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Landscape Approach to Watershed Assessment and Management ...

San Pedro and Catskill/Delaware Studies

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Abstract

The assessment of land use and land cover is an extremely important activity for contemporary land management. A large body of current literature suggests that human land-use practice is the most important factor influencing natural resource management at multiple scales. During the past two decades important advances in the integration of remote imagery, computer processing, and spatial analysis technologies have improved our ability to examine environmental change over large geographic areas. Recently, changes have been documented over a period of approximately 25 years in two watersheds with contrasting climatic regimes using a series of remotely sensed images. Landscape change analysis has been linked with distributed hydrologic models to evaluate consequences of land cover change to hydrologic response. A landscape assessment tool using a geographic information system (GIS) has been developed that automates the parameterization of the Soil Water Assessment Tool (SWAT) and KINEmatic Runoff and EROSion (KINEROS) hydrologic models. This tool was used to prepare parameter input files for the San Pedro Basin, a watershed originating in Sonora, Mexico and flowing into southeast Arizona which has undergone significant land cover change and for the Cannonsville Basin within the Catskill/Delaware watershed in New York. Runoff and sediment yield were simulated using these models. Simulation results for the San Pedro indicate that increasing urban and agricultural areas and the correlative decline of grasslands resulted in increased annual runoff volumes, flashier flood response, and decreased water quality due to sediment loading; in Cannonsville, land cover change had a beneficial impact on modeled watershed response due to the transition from agriculture to forest land cover. These results demonstrate the usefulness of integrating landscape change analysis and distributed hydrologic models through the use of GIS for assessing watershed condition and the relative impacts of land cover transitions on hydrologic response.

Introduction

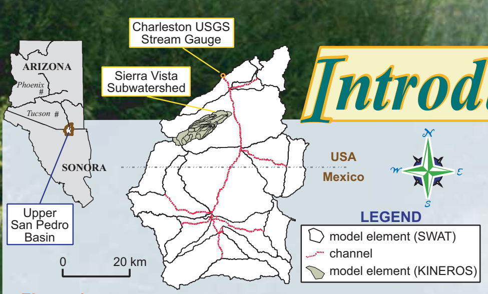

Figure 1. *Locations of two study areas within the upper San Pedro River Basin. The larger basin (3150 km²) was modeled using SWAT and drains to a pour point associated with the Charleston USGS gauging station; it encompasses the smaller Sierra Vista subwatershed (92 km²) that was modeled using KINEROS.*

Studying relationships among land use, habitat change, the amount of runoff, and water quality at the landscape scale can be used to compare watersheds, identify communities at-risk, and aid in management attempts to limit undesired impacts.

Two distinctly different study areas were selected for inclusion in this study: the Upper San Pedro Basin, located in southeastern Arizona and northeastern Sonora, Mexico (Figure 1), and the Catskill/Delaware watershed region in southeastern New York (Figure 2). The San Pedro Basin is a region in socioeconomic transition as a shift occurs from the previously dominant rural ranching economy to increasing areas of irrigated agriculture and urbanization. The San Pedro study area is classified as a semi-arid climate and 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, there is a higher potential evaporation rate, lower annual runoff but flashier runoff events, and relatively sparse vegetation.

The Catskills area of southeastern New York State serves as the primary water source for metropolitan New York City. Water quality and quantity are consequently a major concern to city and state managers and planners. Hydrologically, the Catskills study area differs significantly from the semi-arid San Pedro region. Being 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 is derived from snowmelt. Contributions, not losses, are made to runoff from groundwater within stream and river channels.

Remotely sensed imagery has been acquired over the two study areas covering the past 25 years. Hydrologic response is an integrated indicator of watershed condition, and changes in land cover may affect the overall health and function of a watershed. The objective of this project is to evaluate the effects of historic land cover change on watershed response by applying the Soil Water Assessment Tool (SWAT; Arnold et al., 1994) 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. Land cover changes were evaluated through the use of interpreted satellite imagery taken by Landsat Multi-Spectral Scanner and Thematic Mapper sensors. Simulated watershed response in the form of runoff volume, peak runoff rate, and total sediment yield were used as indicators of condition and as predictors for ramifications of observed land cover change over the past quarter-century.

