CHAPTER 15

EVALUATING HYDROLOGICAL RESPONSE TO FORECASTED LAND-USE CHANGE

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ABSTRACT

It is currently possible to measure landscape change over large areas and determine trends in environmental condition using advanced space-based technologies accompanied by geospatial analyses of the remotely sensed data. There are numerous earth-observing satellite platforms for mapping and monitoring land cover and land-cover change; however, the traditional workhorses have been the Landsat Multi-Spectral Scanner (MSS) and Thematic Mapper (TM) sensors. Landsat has had a long history of commercial availability (first launch July 1972), a well developed global archive, and has been widely used for land-cover change detection and monitoring. 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 within hydrologic models to determine long-term change and make predictive inferences about the future. This article presents two studies in which future land-use scenarios were examined 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 twenty to sixty years into the future and the consequences of landscape change were evaluated relative to the selected future scenarios. A third study utilized historical land-cover data to validate the approach and explore the uncertainty associated with scenario analysis. These studies provide examples of integrating modeling with advanced Earth-observing technology to produce information on trends and make plausible forecasts for the future from which to understand the impact of landscape change on ecological services.

Key words: *landscape characterization, hydrological process models, alternative futures, scenario analysis, watershed assessment, ecosystem services, San Pedro River, Willamette River.*

INTRODUCTION

Inferring biophysical processes on the Earth's surface by measuring reflected electromagnetic spectra at the edge of the troposphere and organizing the information into meaningful representations that relate to vegetative composition, extent, and distribution seems like a difficult if not impossible task. Nevertheless, Earth-observing satellites and algorithm technology represent two of the most important scientific achievements of our time for observing and characterizing the Earth's surface in regard to natural phenomena, environmental hazards, and the direct effects of human-induced impacts on natural resources and the ecological goods and services they provide.

Over the last decades, numerous advances have been made in the development of remote sensors and geographic information systems (GIS) and their linkage with land-use change models to assess the influence of land cover on biophysical processes and conditions, e.g. land degradation, ecosystem vulnerability, watershed condition, and biodiversity (Guisan and Zimmermann 2000; Kepner et al. 2005; Petrosillo et al. 2008).

GIS is a widely accepted tool for ecosystem management and has provided an enhanced capability for research scientists to develop and apply land-use models because of the capacity to work with and organize large datasets in addition to the ability to integrate with most image analysis and processing systems. Today, remotely sensed data in the form of classified land cover are used to derive input variables for a wide variety of environmental models, e.g. hydrologic-response and habitat models (Scott et al. 1993; Edwards et al. 1996; Miller et al. 2007).

This is especially important because of the current attention provided to sustaining ecosystem goods and services and the changes in ecosystem state or condition that are perceived throughout the world (Millennium Ecosystem Assessment 2005b; Farber et al. 2006). Space-based sensor data provide multi-temporal and multi-spectral datasets that support monitoring ecosystem change and testing our understanding of key processes in land-use change, irrespective of their causal agents (Lunetta and Sturdevant 1993; National Science and Technology Council Committee on Environment and Natural Resources Research 1996; Homer et al. 2004). Additionally, it is possible to examine ecosystem state at a variety of scales and these data especially support working at regional, continental, and global scales and the contemporary interest in large-area processes.

The ability to assess, report, and forecast the life-support functions of ecosystems is absolutely critical to our capacity to make informed decisions that will maintain the sustainable nature of our ecosystem services and secure these resources into the future (Liu et al. 2008; SCEP 1970). This chapter explores the emerging field of scenario analysis that allows users to project alternative pathways into the future and test the sensitivity of selected variables to land-cover conversion and changes in land-use pattern. In the following case studies, the alternative future courses of action relate to two urbanizing watersheds and the assessment of the subsequent impacts of land-cover change on watershed response, i.e. surface runoff, erosion, channel discharge, and percolation.

SCENARIO ANALYSIS

Scenarios, as defined by the Intergovernmental Panel on Climate Change (IPCC 2001), 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." Thus 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 multi-disciplinary framework within which scenario characteristics may be analyzed (Turner et al. 1995; Clayton and Radcliffe 1996; Millenium Ecosystem Assessment 2005a). Scenarios are also usually conducted over long time periods (20-50 years) and develop a range of stakeholder-driven perspectives (scenarios), which are analyzed in detail for the consequences or benefits of their selection.

