Evaluating Hydrological Response to Forecasted Land-Use Change: Scenario Testing with the Automated Geospatial Watershed Assessment (AGWA) Tool

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Abstract

Envisioning and evaluating future scenarios has emerged as a critical component of both science and social decision-making. The ability to assess, report, map, and forecast the life support functions of ecosystems is absolutely critical to our capacity to make informed decisions to maintain the sustainable nature of our ecosystem services now and into the future. During the past two decades, important advances in the integration of remote imagery, computer processing, and spatial-analysis technologies have been used to develop landscape information that can be integrated with hydrologic models to determine long-term change and make predictive inferences about the future. Two diverse case studies in northwest Oregon (Willamette River basin) and southeastern Arizona (San Pedro River) were examined in regard to future land use scenarios relative to their impact on surface water conditions (e.g., sediment yield and surface runoff) using hydrologic models associated with the Automated Geospatial Watershed Assessment (AGWA) tool. The base reference grid for land cover was modified in both study locations to reflect stakeholder preferences 20 to 60 yrs into the future, and the consequences of landscape change were evaluated relative to the selected future scenarios. The two studies provide examples of integrating hydrologic modeling with a scenario analysis framework to evaluate plausible future forecasts and to understand the potential impact of landscape change on ecosystem services.

Keywords: hydrological process models, alternative futures, scenario analysis, watershed assessment, ecosystem services, San Pedro River, Willamette River

Introduction

The Environmental Protection Agency (EPA) ecological research program is currently engaged in a major new National project centered on "ecosystem services," a core international theme which was brought to the global forefront by the Millennium Ecosystem Assessment (MEA; 2005). The central premise of the MEA is that human condition is intrinsically linked to the environment and that human health and well-being (including economic prosperity) depends on important supportive functions as well as regulating, provisioning, and cultural services provided by our surrounding ecosystems. The EPA is in the process of redirecting its ecological research program to respond to the challenges identified by the MEA and is providing a new emphasis on integration, application, and transformative research and education.

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EPA scientists in Las Vegas, NV, along with their U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) and University of Arizona colleagues in Tucson have teamed together to develop a geographical information systems (GIS) interface to rapidly apply two hydrological process models: Soil and Water Assessment Tool (SWAT; Arnold and Fohrer 2005) and KINematic Runoff and EROSion (KINEROS2; Semmens et al. 2008; Smith et al. 1995). The two models have been combined into the Automated Geospatial Watershed Assessment (AGWA) tool for the purpose of conducting watershed assessments at multiple temporal and spatial scales (Miller et al. 2007). AGWA's current outputs are runoff (volumes and peaks) and sediment yield, plus nitrogen and phosphorus with the SWAT model.

Scenarios, as defined by the Intergovernmental Panel on Climate Change, are "plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships" (Houghton et al. 2001) Scenario analysis is an approach for evaluating various rational choices and the respective trajectories that lead to alternative future events. In the realm of natural sciences this is typically accomplished by using a combination of land-use change and process models to develop an artificial representation of the physical manifestations of scenario characteristics and to establish a multidisciplinary framework within which scenario characteristics may be analyzed. Scenarios are also usually conducted over long time periods (20–50 yrs) and develop a range of stakeholder-driven perspectives (scenarios), which are analyzed in detail for the consequences or benefits of their selection.

The purpose of this study was to examine the impact of urban development relative to the sustainability of water resources, a crucial asset of the western United States, with the intent of providing answers and a process for determining whether urban/agricultural growth patterns can be managed to minimize hydrologic and ecologic impacts.

