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INTEGRATING LANDSCAPE ASSESSMENT AND HYDROLOGIC MODELING FOR LAND COVER CHANGE ANALYSIS[1]

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ABSTRACT: Significant land cover changes have occurred in the watersheds that contribute runoff to the upper San Pedro River in Sonora, Mexico, and southeast Arizona. These changes, observed using a series of remotely sensed images taken in the 1970s, 1980s, and 1990s, have been implicated in the alteration of the basin hydrologic response. The Cannonsville subwatershed, located in the Catskill/Delaware watershed complex that delivers water to New York City, provides a contrast in land cover change. In this region, the Cannonsville watershed condition has improved over a comparable time period. A landscape assessment tool using a geographic information system (GIS) has been developed that automates the parameterization of the Soil and Water Assessment Tool (SWAT) and KINEmatic Runoff and EROSion (KINEROS) hydrologic models. The Automated Geospatial Watershed Assessment (AGWA) tool was used to prepare parameter input files for the Upper San Pedro Basin, a subwatershed within the San Pedro undergoing significant changes, and the Cannonsville watershed using historical land cover data. Runoff and sediment yield were simulated using these models. In the Cannonsville watershed, land cover change had a beneficial impact on modeled watershed response due to the transition from agriculture to forest land cover. Simulation results for the San Pedro indicate that increasing urban and agricultural areas and the simultaneous invasion of woody plants and decline of grasslands resulted in increased annual and event runoff volumes, flashier flood response, and decreased water quality due to sediment loading. These results demonstrate the usefulness of integrating remote sensing and distributed hydrologic models through the use of GIS for assessing watershed condition and the relative impacts of land cover transitions on hydrologic response.
(KEY TERMS: GIS; remote sensing; AGWA; landscape characterization.)

INTRODUCTION

Hydrologic response is an integrated indicator of watershed condition, and changes in land cover may affect the overall health and function of a watershed. Such changes vary spatially and occur at different rates through time. In this study, hydrologic change was assessed both spatially, using distributed hydrologic models, and temporally, using satellite imagery acquired over 25 years. The objective of this paper is to evaluate the effects of historic land cover change on watershed response by applying the Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998) on the San Pedro River Basin and on one of the Catskill/Delaware basins in upstate New York, and the KINEmatic Runoff and EROSion model (KINEROS) (Smith *et al.*, 1995) on a small contributing watershed in the San Pedro Basin. A landscape assessment of the spatial distribution of land cover changes was performed using classified satellite imagery. Simulated watershed response in the form of runoff volume, peak runoff rate, and total sediment yield were used as indicators of watershed condition. Using this approach, trends and direction of land cover change over time can be used to predict trends and direction of watershed hydrologic response.

Direct and powerful linkages exist among spatially distributed watershed properties and watershed processes. Stream water quality changes, especially due

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to erosion and sediment discharge, have been directly linked to land uses within a watershed. For example, erosion susceptibility increases when agriculture is practiced on relatively steep slopes (Wischmeier and Smith, 1978), while severe alterations in vegetation cover can produce up to 90 percent more runoff than in watersheds unaltered by human practices (Franklin, 1992). The principal degradation processes that have occurred in these Western rangelands involve changes of vegetative cover; i.e., decrease in above ground biomass and compositional diversity (primarily manifested by the introduction of exotic annual species or native woody xerophytic shrubs and trees) and the acceleration of water and wind erosion processes. Historically, these have been linked to both human-induced and natural stressors such as livestock grazing, short-term drought, timber harvesting, and fire suppression (Grover and Musick, 1990; Novotny and Olem, 1994; Swetnam and Betancourt, 1998). Additionally, fertilizers, pesticides, and other pollutants can be readily transported into streams that flow through or very close to agricultural or urban land more easily than into streams that flow through well vegetated areas.

In general, the three primary watershed properties governing hydrologic variability in the form of rainfall runoff response and erosion are soils, land cover, and topography. While topographic characteristics can be modified on a small scale (for example, by implementing, terracing, or contour tillage), variation in watershed-scale hydrologic response through time is primarily due to changes in the type and distribution of land cover. Improved understanding of the relationships among land use, habitat change, runoff, and water quality at the landscape scale can be used to compare watersheds, identify those that are at risk or susceptible to change, and aid in management attempts to limit undesired impacts. Watershed processes are highly variable in both time and space (Bloschl and Sivapalan, 1995), and spatially explicit hydrologic models can serve as useful tools in the investigation of such relationships. Studies increasingly have used GIS to prepare spatial data for input to hydrologic models (deVantier and Feldman, 1993; Wilkinson, 1996; Bhaduri *et al.*, 2000; Pullar and Springer, 2000). In this study, two hydrologic models that operate at different scales were used in conjunction with multi-date classified remote sensing imagery to investigate the hydrologic impacts of decadal-scale land cover change.

Two distinctly different study areas were selected for inclusion in this study: the Upper San Pedro Basin, in southeastern Arizona and northeastern Sonora, Mexico, and the Catskill/Delaware watershed region in southeastern New York. Remotely sensed imagery was acquired over the two study areas covering the past 25 years. These images were classified into land cover, and the results indicate that the San Pedro and Catskill/Delaware watersheds offer a study in contrasts with respect to their hydrology. Since the mid-1970s (our earliest imagery) the San Pedro Basin has undergone significant transformations in its land cover. Transitions in the native vegetation assemblages have occurred, along with an increase in the amounts of urban and agricultural area. These transitions theoretically have affected the hydrologic regime within the basin, as the vegetation changes have altered the rainfall-runoff response and ground water pumping has increased. The Catskill/Delaware region, on the other hand, has remained relatively stable, with some transition from agriculture to forest cover. This stability bodes well for the New York metropolitan area, which relies on a series of reservoirs in this region for most of its drinking water.

Modeling and estimation of the trends and direction of hydrologic watershed response due to land cover change are predicated on three assumptions: (1) that the chosen hydrologic model is sensitive to changes in the landscape; (2) that the input data are adequate and accurate and that observed changes are not artificial; and (3) that the model is responding to changes in cover correctly. The models chosen in this study have been extensively validated for runoff in semi-arid areas in the United States (Arnold *et al.*, 1999; Smith *et al.*, 1995). Accuracy assessments of the classified remote sensing imagery indicated that the land cover data were of a sufficiently high quality for this study.

The major shortcoming of rainfall-runoff modeling, particularly in ungauged basins, is the lack of both long-term rainfall observations with sufficient spatial coverage and corresponding runoff observations that would allow for adequate model calibration and validation. For the models employed in this study, sensitivity analyses and hydrologic model calibration and validation have been successfully carried out on well instrumented watersheds (Hernandez *et al.*, 2000; Syed, 1999; Goodrich, 1990). These studies lend confidence that the trends and direction in hydrologic response can be correctly inferred from the corresponding trends and direction in land cover change, predicated upon the use of comparable rainfall data in conjunction with differing land cover.

