflow and percolation and contributed to the increase of ET in the upper San Pedro watershed.

Increase in surface runoff was considered as a negative impact on the upper San Pedro River Basin (Kepner et al., 2004). It may further strengthen environmental stress through generating more sediment yield and erosion that were usually directly related to runoff volume and velocity. Thus, urbanization, the strongest contributor for surface runoff and water yield, can be considered as a major environmental stressor controlling hydrological components, including runoff, water yield, and ET, for the upper San Pedro River Basin. A decline in percolation would directly decrease recharge for the shallow and/or deeper aquifers and thus be considered a negative impact for watersheds (Kepner et al., 2004). Hence, replacement of grassland/desertscrub by mesquite woodland was another important environmental stressor affecting water resources in the upper San Pedro River Basin.

The approach used in this study simply determined contributions of changes for LULCs to hydrological components, providing quantitative information for stakeholders and decision makers to make better choices for land and water resource planning and management. Lastly, this approach provides a solid example of integrating hydrologic modeling (using remotely sensed digital LULCs) with a multiple regression analysis to understand the potential impact of landscape change on water provisioning, a vital ecosystem service in the western US. It can be widely applied to a variety of watersheds, where time-sequenced digital Landcover is available, to predict hydrological consequences to LULC changes.

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