Climate and Land-cover Change Impacts on Stream Flow in the Southwest U.S.

Wenming Nie, Paula E. Allen, Yongping Yuan, Maliha S. Nash, and William G. Kepner; U.S. EPA, Office of Research and Development, National Exposure Research Laboratory, Environmental Sciences Division, Las Vegas, NV

INTRODUCTION

Vegetation change in arid and semi-arid climatic regions of the American West are a primary concern for sustaining key ecosystem services such as clean, reliable water sources for multiple uses. Land cover and climate change impacts on stream flow were investigated in a highly valued southeast Arizona and northeast Sonora, Mexico watershed. To gain a historic perspective on climate change and its impact on stream flow in this watershed over time, we used the site-specific Bryson Macrophysical Climate Model to model climate, calibrated to 1961-1990 climate normals, and stream flow, calibrated to USGS gauge data for the Holocene at a 100-year resolution. Using AGWA/SWAT hydrological models in combination with land cover change measurements (1973-1997), we investigated the relationships between climate, land use, and stream flow.

The relationship of stream flow with mesquite cover and rainfall was analyzed identifying stages of changes in land cover to be linked to either anthropogenic or climate causes. The process demonstrates a simple procedure to document changes and determine ecosystem vulnerabilities through the use of change detection and hydrological process modeling, especially in regard to human-induced degradation processes and natural phenomena that have occurred throughout the western rangelands. These technologies provide the basis for developing landscape composition indicators and surface hydrological attributes as sensitive measures of large-scale environmental change and thus may provide an effective and economical method for evaluating watershed condition related to disturbance from human and natural stresses.

Site Description

The Upper San Pedro Watershed (U.S./Mexico) represents a transition area between the Sonoran and Chihuahuan Deserts and is internationally renowned for its biodiversity (Figure 1). The riparian zone has been acquired by the U.S. Department of the Interior and has been assigned special land status as a National Conservation Area. Topography, climate, and vegetation vary across the watershed. Elevation ranges from 900 - 2,900 m and annual rainfall ranges from 300 to 750 mm. Biome types include desertscrub, grasslands, oak woodland, mesquite woodland, riparian forest, coniferous forest, and agriculture. The upper watershed encompasses an area of approximately 7,600 km² (5,800 km² in Arizona and 1,800 km² in Sonora, Mexico).

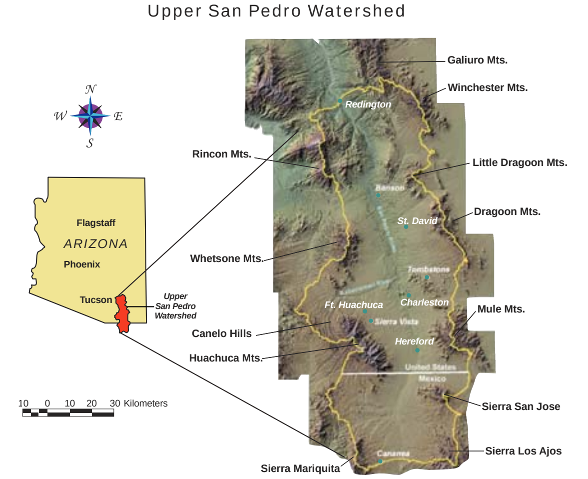

Figure 1. Location of the Upper San Pedro River Basin, Arizona/Sonora

Data

Land Cover

For this project, remote imagery was derived from Multi-spectral Scanner (MSS) and Thematic Mapper (TM) sensors via Landsat earth observing satellites (path/row 35/38 and 35/39). Landsat-MSS satellite scenes were selected from the North American Landscape Characterization (NALC) project. The scenes available in the NALC database (1973-92) and Landsat TM (1997) are from four pre-monsoon dates for a period of approximately 25 years (i.e., 5 June 1973, 10 June 1986, 2 June 1992, 8 June 1997). Digital land cover maps were developed separately for each year using 10 classes: Forest, Oak Woodland, Mesquite Woodland, Grassland, Desertscrub, Riparian, Agriculture, Urban, Water, and Barren (Kepner et al., 2003; Figure 2). All digital land cover modeling, accuracy assessments, and change detection results have been previously reported (Kepner et al., 2000, Skirvin et al., 2004, Kepner et al., 2006). Results about changes in land cover for the study period indicate that extensive, highly connected grassland and desertscrub areas are the most vulnerable ecosystems to fragmentation and actual loss due to encroachment of xerophytic mesquite woodland and urbanization. Our hypothesis is that these changes have likely impacted the hydrology of the region, since the energy and water balance characteristics for these cover types are significantly different.