Scenario analysis is gaining widespread acceptance among decision-makers as a practical tool for addressing uncertainty about the future. The process provides the ability to explore the potential impacts, risks, benefits, and management opportunities that stem from a variety of plausible future conditions. The first step in this process, i.e., scenario definition, is a critical part of scientific and social decision-making with the purpose of creating a shared vision for both desirable and sustainable future outcomes. Scenario studies require experts and models from widely different disciplines and involve substantial interaction among scientists and stakeholders, as well as expert judgment. The information is combined in an iterative process of scenario definition, construction, analysis, assessment, translating model outputs to forms relevant to stakeholders, quantification and communication of scenario uncertainty, linking scenario outcomes to decision-making strategies or operational monitoring, and response, i.e. risk management (Liu et al. 2008). Scenario analysis, combined with landscape sciences, can be used to 1) test possible impacts, 2) assist strategic planning and policy information, and 3) structure current knowledge to scope the range of potential future conditions. In particular, it helps us address the key contemporary question of how ecological systems are affected by changes in land use and climate across a range of spatial and temporal scales.

This chapter summarizes the results from two studies that examined the impact of urban development relative to the sustainability of water resources, a crucial asset of the western U.S. Specifically, it examines extreme positions related to future urbanization in the Willamette River Basin (Oregon) and the San Pedro River (U.S./Mexico borderland of Arizona) 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. Results from a third study are also presented to provide a means of gauging the utility of hydrologic analysis of future scenarios by looking back at past land-use change.

HYDROLOGICAL PROCESS MODELING

Typically, scenario analysis uses a model-based approach to identify the key variables that reflect environmental change and to examine landscape change relative to specific issues or endpoints. This involves first modeling land-use change that is consistent with scenario definitions and then using it as input to hydrologic process models to examine hydrologic change. Generally models are selected with the idea of using available contemporary datasets such as digital land cover to construct the reference or baseline condition and the various alternative future options. It is the combined model output information for each scenario definition that is utilized for comparison of the options and represents the core of the actual scenario assessment (Liu et al. 2008).

In the two example case studies, the focus was directed at examining surface hydrological features associated with each watershed. Consequently, we chose to employ the Automated Geospatial Watershed Assessment (AGWA) tool, a GIS interface jointly developed by the U.S. Environmental Protection Agency, U.S. Department of Agriculture (USDA) Agricultural Research Service, and the University of Arizona to automate the parameterization and execution of the Soil Water Assessment Tool (SWAT) (Arnold and Fohrer 2005), and KINEmatic Runoff and EROSion (KINEROS2) (Smith et al. 1995; Semmens et al. 2007) hydrologic models (Miller et al. 2007). The application of these two models allows AGWA to conduct hydrologic modeling and watershed assessments at multiple temporal and spatial scales; for large river basins typically SWAT is employed. AGWA's current outputs are runoff (volumes and peaks) and sediment yield, plus nitrogen and phosphorus with the SWAT model.

AGWA uses commonly available GIS data layers to fully parameterize, execute, and spatially visualize results from both SWAT and KINEROS2. Through an intuitive interface the users select an outlet from which AGWA delineates and discretizes the watershed using a Digital Elevation Model (DEM) based on the individual model requirements. 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 STATSGO, SSURGO, and FAO soils and nationally available land-cover/use data such as the National Land Cover Data (NLCD) 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 visualization. This allows decision-makers to identify potential problem areas where additional monitoring can be undertaken or mitigation activities can be focused. AGWA can difference results from multiple simulations to examine and 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, implementation of stream buffer zones, and installation of retention and detention structures. A land-cover modification tool is provided for the development of prescribed land-cover change scenarios, with a number of options for uniform, spatially random, and patchy change to single or multiple land-cover classes. 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).

The required input data for AGWA include a DEM, polygon soil map, e.g. STATSGO, and classified digital land-cover/use grid. Landsat Thematic Mapper (TM) has routinely been used as the classified imagery source for these analyses. Landsat has a reasonably long acquisition history, covers a large aerial extent of the Earth's surface, and has a well developed data archive for easy access at nominal cost. Most importantly it is provided at a spatial resolution (30-meter pixel ground resolution) that is appropriate for many of the common biophysical process models, e.g. wildlife habitat and hydrological response, which are currently applied to establish current condition or to assess the impact of land-cover change.

