

Integrated Landscape/Hydrologic Modeling Tool for Semiarid Watersheds

Mariano Hernandez¹ and Scott N. Miller¹

Abstract.—An integrated hydrologic modeling/watershed assessment tool is being developed to aid in determining the susceptibility of semiarid landscapes to natural and human-induced changes across a range of scales. Watershed processes are by definition spatially distributed and are highly variable through time, and this approach is designed to account for their spatial and temporal variability. This tool will integrate geographical information systems and distributed hydrologic models in a user-friendly graphical environment. The hydrologic models work under a watershed analysis framework to simulate the influences of vegetation and land use characteristics on watershed response and will accommodate scientific advances in the quantification of watershed assessment via hydrologic process modeling.

Introduction

As populations grow and economic activity increases in the Western semiarid regions of the United States, there is increasing demand for scarce water resources. This focuses attention on maximizing the development and protection of renewable water resources. It is therefore essential to develop modeling techniques that can represent the dominant hydrological processes and their temporal variability so that the vulnerability of semiarid landscapes to a variety of natural and anthropogenic stressors at multiple scales can be investigated.

Watershed or ecosystem management requires a solid understanding of landscape-level ecosystem processes, and in particular the interaction of geomorphological, hydrological and biological processes (Stanley, 1995). At present, poor understanding and a lack of information regarding landscape-scale processes generally hinders assessment of the ecological consequences of human actions and helps institutionalize land use conflicts (Montgomery et al., 1998). Landform analysis can provide an understanding of geomorphological processes that influence hydrological and ecological processes and systems. Environmental impact analysis protocols developed in response to environmental legislation generally focus on site-, ownership-, or species-specific issues at scales inadequate for assessing ecosystem processes and condition

(Montgomery et al., 1995). Hence, the integrated effects of local management decisions can be incompatible with broader-scale management objectives. Implementing ecosystem management requires a framework for gathering and interpreting environmental information at a scale and resolution necessary for addressing the tradeoffs between economic and ecological considerations inherent to making land management decisions (Slocumbe, 1993).

Although a number of initiatives and strategies focus on large scales (WFPB, 1992; FEMAT, 1993), there is not yet a consensus on how to implement ecosystem management (Montgomery et al., 1998). A key element is the development of a practical operational framework for integrating ecosystem management into land use decision making. Watersheds define basic, hydrologically, ecologically and geomorphologically relevant management units (Chorley, 1969; Likens and Bormann, 1974; Lotspeich, 1980) and watershed analysis provides a practical analytical framework for spatially-explicit, process-oriented scientific assessment that provides information relevant to guiding management decisions.

The purpose of this paper is to present an approach for providing operational hydrologic modeling tools under a watershed analysis framework for determining the vulnerability of semiarid landscapes to natural and human-induced landscape pattern changes across multiple scale domains.

Semiarid Watershed Modeling

Site Descriptions

Walnut Gulch Experimental Watershed

The Walnut Gulch Experimental Watershed (WGEW) encompasses approximately 150 km² in southeastern Arizona, USA (figure 1) surrounding the historical western town of Tombstone. Walnut Gulch is a tributary of the San Pedro River, which originates in Sonora, Mexico and flows north into the United States. The watershed is representative of the brush and grass covered rangeland found throughout the semiarid Southwest and is a transition

¹ School of Renewable Natural Resources, University of Arizona, Tucson, AZ

zone between the Chihuahuan and Sonoran Deserts. Elevation of the watershed ranges from 1,220 m to 1,890 m. For further details on the description of the Walnut Gulch Experimental Watershed see Renard et al. (1993).

San Pedro River Basin

The Upper San Pedro River Basin (SPRB) covers about 6,600 km² and spans the Mexico-US Border from northern Sonora into southeastern Arizona (figure 1). It has high topographic variability (1,200 m – 2,900 m) providing ecological and climatic diversity over distances as short as 20 km and significantly different cross-border land uses visible from satellite multi-spectral images. Diverse veg-

etation types include both Sonoran and Chihuahuan desertscrub, grasslands, chaparral, Madrean evergreen woodlands, and high-elevation conifer forests (McClaran and Brady, 1994). For further details on the description of the San Pedro River Basin see Goodrich (1994). While current research focuses on the Walnut Gulch and San Pedro watersheds, this research will be extended to a range of basins across the semiarid western United States. A range of basins with rainfall and runoff data will be selected to validate the assessment tool. These basins will be selected based on watershed characteristics such as size, geomorphology, ecology, land use, topography, and data availability.

