United States
Environmental Protection
Agency

Office of Research and
Development
Washington, D.C. 20460

EPA/600/R-00/042
February 2000
(07)

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EPA

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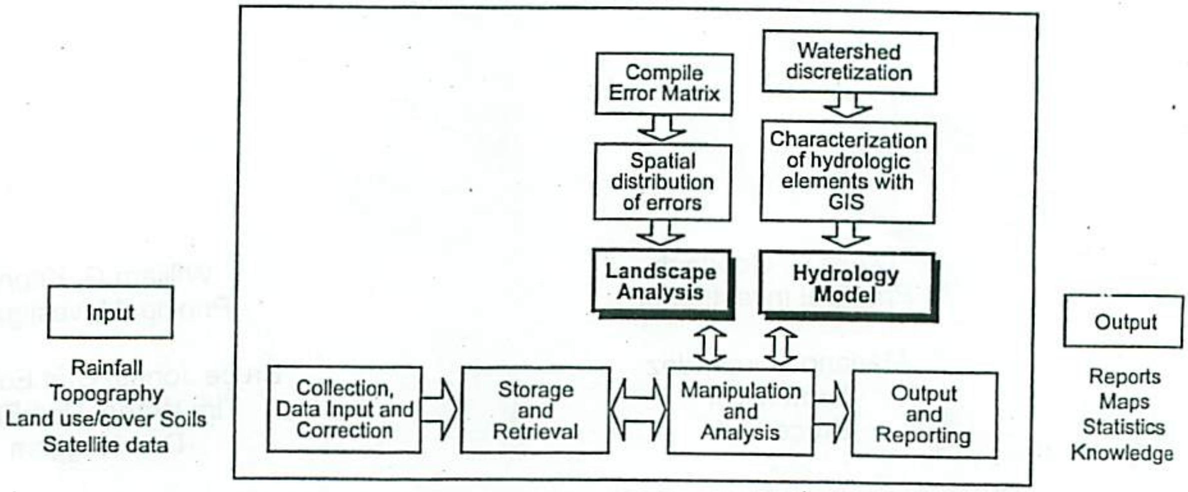

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Landscape Indicator Interface with Hydrologic Models

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Acknowledgements

We gratefully acknowledge Dr. Everett P. Springer, Environmental Science Group, Los Alamos National Laboratory, Los Alamos, NM; Dr. Ward Brady, Environmental Resources Program, Arizona State University, Tempe, AZ; Dr. Xiaohui Zhang, Advanced Resource Technology Group, University of Arizona, Tucson, AZ; and Dr. Ronald Parker, U.S. EPA, Office of Prevention, Pesticides, and Toxic Substances, Washington, DC for their helpful criticism and suggestions as reviewers for this Research Proposal.

Notice: The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development (ORD), partially funded and managed the research described here. It has been peer reviewed by the EPA and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation by EPA for use.

Table of Contents

Abstract

Critical gaps in our understanding of scale effects on hydrological and ecological processes, biological community factors and their interactions affecting semi-arid ecosystems limit our ability to scale up from point processes to broader areas of the landscape. The proposed research will narrow this gap and determine the vulnerability of arid and semi-arid landscapes to a variety of natural and anthropogenic stressors at multiple scales. A fundamental project task is the modification of existing watershed models to consider human-induced changes in landscape pattern. The research utilizes the 40-year record of vegetation, soils, and hydrological data collected at the Walnut Gulch Experimental Watershed and remotely sensed and ground-based data to develop process models that relate landscape composition and pattern attributes to the hydrologic condition of the watershed (water storage and availability, infiltration, surface water quality; erosion, flood frequency, duration and intensity). The long-term goal of this research is to provide operational models that relate landscape pattern to watershed condition and can be extrapolated across multiple scales including subwatershed, watershed, and basin, for a variety of arid and semi-arid basins.

In the first phase of the research project, two hydrological models were selected for watershed assessment across multiple scales. The two models were selected based upon the influence of vegetation characteristics on watershed response. Both models are currently being applied at the Walnut Gulch Experimental Watershed and at the San Pedro River Basin to evaluate the effects of land cover on watershed response. Particular research objectives being investigated in this phase of the project are: (1) evaluation of the effects of misclassification error of Landsat land use/ land cover imagery on watershed response and, (2) assessment of the number of subwatershed elements (basin delineation) and averaged land cover information on hydrologic response as a function of scale. Future research will focus on developing and implementing a PC landscape/hydrologic modeling tool for ecosystem risk assessment across multiple scale domains. The modeling tool will accommodate scientific advances in the quantification of risk assessment via hydrologic process modeling and landscape analysis.

Section 1
Introduction

In June 1997, the United States Environmental Protection Agency (EPA), National Exposure Research Laboratory (NERL), Landscape Science Program and the United States Department of Agriculture, Agricultural Research Service (ARS) entered into an Interagency Agreement for the purpose of improving ecosystem risk assessment via characterization research, process modeling, and long-term monitoring studies.

1.1 Goal and Objectives

The primary goal of this project is to develop methods and provide operational hydrologic modeling tools for determining the vulnerability of arid and semi-arid landscapes to natural and human induced landscape pattern changes across multiple scale domains.

The specific objectives of this project are to: (1) Develop a sound modeling approach through calibration and validation on the Walnut Gulch and Upper San Pedro River watersheds; (2) Assess the impacts of data resolution and misclassification error on watershed response; (3) Determine model sensitivity to watershed variability and input data; (4) Determine the degree of complexity required for accurate modeling and assessment at a range of scales; (5) Apply defensible modeling techniques to a number of basins throughout the semi-arid Southwest; (6) Assess the impacts of land cover change for a variety of basins with differing topographic, hydrologic, and land cover pattern characteristics; (7) Develop a desktop computer application for assessing the hydrologic impacts of land cover change in semi-arid regions; and 8) Publish methodology and results in peer-reviewed journals.

1.2 Problem Statement

Environmental quality affects our health, our quality of life, and the sustainability of our economies. Yet pressures from an increasing population coupled with the need for economic development and an improved standard of living often have multiple negative effects on our natural resources.

Natural resources of semi-arid regions, such as timely water supplies, fertile soils, vegetation and wildlife, tend to be scarce, and existing resources are easily damaged by changes in precipitation pattern and by human action.

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 (Slocombe, 1993).

Although a number of initiatives and strategies focus on larger-scales (WFPB, 1992; FEMAT, 1993; SAT, 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. Watershed analysis has been adopted to implement ecosystem-oriented management on state and private (WFPB, 1992; 1993) and federal (FEMAT, 1993) lands in the Pacific Northwest.

This research project will develop methods and provide operational hydrologic modeling tools under a watershed analysis framework for determining the vulnerability of semi-arid landscapes to natural and human-induced landscape pattern changes across multiple scale domains.

Section 2
Background

As populations grow and economic activity increases in the western semi-arid 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 vulnerability of semi-arid landscapes to a variety of natural and anthropogenic stressors at multiple scales can be investigated.

2.1 Effects of Land Cover on Ecological and Hydrological Processes

Many studies have shown that the land uses within a watershed can account for much of the variability in stream water quality (Omernick, 1987; Hunsaker et al., 1992; Charbonneau and Kondolf, 1993; Roth et al., 1996). Agriculture on slopes greater than three percent, for example, increases the risk of erosion (Wischmeier and Smith 1978). A drastic change in vegetation cover, such as clear cutting in the Pacific Northwest, can produce 90% more runoff than in watersheds unaltered by human practices (Franklin, 1992). The linkage between intact riparian areas and water quality is well established (Karr and Schlosser, 1978; Lowrance et al., 1984; 1985). For example, riparian habitats function as "sponges", greatly reducing nutrient and sediment runoff into streams (Peterjohn and Correll, 1984).

The percentage and location of natural land cover influences the amount of energy that is available to move water and materials (Hunsaker and Levine, 1995). Forested watersheds dissipate energy associated with rainfall, whereas watershed with bare ground and anthropogenic cover are less able to do so (Franklin, 1992). The percentage of the watershed surface that is impermeable, due to urban and road surfaces, influences the volume of water that runs and increases the amount of sediment that can be moved (Arnold and Gibbons, 1996). Watersheds with highly erodible soils tend to have greater potential for soil loss and sediment delivery to streams than watersheds with non-erodible soils.

Moreover, intense precipitation events may exceed the energy threshold and move large amounts of sediments across a degraded watershed (Junk et al., 1989; Sparks, 1995). It is during these events that human-induced landscape changes may manifest their greatest negative impact.

A direct and powerful link exists between vegetation and hydrological processes in semi-arid environments. Vegetation plays a pivotal role in determining the amount and timing of the runoff, which ultimately supplies mass and energy for the operation of hydrologic and erosive processes (Graf, 1988). Most analyses that assess the variability of sediment yield demonstrate that at the lower end of the precipitation scale (representing semi-arid conditions), small changes in annual precipitation bring about major changes in vegetation communities and associated sediment yields (Graf, 1988). For example, for a mean annual temperature of 10° C, the Langbein and Schumm (1958) curve reaches a peak at an effective precipitation of about 300 mm

(Figure 1), trailing off at lower values because of lower runoff totals and at higher ones because an increasingly abundant vegetation cover affords better protection against erosion.

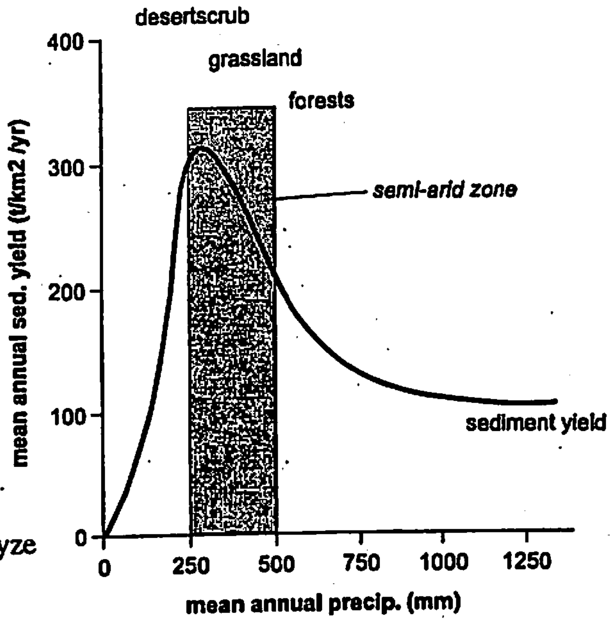

Figure 1. Erosion as a function of precipitation. After Langbein & Schumm (1958)

2.2 Effects of Aggregation of Landscape Attributes on Watershed Response

Recent papers (e.g., Roth et al., 1996; Weller et al., 1996) suggest that the importance of landscape features may change in different environmental settings, or when moving from one spatial scale to another. Therefore, methods to analyze and interpret broad spatial scales are becoming increasingly important for hydrological and ecological studies. Parameters and processes important at one scale are frequently not important or predictive at another scale, and information is often lost as spatial data are considered at coarser scales of resolution (Meentemeyer and Box, 1987). Furthermore, hydrological problems may also require the extrapolation of fine-scale measurement for the analysis of broad-scale phenomena. Therefore, the development of methods that will preserve information across scales or quantify the loss of information with changing scales has become a critical task.