DESCRIPTIONS OF THE STUDY AREAS

Upper San Pedro Basin to the Charleston Gauge

The San Pedro River flows north from Sonora, Mexico into southeastern Arizona (Figure 1). With a wide variety of topographic, hydrologic, cultural, and political characteristics, the basin is an exceptional example of desert biodiversity in the semi-arid Southwest and a unique study area for addressing a range of scientific and management issues. It is also a region in socioeconomic transition, as the previously dominant rural ranching economy is shifting to irrigated agriculture and urban development. The area is a transition zone between the Chihuahuan and Sonoran deserts and has a highly variable climate with significant biodiversity. The tested watershed is approximately 3,150 km^2 and is dominated by desert shrub-steppe, riparian, grasslands, agriculture, oak and mesquite woodlands, and at higher elevations, pine forests. The basin supports among the highest number of mammal species in the world and the riparian corridor provides nesting and migration habitat for more than 400 bird species.

An examination of the spatial distribution of land cover change and its impact on hydrology through the Curve Number is presented in Figure 1. The Automated Geospatial Watershed Assessment tool (AGWA) (Miller *et al.*, 2002) was used to derive the change in Curve Number between 1973 and 1997 as a function of land cover transitions. The entire basin contributing runoff to the USGS gauging station at Charleston was subdivided into subwatersheds, and area-weighted Curve Numbers are presented to illustrate the spatial variability of change within the basin. This analysis shows that a small watershed running through the developing city of Sierra Vista, noted in Figure 1 as "Sierra Vista Subwatershed," underwent changes in its land cover that profoundly affected the hydrologic regime. This area was investigated using the distributed rainfall event model KINEROS. This subwatershed was chosen for its size (92 km^2) and degree of land cover change. KINEROS is an effective tool for predicting the runoff from relatively small watersheds, but recent research in semi-arid regions indicate that, due to decreasing runoff ratios with increasing watershed area, accurate results become difficult to obtain on large watersheds for all but very large flood events (Syed, 1999). The size of the subwatershed is large enough to illustrate the impacts of changing land cover at the regional management scale, yet small enough to be within the effective range of KINEROS for semi-arid regions. This is a challenge for any rainfall-runoff model as the signal (runoff) to noise (uncertainty in rainfall) ratio becomes small.

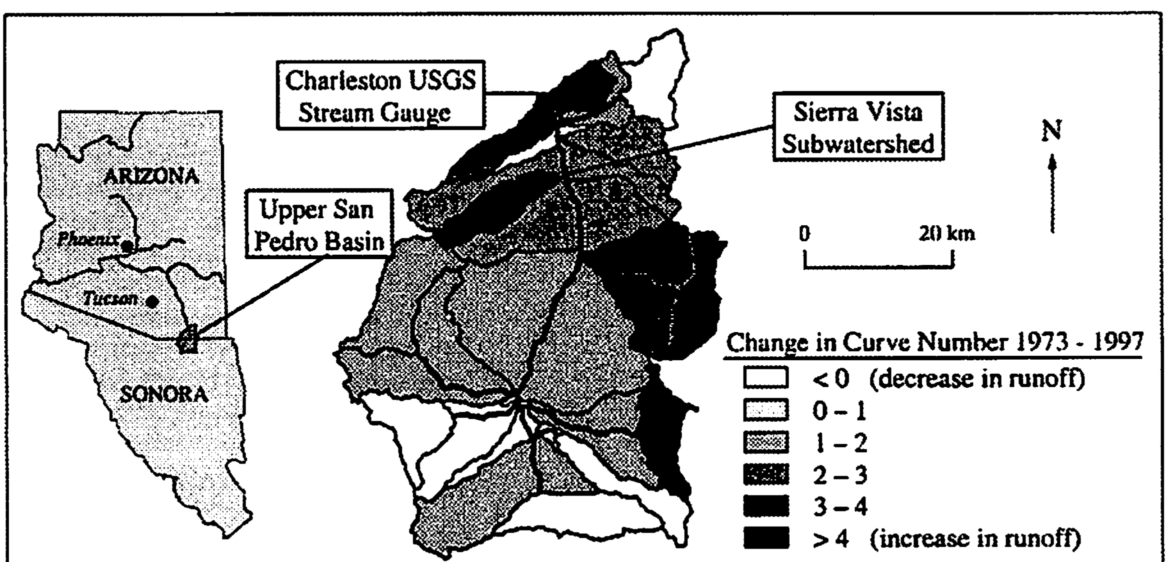

Figure 1. Locations of the Two Study Areas Within the Upper San Pedro River Basin. The larger basin (3,160 km^2) was modeled using SWAT and drains to the Charleston USGS runoff gauging station. This basin encompasses the smaller watershed (92 km^2), labeled here as "Sierra Vista subwatershed," that was modeled using KINEROS. The spatial variability of the change in Curve Number from 1973 to 1992 as predicted using AGWA is shown in the San Pedro Basin to illustrate why the Sierra Vista Subwatershed was chosen for intensive study.

Cannonsville Watershed

The Catskills area of southeastern New York State supplies more than 90 percent of the 1.4 billion gallons of drinking water consumed in New York City annually (Mehaffey *et al.*, 1999). Water quality and quantity are a major concern to city and state managers and planners. In this study, a subbasin of the Catskills area called the Cannonsville watershed was chosen for intensive investigation. The watershed (Figure 2) is approximately 1,200 km^2 in size, draining an area dominated by forests and agriculture; water not routed to New York City eventually contributes to the Delaware River. Mehaffey *et al.* (1999) summarized the characteristics of this region and identified it as a critical research site due to the potential impacts on New York of a transition in land cover from human pressures.

Hydrologically, the Catskills study area differs significantly from the semi-arid San Pedro region. In a humid climate with strong seasonal variability, the Catskills are characterized by higher precipitation volumes but lower rainfall intensities, higher storage, higher annual runoff with less flashy events, and a significant portion of the annual runoff derived from snowmelt. Contributions are made to runoff from ground water within stream and river channels. Classified as semi-arid, the San Pedro study area is characterized by larger relative extremes in components of the hydrologic cycle than the Catskill/Delaware study area. Specifically, semi-arid zones are typified by lower annual precipitation, but much of the annual rainfall occurs in highly localized, intense rainfall events with high potential for runoff and erosion. Since the stream channels are predominantly ephemeral in the San Pedro Basin, transmission losses occur during runoff events. Due to the aridity of the region, it has a higher potential evaporation rate, lower annual runoff but flashier runoff events, and relatively sparse vegetation. This relative lack of vegetation makes this region prone to erosion. Hydrologic models applied in semi-arid areas must adequately account for these factors if they are to be useful in investigating hydrologic response as a function of land cover change.

METHODS

The general approach used in this study was to acquire suitable geospatial information relating to land cover, topography, and soils for the two study areas, assess the overall land cover trends of the past quarter-century, and analyze the consequent impacts on simulated runoff. An ArcView (ESRI, 1998a) GIS software package called Automated Geospatial Watershed Assessment (AGWA) was created to aid in creating the complex input files required by these models. Figure 3 is a schematic detailing of some of the relevant interrelationships among land cover and hydrologic variables treated by AGWA. AGWA was developed during the course of this research to automate the transformation of GIS data into SWAT and KINEROS parameter input files.