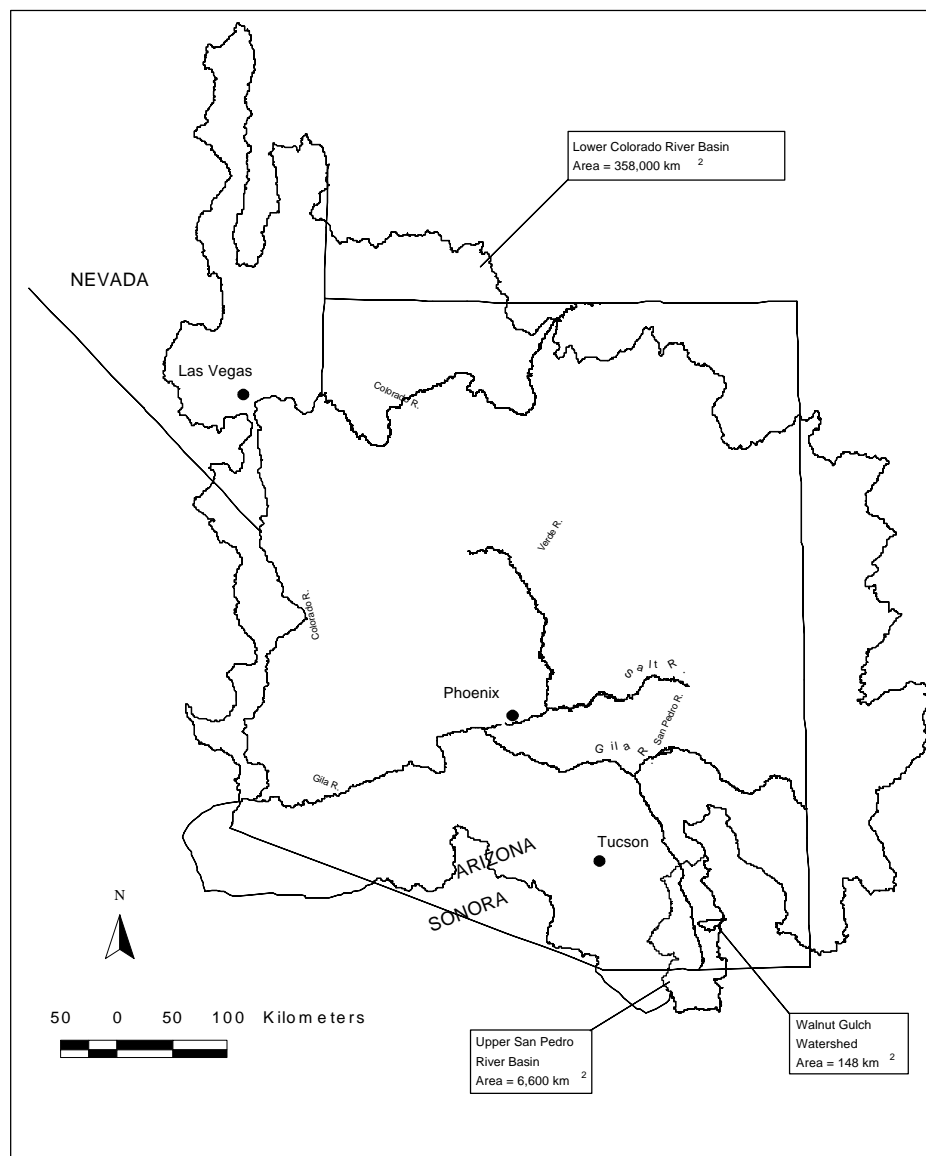


Figure 1. The Upper San Pedro River Basin.