Wood et al. (1988) carried out an empirical averaging experiment to assess the impact of scale. They averaged runoff over small subwatersheds, aggregating the subwatersheds into larger watersheds, and repeating the averaging process. By plotting the mean runoff against mean subwatershed area, they noted that the variance decreased until it was rather negligible at a watershed scale of about 1 km^2. That analysis has been repeated for the runoff ratio (Wood, 1994) and evaporation (Famiglietti and Wood, 1995) using data from Kings Creek, Kansas, which was part of the FIFE '87 experiment. Results from the experiment show that at small scales there is extensive variability in both runoff and evaporation. This variability appears to be controlled by variability in soils and topography whose correlation length scales are on the order of $10^2 - 10^3$m, typical of hillslopes. At an increased spatial scale, the increased sampling of hillslopes leads to a decrease in the difference between subwatershed responses. At some scale, the variance between hydrologic response for watersheds of the same scale should reach a minimum.

2.3 Integration of GIS and Remote Sensing in Hydrologic Modeling

Spatially distributed models of watershed hydrological processes have been developed to incorporate the spatial patterns of terrain, soils, and vegetation as estimated with the use of remote sensing and geographic information systems (GIS) (Band et al., 1991; 1993; Famiglietti and Wood, 1991; 1994; Moore and Grayson, 1991; Moore et al., 1993; Wigmosta et al., 1994; Star et al., 1997). This approach makes use of various algorithms to extract and represent watershed structure from digital elevation data. Land surfaces attributes are mapped into the watershed structure as estimated directly from remote sensing imagery (e.g., canopy leaf area index), digital terrain data (slope, aspect, contributing drainage area) or from digitized soil maps, such as soil texture or hydraulic conductivity assigned by soil series.

Over the past decade numerous approaches have been developed for automated extraction of watershed structure from grid digital elevation models (e.g., Marks et al., 1984; O'Callaghan and Mark, 1984; Band, 1986; Jenson and Dominque, 1988; Moore et al., 1988; Martz and Garbrecht, 1993; Garbrecht and Martz, 1993; 1995; Garbrecht et al., 1996). O'Callaghan and Mark (1984) define a digital elevation model (DEM) as any numerical representation of the elevation of all or part of a planetary surface, given as a function of geographic location. The most widely used method for the extraction of stream networks that has emerged is to accumulate the contributing area upslope of each pixel through a tree or network of cell to cell drainage paths and then prune the tree to a finite extent based on a threshold drainage area required to define a channel or to seek local morphological evidence in the terrain model that a channel or valley exists (Band and Moore, 1995).

The techniques used for delineation of the drainage path network by surface routing of drainage area and local identification of valley forms are ultimately dependent on a topographic signal generated in a local neighborhood on the DEM. As the approach is used to extract watershed structure with increasingly lower resolution terrain data, higher frequency topographic information is lost as the larger sampling dimensions of the grids act as a filter. Therefore, if watershed structural information is used to drive the hydrological model, the scaling behavior and consistency of the derived stream network with grid dimension needs to be addressed. One of the primary questions dealing with automated extracted channel network is that of the appropriate drainage density. Some authors suggest criteria to find this appropriate scale. For example, Goodrich (1991) found a drainage density of approximately 0.65 to 1.52 x 10^{-3}m for watersheds greater than 1 hectare was adequate for kinematic runoff modeling in semi-arid regions. Similarly, La Barbera and Roth (1994) proposed a filtering procedure based on the identification of threshold value for the quantity AS^k, where A is the contributing area, S the stream slope and k = 2. This procedure consists in the progressive removal from the drainage network of the first order stream which presents the minimum AS^k value; the procedure is iterated up to a given target value for the area drained by first order streams. Calore et al. (1997) found that above a certain threshold, an increase in resolution in the spatial description of drainage networks obtained from a DEM cannot be directly linked to an increase of information. The criterion they used for assessing the amount of information contained in the drainage was based on the information entropy concept of Shannon (1948).

Land use is an important watershed surface characteristic that affects infiltration, erosion, and evapotranspiration. Thus, almost any physically based hydrologic model uses some form of land use data or parameters based on these hydrologic processes (Spanner et al., 1990; 1994; Nemani et al., 1993). Distributed models, in particular, need specific data on land use and their location within the basin. Some of the first research for adapting satellite-derived land use data was done by Jackson et al. (1976) with the US Army Corps of Engineers STORM Model (US Army Corps of Engineers, 1976). However, most of the work on adapting remote sensing to hydrologic modeling has been with the Soil Conservation Service (SCS) runoff curve number model (US Department of Agriculture, 1972). The SCS model has been widely used in hydrology and water resources planning of agricultural areas. The model was originally developed for predicting runoff volumes from agricultural fields and small watersheds. However, it has been expanded for subsequent use in a wide variety of conditions at many basin sizes including urban and suburban areas. In early work with remotely sensed data, Jackson et al. (1977) demonstrated that land cover (particularly the percentage of impervious surface) could be used effectively in the STORM Model (US Army Corps of Engineers, 1976). In a study of the upper Anacostia River basin in Maryland, Ragan and Jackson (1980) demonstrated that Landsat-derived land use data could be used for calculating synthetic flood frequency relationships. Results can be erroneous if land use is mislabeled. A study by the US Army Corps of Engineers (Rango et al., 1983) estimated that any individual pixel may be incorrectly classified about one-third of the time. However, by aggregating land use over a significant area, the misclassification of land use can be reduced to about 2% (Engman and Gurney, 1991).

More recently, vegetation classification studies implementing digital satellite data have utilized higher spatial, spectral, and radiometric resolution Landsat Thematic Mapper (TM) data with much more powerful computer hardware and software. These studies have shown that the higher information content of TM data combined with the improvements in image processing power result in significant improvements in image processing power resulting in significant enhancement in classification accuracy for more distinctive classes (Congalton et al., 1998).

A detailed analysis of the effects of the thematic accuracy of land cover is necessary before any attempt on using the hydrologic modeling tool to determine the vulnerability of semi-arid landscapes to land cover changes. The accuracy of maps made from remotely sensed data is measured by two types of criteria (Congalton and Green, 1999): location accuracy and, classification or thematic accuracy. Location accuracy refers to how precisely map items are located relative to their true location on the ground. Thematic accuracy refers to the accuracy of the map label in describing a class or condition on the earth. For example, if the earth's surface was classified as forest, thematic map accuracy procedures will determine whether or not forest has been accurately labeled forest or inaccurately labeled as another class, such as water.

The widespread acceptance and use of remotely sensed data has been and will continue to be dependent on the quality of the map information derived from it. However, map inaccuracies or error can occur at many steps throughout any remote sensing project. According to Congalton and Green (1999), the purpose of quantitative accuracy assessment is the identification and measurement of map errors. Quantitative accuracy assessment involves the comparison of a site on a map against reference information for the same site. The reference data is assumed to be correct.

The history of accuracy assessment of remotely sensed data is relatively short, beginning around 1975. Researchers, notably Hord and Brooner (1976), van Genderen and Lock (1977), proposed criteria and techniques for testing map accuracy. In the early 1980s more in-depth studies were conducted and new techniques proposed (Rosenfield et al., 1982; Congalton et al., 1983; and Aronoff, 1985). Finally, from the late 1980s up to present time, a great deal of work has been conducted on accuracy assessment. An important contribution is the error matrix, which compares information from reference sites to information on the map for a number of sample areas. The matrix is a square array of numbers set out in rows and columns that express the labels of samples assigned to a particular category in one classification relative to the labels of samples assigned to a particular category in another classification. One of the classifications, usually the columns, is assumed to be correct and is termed the reference data. The rows usually are used to display the map labels or classified data generated from remotely sensed data. Error matrices are very effective representation of map accuracy, because the individual accuracy of each map category are plainly described along with both errors of inclusion (commission errors) and errors of exclusion (omission errors) present in the map (Congalton and Green, 1999). A commission error occurs when an area is included in an incorrect category. An omission error occurs when an area is excluded from the category to which it belongs. In addition to clearly showing errors of omission and commission, the error matrix can be used to compute overall accuracy.

Soils information derived from a GIS are generally gathered in a similar manner to vegetation, with the exception that remote sensing often cannot provide critical information about soil properties, especially if the soil is obscured by a vegetation canopy (Band and Moore, 1995). Substantial progress has been made in estimating near-surface and profile soil water content with active and passive microwave sensors and in the estimation of hydraulic properties by model inversion (e.g., Entekhabi et al., 1994). However, in general, soil spatial information is the least known of the land surface attributes relative to its well-known spatial variability that has been observed in many studies (Nielsen and Bouma, 1985).

2.4 Model Selection and Development

Hernandez et al. (1998 a) provided an extensive review and evaluation of existing hydrologic models that might possibly be used in the analysis of landscape effects on watershed response at various spatial scales. Those models that met certain selection criteria were then examined and described in greater detail. The authors presented an overview of the availability of required model input data in US and Mexico. They then discussed the primary hydrologic processes important for multi-scale hydrologic modeling in the Lower Colorado River basin.

In a subsequent report, Hernandez and Goodrich (1998 b) examined the relationship between vegetal cover and surface runoff, erosion, and sediment yield from watersheds. The authors conducted a more detailed examination of likely hydrological models and determined that the SWAT (Arnold et al., 1994) and KINEROS (Smith et al., 1995) models were the most appropriate for evaluating watershed-scale and river basin-scale landscape effects, respectively. In order to conduct watershed scale assessment at the scale of the San Pedro River Basin and the Walnut Gulch Watershed, it is necessary to allow characterization of a variety of hydrologic process at different spatial and temporal scales. With the available data, the hydrologic model SWAT appears to be the best model suited for characterizing the hydrological and erosion processes at the scale of the San Pedro River Basin. The SWAT model offers flexible watershed configuration, reach routing transmission losses, irrigation and water transfer, lateral flow, groundwater, and detailed lake water quality components. Four strategies for parameterizing the subwatersheds in the SWAT model include: a three dimensional grid, two-dimensional hillslope, multiple one-dimensional, and lumped one-dimensional. The effects of land cover and land use can be incorporated explicitly in the basin modeling by using the grid, two dimensional, and multiple one-dimensional configurations. In addition, SWAT operates on a daily time step and more seasonal framework. This feature allows the simulation of precipitation, snowmelt, evapotranspiration, soil moisture, and infiltration at a limited complexity level.