Study Areas

The early 1990s and the year 2000 were used as a baseline for two western United States study basins, the Willamette River in Oregon and the San Pedro River on the U.S./Mexico border, respectively (Figure 1). Land use was then projected 60 yrs (Willamette) and 20 yrs (San Pedro) into the future for three development options related to conservation, existing land-use and planning trends, and full open urban development (Table 1). The three scenarios for both watersheds reflect changes in population, patterns of growth, and development practices and constraints. In essence, the Conservation Scenario is regarded as the most ecosystem protected or restoration-oriented option. The Plan Trend Scenario reflects current census predictions with zoning options designed to accommodate reasonable urban growth. The Development Scenario is considered the least conservation-oriented option and is most positioned towards a market economy. Typically, as in these examples, scenario (or alternative futures) analysis uses a model-based approach to identify the key variables that reflect environmental change or to examine landscape change relative to specific issues or ecosystem services (Mohammed et al. 2009; Liu et al. 2008 a; Liu et al. 2008 b). The hydrologic responses resulting from the three development scenarios for both the Willamette and San Pedro River basins were evaluated using AGWA. The environmental endpoints related to surface hydrology were selected because they represent fundamentally important ecosystem services (Farber et al. 2006). This research presents an integrated approach to identify areas with potential water-quality problems as a result of land cover change projected by stakeholders within the two river basins. Initially the study areas were examined and reported separately, though the approach is largely similar for both locations. The land cover/use scenarios were obtained from Steinitz et al. (2003) and Baker et al. (2004), in which the alternative courses of action were developed in consultation with local stakeholders for the three basic options listed in Table 1. Other details in regard to hydrological response relative to the future scenarios at each location can be found in Kepner et al. (2008a; Willamette) and Kepner et al. (2004; San Pedro River). Also see Kepner et al. (2008b) for a combined summary.

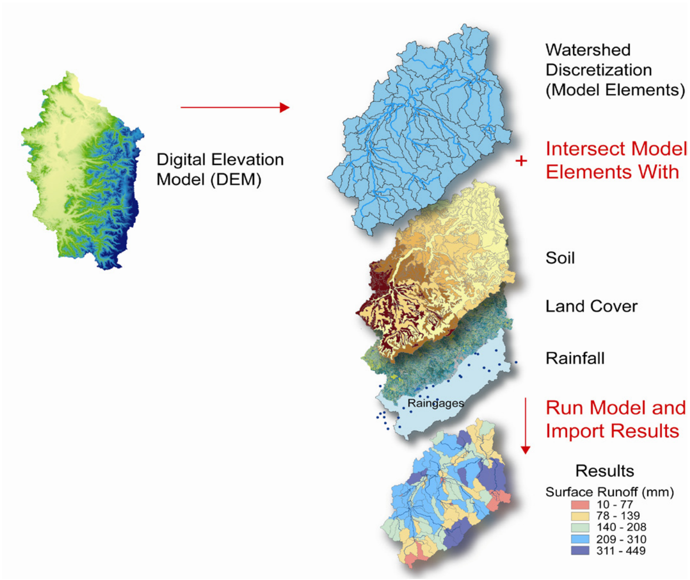
Figure 1. Location of the study areas.

Table 1. Alternative-future scenarios in the Willamette River (OR) and the San Pedro River (U.S./Mexico) basins.

Scenario	Description
Conservation (Constrained)	Places greater priority on ecosystem protection and restoration, although still reflects a plausible balance between ecological, social, and economic considerations as defined by citizen stakeholders.
Plan Trend	Assumes existing comprehensive land-use plans are implemented as written, with few exceptions, and that recent trends continue.
Development (Open)	Assumes current land use policies are relaxed and a greater reliance on market-oriented approaches to land and water use.