Semi-arid Watershed Hydrology

A large proportion of the Western United States is classified as arid or semi-arid. These regions are characterized by larger relative extremes in components of the hydrologic cycle than in the humid climates, including: 1) low annual precipitation but high-intensity storms with significant spatial variability, 2) high potential evaporation, 3) low annual runoff but short-term high volume runoff, and 4) runoff losses in ephemeral channels (Branson et al., 1981). Furthermore, these regions are especially prone to erosion. Hydrologic models must therefore adequately account for these factors if they are to be used to assess the impacts of landscape change on hydrologic response in the Western United States.

Vegetation cover represents one of the most powerful factors influencing the runoff regime, since it modifies and moderates many others. It should be noted that methods for transforming various land cover and land use characteristics into distributed hydrologic model parameters are not well developed for a wide range of conditions. For management purposes, many approaches rely largely on empirical studies of small plots and watersheds to relate land cover and land use to hydrologic model parameters. The curve number method (USDA-SCS, 1972) is an example of this type of approach to relate land cover and land use to hydrologic model parameters.

Landscape/Hydrologic Modeling Tool

The landscape/hydrologic modeling tool is designed within a database management system framework, which comprises the following elements: database, simulation, and a graphical-user-interface. The integrated landscape/hydrologic modeling tool is described in figure 2. Each element is described in the following sections.

Database

This module covers all aspects of capturing spatial data from existing maps, field observations, and sensors (including aerial photography, satellites, and recording instruments) and converting them to a standard digital form. Once entered, the data will be checked for inaccuracies, omissions, and other errors.

The fundamental spatially distributed geographic information system (GIS) data that will serve as input to the hydrologic models are soils, land cover, and topography. It is proposed that topography be derived from available USGS 7.5' digital elevation models (DEMs), that soils

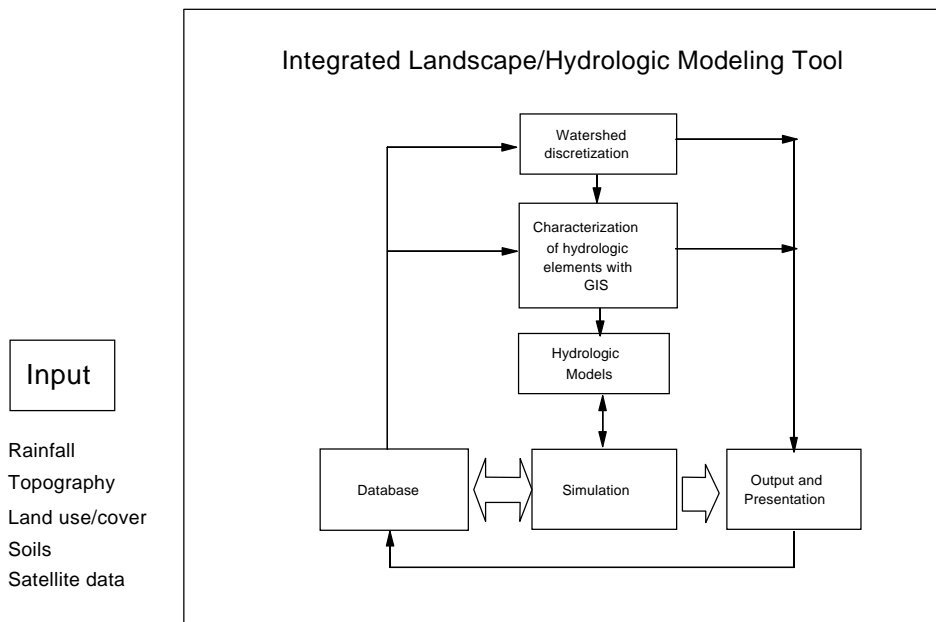


Figure 2. An integrated landscape/hydrologic modeling tool.

information be derived from USDA-NRCS STATSGO soil polygons, and that land cover come from Multi-Resolution Land Characteristics (MRLC) products. On Walnut Gulch, rainfall information will be compiled from historical 85-raingauge network data. Runoff data will come from various historical and current gaging structures. For the San Pedro Basin, rainfall data will be retrieved from the National Climatic Data Center database (US Department of Commerce, 1995), and stream flow data at Charleston will be obtained from the USGS database (USGS, 1999).