KINEROS is suitable for a smaller scale such as the Walnut Gulch Experimental Watershed and more focused, detailed investigations of runoff an erosion because is a distributed, event-oriented, physically based model describing the processes of surface runoff and erosion from small agricultural and urban watersheds. However, the greater complexity of KINEROS also entails greater data requirements. It has been developed and validated largely in arid and semi-arid setting with explicit treatment of channel losses. In addition, KINEROS has a specially developed space-time rainfall interpolator that allows it accurately treatment of highly variable thunderstorm rainfall. KINEROS infiltration and erosion parameters are primarily derived through soil characteristics with modifications made for surface cover conditions. For watersheds larger than 1000 ha, application of a detailed, process based model, such as KINEROS, may be difficult to justify in the absence of distributed rainfall data, given comparable results from a simpler model which does not entail the costs associated with detailed basin characterization required for KINEROS model inputs.

The combination of these two models will allow users to identify hydrological and ecological problems at the basin scale using the SWAT model, once the problem area has been defined, if enough data is available, the KINEROS model can be applied to further investigate possible solutions to the problem.

In a third report, Hernandez et al. (1998 c) tested the response of these two models on a subset within the Walnut Gulch Experimental Watershed in Tombstone, Arizona. Based on the results, calibration and validation of the hydrologic models were recommended to improve the reliability of the models as a function of model input data. Furthermore, a sensitivity analysis was advised to support the integration of The North American Landscape Characterization (NALC) (USGS, 1999b) based land cover class and the State Soil Geographic (STATSGO) Database (USDA-NRCS, 1994) with the hydrologic simulation models.

The NALC project is a component of the Multi-Resolution Land Characteristics (MRLC) Consortium. The MRLC vision is to facilitate the development of a national multi-resolution land cover database from both coarse (Advanced Very High Resolution Radiometer [AVHRR]) and medium resolution (Landsat Thematic Mapper [TM]) satellite imagery and field data. The main objective of the NALC project is to produce standardized remote sensing data sets that consists of three or more registered Landsat Multi-Spectral Scanner (MSS) images corresponding to the 1990s, 1980s, and 1970s time periods. On average, a NALC data set consists of one scene from the 1990s and 1980s and two from the 1970s.

The STATSGO database was designed primarily for regional, multi-state, river basin, multi-county resource planning, management, and monitoring. This data is not detailed enough to make interpretations at a county level. Soil maps for STATSGO are compiled by generalizing more detailed soil survey maps. Where more detailed soil survey maps are not available, data on geology, topography, vegetation, and climate are assembled, together with Landsat images.

Section 3
Conceptual Model

The conceptual model of the integrated landscape/hydrologic modeling tool is described in Figure 2. The conceptual model is designed within a data base management system framework which comprises the following elements: collection, input & correction; storage and retrieval; manipulation & analysis; and output & reporting. Each element is described in the following sections.

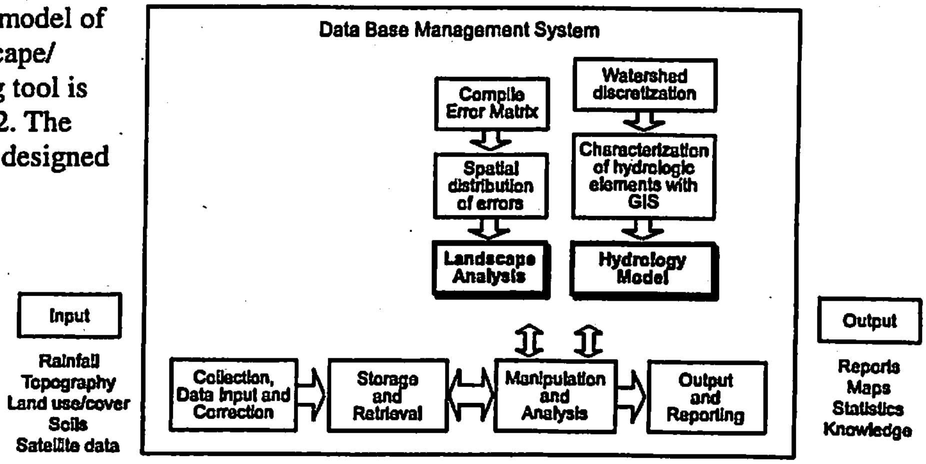

Figure 2. Conceptual model of integrated landscape/hydrologic modeling tool.

Collection, Data Input and Correction

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 the data have been entered, the data will be checked for errors such as possible inaccuracies, omissions, and other problems.

Storage and Retrieval

Building a digital database is costly and time-consuming process and it is essential that the digital map information is transferred from the magnetic media of the computer to a more permanent storage medium where it can be safely preserved.

Manipulation and Analysis

The landscape analysis and the hydrologic modeling will be carried out in this module. The landscape analysis consists of an error matrix for land cover; a computer program to simulate the spatial distribution of errors; and a computer program to calculate landscape metrics. The hydrologic modeling component consists of a computer program to characterize watershed complexity; a user-friendly GIS interface to parameterize the hydrologic models; and hydrologic models. Results from the landscape analysis will provide information to the hydrologic model for evaluating the effects of misclassification error of Landsat land use/cover on watershed response. Furthermore, the effects of drainage network density and land cover on watershed response will be carried out in this module.

Output and Presentation

The data output and presentation module is concerned with the way the data are displayed and how the results of the analyses are reported to the users. Data 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.

Section 4
Technical Approach

This section focuses primarily on describing the tasks to be carried out on the research proposal. A tentative schedule and milestones for calendar years 1999-2002 is presented in Table 1 (Appendix). This section includes description of the area, study design/methodology, data acquisition, and quality assurance.

4.1 Description of the Area

Walnut Gulch Experimental Watershed

The Walnut Gulch Experimental Watershed (WGEW) encompasses approximately 150 km² in southeastern Arizona, USA (Figure 3) 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 semi-arid Southwest and is a transition zone between the Chihuahuan and Sonoran Deserts. Elevation of the watershed ranges from 1,220 m to 1,890 m. Cattle grazing is the primary land use with mining, distributed urbanization, wildlife habitat and recreation making up the remaining uses. The city of Tombstone is undergoing relatively fast growth, and the urban area within the watershed is growing. For further details on the description of the Walnut Gulch Experimental Watershed see Osborn (1983) and Renard et al. (1993).

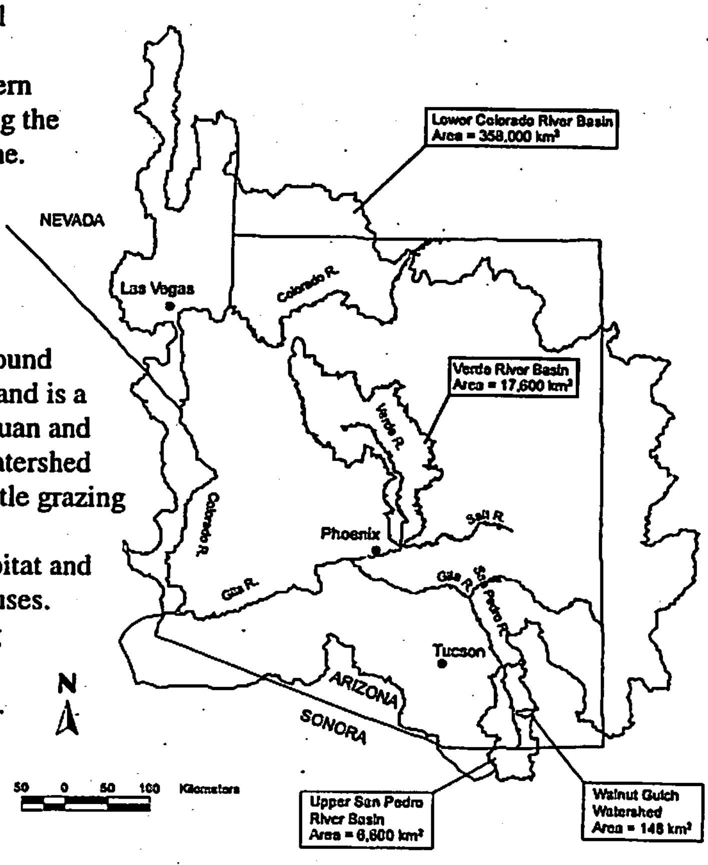

Figure 3. Locations of the Walnut Gulch Experimental Watershed and the Upper San Pedro Basin within the Lower Colorado River Basin.

The San Pedro Basin

The Sonoran desert and surrounding vegetation extend from central Sonora, Mexico, up through southern Arizona, USA, providing an exceptionally diverse ecosystem that is being studied by scientists in many disciplines on both sides of the border. The San Pedro River Basin (SPRB) covers about 12,000 km^2 and spans the Mexico-US Border from northern Sonora into southeastern Arizona (Figure 3). It has particularly interesting characteristics: significant topographic variability (1,200 – 2,900 m) providing ecological and climatic diversity over distances as short as 20 km; significantly different cross-border land uses visible from satellite multi-spectral images. Diverse vegetation types include Sonoran and Chihuahuan desertscrub, grasslands, chaparral and Madrean evergreen woodlands, and high-elevation conifer forests (McClaran and Brady, 1994).

The San Pedro riparian corridor is a narrow area sustained many times of the year by the regional aquifer. It has been declared one of the '12 Last Great Places of the Western Hemisphere' by The Nature Conservancy and the No. 4 most endangered U.S. river by American Rivers (1997). For further details on the description of the San Pedro River Basin see Goodrich (1994).

4.2 Study Design/Methodology

Pursuant to the primary objective of modeling hydrologic response to land use, the life cycle of this research project will be divided into several overlapping phases that build in complexity and understanding towards the development of a robust scientifically defensible application. Throughout the project, user interface programs will be designed and developed to ease model application. The first phase will be devoted to model development and application on relatively small, homogeneous areas. Once the fundamental validity of this modeling approach has been demonstrated, significant model testing and optimization will be used to determine potential sources of error and the best techniques and tools at a range of basin scales and complexities. Model application on a variety of basins throughout the semi-arid Southwest will be used to further refine the approach. Ultimately, the model will be implemented as a unified GIS/hydrologic modeling tool for desktop applications.

4.2.1 Model development

Compile climatic and hydrologic data for the WGEW and SPRB

On Walnut Gulch, rainfall information will be compiled from the 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 streamflow data at Charleston will be obtained from the USGS database (USGS, 1999a).

Assemble GIS data at high/low resolution for the WGEW and SPRB

Input data is the driving force behind model development and implementation. One of the first steps in the evolution of this 4-year research project will be the assemblage of these input data layers for three intensive study watersheds. To date, the emphasis on modeling has been placed at the sub-watershed level to demonstrate model functionality given the range of input data. During the next phase of research, these findings will be expanded to include the entire WGEW and the SPRB. As such, we will be acquiring and error-checking the input data required for model application on the WGEW and the SPRB.