CASE STUDIES

In this chapter, potential impacts from three wide-ranging scenarios are compared to current conditions in two different watersheds in the western U.S. in terms of a set of processes that are modeled in a GIS. Alternative futures landscape analysis involves 1) describing development patterns and significant human and natural processes that affect a particular geographic area of concern; 2) constructing GIS models to simulate these processes and patterns; 3) creating changes in the landscape by forecasting and by design; and 4) evaluating how the changes affect pattern and process using models (USEPA 2000). This study 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. The information is summarized from two separate studies (Kepner et al. 2004; Kepner et al. 2008) for the San Pedro and Willamette, respectively (Figure 1). The approach was largely similar for both locations. In the case of the San Pedro, the reference condition was the baseline year of 2000 that was established from a geospatial database developed specifically for the San Pedro (Kepner et al. 2003). In the case of the Willamette the reference condition was circa 1990 (Vogelmann et al. 2001). The land-cover/

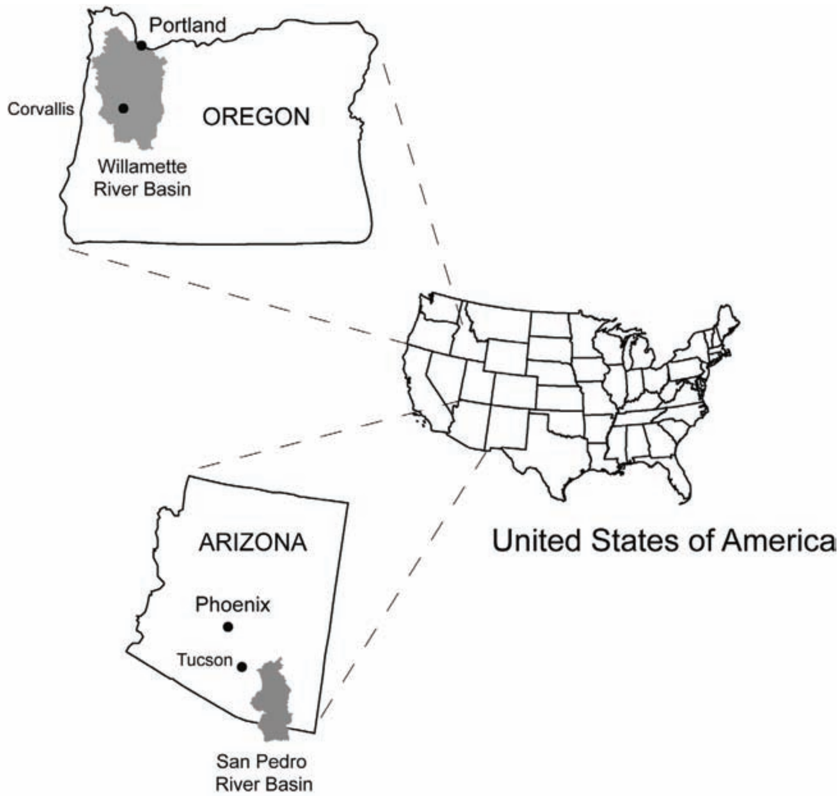

Figure 1. Location of the San Pedro and Willamette River Basins.

use scenarios were provided from separate studies (Steinitz 2003; Baker 2004) in which alternative courses of action were developed in consultation with local stakeholders for three basic options which reflected important contradictions in desired future policy based on stakeholder input. The scenarios are listed in Table 1 for both watersheds and reflect changes in population, patterns of growth, and development practices and constraints. The Conservation Scenario is characterized as the most ecosystem protection/restoration-oriented option, the Plan Trend Scenario reflects the most likely census predictions with zoning options designed to accommodate growth, and the Development Scenario is the least conservation and most market-economy positioned option. The future conditions for the San Pedro were projected to the year 2020 and to the year 2050 for the Willamette.

