Integrating a Landscape/Hydrologic Analysis for Watershed Assessment

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Abstract

Methods to provide linkages between a hydrologic modeling tool (AGWA) and landscape assessment tool (ATtILA) for determining the vulnerability of semi-arid landscapes to natural and human-induced landscape pattern changes have been developed. The objective of this study is to demonstrate the application of ATtILA and AGWA to investigate the spatial effects of varying levels of anthropogenic disturbance on runoff volume and soil erosion in the San Pedro River Basin. Results were particularly useful for assessing the effects of land cover change in the watershed and highlighting subwatersheds that require careful management.

Keywords: watershed assessment, landscape analysis, hydrologic models, sediment yield

Introduction

Empirical studies have established the significant causal relationship between watershed characteristics and sediment loads (Yates and Sheridan 1983). Agriculture on slopes of greater than 3% increases the risk of soil erosion (Wischmeier and Smith 1978), and this can lead to increases in sediment loadings to surface waters. A decrease in natural vegetation indicates a potential for future water quality problems (Likens et al. 1977; Hunsaker and Levine 1995; Jones et al. 2001).

This study presents an integrated approach to identify areas with potential water quality problems in particular high sediment loadings as a result of land cover change. Landscape metrics describing spatial composition and spatial configuration were computed using the Analytical Tools Interface for Landscape Assessments (ATtILA) (Ebert et al. 2002). These landscape metrics were used along with the Automated Geospatial Assessment Tool (AGWA) (Miller et al. 2002) to examine the contribution of land cover type to sediment yield and identify subwatersheds with high sediment production for the period 1993 to 1997.

Study area

The San Pedro Basin is located in the northern portion of Sonora, Mexico and southeastern Arizona. The basin is traditionally divided into two sections, the Upper and Lower San Pedro Basins, which are separated by the geologic formation known as “The Narrows.” This study includes the Upper San Pedro Basin and a portion of the Lower San Pedro Basin to the Redington stream gauge. For convenience, all references to the Upper San Pedro Basin in this text refer to the entire study area (Figure 1).

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The Upper San Pedro Basin contains approximately 7598 km^2. The Upper San Pedro Basin is bounded by generally north-northwest trending mountains, which range in elevation from 1524 m to nearly 3048 m. The San Pedro River enters the basin at the International Boundary near Palominas, Arizona, and flows northwest for about 120 km before leaving the basin at Redington. The San Pedro River is mostly ephemeral and only flows in response to local rainfall. The river does have a perennial stretch of about 29 km between Hereford and a point just south of Fairbanks (Putman et al. 1988). The Upper San Pedro Basin represents a transition area between the Sonoran and Chihuahuan deserts and topography, climate, and vegetation vary substantially across the watershed. Annual rainfall ranges from 300 to 750 mm. Biome types include riparian forest, coniferous forest, oak woodland, mesquite woodland, grasslands, desertscrub, and agriculture.

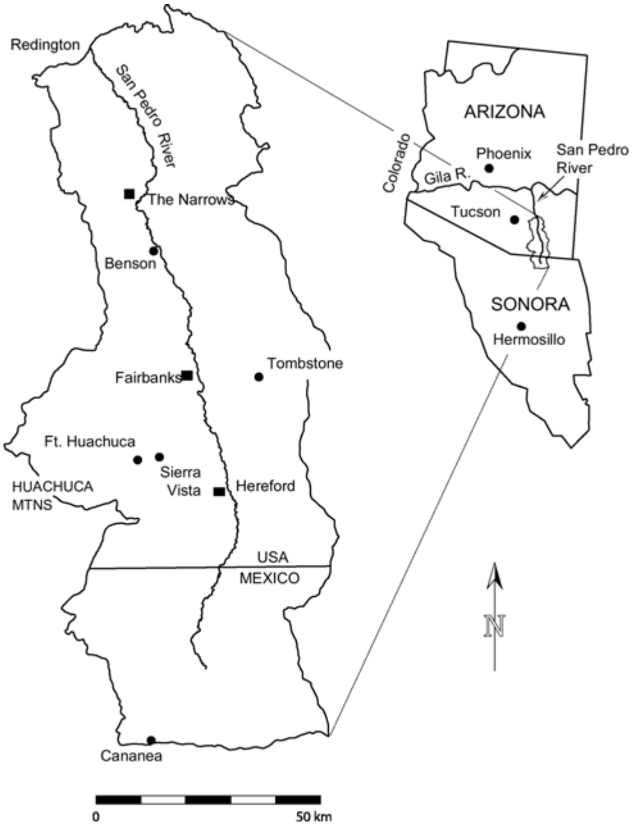

Figure 1. Location of the study area.