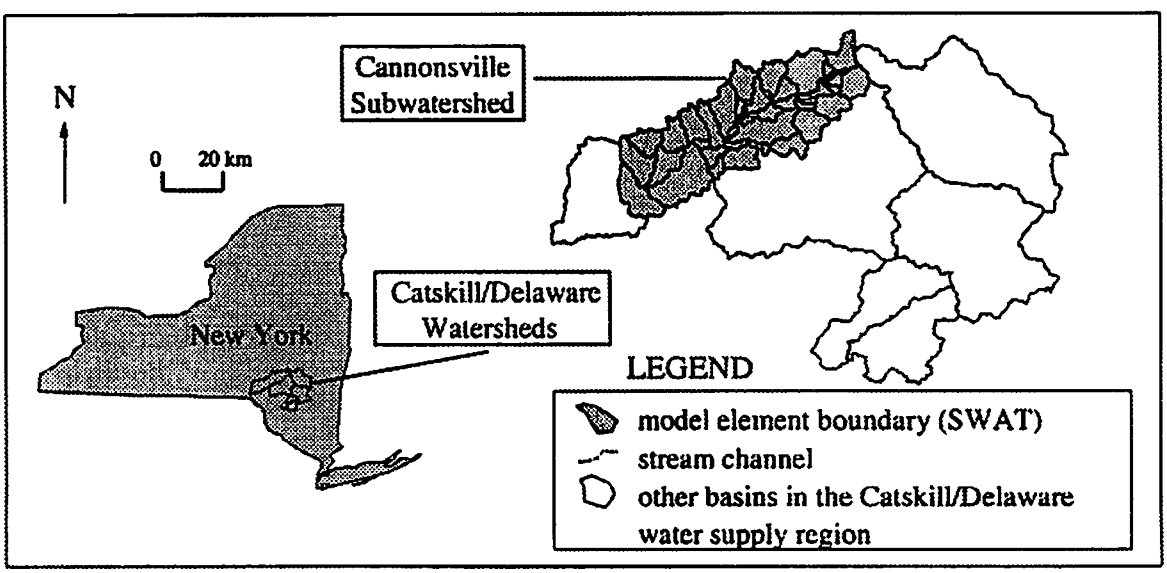

Figure 2. Location of the Cannonsville Study Area (1200 km^2) Within the Catskill/Delaware Watersheds Used to Supply Water to the City of New York. Upland and channel elements are shown as they were used in the SWAT runs.

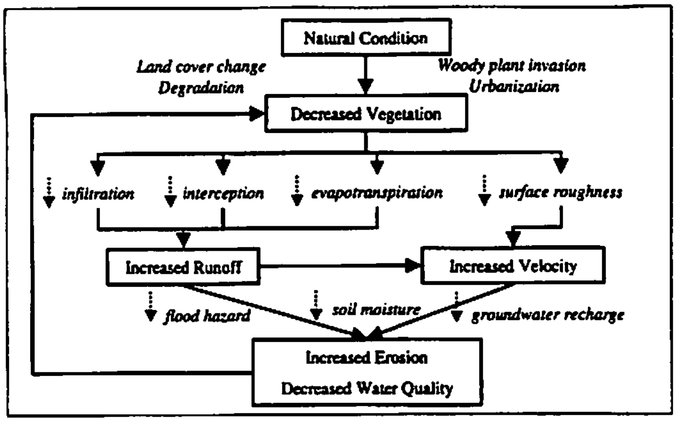

Figure 3. Schematic Illustrating the Role of Land Cover Change in Altering the Hydrologic Response of a Watershed With Particular Attention to Runoff and Erosion. Dashed arrows indicate the direction of change of the parameter, flux, or state variable.

The rapid and repeatable subdivision of a watershed into hydrologic response units is performed by AGWA, thereby sparing the user from the task of preparing input files by hand and allowing for a more far-reaching investigation into the impacts of land cover change. Input parameters required by SWAT and KINEROS are estimated by AGWA as a function of the topographic, soil, and cover characteristics of the individual watershed response units. Look-up tables relating soil and land cover associations to relevant hydrologic parameters (e.g., Curve Number, saturated hydraulic conductivity, surface roughness) were defined through literature review and calibration exercises. Hernandez *et al.* (2000) describe the derivation of input parameters for KINEROS and SWAT used in this approach. In their paper, the feasibility of modeling hydrologic response to changing land cover was demonstrated on a small watershed within the San Pedro Basin by applying land cover transformation scenarios and examining the simulated results. Hernandez *et al.* (2000) carried out a sensitivity analysis to determine the parameters most critical for accurate hydrologic modeling using KINEROS and SWAT. As an extension of their research, in the present paper, larger basins with greater variability and distinct hydrologic characteristics are investigated using historical data. Historical rainfall records were used to provide input to the SWAT model and define return period rainfall events for the KINEROS model.

Landscape Change Analyses

Land use/cover information is of critical importance in hydrologic modeling, as it helps determine model variables that account for the volume, timing, and quality of runoff. The amount of expected runoff from vegetated land use types is influenced not only by the surface and soil physical properties but also by the uptake capacity of the flora present. Remote imagery for the San Pedro Basin was derived from the Landsat MSS (1973, 1986, and 1992) and TM (1997) earth observing satellite sensors. These images are georectified and have been corrected for elevation using a DEM. Images included in this effort had less than 30 percent cloud cover and have been atmospherically corrected (Lunetta *et al.*, 1998). All images were captured in early June of the recorded year to reduce the influence of annual plant phenology changes. The MSS imagery has been remapped and projected to Universal Transverse Mercator ground coordinates, commensurate with other GIS data, at 60-meter resolution; the 30-meter TM has been resampled and mapped at 60-meter resolution for comparison. Derivative products (digital land cover maps) were developed for the image sets using ERDAS IMAGINE 8.3 (ERDAS, 1998) software and analyzed in a GIS system using ARC/INFO (ESRI, 1998b) software.

Image classification was first accomplished by unsupervised classification using the bands 1 (green), 2 (red), and 4 (near infrared) to produce a map with 60 classes. Each class was then displayed over the false-color image, and classes were assigned into a land cover category. Mixed classes were separated into different categories using other vegetation maps from a variety of sources and scales, including 1:250,000 scale maps from Mexico's National Institute of Statistics, Geography, and Information (INEGI), U.S. Department of the Interior GAP; topographic maps from INEGI at a 1:50,000 scale, 1:24,000 scale U.S. Geological Survey (USGS) data, and maps derived from field visits. The classified maps were revised with particular attention to boundaries by displaying the classes over the satellite image. The resulting digital land cover maps have 10 classes: forest, oak woodland, mesquite woodland, grassland, desertscrub, riparian, agriculture, urban, water, and barren. Proportions by land cover type for each time sequence are described in Table 1.

Detailed accuracy assessments of the 1992 and 1997 land cover maps for the San Pedro have been published previously (Maingi *et al.*, 1999; Skirvin *et al.*, 2000, respectively). Airborne videography was used to isolate a random sample of 527 points stratified by map class. Following Congalton (1991), an error matrix was assembled, and Cohen's Kappa and Kendall's Tau-b statistics were used to quantify the producer's, user's, and overall classification accuracies. These assessments show that the comparison between observed and classified land cover generally fall between 60 and 90 percent. These data may be

TABLE 1. Proportional Land Cover Extent as Total Hectares and Percent for the Upper San Pedro Watershed (1973, 1986, 1992, and 1997).