In both cases the AGWA tool was used to model each basin using SWAT and to evaluate the relative hydrologic consequences of anticipated future urban and suburban development. In the San Pedro case study (a preliminary demonstration of the method), SWAT was not calibrated to baseline conditions and the results were presented qualitatively. For the follow-on Willamette study SWAT was calibrated for base flow, surface runoff, and water yield. Results from the automated base flow separation program (Arnold et al., 1994) were used to identify the groundwater contribution to the total water yield. Both studies were designed to evaluate hydrologic conditions at distinct points in the future, which were represented as land-cover grids, and compare them to the present. Since future rainfall is unknown, 10-year observed, distributed baseline rainfall records were used in all simulations. By holding rainfall constant the analyses isolated the impacts of land-use change, but did not account for the sensitivity of those impacts to variable climatic conditions. Readers are referred to Kepner et al. (2004, 2008) for more details on the study areas and their respective approaches.

A third study (Semmens et al. 2006) utilized historic land-use/cover observations to validate the general scenario-assessment approach that was employed in the San Pedro and Willamette Basins. This retrospective analysis used repeat land-use/cover maps as proxies for future scenarios, with the earliest representing the baseline conditions. By working with known conditions it was possible to evaluate the effects of calibration on model performance and predicted hydrologic change. The ability to forecast land-use change associated with specific alternative future scenarios was not evaluated in this analysis. Instead, it endeavored to identify the strengths and weaknesses of utilizing hydrologic models to compare and contrast land-use/cover scenarios as was done in the San Pedro and Willamette Basins.

Scenario	Description
Conservation (Constrained)	Places greater priority on ecosystem protection and restoration, although still reflecting 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 recent trends continue.
Development (Open)	Assumes current land-use policies are relaxed and greater reliance on market-oriented approaches to land and water use.