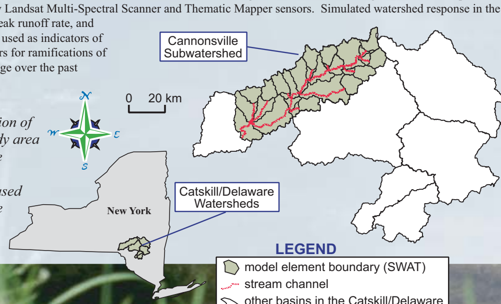

Figure 2. *Location of the Cannonsville study area (1200 km²) within the Catskill/Delaware watersheds that are used to supply water to the City of New York.*

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Methods

The general approach used in this study was to a) acquire suitable geospatial information relating to land cover, topography, and soils for the two study areas; b) assess the overall land cover trends over the past quarter-century; and c) analyze the consequent impacts on simulated runoff. A personal computer-based tool was developed during the course of this research that allows the user to automate the transformation of GIS data into parameter input files necessary for running the hydrologic models. This tool allows for the rapid and repeatable subdivision of a watershed into hydrologic response units, 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. Historical rainfall records were used to provide input to the SWAT model and define return period rainfall events for the KINEROS model. Hernandez et al. (2000) demonstrated the feasibility of this approach on a small watershed within the San Pedro Basin by applying land cover transformation scenarios and examining the simulated results. This poster represents an extension of their research, in which larger basins with greater variability and distinct hydrologic characteristics are investigated using historical data.

Landscape Change Analysis

Remote imagery for the San Pedro Basin was derived from the Landsat Multi-Spectral Scanner (MSS) imagery for 1973, 1986 and 1992 and Landsat Thematic Mapper (TM) imagery for 1997 (Figure 3). The Cannonsville watershed was classified using 1975 Landsat MSS imagery and Landsat TM imagery for 1984, 1990, and 1998 (Figure 4). 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 software and analyzed in a geographical information system using ARC/INFO software. The San Pedro watershed was mapped to 10 cover classes and the Cannonsville to 5 cover classes. Details regarding land cover classification, accuracy assessment, and change detection analysis can be found in Kepner (2000) and Mehaffey (1999).

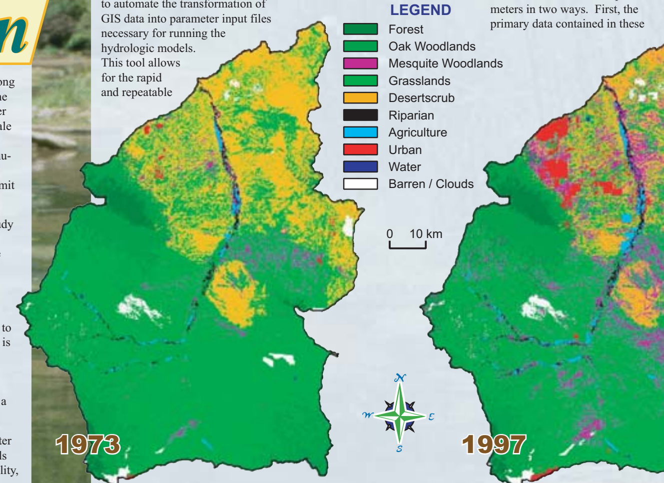

Figure 3. *Land cover change within the San Pedro Basin from 1973 to 1997 (Landsat MSS and TM). Note the distinct increases in urban, mesquite, and agriculture and a commensurate decline in grassland and desertscrub.*

GIS Processing and Database Development

The primary data layers of soil, topography, and land cover were used 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, such as estimates of the Curve Number, saturated hydraulic conductivity, channel dimensions, and roughness. Landscape features for the San Pedro River Basin were determined from a composite Digital Elevation Model (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 (1:250,000) served as the basis for soil-derived parameters.

Hydrologic Simulation

The SWAT model is used primarily as a strategic planning tool (Arnold et al., 1994). The model operates on a daily time step and allows a basin to be sub-divided into natural subwatersheds and is characterized by its focus on land management, water quality loadings, and continuous simulation over long time spans. An attempt was made to simulate the major hydrologic components and their interactions as simply and yet as realistically as possible with readily available input data over large areas so the model can be used in routine planning and decision-making.

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. Spatial variability of rainfall and infiltration, runoff, and erosion parameters can be accommodated.

Precipitation Data for Hydrologic Modeling

The conceptual approach is to derive a standard, complete multi-year period of rainfall for each of the study areas from long-term records. This rainfall would then be applied over each of the observed land cover/watershed configuration combinations, and a hydrograph would be produced through modeling. This technique assures that any modeled changes in the hydrograph are due solely to changes in land cover and are not confounded by changing patterns in rainfall. For this effort, nine gauges that record rainfall in the San Pedro study area contain long-term historical data for input to SWAT. Likewise, six gauges were available for long-term data in the Cannonsville watershed. 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 both 30- and 60-minute duration storms. The KINEROS model was run using this series of design rainfall events, with the same rainfall data applied over each land cover scenario.