Land Cover	1973 Hectares	1973 Percent	1986 Hectares	1986 Percent	1992 Hectares	1992 Percent	1997 Hectares	1997 Percent
Forest	7,446	0.98	7,437	0.98	7,045	0.93	7,071	0.94
Oak Woodland	93,612	12.38	93,464	12.36	88,894	11.76	90,270	11.94
Mesquite	20,821	2.75	106,968	14.15	105,192	13.91	101,602	13.44
Grassland	312,850	41.37	267,321	35.35	265,231	35.08	263,432	34.84
Desertscrub	296,330	39.19	243,502	32.20	235,480	31.14	229,953	30.41
Riparian	8,665	1.15	8,852	1.17	8,889	1.18	9,218	1.22
Agriculture	8,775	1.16	11,507	1.52	14,859	1.97	14,530	1.92
Urban	3,205	0.42	10,002	1.32	12,574	1.66	16,494	2.18
Water	264	0.03	294	0.04	337	0.04	415	0.05
Barren	4,177	0.55	6,799	0.90	6,792	0.90	6,769	0.90
Clouds	0	0.00	0	0.00	10,850	1.44	16,388	2.17

TABLE 2. Proportional Land Cover Extent as Total Hectares and Percent for the Cannonsville Watershed (1975, 1985, 1991, and 1998).

Land Cover	1975 Hectares	1975 Percent	1985 Hectares	1985 Percent	1991 Hectares	1991 Percent	1998 Hectares	1998 Percent
Forest	87,030	75.31	86,634	75.00	90,613	78.51	92,097	79.75
Urban	559	0.48	697	0.60	715	0.62	731	0.63
Agriculture	27,651	23.93	27,823	24.09	23,772	20.60	22,275	19.29
Barren	320	0.28	352	0.30	314	0.27	384	0.33

characterized as having "good to excellent accuracy" (Skirvin *et al.*, 2000), with the heterogeneous class labeled "mesquite woodlands" having the lowest accuracy. Since the 1973 and 1986 maps were created using the same approach as the 1992 and 1997 data sets, it was assumed that they shared similar accuracy characteristics, and the quality of the data were high enough that classified changes in land cover were considered correct.

Landsat TM and MSS imagery were used to classify land cover within the Cannonsville subwatershed, which is shown to have been relatively stable throughout the period for which remotely sensed imagery was collected. MSS imagery was used to classify land cover in 1973, while TM data were used for three additional scenes for 1984, 1990, and 1998. These images were corrected for elevation and georectified. Images for the various years were taken within one month of each other to account for plant phenology. The selected images were relatively cloud- and haze-free. Unsupervised classification was used in conjunction with National High Altitude Aerial Photography (NHAAP) images to assign land cover classes to spectrally similar areas. Ancillary data such as population, elevation, and site surveys were used to improve the accuracy of the classification, and training sites of known land use were identified to improve the defined spectral characteristics of the various land cover classes. The final land cover maps are classified into four classes: forest, urban, agriculture, and barren. Proportions for each of the land cover type for each time sequence are detailed in Table 2.

An accuracy assessment of the Catskill region including the Cannonsville watershed was performed in which accuracy assessment points were chosen using a stratified random sample technique (Fitzpatrick-Lins, 1981; Skirvin *et al.*, 2000). Because the change in the area was very small, the area proportions for the early 1990s were used for all dates. Sample points were selected randomly within the correct cover type with one restriction. Aerial photographs and other available independent imagery were used as reference or "truth" to determine the accuracy of the Landsat classifications. To minimize error due to landscape change, the acquisition dates of the reference data were within two years of the acquisition of the Landsat data. Error matrices illustrating errors of omission and commission using the Cohen Kappa and Kendall's Tau-B tests were created to determine the producer's and user's accuracies errors (Congalton, 1991). Overall accuracy was quite high for all four dates, with results near 90 percent. The accuracies of the classification data were thus deemed appropriate for investigations of land cover change and hydrologic modeling at the scale of the Cannonsville watershed.

GIS Processing and Database Development

The AGWA tool uses GIS data layers of soil, topography, and land cover to derive watershed parameters in two ways. First, the primary data contained in these data sets were used as direct input to the hydrologic model for topographic and soil characterizations such as slope, area, and hydrologic soil group. Second, these primary data were used in conjunction with look-up tables constructed from a literature review to determine secondary watershed parameters not contained in the original data. Examples of these secondary variables include Curve Number (SWAT only), saturated hydraulic conductivity, channel dimensions, and surface roughness.

Topography plays an important role in the distribution and flux of water and energy within the natural landscape. Classic examples include surface runoff, evaporation, infiltration, and erosion (i.e., hydrologic processes that take place at the ground-atmosphere interface). The quantitative assessment of these processes depends on the topographic configuration of the landscape, which is one of several controlling boundary conditions. Landscape topography can be digitized into an array of elevation values called a Digital Elevation Model (DEM), which can be used to rapidly and reliably determine landscape features such as slope, aspect, flow length, contributing areas, drainage divides, and channel networks (Tarboton *et al.*, 1991; Garbrecht and Martz, 1995). Landscape features for the San Pedro River Basin were determined from a composite DEM formed from USGS 7.5-minute 30 m data for the U.S. portion of the basin and a 50 m DEM in Mexico resampled to 30 m to match the U.S. data. A 10 m DEM served as the basis for analysis in the Cannonsville watershed.

Soils data were used to characterize infiltration and soil storage capacity properties of the upper soil layers that interact with runoff processes. The State Soil Geographic (STATSGO) database served as the basis for soil-derived parameters. With a mapping scale of 1:250,000, STATSGO is relatively generalized and more suitable for river basin, state, and regional resource planning, management, and monitoring. It is recognized that STATSGO presents limitations in smaller-scale, physically based modeling due to its generalized nature; for the purposes of these investigations, however, STATSGO is adequate since the focus on hydrologic response was on land cover change.

The automated extraction of surface drainage, channel networks, drainage divides, and other hydrologic data for both watersheds from DEMs was carried out using AGWA. When using this tool, the user specifies the smallest allowable upland area, and the watershed is automatically subdivided into upland and channel model elements. This tool also determines the hydrologic parameters required by KINEROS and SWAT for each of the model elements. As a demonstration of this approach, Figure 2 shows the resultant watershed configuration for the Cannonsville watershed as prepared for SWAT.

Hydrologic Simulations

The SWAT model is used primarily as a strategic planning tool (Arnold *et al.*, 1998). The model operates on a daily time step, allows a basin to be subdivided into natural subwatersheds, and is characterized by its focus on land management, water quality loadings, and continuous simulation over long time spans. Rainfall excess is determined by SWAT primarily through a modified Curve Number approach on each subwatershed. The rainfall excess is then partitioned into hydrologic processes such as evapotranspiration, infiltration, return flow, channel routing, transmission losses, and soil moisture. An attempt was made to simulate the major hydrologic components and their interactions as simply yet realistically as possible with readily available input data over large areas so the model can be used in routine planning and decision making. As reported by Arnold *et al.* (1999), SWAT has been extensively used and validated for runoff.

