Scenario Analysis for the San Pedro River: Analyzing Hydrological Consequences of a Future Environment

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1. Abstract

EPA's Office of Research and Development established a goal within the 2001 Strategic Plan "*To anticipate future environmental issues.*" Under this goal, we expect to identify, understand, and manage potential future risks to human health and the environment and conduct pilot studies with a 10-20 year analysis window into the future. Studies of future management and policy options based on different assumptions provide a mechanism to examine possible outcomes and especially their likely benefits and consequences. The San Pedro River in Arizona and Sonora, Mexico, is an area that has undergone rapid changes in land use and cover, and subsequently is facing keen environmental crises related to water resources. It is the location of a number of studies that has dealt with change analysis, watershed condition, and most recently, alternative futures analysis. The previous work has dealt primarily with resources of habitat, visual quality, and groundwater related to urban development patterns and preferences. In the present study, previously defined future scenarios, in the form of land-use/land-cover grids, were examined relative to their impact on surface-water conditions (e.g., surface runoff and sediment yield). These hydrological outputs were estimated for the baseline year of 2000 and predicted 20 years in the future as a demonstration of how new geographic information system-based hydrologic modeling tools can be used to evaluate the spatial impacts of urban growth patterns on surface-water hydrology.

Keywords: alternative futures analysis, hydrologic modeling, watershed assessment, scenario analysis, future environments, geographic information systems, San Pedro River

2. Introduction

The assessment of land use and land cover is an extremely important activity for contemporary land management. A large body of literature suggests that human land-use practices (including type, magnitude, and distribution) are the most important factors influencing natural resource management at local, regional, and global scales. Today's environmental managers, urban planners, and decision-makers are increasingly expected to examine environmental and economic problems in a larger geographic context. To accomplish this, it is necessary to 1) understand the scale at which specific management actions are needed; 2) conceptualize environmental management strategies; 3) formulate sets of alternatives to reduce environmental and economic vulnerability and uncertainty in their evaluation analyses; and 4) to prioritize, conserve, or restore valued natural resources, especially those which provide important economic goods and services.

This poster presents the results of a study that examines the impact of urban development in a semi-arid environment relative to sustainability of water resources, its most crucial asset. In particular, it attempts to answer questions that relate to future scenarios that describe extremes in position (e.g., build-out options that are most development and least conservation oriented and vice versa) with the idea that urban growth patterns can be managed to minimize hydrologic and environmental impacts.

3. Materials and Methods

A scenario-based approach to regional land planning offers an organizational basis to explore decision analysis and opportunities for public resources. In these studies, potential impacts from a number of wide-ranging scenarios are compared to current conditions of a region in terms of a set of processes that are modeled in a geographic information system (GIS). Alternative future landscape analysis involves describing the patterns and significant human and natural processes affecting a geographic area of concern, constructing GIS models to simulate these processes and patterns, creating changes in the landscape by forecasting and by design, and evaluating how the changes affect pattern and process using models (USEPA, 2000).

The application of several advanced technologies to assess the hydrological consequences of future human development in a moderately sized southwestern watershed is described below. The primary source data were three land-cover/land-use grids representing alternative futures for the San Pedro River Basin in the year 2020. These data were derived from a study of changing landscape patterns, in which they were compared to a baseline year of 2000 for the purpose of assessing groundwater and biological impacts (Steinitz et al., 2003; Kepner et al., 2002). The case study area was selected for a variety of reasons, including data richness and stakeholder involvement.

The Upper San Pedro River Basin originates in Sonora, Mexico, and flows north into southeastern Arizona (Figure 1). Elevations range over 900–2,900 m and annual rainfall ranges from 300 to 750 mm. Biome types include desert scrub, grasslands, oak woodland-savannah, mesquite woodland, riparian forest, coniferous forest, and agriculture (Kepner et al., 2000). The upper watershed encompasses an area of approximately 7,600 km^2 (5,800 km^2 in Arizona and 1,800 km^2 in Sonora, Mexico) and is the only unimpounded river in Arizona. All municipal and most agricultural water is derived from groundwater sources.

The Automated Geospatial Watershed Assessment (AGWA) tool is a GIS-based interface for watershed modeling and assessment that has been developed jointly by the U.S. EPA Office of Research and Development, USDA Agricultural Research Service, and the University of Arizona. AGWA provides the functionality to conduct all phases of a watershed assessment for two widely used watershed hydrologic models: the Soil & Water Assessment Tool (SWAT; Arnold et al., 1994) and the Kinematic Runoff and Erosion Model (KINEROS2; Smith et al., 1995). SWAT is a continuous simulation model for use in large (river-basin scale) watersheds. KINEROS2 is an event-driven model designed for watersheds characterized predominantly by overland flow. The AGWA tool combines these models in an intuitive interface for performing multi-scale change assessment. Data requirements include elevation, land cover, soils, and precipitation data, all of which are readily available over the Internet. AGWA is provided at no cost via the Internet as a modular, open-source suite of programs (www.tucson.ars.ag.gov/agwa/ *or* www.epa.gov/nerlesd1/land-sci/agwa/).