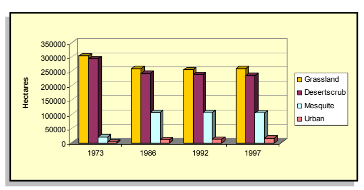

Figure 2. Change in areal extent (total hectares) for four land cover classes in Upper San Pedro Watershed (1973-1997).

Macrophysical Climate Model (MCM)

To gain a historic perspective on climate change and its impact on stream flow in this watershed, we used the site-specific Bryson Macrophysical Climate Model (Figure 3) to simulate climate and stream flow over the Holocene (past 10,000 years). We calibrated our precipitation model to the 1961-1990 climate normals for NOAA climate station #27036 near Redington (R^2 = 0.9616). Measured stream flow values collected from the USGS stream gauge #9472000 on the San Pedro near Redington, AZ (1985-1995) were used to calibrate the Bryson Macroclimate Model for stream flow at the site (R^2 = 0.9621) with a temporal resolution of 100 years.

Stream Flow Simulation

Data used for the SWAT model include the digital elevation model (DEM) derived from the National Elevation Dataset (NED) of USGS, soil theme layer from the State Soil Geographic (STATSGO) database, and land use land cover datasets described above. The climate data (maximum and minimum precipitation and temperature) for the period January 1, 1960 to April 30, 2008 were derived from 12 meteorological stations located in the Upper San Pedro river basin. The monthly channel discharge data derived from the USGS Redington gage station were used to calibrate the SWAT model (October 1985-September 2009; Figure 5).

METHODS/RESULTS

Macrophysical Climate Model (MCM)

1. Uses measured solar radiation as it varies with Milankovitch cycles and probability of volcanic eruptions (Volcanicity Index).
2. Calculates net surface radiation for each hemisphere using the albedo, irradiance and volcanic aerosol values.
3. Derives monthly mean hemisphere temperatures from seasonal hemisphere temperatures and modern mean surface temperatures as a control.
4. Calculates large scale meridional temperature gradients, combines this with modern synoptic data (locations of centers of action like ITCZ, etc.) using monthly hemisphere temperatures.
5. Creates site-specific MCMs using multiple non-linear regression techniques to link modern positions of the synoptic features to monthly weather station data (temperature, rainfall, storm frequency, snowfall, etc.) and stream gauge data (river, sediment, nutrient discharge, etc.).