A calibration exercise was undertaken for SWAT modeling runoff to the Charleston USGS gauging station that served as the outlet for subsequent SWAT model runs. A sensitivity analysis was used to determine the appropriate model parameters that could best improve the model performance. In this calibration exercise, the model was run for a 14-year period of record, and the model was optimized on total annual water yield at the watershed outlets. Minimizing the objective function through systematic variation of the SWAT input variables yielded a Nash-Sutcliffe efficiency coefficient of 0.44 in the Upper San Pedro. When the calculated long-term average annual runoff values are compared with model results, however, model performance is within 10 percent error. Nine rainfall gauges were available to provide input to SWAT for the calibration exercise. Given that Osborn *et al.* (1980) found that gauges separated by more than approximately four kilometers are effectively independent in the semi-arid Southwest, this number appears insufficient for highly detailed and accurate modeling and serves as a limitation on the effective determination of input parameters to SWAT.

KINEROS has evolved over a number of years primarily as a research tool (Smith *et al.*, 1995). KINEROS is an event-oriented, physically based model describing the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds. The watershed is represented by a cascade of overland flow and channel model elements, and the partial differential equations describing overland flow, channel flow and erosion, and sediment transport are solved by finite difference techniques. Runoff is generated as infiltration-excess overland flow, and water is dynamically routed using the kinematic equations during the runoff event. Spatial variability of rainfall and infiltration, runoff, and erosion parameters can be accommodated.

Calibration of KINEROS on the Sierra Vista subwatershed was not possible due to the lack of a runoff gauging station. However, input parameters were estimated from prior research on the Walnut Gulch Experimental Watershed, which is near the study area and has approximately the same plant assemblage and rainfall characteristics. In these studies (Goodrich, 1990; Syed, 1999), KINEROS was calibrated to very high efficiencies depending on scale. Correlation coefficients in these calibration exercises ranged from 0.98 at the sub-hectare scale to 0.86 at the small watershed scale (60 km^2). While it is unfortunate that gauge data do not exist for the Sierra Vista watershed, the Walnut Gulch data serve as good proxies for parameter estimation.

Precipitation Data for Hydrologic Modeling

Confidence in the hydrologic modeling effort depends to a large extent on the availability of extensive high quality rainfall data. Traditionally, rainfall estimated from sparse rain gauge networks has been considered a weak link in watershed modeling. In this study the variability in rainfall through time serves as a confounding variable in the interpretation of the impacts of cover transition on hydrologic response, so it was necessary to apply the same rainfall data to each parameter set associated with the different land cover scenes. Problems associated with the nonstationarity of rainfall through time also are obviated in this process. Since rainfall is held constant for each model run, changes in model results are due solely to changes in input parameters affected by land cover change.

The SWAT model uses daily rainfall input data for a multi-year simulation. In our approach, multi-year rainfall for each of the study areas was extracted from long-term National Weather Service records and input to the SWAT model. These rainfall records represent periods in which a minimum of data were missing from the long-term records. For this effort, nine gauges that record rainfall in the San Pedro study area contain long-term historical data for input to SWAT. A 14-year period of record was extracted for this area. Likewise, six gauges were available for long-term data in the Cannonsville watershed; in this case, a complete 24-year period of record was extracted from the rainfall data.

Since KINEROS requires rainfall to be input on a per-event basis, design storms were created for the Sierra Vista subwatershed. These design storms were taken from Osborn *et al.* (1985), who used extensive long-term records on a separate but very similar watershed within the San Pedro Basin to derive 5-, 10-, and 100-year events for storms of both 30- and 60-minute duration. Since applying point estimates for design storms across larger areas tends toward overprediction of runoff due to the lack of spatial heterogeneity in input data, an area-reduction method developed by Osborn *et al.* (1980) was used to reduce rainfall estimates. The KINEROS model was run using this series of design rainfall events, with the same rainfall data applied over each land cover scenario. By using the same rainfall input files, simulated changes in peak runoff or volume were due solely to altered land cover within the watershed and *not to* differences in rainfall input.

RESULTS

Assessment of Landscape Change

As illustrated in Figure 4a, significant land cover change occurred within the San Pedro Basin between 1973 and 1997. A matrix illustrating the relative change within each cover class for the different scenes (1973, 1986, 1992, 1997) is presented as Table 3. The most significant changes were large increases in urbanized area, mesquite woodlands, and agricultural communities and commensurate decreases in grasslands and desertscrub. This overall shift indicates an increasing reliance on ground water (due to increased municipal water consumption and agriculture) and potential for localized large-scale runoff and erosion events (due to the decreased infiltration capacities and roughness associated with the land cover transition). Change within the study area was not steady