A high-resolution, highly accurate geographic information system (GIS) database has been created for the WGEW. A detailed soil survey (Breckenfield et al., 1995) was digitized as part of the effort for capturing detailed geographic data. This soil survey provides an opportunity for determining the impact of input data quality and resolution on model efficiency (defined as the degree to which model prediction is similar to observed data). Towards this end, data will be assembled for model input for both high and standard resolutions within WGEW, and at the standard resolutions on the SPRB.

Assess input parameters and construct look-up tables for GIS

The hydrologic models that will be used in this research are spatially distributed, and hence require a large number of input parameters. These parameters describe the physical properties of the model area, and it is critical that the methods used to determine these values be as consistent, accurate and repeatable as possible under the constraints of the base input data across a range of applications. Many of the model parameters, such as those relating to topography and vegetation type, will be determined directly from available spatial data stored in a GIS (Martz and Garbrecht, 1992; Garbrecht et al., 1996; DiLuzio et al., 1998). However, a large number of parameters vary widely in space and time, and are not directly measurable. These parameters must be derived through empirical relationships that relate quantifiable parameters to those that must be estimated (Brakensiek and Rawls, 1983; Shen and Julien, 1993).

A thorough vetting of the required parameters and the methods used to estimate their values throughout the study areas is of primary importance to the early phases of this project. Input parameter tables are available for both KINEROS and SWAT, and we will develop and report on the manner by which each of the parameters will be determined. Such a report will be critical to future interests towards quality assurance and control since the measures will be repeatable and clear.

Once the methods used to determine the input parameters have been decided upon, techniques for implementing their application across the study area will be developed. Many of these procedures have already been developed and utilized in the preliminary modeling exercise (Hernandez et al., 1998c), but more research is needed on variable terrain (such as exists on the entire Walnut Gulch watershed and the San Pedro basin) to validate and finalize these procedures.

The goal of this phase of the research project is to create automated methods for characterizing modeled basins and parameterizing the hydrologic models. Neither SWAT nor KINEROS may be characterized as possessing simple input requirements for successful implementation. The complexity of the models requires complex input, and parameterizing these models at the necessary detail on large basins would be onerous and beyond the scope of this project in the absence of GIS and automated methods.

Calibrate and validate hydrologic models for the WGEW and SPRB at various model resolutions with KINEROS and SWAT

The calibration and validation process will be carried out using historical stream flow values along the San Pedro River at Charleston, Arizona and at the outlet of the WGEW. A statistical analysis of the historical records will be performed to determine the most appropriate periods for calibration and validation.

A detailed analysis will be carried out to determine the influence of land cover changes on hydrologic and erosion parameters as part of the calibration process. Furthermore, data from channel reaches and storm events on Walnut Gulch will be selected to estimate and calibrate transmission losses. That is, the transmission loss magnitude will be estimated by comparing the measured hydrographs at the upstream and downstream stations of a channel reach from storm events with all runoff originating above the upper station. The calibration procedure will be performed with the assistance of a computer-based optimization routine (PEST; Doherty, 1998) to adjust the parameters until simulated outputs fit the observed data as closely as possible. The selection of a criterion of model accuracy is an important aspect of the model calibration procedure since it provides the basis for adjusting parameter values. The Nash-Sutcliffe (1970) efficiency coefficient will be used as a criterion of goodness of fit in the calibration process.

There is the potential for introducing uncertainty and error both in calibrating the model parameters and in obtaining field data with which to compare the simulated output. Therefore, in order to reach some objective conclusion as to whether or not the model is performing to satisfaction, a validation procedure will be implemented. As in the calibration phase, the process of validation will involve a comparison of the observed and simulated outputs. However, in the validation phase, hydrologic parameters will not be adjusted, and a separate set of observed data will be used to compare total runoff, peak discharge, and suspended sediment concentration.

Results from the validation procedure illustrate model stability for a range of input data. Instability may exist due to the presence of either interdependent parameters or a parameter that was inadequately accounted for during calibration suddenly becoming crucial to model efficiency. If neither of these reasons for parameter variation can be substantiated, it may be an indication that the model itself can only fit observed data when optimized, and is therefore inadequate as a predictive tool for a non-calibrated situation (Beck, 1987).

Development of criteria for selecting watersheds based on hydrologic, ecological, and geomorphic characteristics

Model calibration and validation will be performed for the Walnut Gulch watershed and San Pedro Basin; investigations performed on these areas will provide the scientific justification for model application at a range of scales. Methodologies developed on Walnut Gulch and the San Pedro will be extended to a several (3-4) other basins in the semi-arid Southwest for intensive study.

Selection of the basins for future intensive study will be made on the basis of basin hydrologic, ecological, and geomorphic characteristics. The Walnut Gulch watershed and San Pedro Basin allow for investigations into the effects of scale, data error, and land use change on model efficiency and can provide insight into appropriate applications of this emerging technology. These study areas are located in the transition zone between the Chihuahuan and Sonoran deserts. However, they do not provide a means for investigating the impact of differences in basin physiographic characteristics nor basin input processes such as snowmelt, and hydrologic regime on the model application. Other gauged basins will be selected to provide spatial variability in model input across a broad range of basin scales.

The set of criteria for selecting the intensive study basins will be finalized within the next year. The possible selection criteria include basin size, climate, data availability, and hydrologic response. In order to investigate scaling issues, the selected basins will range in size from 3000-10,000 km^2, thereby bracketing the Upper San Pedro Basin. A range in climate and hydrologic response is desired; therefore, basins will be selected from different climatic regimes, potentially including the Sonoran desert (runoff caused by winter and summer rainfall), Colorado Plateau (runoff driven primarily by snowmelt) and Mohave desert (runoff from winter rains). The selection of basins may be refined by ecological region such as those outlined by Omernik (1987). Because the approach outlined in this research plan relies on the calibration and validation of the watershed models, it is a prerequisite that the chosen basins have an abundant data history. Necessary data include accurate spatial data describing topography, soils, and land cover derived from remote sensing (NALC, MRLC), and extensive runoff gaging data for the time period in which the land classification took place.

In addition, watersheds will be selected based on criteria that identify distinct landscape scale and form. Three attributes that quantitatively distinguish landscapes are drainage density (D), slope (S), and relief (H) (Dietrich and Montgomery, 1998). Strahler (1964) combined these attributes to form the geometry number: G=HD/S. The drainage density, slope, relief, and the geometry number will be calculated for a number of watersheds of different sizes from available DEMs.

Assess model efficiency relative to data resolution

Spatially distributed data that will serve as input to the hydrologic models will be developed from GIS map layers. Topographic, soil, and vegetation data will come from the three primary sources: the USGS DEM (USGS, 1999a) products; the NRCS STATSGO (USDA-NRCS, 1994) soil data; and the NALC (USGS, 1999b) land classification products. These data are served at relatively low levels of resolution (30 m, 30 m, and 60 m, respectively), and the impact of this resolution on model response needs to be investigated.

An investigation into the role of GIS data resolution will be carried out using the two soil maps at a range of scales on Walnut Gulch. The hydrologic models KINEROS and SWAT will be parameterized using primary and secondary data derived from the soil maps, and the impact of these data on model response will be determined. The hypothesis put forth for this phase of the research is that the more detailed soil map will improve model efficiency. However, the question of spatial scale must also be addressed to determine whether model behavior will be altered at the basin scale, where variability in soil classification tends to be less hydrologically significant.

4.2.2 Model testing and optimization

Analyze land cover misclassification based on error matrix

One of the most significant sources for model parameterization will be the NALC land classification data. The NALC data set contains information regarding the spatial distribution and temporal change in vegetation and land use across the study areas. These data are important because they not only contain relevant model data (estimates of canopy and ground cover, for examples), but also dynamically affect a host of hydrologic parameters (e.g., curve number, infiltration). The impact of misclassification of NALC data must therefore be addressed for better understanding model response and providing for quality assurance and control.

Land cover accuracy assessment

An accuracy assessment of 1997 Landsat Thematic Mapper (TM) land cover classification of the Upper San Pedro River Basin is being carried out in cooperation with the University of Arizona, Office of Arid Lands Studies. The accuracy assessment will produce an array of numbers set out in rows and columns that express the sample units assigned to a particular category in one classification relative to the number of samples units assigned to a particular category in another classification.

Determine impact of land cover misclassification errors on model efficiency

The effects of misclassification among inter-class land cover will be evaluated using a simulation model developed by Wickham et al. (1997). The error simulation model, written using the Arc/Info GRID module (ESRI, 1994), is based on (1) misclassification calculated from an error matrix, and (2) spatial autocorrelation in land cover classification error (Congalton, 1988). The model will be used to randomly introduce error into the San Pedro River Basin land cover map. The simulation model will provide different spatial distribution patterns of error. An error matrix supplied by Dr. Stuart Marsh, the University of Arizona, Office of Arid Lands Studies, will serve as the source data for the simulation model. For each error distribution pattern, the hydrologic parameters will be altered and the hydrologic simulation models will be run to evaluate the response of the watershed. Furthermore, errors of commission and omission will be interpreted with respect to the extent that these errors significantly alter parameter estimation; offsetting errors may mitigate the impact on model efficiency, while compounding errors may yield unrealistic results.

Sensitivity Analysis

A sensitivity analysis will be performed to examine the response of the hydrologic models as a function of land cover changes on the WGEW and SPRB. Sensitivity analysis is normally conducted by assessing the effect on the model output of a fixed percentage change in each model parameter, while holding all other parameter values constant (McCuen and Snyder, 1986). However, in this case a sensitivity analysis based on a fixed percentage change for each parameter value may be unrealistic due to the range of variation that is observed for each parameter in the field (Kirkby et al., 1993). Consequently, an alternative approach taken will be used employing frequency distributions for each hydrologic parameter. Model parameter changes will be a function of the parameters' standard deviations. Results from the sensitivity analysis will provide sound information as to whether land cover maps resolution being used as an input for the hydrologic models are adequate for multi-scale watershed assessment. Furthermore, a sensitivity analysis within each class cover will be carried out to examine the response of the hydrologic models as a function of canopy cover conditions. That is, hydrologic parameter values will be changed to consider canopy cover conditions such as poor, fair, and excellent for each class.

Create subwatershed maps at varying levels of complexity and assess model efficiency relative to network complexity for the WGEW and SPRB

Evaluation of the effects of the number of subwatershed elements and the averaging of land cover information on hydrologic response will be carried out. To address the issue of number of subwatershed elements necessary for adequate model behavior, the WGEW and SPRB will be divided into several scenarios with differing complexities. The criterion for delineating the watersheds is based on the critical source area concept wherein the initiation of channel routing is adjusted. Each of the watershed configurations will be modeled for runoff and sediment yield. On Walnut Gulch, KINEROS and SWAT will be used for single storm and continuous analyses, respectively, while only SWAT will be applied on the San Pedro. Model efficiency will be determined for the various simulation runs. It is predicted that an inverse relationship between watershed size and geometric complexity will be found. Determining this relationship is necessary for the distribution of model implementation since there is a need for a standardized approach to the determination of watershed configuration and minimum data requirement.