Simulation

The simulation component consists of a computer program to characterize watershed complexity and hydrologic models.

Watershed Complexity

The watershed discretization and characterization tool TOPAZ (TOPographic PARAMeterization) (Garbrecht and Martz, 1995) is used to delineate the hydrologic elements of a watershed. TOPAZ is a software package for automated analysis of digital landscape topography. A raster digital elevation model (DEM) is used by TOPAZ to identify and measure topographic features, define surface drainage, subdivide watersheds along drainage divides, quantify the drainage network, and calculate representative subcatchment parameters. TOPAZ is designed primarily to assist with topographic evaluation and watershed parameterization in support of hydrologic modeling and analysis.

Hydrologic models

In the selection process of the hydrologic models, strong emphasis was placed on models that were able to characterize complex watershed representations to explicitly account for the spatial variability of soils, distribution of rainfall, and heterogeneity of vegetation. The effects of land use and land cover on surface runoff and sediment yield were also stressed in the model selection criteria. Furthermore, models were chosen that adequately characterize the mechanism that produce surface runoff and sediment yield producing mechanisms. That is, the models are governed by equations based on fundamental principles of physics or robust empirical methods widely used in computing surface runoff and sediment yield. The following discussion provides an overview of the hydrologic models.

The "Soil and Water Assessment Tool" (SWAT) (Arnold et al. 1994) is public domain software developed and actively supported by the USDA-Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas. SWAT is a continuous-time model that operates on a daily time step to predict the impact of management on water, sediment and agricultural chemi-

cal yields in large ungaged basins. To satisfy the objective, the model (a) uses readily available inputs; (b) is computationally efficient to operate on large basins in a reasonable time; and (c) is continuous time and capable of simulating long periods for computing the effects of management changes. The SWAT components can be placed into eight major divisions: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management.

KINEROS, an acronym for the KINematic runoff and EROsion model, has evolved over a number of years primarily as a research tool (Smith et al., 1995). KINEROS is public domain software developed by the USDA-Agricultural Research Service, and supported by the Southwest Watershed Research Center in Tucson, Arizona. KINEROS is an event oriented, physically based model that describes the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds. The watershed is represented by a cascade of planes and channels; and 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.

Graphical User Interface

As the models are integrated with the GIS data, a suite of programs will be developed to automate the parameterization of the hydrologic models. The development of graphical-user-interface (GUI) tools is a critical step towards implementing the techniques across a range of scales by a variety of clients. The largest drawbacks to hydrologic modeling at larger scales are the complexity of the input data and expert knowledge and proficiency required to initiate the model runs. The GUI will allow for the rapid and accurate application of SWAT and KINEROS at a range of basin scales given a minimum of expertise and input data. These tools will be critical for transferring this technology to resource managers and regional planners who are interested in projecting the impact of land use change on hydrologic response. Data output will be presented in a variety of ways ranging from the image on the computer screen, through hardcopy output drawn on printer or plotter to information recorded on magnetic media in digital form.

Conclusions

Simulation models can be used to quantify the interactions among variables across multiple scales domains.

Used together, the SWAT and KINEROS models comprise a viable tool for characterizing hydrologic processes in semiarid regions. The watershed function of complex watershed systems at a range of scale can be interpreted based on relationships among influential variables described by the models. Understanding these relationships and developing the mathematical expressions describing them is a goal of natural resources scientist. Additionally, the technology exists to extend research results and applications to decision makers and land managers. A landscape/hydrologic tool will provide an accessible scientific basis for land planning and decision making.

Acknowledgments

The authors wish to thank Dr. Vince Lopes, School of Renewable Natural Resources, University of Arizona and Dr. Hector Arias Rojo, Instituto del Medio Ambiente y el Desarrollo Sustentable del Estado de Sonora, Mexico for their comprehensive technical reviews of this paper.