Methods

The general approach used in this study was carried out in three steps. The first step consisted of subdividing the Upper San Pedro Basin into subwatersheds or reporting units and computing landscape metrics using ATtILA to quantify the percent cover and spatial pattern on each subwatershed. The second step consisted of applying the AGWA tool to parameterize the Soil Water Assessment Tool (SWAT) (Arnold et al. 1994) and calibrate it using the USGS stream flow gauge at Redington. The third step consisted of identifying subwatersheds with high potential of water quality problems based on sediment load for the period 1993 to 1997.

Description of ATtILA & AGWA

The U.S. Environmental Protection Agency, Landscape Ecology Branch has developed a user-friendly interface (ArcView extension) ATtILA to compute a wide variety of landscape metrics for categorical map patterns. Four families of metrics are included in the software: landscape characteristics, riparian characteristics, human stressors, and physical characteristics. Each group has a dialog box to accept user input on which metrics to calculate and what input data to use. Landscape characteristics are related to land cover proportions and patch metrics. Riparian characteristics describe land cover adjacent to and near streams. Human stressors are concerned with population, roads, and land use practices. Physical characteristics provide statistical summaries of such attributes as elevation and slope. Once metrics have been calculated, ATtILA has three types of output display available. The first displays areas ranked by individual metric value, the second ranks areas by a weighted index made up of two or more metrics, and the third displays a bar chart of selected areas and metrics.

The AGWA tool uses widely available standardized spatial data sets to develop input parameter files for two watershed runoff and erosion models: KINematic EROSion (KINEROS) (Woolhiser et al. 1990) model and SWAT. Using digital data in combination with the automated functionality of AGWA greatly reduces the time required to use these two watershed models. The user selects an outlet from which AGWA delineates and discretizes the watershed using the Digital Elevation Model (DEM). The watershed elements are then intersected with the soil, land cover, and precipitation (uniform or distributed) data layers to derive the essential model input parameters. The model is then run, and the results are imported back into AGWA for visual display. AGWA is an ArcView extension designed to provide qualitative estimates of runoff and erosion relative to landscape change. Managers can use it to identify problem areas where management activities can be focused, or to anticipate sensitive areas in association with planning efforts.

Landscape metrics computation

Spatial analyses were carried out to (1) describe structural landscape patterns and (2) relate overall land use changes to hydrological processes. Kepner et al. (2002) used remote sensing techniques for detecting change by analyzing multi-date imagery. Landsat-MSS 1973 was used for the baseline condition. They computed land use change between time intervals 1973, 1986, 1992, and 1997. Digital land cover maps were developed separately for each year using 10 classes: Forest, Oak Woodland, Mesquite Woodland, Grassland, Desertscrub, Riparian, Agriculture, Urban, Water, and Barren. The delineation of the subwatersheds or reporting units was carried out using AGWA dividing the basin into 68 subwatersheds.

Landscape metrics for each patch and cover class within a subwatershed on the 1997 analysis map were calculated using the ATtILA extension. All metrics included in the analysis are listed in Table 1.

Table 1. Landscape metrics included in the analysis

Category	Index Name
Spatial Composition	Land use proportions
	Shannon’s diversity index
Spatial Configuration	Number of patches
	Patch density
	Largest patch index
	Average patch size
	Connectivity

Hydrologic simulation

The purpose of the simulation model was to assess the contribution of different land cover types to surface runoff and sediment yield for the period 1993 to 1997. The modeling was based on the subdivision of each of the 68 subwatersheds or reporting units into smaller units by generation of the so-called “Hydrological Response Units” (HRUs) (Leavesly et al. 1983; Maidment 1991). In general, HRUs are defined by combining spatial attributes relevant to the model into discrete spatial features. The definition of HRUs varies depending on the model’s conceptualization. In the case of SWAT, HRUs are response units that have similar hydrological response characteristics and lie within a subwatershed element but need not be contiguous. Runoff contributions from similar areas (HRUs) such as forest, grassland, desertscrub, agriculture, and urban, etc., within a subwatershed element are calculated separately and then summed before routing in the stream and river network.

In this study, the characterization of each HRU within each subwatershed was established based on the landscape metrics computed with ATtILA. In particular we used the proportion of land use, slope, number of patches, and average patch size. The total number of HRUs was 384; the HRU mean area was 19.78 km^2 and the maximum and minimum areas were 275 km^2 and 0.0035 km^2, respectively. Sixty-five percent of all HRUs had areas less than 12 km^2. The hydrologic parameter most affected by the characteristics of the landscape metrics was the Curve Number.