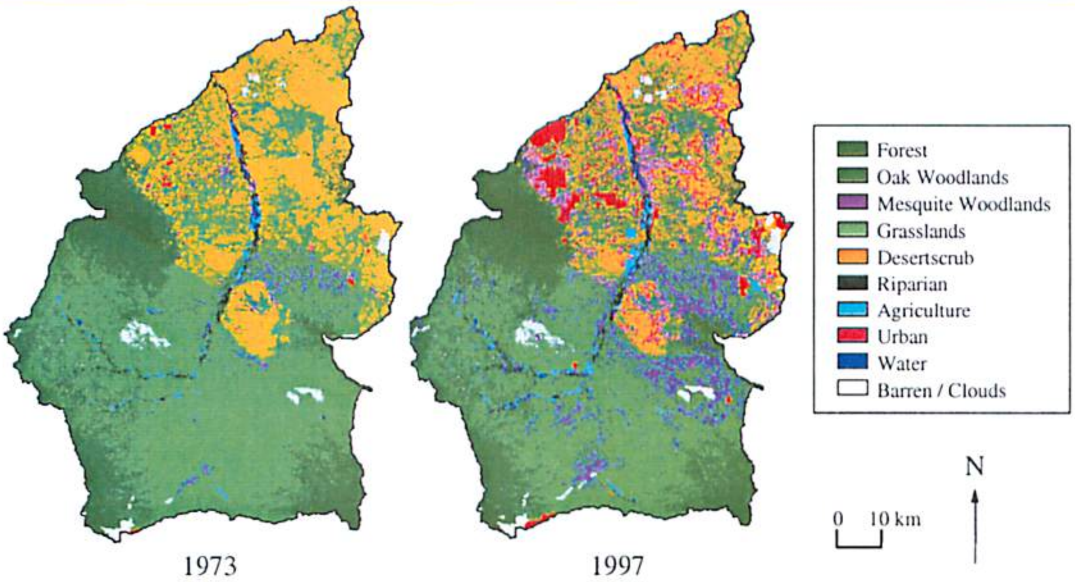

Figure 4a. Land cover change within the Upper San Pedro Basin

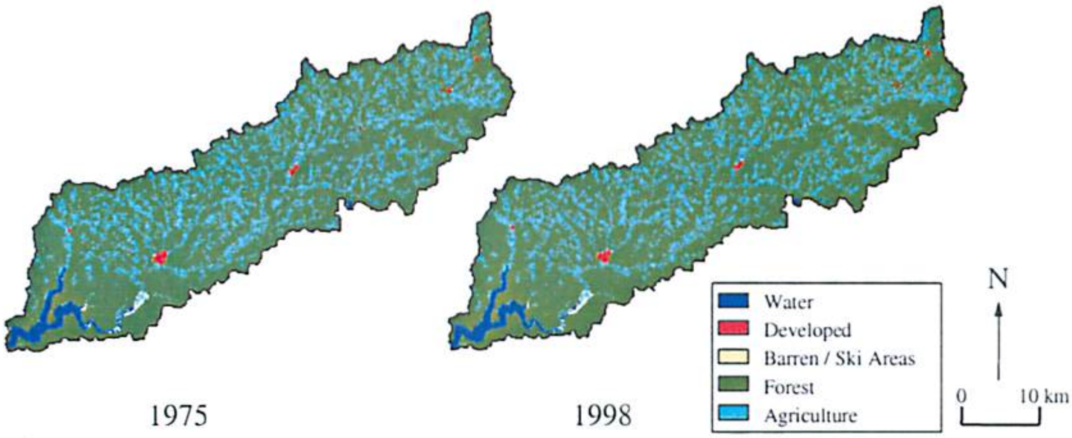

Figure 4b. Land cover change within the Cannonsville watershed

Figure 4. Land Cover Within the Study Areas as Classified From the End Members of their Respective Satellite Images. A contrast in the trends of land cover transition between the study areas is evident. Note increases in urban, mesquite, and agriculture and the commensurate decline in grassland and desertscrub communities in Figure 4a. A small increase in forested area and commensurate decline in agriculture can be seen in Figure 4b.

throughout the evaluation period. It can be seen that the percent changes in various land covers do not always increase or decrease between scenes, indicating that the trend toward urbanization and mesquite invasion occurred at different rates.

The Sierra Vista subwatershed experienced significant land cover change between 1973 and 1997 (Table 4), with the dominant transitions within this watershed being the declines in grasslands and desertscrub and increases in urban and mesquite woodlands.

Figure 4b illustrates the change in land cover over the study period within the Cannonsville watershed. The overall land cover has remained relatively static, with some slight increases in urban area, but with a larger overall trend of decreasing agriculture and increasing forest. Human pressures have remained minimal in this region over the past 30 years, as the population has increased by only 17 percent. The continued effluent from waste treatment plants, nonpoint agricultural sources, and urban runoff imply a potential for diminished water quality, especially with respect to fecal coliforms, nutrients, and sedimentation (Mehaffey *et al.,* 1999). Furthermore, the topography of the area often constrains human use to the

TABLE 3. Percent Relative Land Cover Change for the Upper San Pedro Watershed (1973 to 1986, 1986 to 1992, 1992 to 1997, and 1973 to 1997). A positive value in a difference column indicates an increase in area between dates.

Land Cover	1973 to 1986	1986 to 1992	1992 to 1997	1973 to 1997
Forest	-0.12	-5.27	0.37	-5.04
Oak Woodland	-0.16	-4.89	1.55	-3.57
Mesquite	413.75	-1.66	-3.41	387.98
Grassland	-14.55	-0.78	-0.68	-15.80
Desertscrub	-17.83	-3.29	-2.35	-22.40
Riparian	2.16	0.42	3.70	6.38
Agriculture	31.13	29.13	-2.21	65.58
Urban	212.07	25.71	31.18	414.63
Water	11.36	14.63	23.15	57.20
Barren	62.77	-0.10	-0.34	62.05

TABLE 4. Percent Relative Land Cover Change Within the Sierra Vista Subwatershed (1973 to 1986, 1986 to 1992, 1992 to 1997, and 1973 to 1997). A positive value in a difference column indicates an increase in area between dates.

Land Cover	1973 to 1986	1986 to 1992	1992 to 1997	1973 to 1997
Forest	0.00	0.00	0.00	0.00
Oak Woodland	-0.48	-1.17	-1.47	-3.09
Mesquite	306.25	-5.98	-12.67	233.57
Grassland	-34.65	0.00	-9.01	-40.54
Desertscrub	-36.67	-5.38	-7.09	-44.32
Urban	302.78	19.62	36.34	556.89

flatter riparian corridor, thereby increasing the risks to stream water quality.

Change has been fairly consistent throughout the past 23 years in the Cannonsville watershed, with the exception of a slight increase from agriculture to forest from 1985 to 1990. A total of 9.14 percent of the Cannonsville watershed area was converted from agriculture to forest between 1975 and 1998, and 4.7 percent changed from forest to agriculture, resulting in a net increase of forest cover by 4.44 percent (Table 5). Change within the riparian buffer zone has also occurred but to a lesser extent than for the watershed as a whole. There has been an 11.4 percent change from agriculture to forest and 7.6 percent from forest to agriculture, resulting in a net 3.8 percent gain in forest cover in the riparian zone. Although this is an improvement, it is still smaller than for the Cannonsville watershed as a whole, indicating that more agriculture-to-forest conversion is taking place away from the streams.

Hydrologic Modeling of the San Pedro Basin to Charleston Gauge

Runoff was simulated with the SWAT model from the San Pedro Basin using a 14-year continuous rainfall period with input data corresponding the four classified satellite scenes. In general, the total annual runoff volume increased as a function of land cover change within the basin (Figure 5). These results do not necessarily reflect observed changes in runoff volume for the time periods simulated in this study but are illustrative of the effects on hydrologic response of the transition the basin has undergone over the past quarter-century. Given that the 1973 scene serves as the base image from which landscape change is derived, annual runoff results are presented in Figure 5 as the percent change from the 1973 runoff results.

Simulated runoff results show an increase in annual runoff over time commensurate with increasing urbanization and woody plant invasion. Considerable spatial variability in the observed land cover change

TABLE 5. Percent Relative Land Cover Change for the Cannonsville Watershed (1973 to 1985, 1985 to 1991, 1991 to 1998, and 1975 to 1998). A positive value in a difference column indicates an increase in area between dates.

Land Cover	1975 to 1985	1985 to 1991	1991 to 1998	1975 to 1998
Forest	-0.31	3.51	1.24	4.44
Urban	0.12	0.02	0.01	0.15
Agriculture	0.16	-3.49	-1.31	-4.64
Barren	0.03	-0.03	0.06	0.06

(Figure 4a and Table 3) has implications for hydrologic modeling and assessment. As shown in Figure 1, along with the spatial variability in land cover change, there is a strong spatial component to changes in model input parameters.

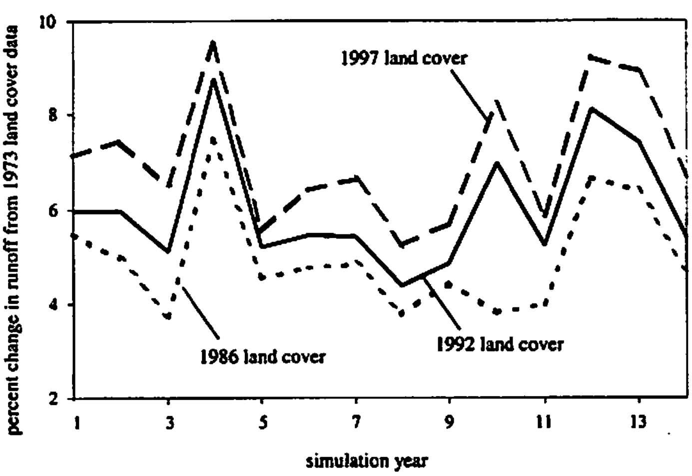

Figure 5. SWAT Simulation Results for the Upper San Pedro Basin. The graph shows the deviation in total annual runoff results from the 1973 land cover results. Note that annual runoff volumes are simulated to increase for each scene relative to the base data.