Literature Cited

- Arnold, J. G., J. R. Williams, R. Srinivasan, K. W. King, and R. H. Griggs, 1994. SWAT-Soil Water Assessment Tool. USDA, Agricultural Research Service, Grassland, Soil and Water Research Laboratory, Temple, Texas.
- Branson, F. A., G. F. Gifford, K. G. Renard, and R. F. Hadley, 1981. Rangeland Hydrology, Range Science Series No.1, Society for Range Management, Denver, CO., 645pp.
- Chorley, R. J., 1969. The drainage basin as the fundamental geomorphic unit. In: Water, Earth and Man, R. J. Chorley (Ed.), Methuen, London, pp. 77-99.
- Forest Ecosystem Management Assessment Team (FEMAT). 1993. Forest ecosystem management: An ecological, economic, and social assessment. Report of the Forest Ecosystem Management Assessment Team. U. S. Government Printing Office 1993-793-071, Washington, D.C.
- Garbrecht, J. and L. W. Martz, 1995. TOPAZ: An automated digital landscape analysis tool for topographic evaluation, drainage identification, watershed segmentation and subcatchment parameterization; overview. ARS Pub. No. NAWQL 95-1, USDA-ARS, Durant, OK, 16 pp.
- Goodrich, D. C., 1994. SALSA-MEX: A large scale semi-arid land surface-atmospheric mountain experiment. Proc. 1994 Int'l. Geoscience and Remote Sensing Symp. (IGARSS '94), Pasadena, CA, Vol. 1, pp. 190-193.
- Likens, G. E. and F. H. Bormann, 1974. Linkages between terrestrial and aquatic ecosystems. *BioScience* 24: 447-456.
- Lotspeich, F. B., 1980. Watersheds as the basic ecosystem: This conceptual framework provides a basis for natural classification system. *Water Resources Bulletin*, American Water Resources Association, 16:581-586.
- McClaran, M. P. and W. W. Brady, 1994. Arizona's diverse vegetation and contributions to plant ecology. *Rangelands* 16:208-217.
- Montgomery, D. R., G. E. Grant, and K. Sullivan, 1995. Watershed analysis as a framework for implementing ecosystem management. *Water Resources Bulletin*, American Water Resources Association, 3(3):369-386.
- Montgomery, D. R., W. E. Dietrich, and K. Sullivan, 1998. The role of GIS in watershed analysis. Chapter 11, In: *Landform Monitoring, Modeling and Analysis*, Lane, S., K. Richards, and J. Chandler, (Eds.) John Wiley & Sons, Chichester, 454pp.
- Renard, K. G., L. J. Lane, J. R. Simanton, W. E. Emmerich, J. J. Stone, M. A. Weltz, D. C. Goodrich, and D. S. Yakowitz, 1993. Agricultural impacts in an arid environment: Walnut Gulch studies. *Hydrological Science and Technology*, 9 (1-4): 145-190, American Institute of Hydrology.
- Slocumbe, D. S., 1993. Implementing ecosystem-based management. *BioScience* 43:612-622.
- Smith, R. E., D. C. Goodrich, D. A. Woolhiser, and C. L. Unkrich, 1995. KINEROS - A kinematic runoff and erosion model, In: *Computer Models of Watershed Hydrology*, V. P. Singh, (Ed.), Water Resources Publications, Highlands Ranch, CO.
- Stanley, T. R. Jr., 1995. Ecosystem management and the arrogance of humanism. *Conservation Biology*, 9, 255-262.
- U. S. Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic Data Center, 1995. Cooperative Summary of the Day, TD3200 - Period of record through 1993.
- USGS, 1999. US GeoData Web Site <http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html>
- U. S. Department of Agriculture, Soil Conservation Service, 1972. National Engineering Handbook, Section 4, Hydrology US Government Printing Office, Washington, D.C.
- Washington Forest Practice Board (WFPB), 1992. Standard methodology for conducting watershed analysis. Washington Forest Practice Act Board Manual, Version 1.0, 13 pp.