Methods

A key feature of AGWA is that it uses commonly available GIS data layers to fully parameterize, execute, and spatially visualize results from both SWAT and KINEROS2 (Figure 2). Through an intuitive interface, users select a watershed outlet from which AGWA delineates and discretizes the watershed using a digital elevation model. The watershed model elements are then intersected with soils and land cover data layers to derive the requisite model input parameters. AGWA can currently use both national (e.g., STATSGO) and international (e.g., FAO) soils data and available land cover/use data such as the National Land Cover Data datasets (Homer et al. 2004). Users are also provided the functionality to easily customize AGWA for use with any classified land cover/use data. The chosen hydrologic model is then executed and the results are imported back into AGWA for visual display. This process allows decision-makers to identify potential problem areas where additional monitoring can be undertaken or mitigation activities can be focused. AGWA can differentiate results from multiple simulations to compare changes predicted for each alternative input scenario (e.g., climate/storm change, land cover change, present conditions, and alternative futures). In addition, a variety of new capabilities have been incorporated into AGWA, including pre- and post-fire watershed assessment, watershed group simulations to cover all watersheds within a political or management boundary, implementation of stream buffer zones, and installation of retention and detention structures. There are currently two versions of AGWA available: AGWA 1.5 for users with Environmental Systems Research Institute (ESRI) ArcView 3.x GIS software (ESRI 2005), and AGWA 2.0 for users with ESRI ArcGIS 9.x (ESRI 2006). AGWA 2.0 utilizes new features in ArcGIS 9.x that are not available in ArcView 3.x to make the tool more powerful, flexible, and easier to use. Both versions have been retained to reach the widest available audience and are provided to users free of charge from both the EPA and USDA/ARS websites (http://www.epa.gov/esd/land-sci/agwa/index.htm and http://www.tucson.ars.ag.gov/agwa/).



KINEROS Outputs	SWAT Outputs
Channel Infiltration (m^3/km)	Precipitation (mm)
Plane Infiltration (mm)	ET (mm)
Runoff (mm or m^3)	Percolation (mm)
Sediment Yield (kg)	Surface Runoff (mm)
Peak Flow (m^3/s or mm/hr)	Transmission Losses (mm)
Channel Scour (mm)	Water Yield (mm)
Sediment Discharge (kg/s)	Sediment Yield (t/ha)
	Nitrate in Surface Runoff (kg N/ha)
	Phosphorous in Surface Runoff (kg P/ha)

Figure 2. AGWA Input/Output variables. SWAT example for surface runoff output in Willamette River Basin, OR.

Results

Results from all AGWA simulation runs for the Willamette River and San Pedro River are displayed in Figures 3 and 4, respectively. The figures show modeled percent change in annual surface runoff, channel discharge, sediment yield, and percolation for each of the three alternative futures, i.e. conservation (constrained), development (open), and plan trend (plans). The baseline year for the Willamette was 1990 and for the San Pedro the baseline year was 2000. The forecasts were provided 60 yrs (Willamette) and 20 yrs (San Pedro) out to the future. For the purpose of this work, negative impact was considered to be any measurable increase in surface runoff, streamflow discharge, and sediment yield and any decrease in percolation volume. In general, considerable spatial variability for simulated hydrological response was demonstrated in both study locations and for all three scenarios which were applied. However, the most significant changes were associated with increasing urbanization under the development scenario.