Calibration

The SWAT model was calibrated separately against observed surface runoff and base flow for the period 1993 to 1997. Base flow was separated from the total observed stream flow according to the USGS HYSEP fixed-interval method (Sloto and Crouse 1996). For the calibration, we assumed stationary land use conditions based on the 1997 land use and land cover characteristics. The Curve Number and Manning’s roughness coefficient were adjusted to provide better comparisons between mean annual measured and simulated surface runoff. Similarly, for mean annual base flow, the values of initial depth of water in the shallow aquifer and the threshold depth parameter that controls the amount of groundwater flow into the stream were adjusted. Eight rain gauges were used in the calibration process. Daily rainfall data were available from the National Climatic Data Center.

The calibration results show that average annual total water yield at the USGS Redington stream flow gauge was calibrated to within 12% of the observed flow. SWAT was calibrated to within 13% and 4% for surface runoff and base flow, respectively. Based on these results, SWAT was able to represent the hydro-dynamics of the watershed at the annual scale. No attempt was made to calibrate the model against measured sediment concentration because insufficient data were available at Redington. For instance, eight, ten, and thirteen mean daily values were available for 1993, 1996, and 1997, respectively. We recognized that these mean estimates might be low because larger events could have occurred on days where data were not recorded. Based on these values, measured mean annual sediment concentration estimates are as follows: 40 mg/L, 73 mg/L, and 48 mg/L for 1993, 1996, and 1997, respectively. Mean annual sediment concentration computed by SWAT are as follows: 115 mg/L, 37 mg/L, and 29 mg/L, for 1993, 1996, and 1997, respectively. SWAT computed sediment yield based on default parameters available in the STATSGO soil database.

The relationship between sediment yield and mean annual surface runoff for Agriculture, Desertscrub, Grassland, and Mesquite Woodland land cover classes is shown in Figure 2. Land use significantly affected the magnitude of sediment through its influence on the degree of protection afforded by the vegetation cover. Kepner et al. (2000) presents land cover descriptions for the vegetative communities in the study area. Desertscrub vegetative communities are characterized as having significant areas of barren ground devoid of perennial vegetation. In contrast, Mesquite Woodland are communities described as dominated by leguminous trees whose crowns cover 15% or more of the ground and resulting in dense thickets. Therefore, areas with Mesquite Woodland and Grassland cover types may produce lower sediment yield estimates than desertscrub areas as shown in Figure 2. Agricultural areas are primarily found along the upper terraces of the riparian corridor and are dominated by hay and alfalfa. They are minimally represented in overall extent (less than 3% total cover) within the basin and are irrigated by groundwater and pivot-sprinkler systems. However, they may represent a potential source for water quality problem in the region. In addition, we investigated the rate at which sediment yield varies with mean annual surface runoff. We fitted straight lines to the data and computed the correlation coefficients and slopes for each land cover type. The correlation coefficient (r^2) and slope (s) are as follows: Agriculture 0.81 and 1.30; Desertscrub 0.65 and 0.93; Grassland 0.54 and 1.11; and Mesquite Woodland 0.16 and 0.83. From the analysis, Agriculture is the land cover type that produces the highest rate of sediment yield.

Because SWAT is a distributed model, it is possible to view model output as it varies across the San Pedro Basin. Figure 3 depicts the spatial variability of average surface runoff and average sediment yield for the period 1993 to 1997.

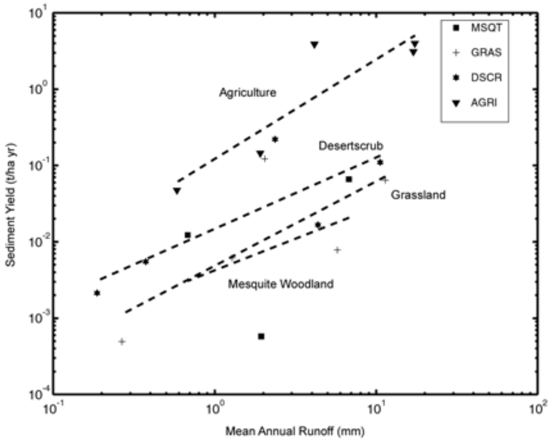

Figure 2. Relationship of sediment yield to mean annual surface runoff for four land use types for the period 1993 to 1997.