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

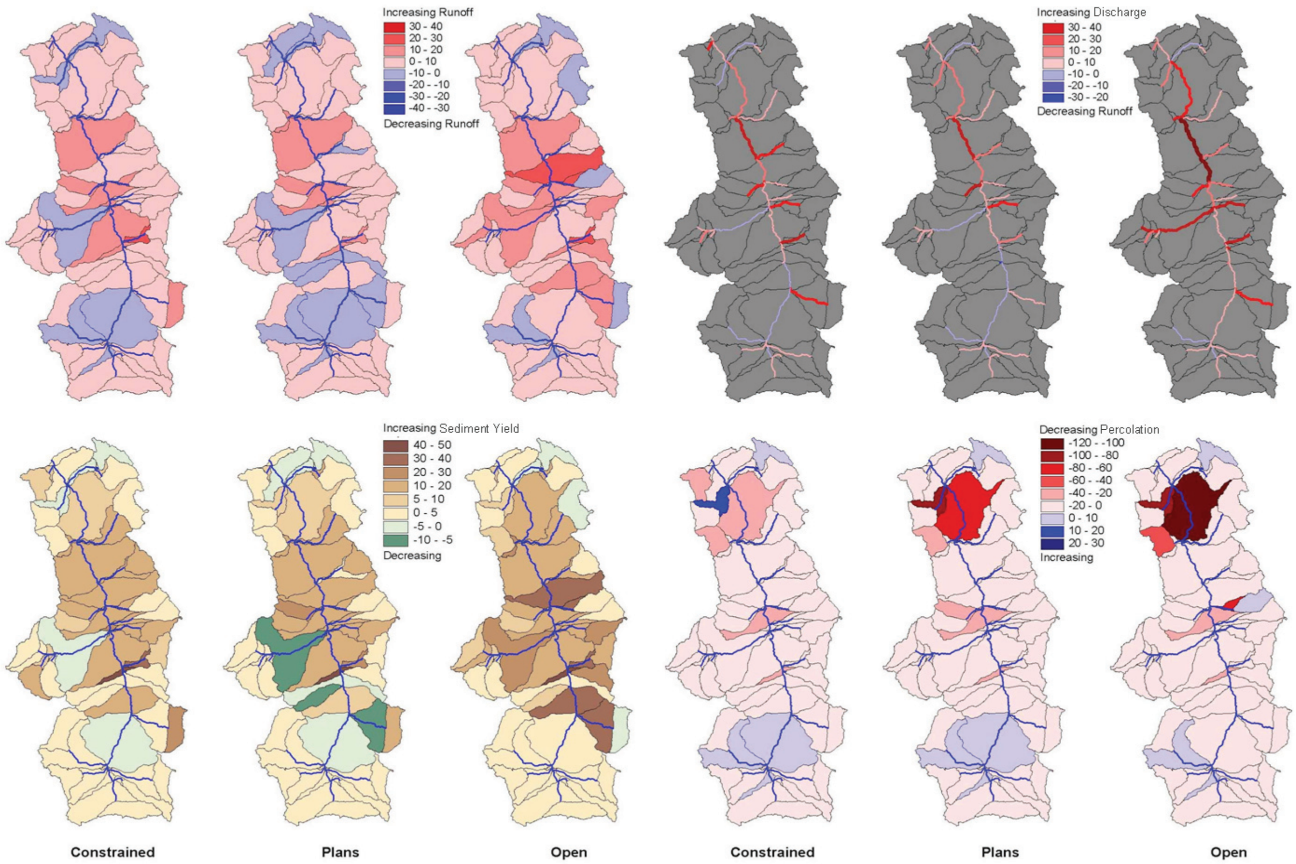

Figure 2. Maps showing modeled percent change in average annual surface runoff (upper left), channel discharge (upper right), sediment yield (lower left), and percolation (lower right) for each of the three alternative future (2020) scenarios for the San Pedro River Basin. Modified after Kepner et al. (2004).

SAN PEDRO CASE STUDY

The San Pedro River represents an area that has undergone remarkable land-cover change. This change has been quantified by satellite sensors (Kepner et al. 2000; Kepner, Edmonds, and Watts 2002) during the last quarter of the twentieth century. Surface runoff, channel discharge, percolation, and sediment yield were simulated using the SWAT model with AGWA for the three 2020 scenarios listed in Table 1. Results from the simulation runs are displayed in Figure 2. For the purpose of these studies, negative impacts are considered to be increases in surface runoff, streamflow discharge, sediment yield, and decline of percolation volume. 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 alter the hydrology of the watershed. Changes are primarily associated with increasing urbanization and the associated replacement of vegetated surfaces with impervious ones. The most notable changes are likely to be increases in the amount of runoff, channel scour, and sediment discharge, and a loss of surface-water access to the groundwater table in the northern reaches of the watershed near Benson, Arizona.

In addition to providing a means of looking to the future, land-use/cover observations in the form of classified satellite imagery have also provided a means of using past observations to retrospectively evaluate the validity of scenario-analysis methodologies and predictions. In the southern portion of the San Pedro, historic observations for a series of dates over a period of 24 years (1973, 1986, 1992, and 1997) were used to evaluate methods and quantify error associated with forecasting future hydrologic response from baseline conditions. In this example, 1973 was taken to be the baseline condition and subsequent dates were treated as future scenarios. Simulations were conducted with and without calibrating the model to baseline conditions, and utilizing both observed and historic (baseline) rainfall. Some of the results from this analysis are presented in Figures 3 and 4, which illustrate two important points. First, climate has a profound influence over the magnitude of predicted changes in water yield. Neither specific modeled values, nor the modeled change in those values should be used for quantitative estimation of future conditions when baseline rainfall is used (Figure 3). However, by holding rainfall constant in such an analysis it is possible to see just the impacts of land-use change, which is a useful means of comparing alternative land-use scenarios. Second, while calibration greatly improved quantitative predictions of water yield for any given scenario, it had no consistent impact on the predicted change in water yield relative to baseline conditions (Figure 4). If this observation holds true for other geographies and models it suggests that calibration may not be necessary for scenario assessment if model results are only to be used for scenario comparison. This would make simple better/worse model-based scenario assessment faster, less expensive, and possible even when observed hydrologic data are unavailable.