Digital data were collected from a variety of public sources (e.g., Kepner et al., 2003). The year 2000 was used as baseline condition and a set of land-cover/land-use maps were developed for the year 2020 based on current land management and projected census growth (Steinitz et al., 2003). For the pupose of this study, the 2020 maps were selected for three scenarios which reflected important contradictions in desired future policy based on stakeholder input. The scenarios are listed in Table 1 and basically reflect changes in population within the watershed, patterns of growth, and development practices and constraints. The Constrained Scenario is the most conservation oriented, the Plans Scenario reflects the most likely census predictions with zoning options designed to accommodate growth, and the Open Scenario is the least conservation and most development positioned option. It also assumes a greater than predicted population and few constraints on land development.

Our modeling approach involved running SWAT using the 2000 baseline land cover to parameterize the model to determine reference condition. SWAT was run using 12 years of continuous daily rainfall and temperature data (1960–1972) from a single gauge in the center of the basin. The watershed was discretized with a contributing source area of 9,200 ha, producing 67 sub-watershed elements (Figures 2–4). The same simulation was performed using each of the three 2020 land-cover scenarios to develop parameter inputs. Average annual outputs from the three alternative futures were then differenced from the baseline values to compute percent change in average daily values over the 20-year period with a focus on the relative magnitude and spatial distribution of the computed changes.

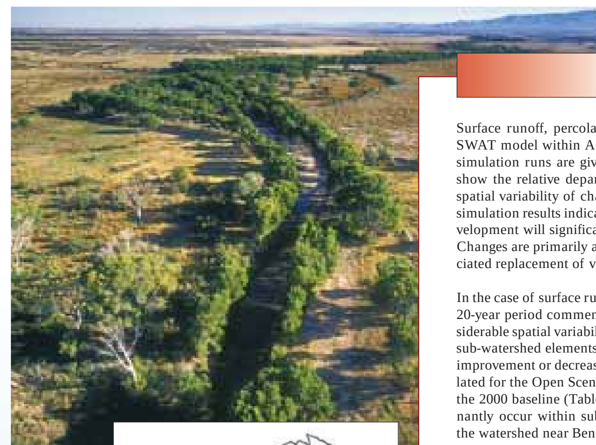

Figure 1. Location of the Upper San Pedro River Basin, Arizona/Sonora.

CONSTRAINED	Assumes lower population (78,500 inhabitants) than presently forecast for 2020. Development is concentrated in mostly existing developed areas (i.e., 90% urban). Removes all irrigated agriculture within the river basin.
PLANS	Assumes population increase as forecast for 2020 (95,000 inhabitants). Development is in mostly existing developed areas (i.e., 80% urban and 15% suburban). Removes irrigated agriculture within a 1-mile buffer zone of the river.
OPEN	Assumes population increase is more than the current 2020 forecast (111,500 inhabitants). Most constraints on land development are removed. Development occurs mostly into rural areas (60%) and less in existing urban areas (15%). Irrigated agriculture remains unchanged from current policy except for prohibiting new expansion near the river.

Table 1. Scenarios for future urbanization of the Upper San Pedro River Basin in the year 2020.

4. Results

Surface runoff, percolation, and sediment yield were simulated using the SWAT model within AGWA for the three 2020 scenarios. Results from the simulation runs are given in Table 2 and Figures 2, 3, and 4. The figures show the relative departure from the 2000 baseline year and illustrate the spatial variability of changes to the surface-water hydrology. In general, the simulation results indicate that land-cover changes associated with future development will significantly alter the hydrologic response of the watershed. Changes are primarily associated with increasing urbanization and the associated replacement of vegetated surfaces with impervious ones.

In the case of surface runoff, the simulations show average increases over the 20-year period commensurate with increases in urbanization. There is considerable spatial variability of simulated hydrologic response. Although most sub-watershed elements exhibited an increase in runoff, other areas showed improvement or decreasing runoff (Figure 2). The greatest change was simulated for the Open Scenario with an average increase of 12,787 m^3/day over the 2000 baseline (Table 2). Simulated increases in surface runoff predominantly occur within sub-watersheds distributed in the northern reaches of the watershed near Benson, Arizona.

Sediment yield and erosion are directly related to runoff volume and velocity. The percent change in sediment yield simulated with SWAT also displayed a high degree of spatial variability across the basin and among the three scenarios (Figure 3). Sub-watersheds with the greatest increase in sediment yield did not necessarily correspond with those exhibiting the greatest change in surface runoff; however, those model elements in the southern headwaters generally showed the least increase in both variables.

Percolation is a hydrologic measure of the water volume that is able to infiltrate into the soil past the root zone to recharge the shallow and/or deep water aquifers. Figure 4 displays the simulated change in percolation for the three development scenarios. Although the model predicts some improvement in the watershed headwaters where human inhabitation is most dispersed, overall percolation is expected to decrease in all options as urban impervious surfaces are expanded, especially under the Open Scenario (Table 2).