The entropy (Shannon, 1948) concept approach will be employed to assess the amount of information lost by averaging subwatershed elements. The performance of the hydrologic models is assessed by computing the entropy information for each watershed configuration and by comparing monthly and annual runoff simulations with observed data. The value of the entropy information increases with increasing the number of watershed elements up to a number of elements that no longer captures new information and the model results are not further improved.

4.2.3 Model application

Define design storms

A statistical analysis will be performed on measured rainfall records to determine the most likely spatial and temporal distribution of design storms. For example, peak rainfall timing will vary within different storm events, as will the loci of intensities. The analysis of measured rainfall hyetographs will show the most likely rainfall distributions, which will be used to develop the design storms. Design storms will be determined for the 2, 5, 10, and 25 year return periods.

Calibrate and validate hydrologic model for the intensive study basins

The calibration and validation process will be carried out using historical stream daily values at several stream gauges along the selected basins. A statistical analysis of rainfall and stream records will be performed to determine the most appropriate time periods. The calibration and validation of these data will be carried out employing the same procedure used for the Walnut Gulch watershed and San Pedro basin described above. However, since only one MRLC scene will be available, the calibration will be carried out using hydrologic information compiled for one-year period prior to the date the image was acquired. Similarly, the validation of the hydrologic model will be carried out using hydrologic information for one-year period after the date the image was acquired.

Model and analyze watershed response as a function of land cover change, spatial distribution of rainfall and design storms for the WGEW the SPRB

The measurement of rainfall during a storm event consists of determining the time over which an increment of rainfall depth occurs at a defined location. Consequently, the measurement of rainfall is a point measurement of a spatially variable parameter. Meteorological data, such as rainfall intensity, for non-measurement locations are not defined by measurement processes and must therefore be inferred, thereby introducing uncertainty and error. Many methods have been developed for the inference of the spatial distribution of rainfall from measured at a specific location (Luk and Ball, 1997). A spline surface method will be implemented for characterizing the spatial distribution of rainfall. This method consists of using low-order polynomials to avoid over-fitting the measurement points by high-order polynomials (Luk and Ball, 1997). Surfaces generated in this fashion have been found to be a robust spatial interpolation for meteorological data. Using digital land cover maps, interpolated rainfall depth and design storms, the hydrologic models will be calibrated and validated for assessing the relative changes of cover on watershed response.

Model and analyze watershed response as a function of land cover change and design storms for intensive study basins

A similar approach used for modeling the WGEW and the SPRB will be carried out for modeling intensive study basins.

4.2.4 Model Implementation

Create/update GIS programs (AML, Avenue) to automate GIS parameterization for delivering GUI-driven GIS/hydrologic modeling tool

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. Without a great deal of complexity, models cannot achieve the desired accuracy, but this complexity restricts their application by persons who are not intimately familiar with their operation. A stated goal of this research project is to develop and apply user-friendly programs that 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.

It is proposed that the GUI tools be designed for personal computer (PC) application. While it is recognized that powerful UNIX-based programs exist, it is probable that users of this technology will be more familiar with and have access to PCs; hence, to appeal to a wide audience, the programs will be tailored for the PC environment. Collaborating scientist at the US-EPA NERL location have been developing a PC-based landscape analysis toolkit (ATtILA-Analytical Tools Interface for Landscape Assessments) integrating GIS data with the derivation of landscape indicators in a GUI-driven environment by embedding the spatial analysis within ArcView (a PC-based GIS). It is proposed that this approach be extended to incorporate the hydrologic modeling work such that a comprehensive suite of landscape analysis tools including ecologic and hydrologic models is available to the interested party via a user-friendly interface.

Furthermore, an effort to link SWAT with ArcView has been undertaken by the USDA-ARS, Blackland Research Center. During the course of this project, collaborative efforts with scientist at the Blackland Research Center will be pursued, and the integration of KINEROS and SWAT with a PC-based GIS should be enhanced by existing research. Sections of the programming and GUI development effort will be developed throughout the life of the project, and intermediate products made available to beta testers, with the delivery and technology transfer targeted for 2002.

4.3 Data Acquisition

Due to the large scale on which model development and implementation will be based, data acquisition will play a critical role in the success of this project. The fundamental spatially distributed 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 freely available USGS 7.5' digital elevation models (DEMs), that soils information be derived from USDA-NRCS STATSGO soil polygons (also freely available), and that land cover come from EPA-NALC and Multi-Resolution Land Characteristics (MRLC) products, to be supplied by the US-EPA for the proposed research study basins. Distributed climatic data is the other primary model input supplied by the National Climatic Data Center (NCDC, 1997).

Data will be acquired on an as-needed basis according to the four project phases. The acquisition and verification of these data will be time-consuming due to the large quantity of data, and as such it will be collected in advance of each subsection of the project and error-checked prior to use. As part of the joint collaboration between the National Exposure Research Lab and the Southwest Watershed Research Center, the EPA will be responsible for providing digital cartographic data (GIS theme layers) to the USDA-ARS for the proposed study basins.

On Walnut Gulch, rainfall information will be compiled from historical 85-raingauge network data. Runoff data will come form 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 a).

Input data is the driving force behind model development and implementation. One of the first steps in the evolution of this long-term research project will be the assemblage input data layers for three study watersheds. To date, emphasis on modeling has been placed at the subwatershed level to demonstrate model functionality given the range of input data. During the next phase of the research, these findings will be expanded to include the entire Walnut Gulch watershed and the larger San Pedro Basin. As such, we will be acquiring and error-checking the input data required for model application on the Walnut Gulch and San Pedro watersheds.

4.4 Quality Assurance

Quality assurance for this project will address the following issues: the rationale to select hydrologic models and how each model captures relevant processes; assessment procedures for identifying and correcting errors in source data; methods to interpret and analyze results from calibration and validation processes; procedures to document performance results; and, procedures to document software development. The following sections will focus on the description of each issue.

4.4.1 Rationale for model selection

In the selection process, strong emphasis was placed on models that were able to characterize complex watershed representations to explicitly account for spatial variability of soils, rainfall distribution, and vegetation heterogeneity. The effects of land use and land cover on surface runoff and sediment yield were also stressed in the model selection criteria. Furthermore, we concentrated on models that characterize surface runoff and sediment yield producing mechanisms. For analysis of large watersheds, where storage characteristics plays a key factor on surface runoff, we selected models that account for channel routing and reservoir storage. Moreover, the governing equations describing the hydrologic and soil erosion processes were a major factor in selecting the models. That is, we were interested in models with 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 theory and structure of both models and verification of model results. First, the basic theory and assumptions of the processes are presented. Next, test results for both models are presented.

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. The objective in model development was to predict the impact of management on water, sediment and agricultural chemical 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. The SWAT model characterizes the main hydrologic processes contributing to runoff and sediment yield as follows.

Weather

The weather variables necessary for driving SWAT are precipitation, air temperature, solar radiation, wind speed, and relative humidity. If daily precipitation and maximum/minimum temperature data are available, they can be input directly to the model. If not, the SWAT weather generator routine can simulate daily rainfall and temperature. Solar radiation, wind speed, and relative humidity are always simulated.

Surface runoff

Runoff volume is estimated with a modification of the SCS curve number method (USDA-SCS, 1972). Peak runoff rate estimates are based on a modification of the Rational Formula. The runoff coefficient is calculated as the ratio of runoff volume to rainfall. The rainfall intensity during the watershed time of concentration is estimated for each storm as a function of total rainfall using a stochastic technique. The watershed time of concentration is estimated using the Manning's Formula considering both overland and channel flow.

Transmission losses

Flow abstractions, or transmission losses, reduce runoff volume as the flood wave travels downstream. SWAT uses Lane's method described in Chapter 19 of the SCS Hydrology Handbook (USDA-SCS, 1983) to estimate transmission losses. Channel losses are a function of channel width and length, and flow duration. Both runoff volume and peak rate are adjusted when transmission losses occur.

Sediment yield

Sediment yield is estimated for each subbasin with the Modified Universal Soil Loss Equation (MUSLE) (Williams and Brendt, 1977). The model runoff component supplies runoff volume and peak runoff values required by the MUSLE.

KINEROS, an acronym for KINematic runoff and EROSion model, has evolved over a number of years primarily as a research tool (Smith et al., 1995). However some consulting firms have been attracted by several of its unique features and KINEROS has been used as an engineering tool in the U.S. and abroad. 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 describing the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds. A cascade of planes and channels represents the watershed; 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.

KINEROS divides the watershed of interest into an equivalent network composed of runoff surfaces or planes, intercepting channels, and ponds or detention storages. Each of these is oriented such that the 1-dimensional flow can be assumed. Runoff surfaces may be composed of a cascade of rectangular surfaces, which allows the simulation of converging flow areas, or areas of non-uniform slope, hydraulic resistance, or soils. Hortonian runoff is then simulated for the network of elements, culminating in the production of a simulated hydrograph at the outlet. The processes simulated will be described in general order of occurrence in the runoff – erosion generation process.

Distributed rainfall data

The model requires information in the form of accumulated depth/time pairs, and converts this data into rainfall rate pulses.

Interception

A total depth of interception can be specified for each runoff element, based on the vegetation or other surface condition. This amount is taken from the earliest rainfall pulses until the potential interception depth is filled. The modified rainfall pulse data then becomes input to the soil surface.

Infiltration

The infiltration model used in KINEROS (Smith and Parlange, 1978) is based on an approximate solution of the basic equation of unsaturated flow.

Overland flow

When the rainfall rate exceeds the infiltration capacity and sufficient water ponds on the surface to overcome surface tension effects and fill small depressions, overland flow begins. The kinematic wave equations are a simplification of the Saint Venant equations and do not preserve all the properties of the more complex equations. Specifically, backwater cannot be simulated. It has been shown that the kinematic wave formulation is an excellent approximation for most overland flow conditions (Woolhiser and Ligget, 1967; Morris and Woolhiser, 1980).

Channel routing

Unsteady, free surface flow in channels is also represented by the kinematic approximation to the equations of unsteady, gradually varied flow. Channels segments can receive uniformly distributed but time-varying lateral inflow from planes on either or both sides of the channel, or from one or two channels at the upstream boundary, or from a plane at the upstream boundary. The dimensions of planes are chosen to completely cover the watershed, so rainfall on the channel is not considered directly.