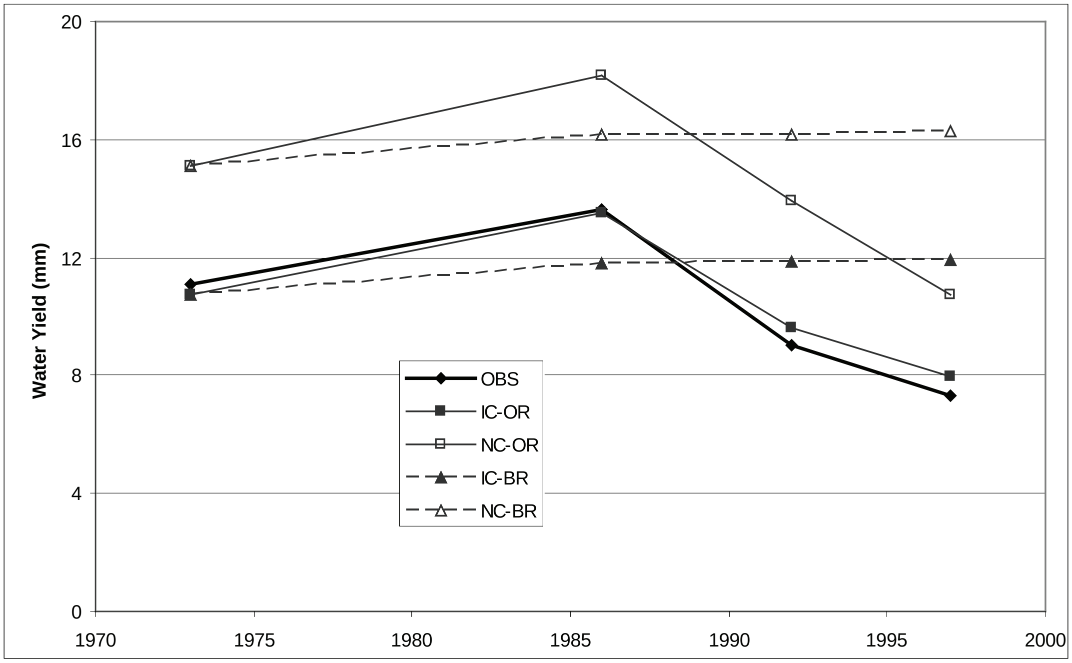

Figure 3. Graph showing modeled and observed (OBS) water yield for each simulation period. Initially calibrated (IC) simulation results are shown with solid symbols and uncalibrated (NC) results are shown with open symbols. Simulation results based on observed rainfall (OR) are shown with square symbols, and those based on baseline rainfall (BR) and shown with triangles.