While increased runoff occurred in some of the subwatershed elements, other regions showed improvements in condition. These compensating changes cancel out changes in annual runoff volume at the watershed outlet. Internal variability and sensitivity to change is therefore much greater than is observed simply by looking at the watershed outlet. In this study, runoff simulation results from SWAT imply that several areas within the Upper San Pedro Basin were responding more than others to the land cover change. A high degree of spatial variability in runoff response was reflected in the simulation: several watershed elements showed a decline in simulated runoff, while the majority of elements indicated an increase in average annual runoff, including an overall increase at the watershed outlet (Figure 5).

Simulated annual runoff from the Sierra Vista subwatershed increased significantly, so the KINEROS model was used to investigate this area in more detail. In this approach, KINEROS is used to "zoom in" both temporally and spatially. SWAT (a daily, continuous lumped parameter model) is used to locate subwatersheds that are responding strongly to change over long time periods, while KINEROS (an event oriented, physically based model) provides more detail and analysis for return period rainfall events.

Hydrologic Modeling of the Sierra Vista Subwatershed

For this smaller subwatershed within the San Pedro Basin, KINEROS was used to simulate runoff and sediment yield for six design storms using watershed data from the classified satellite imagery, resulting in a suite of 24 simulation runs. Results for the simulation runs are given in Table 6, and Figure 6 shows hydrographs from the two endpoint design storms, the 5-year, 30-minute event and the 100-year, 60-minute event. Note the disparity in the hydrographs resulting from the smaller event and their similarities for the larger event. The differences in simulated results decrease with increasing storm size and duration. This trend toward convergence is due to the increasing importance of storm characteristics over watershed characteristics as storm size increases. For smaller storms, changes in the watershed, especially those due to land cover change, may radically alter the hydrologic response. However, the hydrologic response for very large storms is driven by the characteristics of the rainfall, and management may have little ameliorating or exacerbating effect.

As would be expected with design storms, runoff volume and peak runoff rates increased directly with the size of the modeled events. Since erosion and sediment yield are tied closely to the energy of a given runoff event, they are subsequently determined by runoff rates and therefore increase greatly with storm size and duration. In all cases, the hydrographs produced with the 1986, 1992, and 1997 classification data were significantly larger than those produced

TABLE 6. Runoff Simulation Results Using Design Rainfall Events and KINEROS for the Sierra Vista Subwatershed. Design storms are given as return period events (5-, 10-, and 100-year) and storm duration (30- and 60-minute).

Rainfall Event	Rainfall (mm)	Runoff (mm) 1973	1986	1992	1997	Percent Change 1973 to 1997
5 year, 30 minute	17.35	0.057	0.144	0.134	0.158	177.2
5 year, 60 minute	21.08	0.185	0.339	0.367	0.498	169.2
10 year, 30 minute	22.74	1.25	1.64	1.72	1.95	56.0
10 year, 60 minute	26.44	2.07	2.47	2.55	2.79	34.8
100 year, 30 minute	31.79	7.02	7.55	7.65	7.95	13.2
100 year, 60 minute	38.33	10.2	10.7	10.8	11.0	7.8

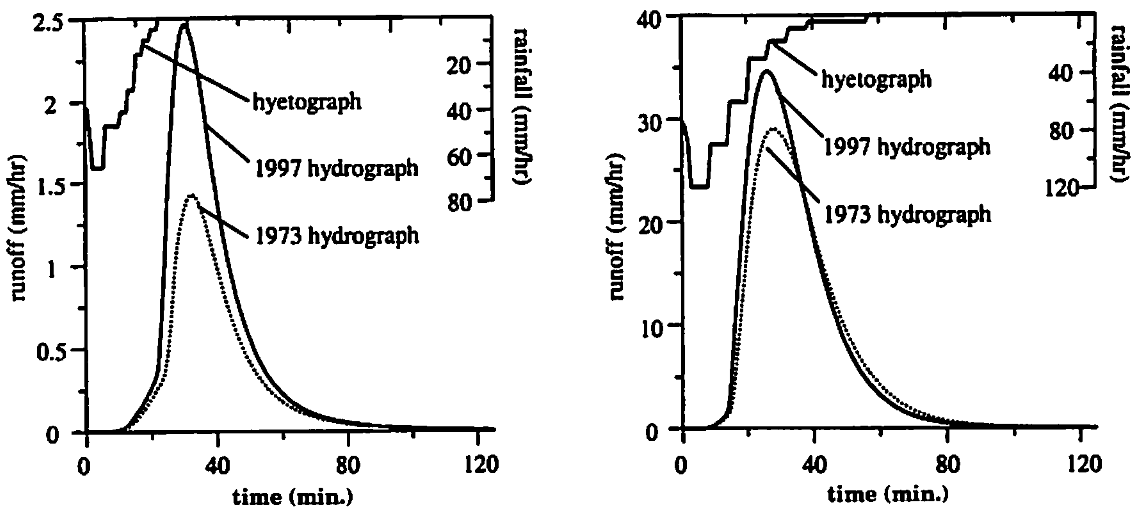

Figure 6. Runoff Hydrographs Simulated Using KINEROS for the Sierra Vista Subwatershed. The five-year, 30-minute storm response is shown in the left panel, while the right panel depicts the 100-year, 60-minute storm. These two events represent the end points in storm intensity and depth used in the modeling exercise. Note the changes in scale on the Y-axes between the panels.

using the 1973 data. The dominant land cover transitions within this small watershed were from grassland and desertscrub to mesquite woodlands and urban. These transitions provide lower surface roughness values, decreased infiltration rates, and less cover, thereby reducing interceptions and exposing the surface to raindrop splash, all of which contribute to increased runoff and erosion.

The sediment yield data depicted in Table 7 reveal a more nuanced response to urbanization within the watershed. Given that erosion and sediment yield are directly related to runoff velocity and volume (KINEROS employs a transport capacity model in its erosion component), as runoff rates increase, the sediment likewise increases. The percent increases in sediment yield from 1973 to 1997 (Table 7) do not equal the percent increases in runoff for the same time periods (Table 6). This apparent dissimilarity can be explained by the complexity of the spatially distributed changes within the watershed. As urbanization increases, so does the percent of impervious and paved area, which is treated in the model with a factor that reduces the erosion on those impervious areas. In this way, proportionately less area is available for surface erosion through raindrop impact or detachment due to increasing shear stress. However, those areas that remain unpaved, including portions of the uplands and the channel bottoms, remain exposed to scour. Thus, competing mechanisms limiting and increasing erosion operate within a watershed undergoing a transition to urbanization, and this is reflected in the simulation results. Importantly, the overall trend toward increasing erosion is reflected in all cases; it is only the proportion of the increase, not the general tendency toward increased erosion and decreased water quality, that is affected by the spatial distribution of the land cover change.