Erosion

The model can simulate the movement of eroded soil along with the movement of surface water. KINEROS accounts separately for erosion caused by raindrop energy and erosion caused by flowing water and continues the simulation through channel and pond elements.

The computer codes and the underlying assumptions of each model have been thoroughly tested with one or more studies. The purpose of code verification is to demonstrate that the model represents accurately the effects of an actual or hypothetical set of processes and forecast one or more possible outcomes. Examples of code verification are included in the user's manual of both models.

The SWAT model has been validated at two different spatial scales: small watershed and river basin. At the small scale Arnold et al. (1994) applied the model to a 17.7 km^2 watershed in Riesel, Texas within the Texas Blackland Prairie Land resource area. They reported efficiency coefficients of predicted annual water yields and sediment yields between 0.70 and 0.80, indicating a reasonable goodness of fit. The hydrologic response of the Lower Colorado River basin in Texas has been simulated and compared to measured USGS streamflow data to test the model on a relatively large river basin (9,000 km^2). At the upstream end of the simulated area, measured outflows from Lake Travis (west of Austin) were input to the model and flow was routed trough the basin until it reached the Gulf of Mexico at Matagora Bay. The only measured data available was streamflow data. Sediment and nutrient loadings were not available for the basin. A comparison of monthly and annual measured and predicted stream flows at Bay City, Texas show efficiency coefficients of 0.60.

The kinematic overland flow routing component of KINEROS has been thoroughly tested using data from the Colorado State University Outdoor Rainfall-Runoff Experimental Facility (ORREF) (Smith et al., 1995). This unique facility allows relatively precise measurement of rainfall and runoff at a scale comparable to small watersheds, and has been described by Dickenson et al. (1967) and Woolhiser et al. (1971). Singh (1974) analyzed data from 210 experiments runs with 50 different configurations and found that the kinematic wave formulation provided a good description of surface runoff from the facility. Kibler and Woolhiser (1970) have demonstrated that the response of a converging section can be well approximated by the response of a cascade of rectangular surfaces as used in KINEROS. The KINEROS model has been applied to several semi-arid watersheds covering a range of basin scales within the USDA-ARS Walnut Gulch Experimental Watershed, in southeastern Arizona (Smith et al., 1995).

A detailed analysis describing model selection, model structure, and model assumptions is provided by Hernandez et al. 1998 b.

4.4.2 Source data

It is critical that the validity of derived information products be tested to provide a reasonable estimation of confidence for use in ecological/hydrological modeling. Accuracy information is required in process modeling in order to understand the risk involved in relying on GIS- and remote sensing-based information products. The type of accuracy assessment required may depend on whether the results are relative or absolute measurements. In cases where simple information on distance or area is derived from a single data source, error such as a simple coordinate offset may not be significant. However, information derived from multiple spatial sources will generally require enforcement of absolute positional accuracy (Star et al., 1997). A similar division applies to thematic accuracy assessment when derived information products are either interval (relative accuracy) or ratio (absolute accuracy) in nature.

Contingency matrices will be used to compare database content with samples derived from ground survey or some other information source in which there is a high degree of confidence. These matrices provide detailed information on the types and magnitudes of error found in original data or derived information products. In remote sensing classification, the matrix relates the class assigned to a pixel in the database with the class determined for the same pixel by ground survey. In GIS applications, the error matrix may compare the class assigned to an entire polygon with the class assessed by visiting the polygon in the field. In addition to assessing the accuracy of attribute measurement within a field, it may also be important to understand the positional accuracy of features. Statistics for describing the probabilistic position of points are the root mean square error (RMSE) and the mean square positional error (MSPE). The majority of image processing and GIS software packages derive the RMSE. In order to track error accumulation effectively, methods are required to assess the generation of error associated with specific processes and to keep an accounting of the spatial, temporal, and attribute characteristics of this accumulating error. Methods for providing a transcript of data processing histories exist in many commercial remote sensing and GIS packages. An integrated solution to tracking the data processing flow, called lineage tracing, is described by Lanter (1989). This approach uses a LISP language shell in which the Arc/Info GIS package (produced by Environmental Systems Research Institute) is run. The described algorithm allows automated backwards and forwards reconstruction of intermediate data products between data inputs and information outputs.

4.4.3 Model application

The following discussion focuses on the calibration and validation of the models, documentation to code, documentation of statistical analyses, and summary of performance results.

The purpose of the calibration is to establish that the model can reproduce observed runoff and sediment yield. During the calibration, a set of values of the parameters describing the main hydrologic processes in the watershed is found that approximates the observed runoff and sediment yield within a pre-established range of error. Figure 4 depicts the procedure that will be carried out in this research project. The calibration procedure begins by estimating initial parameters values of the hydrologic model. Next, the model is executed and results are compared to the observed values from the field system. Based on the error analysis; that is, if the differences between computed and measured output are within the predefined range

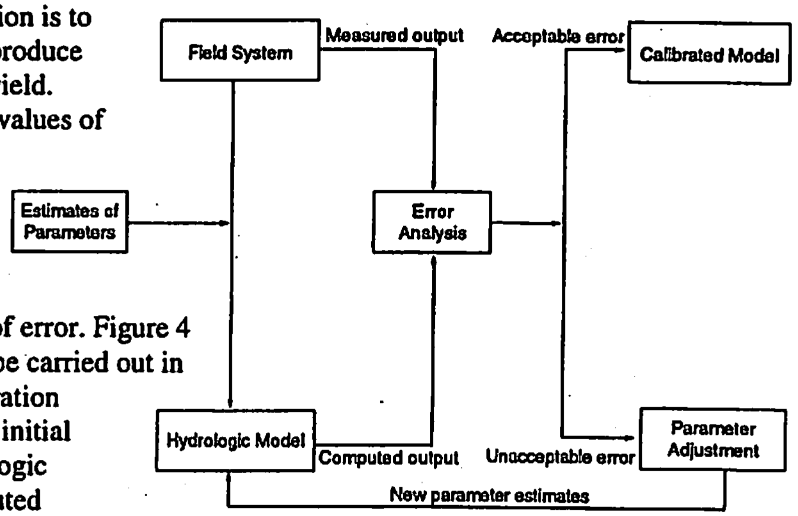

Figure 4. Calibration procedure of hydrologic models.

of error, the model is considered calibrated, otherwise, parameter values are adjusted and the model is run again until acceptable results are achieved.

Owing to uncertainties in the calibration, the set of parameter values used in the calibrated model may not accurately represent observed values. Consequently, the calibrated parameters may not accurately represent the system under a different set of hydrologic conditions. Model validation helps establish greater confidence in the calibration. In the validation process, values of hydrologic parameters determined during calibration are used to simulate a second set of field data. If the calibrated parameters were changed significantly during the validation, it may not be possible to match the calibration within a predefined range of error. Therefore, it will be necessary to repeat the calibration and validation processes until a set of parameter values is identified that produces a good match between simulated and observed values.

The judgment of when the fit between model and reality is good enough is a subjective one. To date, there is no standard protocol for evaluating the calibration and validation processes. The Watershed Management Committee of the Irrigation and Drainage Division of the American Society of Civil Engineers (ASCE, 1993) authorized a Task Committee to define criteria that can be used to evaluate hydrologic models. The Task Committee recommended the following goodness-of-fit criteria for continuous simulation. The deviation of runoff volumes

$$D_v(\%) = \frac{V - V'}{V} \cdot 100 \tag{1}$$

where V is the measured yearly or seasonal runoff volume, and V' is the model computed yearly or seasonal runoff volume. The Nash-Sutcliffe coefficient, E, (Nash and Sutcliffe, 1970)

$$E = 1 - \frac{\sum_{i=1}^{n} (Q_i - Q_i')^2}{\sum_{i=1}^{n} (Q_i - \overline{Q})^2} \tag{2}$$

where Q_i is the measured daily discharge, Q_i' is the computed daily discharge, Q is the average measured discharge, and n is the number of daily discharge values. The average measured discharge is determined from the year or period in question. The E value measures how well the daily simulated and measured flows correspond.

Generally the objectives of single event modeling are the determination of peak flow rates, flow volumes, and hydrograph shape and timing. The Task Committee recommended for event modeling the following goodness-of-fit criteria. To evaluate the peak flow rates, a simple percent error in peak (PEP) is recommended.

$$PEP(\%) = \frac{Q_{ps} - Q_{po}}{Q_{po}} \cdot 100 \tag{3}$$

where Q_{ps} is the simulated peak flow rate, Q_{po} is the observed peak flow rate. For volumetric assessment, a simple comparison using a measure such as the D_v is sufficient. For assessing the shape of a simulated hydrograph, a simple sum of squared residuals, G, is proposed

$$G=\sum_{t=1}^{n}\left[Q_o(t)-Q_s(t)\right]^2 \tag{4}$$

where $Q_o(t)$ is the observed flow rate at time t, $Q_s(t)$ is the simulated flow rate at time t.

During the modeling study there will be many changes in parameter values and initial conditions and possibly even in modeling strategy between the initial runs of the model and the final runs. A log will be kept during the modeling study to chronologically document the changes in input files, the rationale for the changes, and the effects of the changes on the results.

4.4.4 Software development

The development of the software will be under a quality system framework following ISO 9000-3 software development guidelines (Schuler et al., 1996). That is, a software quality manual will be prepared which will serve as a formal procedures manual, and externally as evidence for customers interested in the software development process as subject to quality control by management. The manual will cover all aspects of software development, including:

1. Organizational overview – description of the product to be delivered and the overall structure of the organization.
2. Responsibilities – Who is responsible for which activities and how they are interrelate.
3. Tools – All software development tools that are used in development, which might include such things as third-party compilers, bug tracking systems, and configuration management software.
4. Standards – Programming languages used, internal source code format requirements, user interface guidelines, and so forth.

Basically, the document will reference all quality procedures and activities associated with each step of the development process – from design specification writing to preparation of user documentation.

Emphasis will be placed on the development of a quality plan from a verification and validation stand point, this includes verification of the inputs and outputs of all development phases, criteria for inputs and outputs, and details of validation (schedules, activities, resources).

The software will be tested and validated at the end of the appropriate development phase to insure that it meets all specified requirements. Testing will take place at the variety of stages during the software development life cycle:

1. Unit level – Includes testing one unit or module of the program usually comprised of anywhere from 50 to 500 lines of code.
2. Integration level – Involves testing the interaction of program units.
3. System level – Includes testing the complete system.
4. Acceptance level – Involves testing the delivered software product to the customer's requirements specification.

Section 5
Anticipated Results and Products

The specific results and products for this research effort are linked to the activities discussed in section 4.0 and outlined in Table 1. In general, the anticipated results and products of this research fall into three main categories:

1. Interim reports, documentation, and model products.
2. Manuscripts submitted to peer-reviewed journals for publication.
3. A final landscape/hydrologic assessment modeling tool for use by EPA, model documentation, and a final report on the research program.