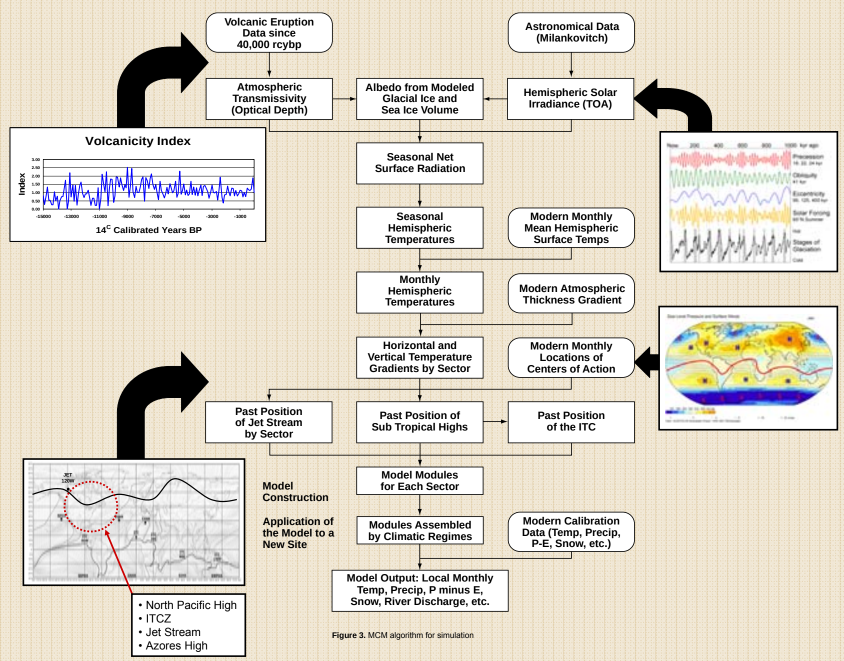

Figure 3. MCM algorithm for simulation

Holocene Precipitation History

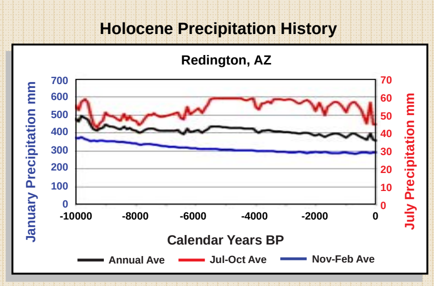

Figure 4a. MCM results – Calibration of precipitation to 1960-1990 climate normals (R^2= 0.9616). Jul-Oct represent the monsoonal rainfall in contrast with that of winter rainfall in this area.

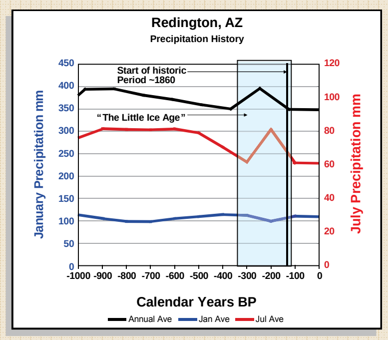

Figure 4b. Precipitation for the last 1000 years. Note the blue area denotes the "Little Ice Age" traditionally considered to have occurred between 1550 and 1850. The black line prior to the end of the Little Ice Age marks the beginning of the Historic Period of European settlement of the area ~1860. The region was settled at a time when winters were drier than today and summers wetter.

Holocene River Discharge History

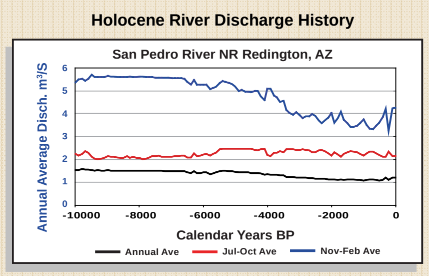

Figure 4c. MCM Results – Calibration of stream flow to USGS gauge near Redington, AZ (R^2 = 0.9621).

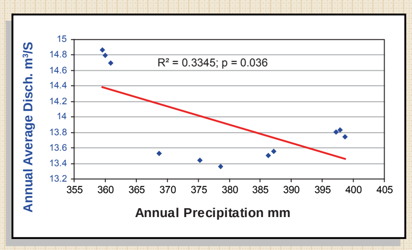

Figure 4d. Modeled stream flow vs. precipitation for the last 1000 years. The non-linear relationship suggested decomposition of the data into its summer (approximate timing of the North American Monsoon) and winter components that resulted in significant positive linear relationships (p<0.0071).

The Soil and Water Assessment Tool

The Soil and Water Assessment Tool (SWAT) version 2005 was used to simulate stream flow in the present study (Neitsch et al., 2005). The simulated hydrology in SWAT comprises of two components: land hydrology and stream hydrology. The land hydrological cycle is based on water balance equation:

$$SW_t = SW_0 + \sum_{i-1}^{t} (R_{day} - Q_{surf} - ET_i - W_{seepi} - Q_{gw})$$

where, SW_t and SW_0 are the final and initial soil water content on day i (mm H_2O), t the time (days) R_{day} the rainfall that reaches the soil surface on day i (mm), Q_{surf} the surface runoff on day i (mm), ET_i the evapotranspiration on day i (mm), W_{seepi} the interflow on day i (mm), and Q_{gw} is the baseflow on day i (mm) (Neitsch et al., 2005). Stream hydrology is based on routing runoff and chemicals through a watershed.