In general, simulation results indicate that land cover changes within this watershed have altered its hydrologic response. These localized changes were

TABLE 7. Sediment Yield Simulation Results Using Design Rainfall Events and KINEROS for the Sierra Vista Subwatershed. Design storms are given as return period events (5-,10-, and 100-year) and storm duration (30- and 60-minute).

Rainfall Event	Rainfall (mm)	Runoff (mm) 1973	1986	1992	1997	Percent Change 1973 to 1997
5 year, 30 minute	17.35	2.02	18.0	15.2	19.2	851
5 year, 60 minute	21.08	20.8	21.9	24.1	26.9	29.3
10 year, 30 minute	22.74	212	208	248	295	39.2
10 year, 60 minute	26.44	283	423	427	449	58.7
100 year, 30 minute	31.79	1803	2070	2180	2420	34.2
100 year, 60 minute	38.33	2580	2550	2890	3090	19.8

associated with vegetation transition and urbanization. Reduced estimates of infiltration, percent vegetated cover, and surface roughness in conjunction with increased impervious surfaces resulted in increased simulated runoff from a variety of rainfall events. Sediment discharge is the dominant water quality concern within the semi-arid Southwest, and these simulated alterations in hydrologic response are associated with increases in the probability of large-scale erosion and sediment yield. In short, model results indicate that the increasing urbanization and shift in dominant vegetative species have had significant effects on watershed hydrology by increasing the amount of runoff and sediment discharge from the watershed.

Hydrologic Modeling of the Cannonsville Watershed

As noted earlier, the Cannonsville watershed has remained relatively stable over the past several decades, and land classification shows that the forested area has increased during that time. Because of the large canopy cover, high root density, and their interactions with soil infiltration properties, forests have some of the lowest ratios of runoff to rainfall. Rainfall representing a continuous period of 24 years was used to simulate runoff using SWAT for each of the land cover classifications. As is shown in Figure 7, the mean annual runoff depth decreased as a function of changing land cover. Results are presented as a deviation from the base 1975 data to illustrate the temporal variability in the results. While some changes in the land cover were observed within the study area, these changes were not particularly significant for two reasons. First, the major transition was from agriculture to forest. Such a transition will not translate to a large change in simulated hydrologic response in SWAT since the differences in Curve Numbers between these land covers are not vast. Had the transition been between barren and forest, for example, the differences in simulated response would have been greater. Second, the total area converted between land cover classes was not a large portion of the watershed area (less than 5 percent change in any category). Thus, the cumulative hydrologic response was muted as spatial averaging of surface cover and hydrologic dynamics dominated the altered hydrology. From a watershed management or planning perspective, these changes were for the better since they indicate a stable watershed under no particular threat of decreased water quality due to erosion and sedimentation or a change in predicted water yield from the upland areas.

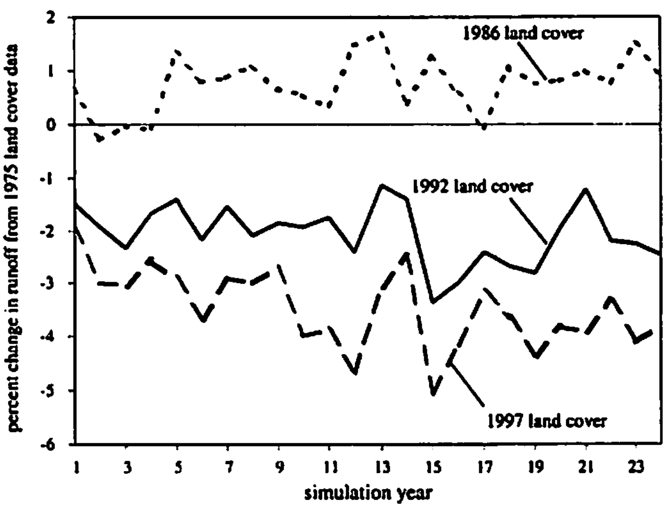

Figure 7. SWAT Simulation Results for the Cannonsville Watershed. The graph shows the deviation in total annual runoff results from the 1975 land cover results. In this case simulated runoff increases slightly from 1975 to 1986 but decreases for each of the subsequent satellite classification scenes.

CONCLUSIONS

The hydrologic responses of three watersheds to land cover change over several decades were modeled using a pair of hydrologic simulation models. These models, SWAT and KINEROS, significantly differ in their representation of hydrologic processes and operate at different temporal and spatial scales. Input parameters for these models were obtained using GIS tools in conjunction with readily available topographic and soil data and a series of classified satellite images detailing land cover over the study areas. Procedures to automatically derive input parameter files for the SWAT and KINEROS runoff models were implemented in AGWA, a GIS tool created as an integrated landscape assessment tool for watershed managers and planners.

Two primary study areas with different characteristics were used: the Upper San Pedro River Basin in southeastern Arizona and northeastern Sonora, Mexico, has undergone a profound transition over the past several decades from a rural watershed to one with significant urban and agricultural regions, while the Cannonsville watershed in southeast New York has remained relatively stable. The Sierra Vista subwatershed within the Upper San Pedro Basin was chosen for more intensive research since it has undergone significant land cover change implicated in increased runoff volumes and rates accompanied by decreased water quality due to erosion and sedimentation. These results follow the conclusions of Kepner *et al.* (2000), who showed that rapid urbanization in the towns within the San Pedro watershed over the past 20 years has become an important factor in altering land cover composition and patterns. In contrast, the eastern New York watershed has undergone little land cover change over the same period and remains largely undeveloped.

Hydrologic modeling results indicate that watershed hydrologic response in the Upper San Pedro Basin has been altered to favor increased average annual runoff due to land cover change during the period from 1973 to 1997, and consequently it is at risk for decreased water quality and related impacts to the local ecology. The small watershed within the San Pedro was modeled using design rainfall events, and the hydrographs resulting from these events showed dramatic increases in runoff volume, runoff rate, and sediment yield. Since the Cannonsville watershed condition improved during the period in which the satellite images were taken, simulated average annual runoff decreased, suggesting that the watershed is in good condition and potentially improving.

Because of the complex spatial and temporal nature of land cover change and watershed response, new technologies such as AGWA are useful tools for such investigations and may lead to improved watershed management and environmental decision making. The authors believe the combination of landscape analysis with hydrological modeling can be widely applied on a variety of landscapes. However, a number of other test watersheds would need to be included in the analysis before the research could be combined and automated into a decision analysis tool for planners and decision makers. This first level testing contrasts the extremes of a rapidly changing environment in the arid and semi-arid Southwest with the more humid and relatively stable conditions of the northeastern United States. With the addition of more case examples, a broadly applicable decision support tool could be developed.

By integrating ecological and hydrological analytic components, this project demonstrates the value of combining the research talents of multiple scientific organizations, including those with differing types of expertise (landscape ecology, hydrology, natural resource management, etc.) to assess potential watershed or regional vulnerabilities. While more work is needed, this small study demonstrates important progress toward more comprehensive large-scale watershed assessments across a range of watersheds. This analysis largely ignored the ground water component of the hydrologic cycle, and future analyses could build on this work by quantifying the impacts of land cover change on ground water through the use of a coupled surface water-ground water modeling approach.

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