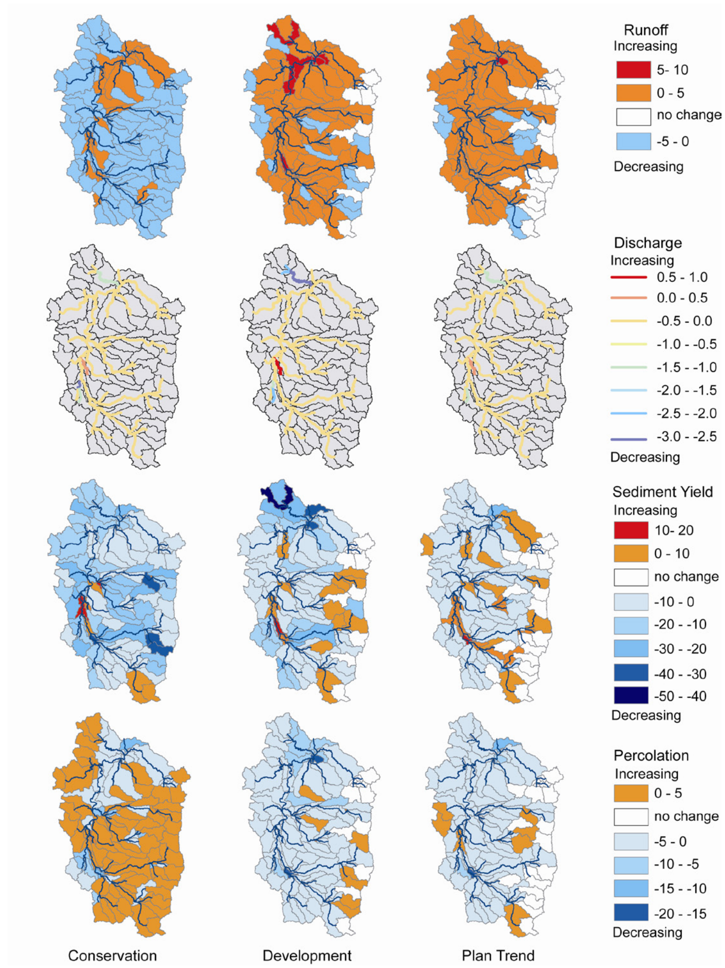


Figure 3. Maps showing modeled percent change in average annual surface runoff, channel discharge, sediment yield, and percolation for each of the three alternative future (2050) scenarios for the Willamette River Basin. Modified after Kepner et al. (2008).

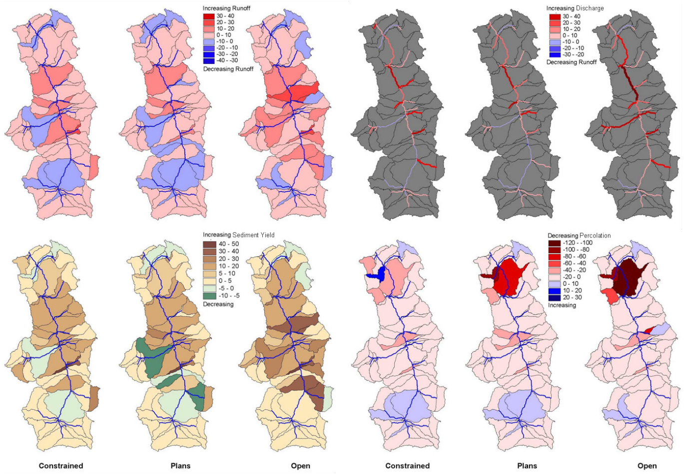


Figure 4. Maps showing modeled percent change in average annual surface runoff (upper left), channel discharge (upper right), sediment yield (lower left), and percolation (lower right) for each of the three alternative future (2020) scenarios for the San Pedro River basin. Modified after Kepner et al. (2004).

Simulation results for the alternative future scenarios indicate that land cover changes associated with potential future development can alter the hydrology of each basin. In addition to the comparative graphic display, results can be quantified and the changes statistically tabulated for comparison. In the example at hand, the purpose was to demonstrate a simple, reliable means for comparing and contrasting some basic options for future urban growth on two diverse watersheds in the western United States.

Conclusions

In general, the simulation results for the alternative future scenarios indicate that land cover changes associated with potential future development can alter the hydrology of each basin, and these changes were quantified and graphically displayed using subwatersheds as a comparative unit. The most significant hydrologic change was associated with urbanization and the associated replacement of vegetated surfaces with impervious ones. The studies demonstrate the ability of integrating digital land cover information (typically derived from satellite sensors) with hydrological process models in the AGWA tool to explore and evaluate options for a future environment. They can provide a scientific underpinning for analyzing one set of ecosystem services related to surface hydrology, and likely both the approach and technologies could apply to other services and locations. Although the findings in this study were not completely unexpected, the authors believe that spatial modeling and analysis tools, such as AGWA, provide one of the more powerful approaches to envisioning and evaluating plausible future scenarios and potential impacts to our ecosystem services.

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