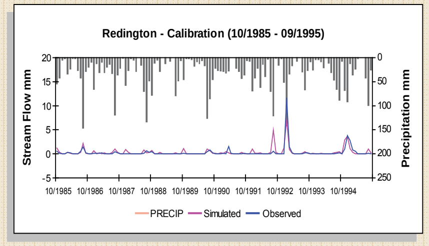

Figure 5. Monthly precipitation, simulated (SWAT) and observed stream flow at the Redington gage (Nash and Sutcliffe coefficient is 0.64 and correlation coefficient is 0.82). The highest stream flow occurring in January 1993 reflects the low evapotranspiration in winter.

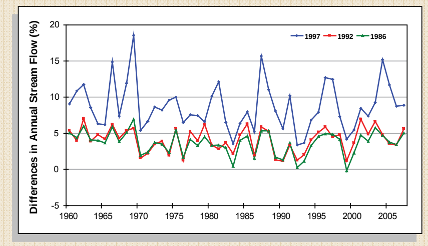

Figure 6. Change in percent stream flow with change in land cover. Comparisons were made based on the deviation in simulated annual stream flow from a 1973 baseline year for rainfall data and land cover change detected in remote sensing data from 1986, 1992, and 1997.

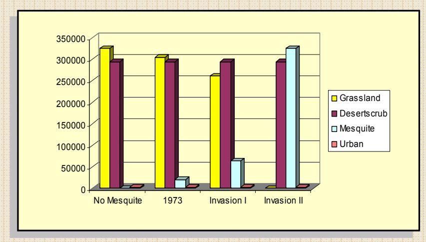

Figure 7. Changes of land cover for four scenarios based on 1973 land use. Baseline was developed by replacing all mesquite in 1973 land cover with grassland. Invasion I and II were developed by increasing mesquite cover and decreasing grassland in the 1973 land cover while keeping urban and desertscrub constant.

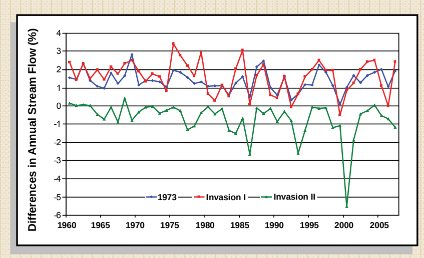

Figure 8. Changes in percent stream flow with change in land cover scenarios. In comparisons of deviation in simulated annual stream flow (1973, Invasion I and Invasion II) from the baseline in the period of 1960 to 2007.

DISCUSSION/CONCLUSIONS

During to the historic period beginning approximately 200 years ago, there was a steady increase in the amount of rainfall and corresponding stream discharge in the San Pedro near Redington, AZ, that corresponds to the climate anomaly known as "The Little Ice Age" (Figure 4b). This time period, from approximately 1550 to 1850 (440 to 140 years before the present based on a 1990 modeled year), was a major period of high stream flow resulting in arroyo cutting and alluvium deposition across the southern Colorado Plateau and within the San Pedro (Hereford 2002). The San Pedro area was settled around 1860 by Europeans migrating from the eastern United States 130 BP and precipitation has been declining since then. Based on pollen, fungal spores and charcoal in sediment cores from the San Pedro, particularly Bingham Cienaga near Redington, AZ (Owen et al., 2002), data document an increase in fungal spores and thus an increase in herbivory in historic times beginning around 1950. A precipitation decline in herbivory is also documented between 1975 and 1988 that coincided with the timing of elimination of grazing and delegation of the area to protected status. A significant decrease in charcoal abundance also corresponds to the era of fire suppression. Data also show a significant increase in Mesquite pollen historically but never constituting more than 10% of the local flora. Prior to historic times, there was variability in Mesquite pollen production; however, the pre-historic average was approximately 1% (Davis et al., 2002).