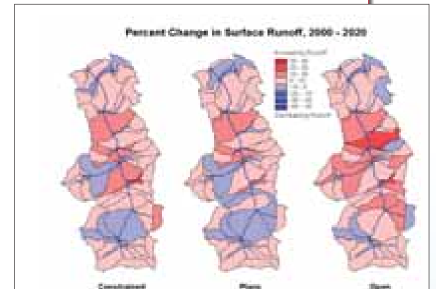

Figure 2. Percent change in surface runoff, 2000 - 2020, Upper San Pedro River Basin, Arizona/Sonora.

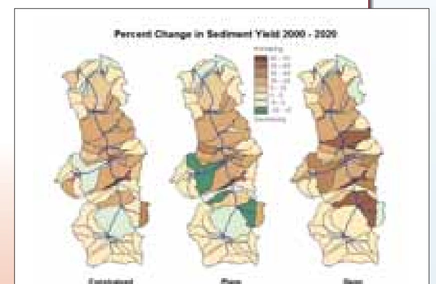

Figure 3. Percent change in sediment yield, 2000 - 2020, Upper San Pedro River Basin, Arizona/Sonora.

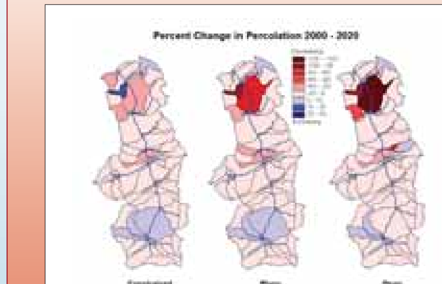

Figure 4. Percent change in percolation, 2000 - 2020, Upper San Pedro River Basin, Arizona/Sonora.

	Baseline 2000	Simulated Percent Relative Change 2000 - 2020		
		Constrained 2020	Plans 2020	Open 2020
Surface runoff (m^3/day)	186,538	4.3	3.7	6.9
Percolation (m^3/day)	42,760	-2.7	-3.0	-4.6
Sediment yield (t/day)	1,042	4.4	3.7	7.0

Table 2. Simulated average daily surface runoff, percolation, and sediment yield for the 2000 baseline conditions and predicted relative change for each of the three development scenarios.

5. Summary and Conclusions

The hydrologic responses resulting from three development scenarios for the Upper San Pedro River Basin were evaluated using AGWA, a GIS tool developed to integrate landscape information with hydrological process models to assess watershed impacts. This differed from previous alternative futures research within the San Pedro watershed in that it examined the spatially variable impact of land-cover/land-use change on the surface-water hydrologic regime. With this type of assessment, it is possible to rapidly evaluate likely changes in surface runoff throughout a basin, as well as the cumulative downstream change as widely distributed tributary impacts are felt in the main channel. In general, under a future urbanizing environment, the model simulation results appear to indicate that important impacts to the watershed hydrology can be expected. The most notable changes are likely to be increases in the amount of runoff, sediment discharge, and a loss of surface-water access to the groundwater table.

For the purpose of this study, negative impacts are considered to be any increase in surface runoff, sediment yield, and/or declines in groundwater percolation. The impacts are summarized graphically by percent change relative to the 2000 reference condition for each of the alternative futures using sub-watersheds as the comparative unit. Urbanization and irrigated agriculture are presumed to be the two major environmental stressors affecting watershed condition of the Upper San Pedro River Basin. The hydrologic modeling results indicate that negative impacts are likely under all three of the future scenarios as a result of predicted urbanization; however, there is remarkable variation in their specific hydrologic responses, particularly between the Constrained and Open scenarios. In general, the Open Scenario has the greatest negative impact on surface water hydrology and results in greater simulated surface runoff and sediment yield than the other options, especially in the downstream reaches near Benson, Arizona. Additionally, percolation and thus groundwater recharge is most reduced under this option. This scenario favors development and allows for the largest future population increase within the watershed.

Although the findings in this study were not completely unexpected, the authors believe that scenario analysis can help better understand and visualize how today's decisions regarding conservation and development act together to change the future. Areas within the watershed are valued both for development and for conservation purposes and this sometimes brings human values into direct conflict. Clearly, policy decisions regarding both population growth (particularly in Arizona) and irrigated agriculture will have an important bearing on future water use and conservation.

The present study endeavors to demonstrate the general potential of integrating spatial data and distributed modeling in natural resource management. The combination of both landscape analysis with hydrological modeling can be widely applied on a variety of landscapes, watersheds, and regions and provides an important tool to assess vulnerability. The use of scenarios thus allows stakeholders and decision-makers to assess the relative impacts of several alternative sets of options and thus provides an important tool to help make better informed choices for an improved future.

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For more information see:

Kepner, W.G., D.J. Semmens, S.D. Bassett, D.A. Mouat, and D.C. Goodrich. 2004. "Scenario Analysis for the San Pedro River, Analyzing Hydrological Consequences of a Future Environment." *Journal of Environmental Monitoring and Assessment*, 94: 115-127. Kluwer Academic Publishers (http://www.epa.gov/nerlesd1/land-sci/pdf/scenario_spedro.pdf).