References

American Rivers, 1997. www.amrivers.org/99endangered.html.

Arnold, C. L. and C. J. Gibbons, 1996. Impervious surface coverage: the emergence of a key environmental indicator. J. American Planning Assoc. 62:243-258.

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.

Aronoff, S., 1985. The minimum accuracy value as an index of classification accuracy. Photogrammetric Engineering & Remote Sensing, 51(1): 99-111.

ASCE, 1993. Criteria for evaluation of watershed models, Journal of Irrigation and Drainage Engineering, 119:429-443.

Band, L. E., 1986. Topographic partition of watersheds with digital elevation models. Water Resources Research, 22(1):15-24.

Band, L. E. and I. D. Moore, 1995. Scale: landscape attributes and geographical information systems, in: scale issues in hydrological modeling (Eds.) Kalma, J. D. and M. Sivapalan, John Wiley & Sons.

Band, L. E., D. L. Peterson, R. Nemani, and S. W. Running, 1993. Forest ecosystem processes at the watershed scale: incorporating hillslope hydrology, Ecol. Modell., 63: 93-126.

Band, L. E., D. L. Peterson, S. W. Running, J. C. Coughlan, R. B. Lammers, J. Dungan, and R. Nemani, 1991. Forest ecosystem processes at the watershed scale: basis for distributed simulation, Ecol. Modell., 56: 151-176.

Beck, M. B., 1987. Water quality modeling: A review of the analysis of uncertainty. Water Resources Research, 23(5), pp. 1393-1441.

Brakensiek, D.L., and W.J. Rawls, 1983. Agricultural management effects on soil water processes Part II: Green and Ampt parameters for crusting soils. Transactions of the ASCE 26(6): 1747-1752.

Breckenfield, D.J., W.A. Svetlik, and C.E. McGuire, 1995. Soil survey of Walnut Gulch Experimental Watershed. USDA, Soil Conservation Service Special Report.

Calore, C., P. La Barbera, and G. Roth, 1997. On the use of informational entropy in GIS. in: Remote Sensing and Geographic Information Systems for Design and Operation of Water Resources Systems, Proceedings of Rabat Symposium, IAHS, Publ. No. 242.

Charbonneau, R., and G.M. Kondolf. 1993. Land use change in California, USA: nonpoint source water quality impacts. Environ. Man. 17:453-460.

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.

Congalton, R. M. and K. Green, 1999. Assessing the accuracy of remotely sensed data: principles and practices. Lewis Publishers, CRC Press, NY.

Congalton, R. G., M. Balogh, C. Bell, K. Green, J. A. Milliken, and R. Ottman, 1998. Mapping and monitoring agricultural crops and other land cover in the Lower Colorado River Basin. Photogrammetric Engineering & Remote Sensing, 64(11): 1107-1113.

Congalton, R. M., R. G. Oderwald, and R. Mead, 1983. Assessing Landsat classification accuracy using discrete multivariate statistical techniques. Photogrammetric Engineering & Remote Sensing, 49(12): 1671-1678.

Congalton, R. M., 1988. Using spatial autocorrelation analysis to explore the errors in maps generated from remotely sensed data. Photogrammetric Engineering & Remote Sensing, 54(5): 587-592.

Dickinson, W. T., M. E. Holland, and G. L. Smith, 1967. An experimental rainfall-runoff facility. Hydrology Paper No. 25, Colorado State University, Fort Collins, CO, 81 pp.

Dietrich, W. E. and D. R. Montgomery, 1998. Hillslopes, channels, and landscape scale. in: Scale dependence and scale invariance in hydrology, (Eds.) Sposito, G., Cambridge University Press, UK.

DiLuzio, M., R. Srinivasen, and S.L. Neitsch, 1998. SWAT ArcView Interface User's Guide for SWAT 98.1, 1998 Beta Release. Blackland Research Center, Texas Agricultural Experimental Station.

Doherty, J., 1998. PEST: Model Independent Parameter Estimation. Watermark Computing, Australia.

Engman, E. T. and R. J. Gurney, 1991. Remote sensing in hydrology. Chapman and Hall, Van Nostrand Reinhold, NY.

Entekhabi, D., H. Nakamura, and E. G. Njoku, 1994. Solving the inverse problem for soil moisture and temperature profiles by sequential assimilation of multifrequency remotely sensed observations. IEEE Trans. Geosci. Remote Sensing, 32: 438-448.

Environmental Systems Research Institute (ESRI), 1994. Cell-based modeling with Grid. Version 7, Redlands, CA.

Famiglietti, J. S. and E. F. Wood, 1995. Effects of spatial variability and scale on areal-average evapotranspiration. Water Resources Research, 31: 699-712.

Famiglietti, J. S. and E. F. Wood, 1994. Multi-scale modeling of spatially variable water and energy balance processes. Water Resources Research, 30: 3061-3078.

Famiglietti, J. S. and E. F. Wood, 1991. Evapotranspiration and runoff for large land areas: land surface hydrology for atmospheric general circulation models. Surv. Geophys., 12: 179-204.

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.

Franklin, J. F. 1992. Scientific basis for new perspectives in forests and streams. pp. 25-72. IN: R. J. Naiman (ed.) Watershed Management. Springer-Verlag, NY.

Garbrecht, J., P.J. Starks, and L. W. Martz, 1996. New digital landscape parameterization methodologies. Proceedings of the 1996 AWRA Symposium on GIS and Water Resources, Sept. 22-26, Ft. Lauderdale, FL.

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.

Garbrecht, J. and L. W. Martz, 1993. Network and subwatershed parameters extracted form digital elevation models: The Bills Creek Experience, Water Resources Bulletin, American Water Resources Association, 29(6): 909-916.

Graf, W. L., 1988. Fluvial Processes in dryland rivers, Springer-Verlag Berlin Heidelberg, Germany.

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.

Goodrich, D. C., 1991. Basin scale and runoff model complexity, University of Arizona, Dep. of Hydrology and Water Resources Technical Report No. HWR 91-010, 361 p.

Hernandez, M., D. C. Goodrich, S. N. Miller, and C. L. Unkrich, 1998a. Landscape indicator interface with hydrologic and ecological models, Report No. 1 (June) prepared as part of EPA/IAG Project No. DW12937916-01-0, USDA-ARS, Southwest Watershed Research Center, Tucson, AZ.

Hernandez, M. and D. C. Goodrich, 1998b. Landscape indicator interface with hydrologic and ecological models, Report No. 2 (October) prepared as part of EPA/IAG Project No. DW12937916-01-0, USDA-ARS, Southwest Watershed Research Center, Tucson, AZ.

Hernandez, M., S. N. Miller, D. C. Goodrich, and B. F. Goff, 1998c. Landscape indicator interface with hydrologic and ecological models, Report No. 3 (November) prepared as part of EPA/IAG Project No. DW12937916-01-0, USDA-ARS, Southwest Watershed Research Center, Tucson, AZ.

Hord, R. M. and W. Brooner, 1976. Land-use map accuracy criteria. Photogrammetric Engineering & Remote Sensing, 42(5): 671-677.

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

Hunsaker, C.T., D.A. Levine, S.P. Timmins, B.L. Jackson, and R.V. O'Neill. 1992. Landscape characterization for assessing regional water quality. Pp. 997-1006, in D.H. McKenzie, D.E. Hyatt, and V.J. McDonald (eds.), Ecological indicators. Elsevier Appl. Sci., New York.

Jackson, T. J., R. M. Ragan, and W. N. Fitch, 1977. Test of landsat-based urban hydrologic modeling. ASCE J. Water Resources Planning Management Division, 103, No. WR1 Proc. Paper 12950, pp 141-158.

Jackson, T. J., R. M. Ragan, and R. P. Shubinski, 1976. Flood frequency studies on ungauged urban watersheds using remotely sensed data. Proc. Natl. Symp. on Urban Hydrology, Hydraulics and Sediment Control, University of Kentucky, Lexington, KY.

Jenson, S. K. and J. O. Domingue, 1988. Extracting topographic structure from digital elevation data for geographical information system analysis. Photogrammetric Engineering and Remote Sensing 54(11):1593-1600.

Junk, W. J., P.B. Bailey, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Can. Spec. Publ. Fish. Aquat. Sci. 106:110-127.

Karr, J. R. and I. J. Schlosser. 1978. Water resources and the land-water interface. Science 201:229-233.

Kibler, D. F. and D. A. Woolhiser, 1970. The kinematic cascade as a hydrologic model, Hydrology Paper No. 39, Colorado State University, Fort Collins, CO, 27 pp.

Kirkby, M. J., P. S. Naden, T. P. Burt, and D. P. Butcher, 1993. Computer simulation in physical geography, John Wiley & Sons, Inc. New York.

La Barbera, P. and G. Roth, 1994. Scale properties and scale problems: network morphology and network identification from digital elevation maps. In: Advances in Distributed Hydrology (Ed.) Rosso et al., 131-148, Water Resources Publication, Colorado.

Langbein, W. B. and S. A. Schumm, 1958. Yield of sediment in relation to mean annual precipitation. Trans. Am. Geophys. Union, 39:1076-1084.

Lanter, D., 1989. Techniques and method of spatial database lineage tracking. Ph.D. dissertation, University of South Carolina.

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.

Lowrance, R. R., R. Leonard, and J. Sheridan. 1985. Managing riparian ecosystems to control non-point pollution. Journal of Soil and Water Conservation 40:87-91.

Lowrance, R. R., R.L. Todd, J. Fail, O. Hendrickson, R. Leonard, and L.E. Asmussen. 1984. Riparian forests as nutrient filters in agricultural watersheds. Bioscience 34:374-377.

Luk, K. C. and J. E. Ball, 1997. Modeling the instantaneous spatial variability of rainfall. International Congress on Modeling and Simulation, Hobart, Tasmania, pp. 71-76.

Marks, D., J. Dozier, and J. Frew, 1984. Automated basin delineation from digital elevation data. GeoProcessing, 2:299-311.

Martz, L.W., and J. Garbrecht, 1993. Automated extraction of drainage network and watershed data from digital elevation models. Water Resources Bulletin, American Water Resources Association, 29(6):901-908.

Martz, L.W., and J. Garbrecht, 1992. Numerical definition of drainage network and subcatchment areas from digital elevation models. Computers and Geosciences 18(6): 747-761.

McClaran, M. P. and W. W. Brady, 1994. Arizona's diverse vegetation and contributions to plant ecology. Rangelands 16:208-217.

McCuen, R. H. and W. M. Snyder, 1986. Hydrologic modeling: Statistical methods and applications. Prentice-Hall, Englewood Cliffs, NJ.

Meentemeyer, V. and E. O. Box, 1987. Scale effects in landscape studies. In: Landscape heterogeneity and disturbance, pp. 15-34. (Ed.) M. G. Turner, Springer-Verlag, NY.