The historic record indicates three major periods of drought (1896-1904, 1947-1964, and 1996-2004) (Goodrich and Ellis 2006) that reduced stream flow, and intervening wet periods (1905-1941 and 1996-2004). Changes in ENSO events affect interannual climate by extending the length of wet and dry periods (Hereford et al., 2006; Mann et al., 2009). Warm El Niño events tend to result in wet winters and high stream flow in the Southwest, whereas La Niña conditions result in dry winters (Hereford et al., 2006). Major flooding and arroyo cutting between 1860 and 1910 likely correspond to El Niño conditions (Hereford 2002).

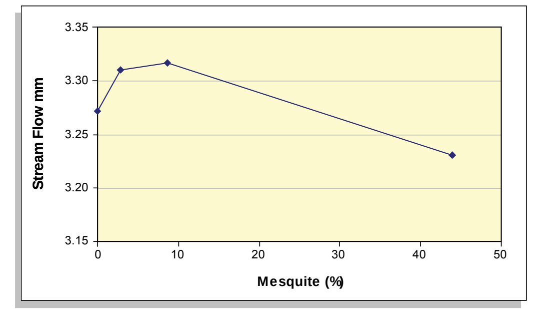

Figure 9a. Increase Mesquite cover with decrease in annual average stream flow in the Upper San Pedro basin.

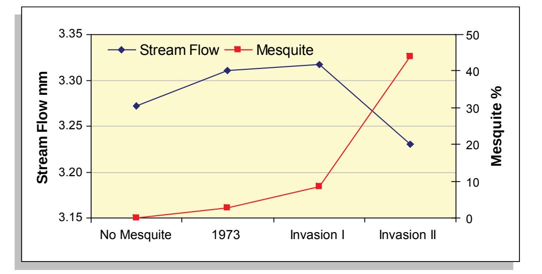

Figure 9b. Mesquite cover and simulated annual average stream flow for four land change scenarios for the Upper San Pedro basin.

Results of our developed scenarios assume that grassland will decrease (Figure 7) in response to invasion of the area by mesquite. Based on this assumption, we then simulated stream flow (Figure 8) for our four scenarios and found that it increases with an increase in mesquite (Invasion I, Figure 9). Following Invasion I, modeled stream flow decreases sharply and as mesquite becomes dominant (Invasion II, Figure 9) stream flow is at its lowest level. Invasion II represents the complete conversion of grassland to mesquite. Although stream flow actually increased with rainfall (ρ = 0.0014) based on data from 1960-1994, overall stream flow decreased with an increase in modeled mesquite cover. Perhaps the microenvironment created by the mesquite (the formation of sand mounds and subsequent colonization of these mounds by animals and other plant communities) promote the interception of the surface runoff, infiltration and groundwater recharge. More data are needed to confirm this behavior and is the subject of ongoing work in this area.

Today the climate of the Desert Southwest can generally be characterized by warm dry winters and hot moist summers. The biennial displacement of winter and summer storm tracks, and variations in the influence of the summer monsoon are all affected by the realignment of several different pressure systems through time (Wigand 2007; Hereford et al., 2006); their influence at specific sites can be modeled using the Bryson MCM (Figure 3). However, the MCM cannot predict the future, CO2 is treated as a dependent variable, and models have a 100-year resolution. SWAT on the other hand can make predictions based on potential future changes in land cover and the effects on stream flow at sub-daily time steps. These two models provide annual, multi-decadal and centennial temporal resolution of stream flow and provide a historical perspective that allows scientists to evaluate the relative contributions of climate and human-induced land cover change through time and to develop testable hypotheses regarding them. Future scenarios based climate extremes; outputs of the MCM; and land cover estimates from pollen studies can be established and modeled using SWAT. We plan on using SWAT for future scenario development to further address relative contributions of climate and land cover change to changes observed in the San Pedro Watershed.

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