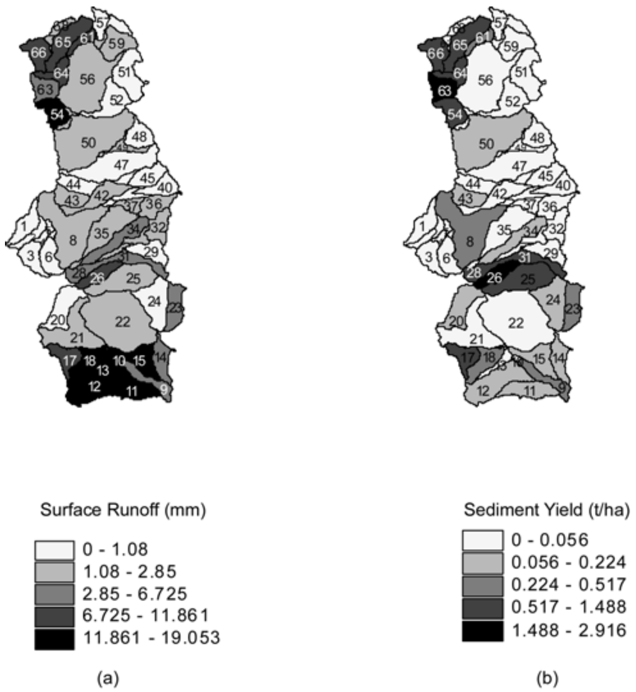

Figure 3. Spatially distributed (a) average surface runoff and (b) average sediment yield for the period 1993 to 1997.

At the watershed scale spatial variability of rainfall, partial area response, gully and alluvial channel densities and properties, and vegetation type largely determine sediment yield (Lane et al. 1997). This influence is apparently primarily through controlling the runoff generation process and channel detachment, transport, and deposition. The spatial variability of sediment yield shown in Figure 3(b) is being controlled primarily by the spatial distribution of surface runoff Figure 3(a).

Assessment

We ranked the HRUs according to high contributing sediment yield areas using the relationship between sediment yield to mean annual surface runoff as a function of land cover type and the landscape metrics. We used as cutoff criteria the average slope (9%) and the average sediment yield (0.8 t/ha) of all HRUs for the period 1993 to 1997. The selection process yielded eight HRUs; six are classified as agriculture and two as desertscrub. The six agricultural HRUs are located within the subwatersheds 54, 61, 65, 28, 52, and 20. The two HRUs with desertscrub land cover are located within the subwatersheds 63 and 66. Only one subwatershed (20) crosses the boundary with Sonora, Mexico and its main contribution to sediment yield comes from agricultural lands. It is important to point out that the proportion of agricultural land in this subwatershed is 1% compared to 50% of forestland. This indicates that a small area can be the major source of sediment and, consequently, a problem to water quality. The ranking of the eight subwatersheds was carried out based on the average sediment load produced during the period 1993 to 1997. We computed the average sediment load based on the average patch size computed with ATtILA and the average sediment yield computed with AGWA. The outcome of the ranking process is listed in Table 2 and depicted in Figure 4.

Conclusions

Landscape pattern analysis was conducted on a subwatershed basis to characterize the heterogeneity of land cover and land use. ATtILA was used to compute metrics associated with landscape characteristics for 1997. Since spatial variability of land cover alters the hydrological structure within the watershed, we used AGWA to examine the watershed response relevant to surface runoff and soil erosion at each subwatershed. We used the concept of HRU to examine the contribution of land cover type to sediment yield for the period 1993 to 1997. The hydrologic model was calibrated against total water yield, surface runoff and base flow using measured stream flow records at Redington. The highest contribution to sediment yield is produced in areas with agriculture and desertscrub land cover types. We used the average slope steepness, the average annual sediment yield, and the average patch size to identify and rank the subwatersheds that require careful management.

Methods for developing integrated planning and management strategies need to be spatially explicit, refer to specific areas, and utilize basic biophysical information together with assessments of both potential uses of individual land units and the potential levels of primary threats in each. The integrated approach presented here allows resource managers to integrate landscape spatial analysis with hydrological modeling to identify problem areas.

Table 2. Sensitive areas with high sediment loads

Rank	**Sub (Id)**	**Slope (%)**	**Syld. (t/ha)**	**Ave. patch size (ha)**	**Sed. load (ton)**
1	54	15	24.87	13.30	330.84
2	61	19	14.01	8.10	113.48
3	65	19	19.23	4.94	95.10
4	28	18	1.44	33.61	48.41
5	52	13	0.84	47.70	40.07
6	20	13	2.21	8.37	18.51
7	63	24	0.94	5.07	4.77
8	66	21	0.82	3.67	3.01