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. In: Landform Monitoring, Modeling and Analysis, Eds. Lane, S., K. Richards, and J. Chandler, John Wiley & Sons.

Moore, I. D. and R. B. Grayson, 1991. Terrain based prediction of runoff with vector elevation data, Water Resources Research, 27: 1177-1191.

Moore, I. D., E. M. O'Loughlin, and G. J. Burch, 1988. A contour-based topographic model for hydrological and ecological applications. Earth Surface Processes Landforms, 13: 305-320.

Moore, I. D., A. K. Turner, J. P. Wilson, S. K. Jenson, and L. E. Band, 1993. GIS and land surface-subsurface modeling. In: Geographic Information Systems and Environmental Modeling, (Eds.) Goodchild, M. F., P. O. Parks, and L. Y. Stayaert, Oxford University Press, Oxford, pp. 196-230.

Morris, E. M. and D. A. Woolhiser, 1980, Unsteady one-dimensional flow over a plane: Partial equilibrium and recession hydrographs, Water Resources Research, 16(2):355-360.

Nash, J. E. and J. V. Sutcliffe, 1970. River flow forecasting through conceptual models. Part I: A discussion of principles. Journal of Hydrology, 10:282-290.

Nemani, R., L. L. Pierce, S. W. Running, and L. E. Band, 1993. Ecological processes at the watershed scale: sensitivity to remotely sensed leaf area index estimates. Int. J. Remote Sensing, 14: 2519-2534.

Nielsen, D. R. and J. Bouma, 1985. Soil spatial variability. In: Proceedings of a Workshop of the International Soil Science Society and the Soil Science Society of America, Pudoc, Wageningen, 243 pp.

O'Callaghan, J. F. and D. M. Mark, 1984. The extraction of drainage networks from digital elevation data. Computer Vision, Graphics and Image Processing, 28:323-344.

Omernik, J.M. 1987. Ecoregions of the United States: Map at a scale of 1:7,500,000. Suppl. Annals American Assoc. Geogr. 77(1).

Osborn, H. B., 1983. Precipitation characteristics affecting hydrologic response of southwestern rangelands. USDA-ARS, Agric. Rev. and Manuals, ARM-W-34, 55p.

Peterjohn, W. T. and D. L. Correll 1984. Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest. Ecology 65:1466-1475.

Ragan, R. M. and T. J. Jackson, 1980. Runoff synthesis using Landsat and SCS model. J. Hydraulic Division, ASCE 106, (HY5), 667-678.

Rango, A., A. Feldman, T. S. George, III, and R. M. Ragan, 1983. Effective use of Landsat data in hydrologic models. Water Resources Bulletin, 19, 165-74.

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.

Rosenfield, G. H. K. Fitzpatrick-Lins, and H. Ling, 1982. Sampling for thematic map accuracy testing. Photogrammetric Engineering & Remote Sensing, 48(1):131-137.

Roth, N.E., J. D. Allan, and D.L. Erickson. 1996. Landscape influences on stream biotic integrity assessed at multiple scales. Landscape Ecology 11:141-156.

Scientific Analysis Team (SAT), 1993. Viability Assessment and Management Considerations for Species Associated with Late-Successional and Old-Growth Forests of the Pacific Northwest. USDA Forest Service, U. S. Government Printing Office 1993-791-566, Region 10, 530 pp.

Schuler, A. C., J. Dunlap, and K. L. Schuler, 1996. ISO 9000 – Manufacturing, Software, and Service, Delmar Publishers, Albany, NY.

Shen, H.W., and P.Y. Julien, 1993. Erosion and sediment transport. Chapter 12 in: Handbook of Hydrology, D.R. Maidment, ed. McGraw-Hill, New York.

Shannon, C. E., 1948. A mathematical theory of communications. Bell System Technology Journal, 27: 379-423, 623-659.

Singh, V. P., 1974. A nonlinear kinematic wave model of surface runoff, Ph.D. Dissertation, Colorado State University, Fort Collins, CO., 282 pp.

Slocombe, 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, edited by V. P. Singh, Water Resources Publications, Highlands Ranch, CO.

Smith, R. E. and J. –Y. Parlange, 1978. A parameter-efficient hydrologic infiltration model, Water Resources Research, 14(3):533-538.

Spanner, M. A., L. Johnson, J. Miller, R. McCreight, J. Freemantle, J. Runyon, and P. Gong, 1994. Remote sensing of seasonal leaf area index across the Oregon transect. Ecol. Appl., 4: 258-271.

Spanner, M. A., L. L. Pierce, D. L. Peterson, and S. W. Running, 1990. Remote sensing of temperate forest leaf area index: influence of canopy closure, understory vegetation and background reflectance. Int. J. Remote Sensing, 11: 96-111.

Sparks, R.E. 1995. Need for ecosystem management of large rivers and their floodplains. Bioscience 45:168-182.

Stanley, T. R. Jr., 1995. Ecosystem management and the arrogance of humanism. Conservation Biology, 9, 255-262.

Star, J. L., J. E. Estes, and K. C. McGwire, 1997. Integration of Geographic Information Systems and Remote Sensing, Cambridge University Press, Cambridge, UK.

Strahler, A. N., 1964. Quantitative geomorphology of drainage basins and channels networks, In: Handbook of Applied Hydrology, (Ed.) Chow, V. T., pp. 4-39-4-76.

U.S. Army Corps of Engineers, 1976. Urban storm water runoff, STORM. Computer program 723-L2520, Hydrologic Engineering Center, Davis, CA.

USDA-NRCS, 1994. State Soil Geographic (SATSGO) Data Base. Miscellaneous Publication No. 1492.

U. S. Department of Agriculture, Soil Conservation Service, 1983. National Engineering Handbook, Hydrology Section 4, Chapter 19, US Government Printing Office, Washington, D.C.

U. S. Department of Agriculture, Soil Conservation Service, 1972. National Engineering Handbook, Section 4, Hydrology US Government Printing Office, Washington, D.C.

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, 1999b. Landsat Pathfinder Program (North American Landscape Characterization Project): http://edcdaac.usgs.gov/pathfinder/pathpage.html

USGS, 1999a. USGS Geographic Data Download: http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html

van Genderen, J. L. and B. F. Lock, 1977. Testing land use map accuracy. Photogrammetric Engineering & Remote Sensing, 43(9): 1135-1137.

Washington Forest Practice Board (WFPB), 1992. Standard methodology for conducting watershed analysis. Washington Forest Practice Act Board Manual, Version 1.0, 13 pp.

Washington Forest Practice Board (WFPB), 1993. Standard methodology for conducting watershed analysis. Washington Forest Practice Act Board Manual, Version 2.0, 85 pp.

Weller, M.C., M.C. Watzin, and D. Wang. 1996. Role of wetlands in reducing phosphorus loading to surface water in eight watersheds in the Lake Champlain Basin. Environ. Man. 20:731-739.

Wickham, J. D., R. V. O'Neill, K. H. Ritters, T. G. Wade, and K. B. Jones, 1997. Sensitivity of selected landscape pattern metrics to land-cover misclassification and differences in land-cover composition, Photogrammetric Engineering & Remote Sensing, 63(4): 397-402.

Wigmosta, M. S., L. W. Vail, and D. P. Lettenmier, 1994. A distributed hydrology-vegetation model for complex terrain. Water Resources Research, 30:1665-1680.

Williams, J. R. and H. D. Berndt, 1977. Sediment yield prediction based on watershed hydrology, Trans. ASAE 20(6):1100-1104.

Wischmeier, W. H., and D. D. Smith. 1978. Predicting rainfall erosion loss: A guide to conservation planning. Agricultural handbook 537. U. S. Department of Agriculture, Washington, D.C.

Wood, E. F., 1994. Scaling, soil moisture and evapotranspiration in runoff models. Advances Water Resources, 17: 25-34.

Wood, E. F., M. Sivapalan, K. Beven, and L. Band, 1988. Effects of spatial variability and scale with implications to hydrologic modeling. Journal of Hydrology, 102: 29-47.

Woolhiser, D. A. and J. A. Ligget, 1967. Unsteady, one-dimensional flow over a plane – the rising hydrograph, Water Resources Research, 3(3):753-771.

Woolhiser, D. A., M. E. Holland, G. L. Smith, and R. E. Smith, 1971. Experimental investigation of converging overland flow, Trans. ASAE, 14(4):684-687.

Appendix

Table 1. Tentative schedule and milestones for fiscal years 1999-2002 beginning in January, 1999, also showing calendar years 1999-2002. Working and completion target dates indicated by quarter. Symbols used in this chart: WG = Walnut Gulch Experimental Watershed; SP = San Pedro River Basin.

Calendar Year	1999				2000				2001				2002		
Calendar Year Quarter	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
Fiscal Year	1999			2000				2001				2002			
Fiscal Quarter	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
• Compile climatic/hydrologic data, WG and SP	✓														
• Assemble GIS data at high/low resolution for WG, SP	✓														
• Analyze climatic data, WG, SP	✓	✓													
• Assess input parameters; construct look-up tables for GIS	✓	✓													
• Develop multi-year research plan suitable for peer review	✓	✓													
• Submit manuscript for publication		✓													
• Calibrate and validate hydrologic models, WG, SP; model at various resolutions with KINEROS, SWAT	✓	✓	✓												
• Submit report			✓												
• Submit manuscript for publication			✓												
• Select criteria for choice of intensive study basins			✓	✓											
• Assess model efficiency relative to data resolution			✓	✓											
• Analyze misclassification errors; dependent on matrix				✓	✓										
• Determine impact of misclassification errors on model efficiency					✓	✓									
• Choose intensive study basins					✓	✓									

Table 1. *Continued*

Fiscal Year	1999			2000				2001				2002			
Fiscal Quarter	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
• Sensitivity Analysis					✓	✓									
• Create subwatershed maps at varying levels of complexity, WG, SP						✓	✓								
• Submit report							✓								
• Submit manuscript for publication							✓								
• Assess model efficiency relative to network complexity							✓	✓							
• Compile climatic and hydrologic data, intensive study basins							✓	✓	✓						
• Assemble GIS data for intensive study basins; dependent on MRLC								✓	✓	✓					
• Define design storms									✓						
• Calibrate and validate hydrologic models, intensive study basins									✓	✓	✓	✓			
• Submit report											✓				
• Submit manuscript for publication											✓				
• Model and analyze watershed response as a function of land cover change and design storms, WG, SP											✓	✓	✓		
• Model and analyze watershed response as a function of land cover change and design storms, intensive study basins													✓	✓	✓
• Submit report															✓
• Submit manuscript for publication															✓
• Create/update GIS programs (AML, Avenue) to automate GIS parameterization; deliver final GUI-driven GIS/ hydrologic modeling tool	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