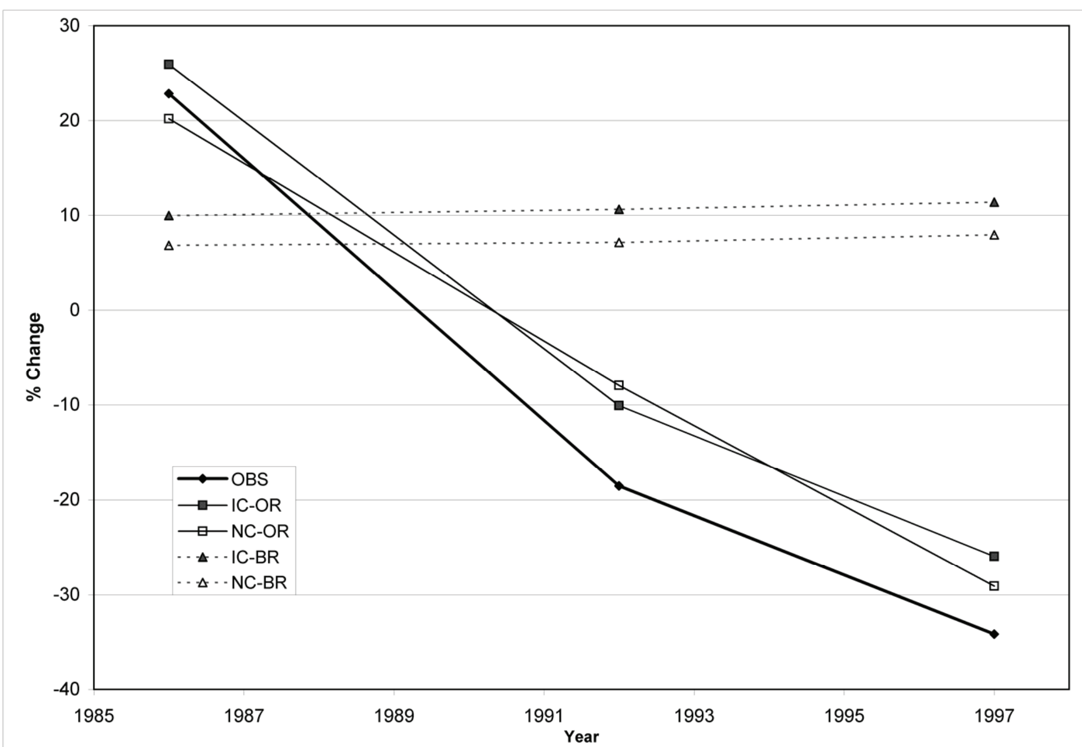

Figure 4. Graph showing modeled and observed (OBS) percent change in basin water yield relative to 1973 baseline land-use conditions for simulations that were initially calibrated (IC) to baseline conditions, and those that were not calibrated (NC). All simulations were repeated with both observed rainfall (OR) and baseline rainfall (BR) inputs.

WILLAMETTE CASE STUDY

The Willamette River demonstrated considerable spatial variability for simulated hydrologic response, similar in nature to the San Pedro, for the three scenarios. As might be expected, surface runoff simulations showed average increases commensurate with increases in urbanization. Although some watershed elements exhibited an increase in surface runoff, other areas showed improvement or decreasing runoff (Figure 4A). The greatest change was simulated for the Development 2050 scenario over the 1990 baseline. Simulated increases in surface runoff predominantly occur within subwatersheds distributed in the northern reaches of the watershed and along the Willamette Valley near Portland, Oregon City, and Eugene. Percent change in simulated channel discharge agreed closely with results from surface runoff. As in the previous example, patterns were variable, however channel discharge increased most under the Development scenario and appears to be concentrated in subwatersheds in the northern portion of the basin and along the Willamette Valley where most new development is anticipated (Figure 4B). Sediment-yield patterns were also quite variable across the subwatersheds; however sediment concentration was greatest under the Development and Plan Trend scenarios (Figure 4C). Lastly, simulated changes for percolation in the three future scenarios is expected to decrease in all options as urban impervious surfaces are expanded, especially under the Development 2050 scenario (Figure 4D).

SUMMARY AND CONCLUSIONS

The hydrologic responses resulting from three development scenarios for both the San Pedro and Willamette River Basins were evaluated using AGWA, a GIS tool developed to integrate landscape information with hydrological process models to assess watershed impacts. Baseline conditions were established for each watershed using map products derived from Landsat TM data. Through a stakeholder/scientist involvement process various plausible future scenarios were defined and constructed from which to evaluate anticipated impacts in a spatially explicit manner.

The environmental endpoints related to surface hydrology were selected because they represent fundamental ecosystem services that are important to maintaining sustainable societies in these geog-