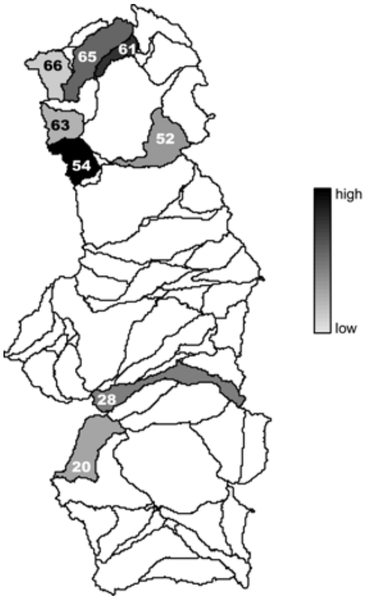

Figure 4. High sediment load subwatersheds based on land cover type, slope steepness, and average patch size for the period 1993 to 1997.

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References

Arnold, J. G., J. R. Williams, R. Srinivasan, K. W. King, and R. H. Griggs. 1994. SWAT: Soil Water Assessment Tool. U.S.D.A., Agricultural Research Service, Grassland, Soil and Water Research Laboratory, Temple, TX.

Ebert, D. W., T. G. Wade, J. E. Harrison, and D. H. Yankee. 2002. Analytical Tools Interface for Landscape Assessments (ATtILA). U.S.E.P.A., Office of Research and Development, National Exposure Research Laboratory, Environmental Sciences Division, Landscape Ecology Branch, Las Vegas, NV.

Hunsaker, C. T., and D. A. Levine. 1995. Hierarchical approaches to the study of water quality in rivers. BioScience 45:193-203.

Jones, K. B., A. C. Neale, M. S. Nash, R. D. Van Remortel, J. D. Wickham, K. H. Ritters, and R. V. O'Neill. 2001. Predicting nutrient and sediment loadings to streams from landscape metrics: A multiple watershed study from the United States Mid-Atlantic Region. Landcape Ecology 16:301-312.

Kepner, W. G., C. J. Watts, C. E. Edmonds, J. K. Maingi, S. E. Marsh, and G. Luna. 2000. A landscape approach for detecting and evaluating change in a semi-arid environment. Environmental Monitoring and Assessment 64:179-195.

Kepner, W. G., C. M. Edmonds, and C. J. Watts. 2002. Remote sensing and geographic information systems for decision analysis in public resource administration: a case study of the 25 years of landscape change in a southwestern watershed. EPA/600/R-02/039, U.S.E.P.A., Office of Research and Development, National Exposure Research Laboratory, Las Vegas, NV.

Lane, L. J., M. Hernandez, and M. Nichols. 1997. Processes controlling sediment yield from watersheds as a function of spatial scale. Environmental Modelling & Software 12:355-369.

Leavesly, G. H., R. W. Lichty, B. M. Troutman, and L. G. Saindon. 1983. Precipitation-Runoff Modeling System User's Manual. 83-4238, U.S.G.S. Water Resources Investigations Report.

Likens, G. E., F. H. Bormann, R. S. Pierce, J. S. Eaton, and N. M. Johnson. 1977. Biogeochemistry of a Forested Ecosystem. Springer-Verlag, New York, NY.

Maidment, D. R. 1991. GIS and Hydrologic Modeling. *In* First international symposium/workshop on GIS and environmental modeling, Boulder, CO.

Miller, S. N., D. J. Semmens, R. C. Miller, M. Hernandez, D. C. Goodrich, W. P. Miller, W. G. Kepner, and D. W. Ebert. 2002. GIS-based hydrologic modeling: the automated geospatial watershed assessment tool. Pages 12 *in* The Second Federal Interagency Hydrologic Modeling Conference. Las Vegas, NV.

Putman, F., K. Mitchell, and G. Bushner. 1988. Water Resources of the Upper San Pedro Basin, Arizona. Arizona Department of Water Resources, Hydrology Division, Tucson, AZ.

Sloto, R. A., and M. Y. Crouse. 1996. HYSEP: A computer program for streamflow hydrograph separation and analysis. 96-4040, U.S.G.S. Water Resources Investigations, Lemoyne, Pennsylvania.

Wischmeier, W. H., and D. D. Smith. 1978. Predicting rainfall erosion loss: A guide to conservation planning. U.S. Department of Agriculture, Washington, D.C.

Woolhiser, D. A., R. E. Smith, and D. C. Goodrich. 1990. KINEROS: A kinematic runoff and erosion model. U.S. Department of Agriculture, Agricultural Research Service.

Yates, P., and J. M. Sheridan. 1983. Estimating the effectiveness of vegetated floodplains/wetlands as nitrate-nitrite and orthophosphorus filters. Agricultural Ecosystems Environmental 9:303-314.