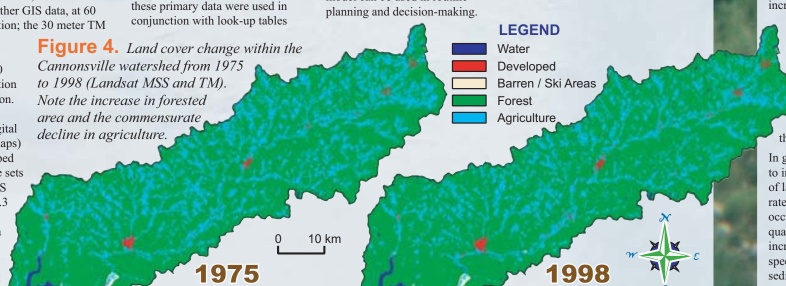

Figure 4. *Land cover change within the Cannonsville watershed from 1975 to 1998 (Landsat MSS and TM). Note the increase in forested area and the commensurate decline in agriculture.*

Results

San Pedro Basin to Charleston Gauge

Runoff was simulated with the SWAT model from the San Pedro Basin using a 14-year period with input data corresponding to the four classified satellite scenes. This 14-year period (1960 - 1973) corresponds to a continuous series of rainfall data for each of the nine rainfall gauges that lie within or near the basin. The same input rainfall was used for the four simulation runs in order to separate influences of land cover change from the vagaries of climate; therefore all changes in simulated runoff may be attributed to changes in land cover. The simulated annual runoff volumes given by SWAT are presented in Table 1. In general, the total annual runoff volume increased as a function of land cover change within the basin. Simulated runoff results show an increase in annual runoff over time commensurate with increasing urbanization.

Year	Observed runoff (mm)	Runoff (mm)				% Change 1973-1997
		1973	1986	1992	1997	
1960	8.73	4.21	4.46	4.44	4.51	7.13
1961	9.16	2.02	2.14	2.12	2.17	7.43
1962	4.67	2.16	2.27	2.24	2.3	6.48
1963	13.36	5.36	5.83	5.76	5.87	9.51
1964	21.66	18.54	19.5	19.38	19.57	5.56
1965	7.11	11.55	12.18	12.1	12.29	6.41
1966	13.62	13.31	14.03	13.95	14.19	6.61
1967	13.07	18.8	19.62	19.51	19.78	5.21
1968	5.93	7.24	7.59	7.56	7.65	5.66
1969	6.81	1.58	1.69	1.64	1.71	8.23
1970	10.51	10.14	10.67	10.54	10.73	5.82
1971	20.79	8.26	8.93	8.81	9.02	9.20
1972	10.36	6.61	7.1	7.03	7.2	8.93
1973	8.24	3.9	4.11	4.08	4.16	6.67
Average:	11.00	8.12	8.58	8.51	8.65	6.57

Table 1. *Simulation results for total annual runoff depth in the San Pedro Basin to the Charleston Gauge. The classified satellite imagery were used to parameterize the SWAT model and the same 14 years of rainfall record were applied over the study area. Note the overall increase in average annual runoff volume due to land cover change.*

Cannonsville Watershed

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 Table 2, the mean annual runoff depth decreased as a function of changing land cover. 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 period.

Year	Runoff (mm)				% Change 1975-1998
	1975	1985	1990	1998	
1972	40.43	40.69	39.83	39.65	-1.93
1973	66.82	66.63	65.53	64.82	-2.99
1974	38.12	38.10	37.23	36.96	-3.04
1975	68.78	68.72	67.64	67.02	-2.56
1976	59.06	59.84	58.23	57.34	-2.91
1977	87.87	88.56	85.96	84.65	-3.66
1978	53.53	53.99	52.70	51.97	-2.91
1979	59.32	59.96	58.08	57.55	-2.98
1980	35.09	35.32	34.44	34.14	-2.71
1981	38.96	39.17	38.21	37.40	-4.00
1982	24.71	24.79	24.28	23.75	-3.89
1983	69.09	70.11	67.42	65.86	-4.68
1984	58.38	59.36	57.72	56.59	-3.07
1985	51.05	51.25	50.33	49.78	-2.49
1986	83.28	84.30	80.48	79.07	-5.06
1987	77.42	77.84	75.10	74.19	-4.17
1988	39.94	39.91	38.98	38.67	-3.18
1989	65.53	66.23	63.77	63.14	-3.65
1990	89.59	90.28	87.07	85.68	-4.36
1991	62.87	63.38	61.66	60.46	-3.83
1992	43.32	43.75	42.79	41.63	-3.90
1993	52.90	53.31	51.74	51.14	-3.33
1994	53.34	54.12	52.14	51.15	-4.11
1995	81.99	82.72	79.97	78.87	-3.81
Average:	58.39	58.85	57.14	56.31	-3.56