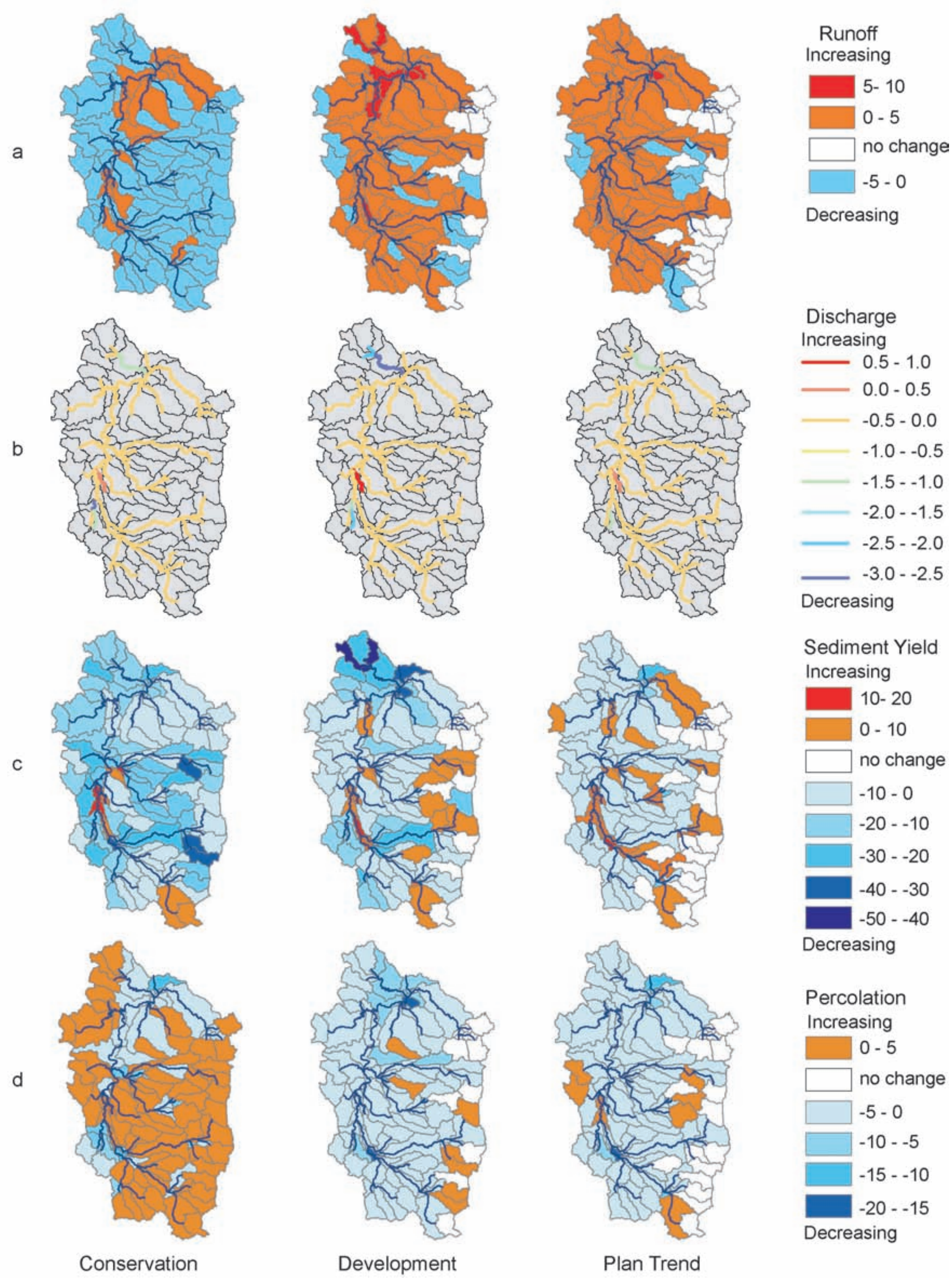

Figure 4. Maps showing modeled percent change in average annual surface runoff, channel discharge, sediment yield, and percolation for each of the three alternative future (2050) scenarios for the Willamette River Basin. Modified after Kepner et al. (2008).

raphies as well as throughout the world (Brauman et al. 2007). Available input datasets (e.g. digital land cover), stakeholder partnerships, and advances in GIS technology relative to representing important biophysical processes all contributed to the success of these projects.

In general, the simulation results for the alternative future scenarios indicate that land-cover changes associated with potential future development will alter the hydrology of each basin. The most significant hydrologic change was associated with urbanization and increasing coverage of impervious surfaces. Although the Development scenario had the greatest negative impact in both locations, it should be noted the results were spatially variable and that negative impacts are likely under all three of the future scenarios as a result of predicted urbanization. Comparative analyses are facilitated by summarizing simulation results graphically in terms of percent change relative to the baseline conditions for each of the scenarios, using subwatersheds as the comparative unit. Additionally, the changes can be quantified and statistically tabulated.

Remotely sensed observations of past land-use conditions were utilized to validate this approach to land-use scenario assessment. Although the magnitude of hydrologic change cannot be predicted with certainty at any point in the future, the results of this analysis suggest that rapid and inexpensive assessments, such as those presented for the San Pedro and Willamette Basins, represent a reliable means of comparing and contrasting a number of plausible future land-use scenarios.

These studies demonstrate the importance of integrating digital land-cover information typically derived from satellite sensors with hydrological process models within an alternative-futures framework to explore and evaluate our options for the future. They provide a scientific underpinning for analyzing one set of endpoints related to surface hydrology, and undoubtedly the approach and technologies may apply to others. This combination of tools provides one of the most powerful approaches to quantify and forecast the relative impacts to ecosystem services, and thus improve our collective decision-making for the future (Millenium Ecosystem Assessment 2005a). The approach is transferable to other landscapes, watersheds, and geographies throughout the world providing the datasets are available and the interest in examining the potential for future environments exists.

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