Table 2. *Simulation results for total annual runoff depth in the Cannonsville subwatershed. The 1984, 1990, and 1998 land cover classification data were used to parameterize the SWAT model and the same 24 years of rainfall record were applied over the study area. Note the slight decrease in average annual runoff due to the increase in forested area over the 25-year time period.*

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

Table 3. *Runoff simulation results using design rainfall events and KINEROS for a small watershed near Sierra Vista, Arizona. Design storms are given as return period events (5 and 10 year) and storm duration (30 and 60 minute).*

Rainfall Event	Rainfall (mm)	Sediment Yield (tons/ha)				% Change 1973-1997
		1973	1986	1992	1997	
5 - 30	17.35	2.02	18.0	15.2	19.2	851
5 - 60	21.08	20.8	21.9	24.1	26.9	29.3
10 - 30	22.74	212	208	248	295	39.2
10 - 60	26.44	283	423	427	449	58.7
100 - 30	31.79	1803	2070	2180	2420	34.2
100 - 60	38.33	2580	2550	2890	3090	19.8

Table 4. *Sediment yield simulation results using design rainfall events and KINEROS for a small watershed near Sierra Vista, Arizona. Design storms are given as return period events (5 and 10 year) and storm duration (30 and 60 minute).*

Sierra Vista Subwatershed

KINEROS was used to simulate runoff and sediment yield for 6 design storms for this smaller subwatershed within the San Pedro Basin resulting in a suite of 24 simulation runs. The differences in simulated results decrease with increasing storm size and duration. Results for the simulation runs are given in Table 3, and Figure 5 shows hydrographs from the two endpoint design storms, the 5-year, 30-minute event and the 100-year, 60-minute event. Erosion and sediment yield are tied closely to the energy of a given runoff event and 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 using the 1973 data. The sediment yield data depicted in Table 4 reveal a 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.

In general, land cover changes within this watershed have led to increased runoff rates and have increased the probability of large-scale erosion and sediment yield. Increased runoff rates imply that less infiltration and groundwater recharge is occurring, and sediment discharge is the dominant water quality concern within the semi-arid Southwest. In short, the increasing urbanization and shift in dominant vegetative species have had an adverse effect on the hydrology and sediment discharge of the watershed.

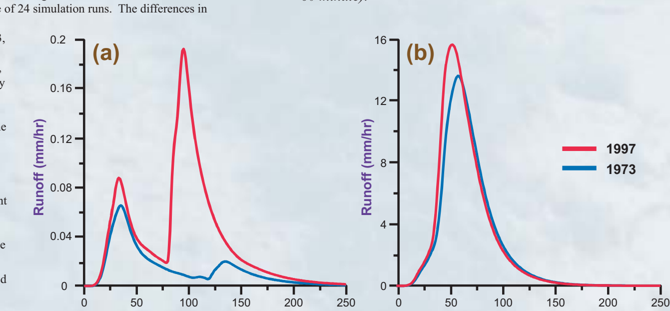

Figure 5. *Runoff hydrographs simulated using KINEROS for a small watershed near Sierra Vista, Arizona. The 5-year, 30-minute storm response is shown in Figure 6(a), while 6(b) depicts the 100-year, 60-minute storm; these two events represent the endpoints in storm intensity and depth used in the modeling exercise.*

Conclusions

The hydrologic responses of three watersheds to land cover change over several decades were modeled using a pair of hydrologic simulation models. 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 for this project, and a GIS tool for such applications was developed as part of 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 that contains significant urban and agricultural regions, while the Cannonsville watershed in southeast New York has remained relatively stable. A subwatershed within the Upper San Pedro Basin was chosen for more intensive research since it has undergone significant land cover change that suggests the potential for increased runoff volumes and rates accompanied by decreased water quality due to erosion and sedimentation.

Results indicate that the Upper San Pedro Basin experienced increased average annual runoff as a function of the land cover change during the period from 1973 to 1997, and is consequently at risk for decreased water quality and related impacts to the local ecology. The small watershed within the San Pedro was modeled using design storms, 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 imagery were taken, simulated average annual runoff decreased, suggesting that the watershed is in good condition and potentially improving.

The purpose of this research was not to determine cause and effect of land cover change, rather it was to explore the integration of new technologies and natural science to improve 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 U.S. With the addition of more case examples, a broadly applicable decision-support tool could be developed.

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