A GIS-Based Adaptive Management Decision Support System to Develop a Multi-Objective Framework: A Case Study Utilizing GIS Technologies and Physically-Based Models to Achieve Improved Decision Making for Site Management

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ABSTRACT. The notion of Adaptive Management (AM) allows for the realization and adjustment of management practices in response to elements of uncertainty. In terms of natural resource management, this will typically integrate monitoring, databases, simulation modeling, decision theory, and expert judgment to evaluate management alternatives and adapt them as necessary to continually improve the natural resource condition as defined by stakeholders. Natural resource management scenarios can often be expressed, viewed, and understood as a geospatial and temporal problem. The integration of Geographic Information System (GIS) technologies and physically-based models provide an effective state-of-the-art solution for deriving, understanding, and applying AM scenarios for land use and remediation. A recently developed GIS-based adaptive management decision support system is presented for the U.S. Department of Defense Yakima Training Center near Yakima, Washington.

KEYWORDS. Adaptive management, modeling, decision theory, Natural Resources Management, Geographic Information Systems, Yakima Training Center

INTRODUCTION

To ensure sustainability and adaptability in managing training operations while minimizing impacts on watersheds, the Department of Defense (DoD) needs to identify activities that contribute to non-point source pollution, and strategically locate and schedule operations accordingly. The potential for extreme spatial and temporal variability in hydrologic conditions during land-based training exercises can directly influence the level of associated environmental impacts from non-point source pollutants such as soil erosion potential and eroded sediment. We are developing GIS-based decision tools to provide information to articulate tradeoffs between alternative management actions and resultant impacts and/or benefits to rangeland training areas or adjacent downstream water bodies. These decision tools, and the data, science, technology, and knowledge upon which they are based, are necessary to bring the best science to bear on practical decision making.

These post training alternative management actions, usually land reclamation at the landscape scale, includes several key objectives. First, the remediated or reclaimed site should be designed such that its hydrologic characteristics should tend to evolve toward stability defined by onsite regulatory requirements, offsite water quality constraints, and the need for minimal additional remediation procedures. This hydrologic stability implies positive feedback between topography, soils, vegetative canopy cover, surface ground cover and hydrologic response. Simply put, this means that a properly designed site will tend to evolve toward a condition of increasing stability through time (i.e., stable topography with soil erosion decreasing through time; increased canopy and ground cover; increased evapotranspiration to reduce soil moisture influencing runoff and mass wasting). Second, site properties should be robust in the sense that departures from stability should be "self-healing" to the extent possible. Third, site behavior should be predictable within the constraints of scientific understanding of the controlling processes and monitoring data limitations. Fourth, the site designs should be amenable to adaptive management depending upon departures from optimal performance as determined by predictive modeling, monitoring, and observations of successful vs. unsuccessful design elements (see, for example, Lane and Wigmosta, 2006). In the context of military training sites and the activities they host, in this study, these objectives relate to minimizing soil erosion impacts and maximizing the effectiveness of rehabilitation measures designed to overcome these impacts.

Natural resource management decisions pertaining to spatially distributed land use and management activities are described in a GIS-based adaptive management framework emphasizing Decision Support Systems (DSS). Specific decisions on timing, location, and intensity or magnitude of training activities and subsequent site rehabilitation and management as they impact soil erosion potential are described and analyzed using the Yakima Training Center (YTC) as a test case.

The objectives of this paper are to describe the developed GIS-based adaptive management system framework, its decisions support system component, and to illustrate their application at the YTC. The analyses are primarily limited to determining the soil erosion potential of training activities and the potential reduction in soil erosion as the result of application of adaptive management alternatives, ranked by the decision support systems component, for site remediation. Specific analyses and findings are for the YTC, but the general concepts and principles have broader natural resource management implications.

CASE STUDY SITE DESCRIPTION

The Department of Defense (DoD) Yakima Training Center (YTC) is a 1,323 km^2 (511 mi^2) training facility located in south-central Washington State (see Figure 1) and is adjacent to the U.S. Department of Energy's

FIGURE 1. Location of the Yakima Training Center in South-Central Washington State.

Hanford Site. The area contains one of the largest remaining tracts of shrub-steppe ecosystem in Washington State and is characterized by infrequent summer rainfall, winter snow, and a wide variation in temperatures. Within the YTC, elevations range from 150 m (500 ft) to 1300 m (4200 ft). As a training facility, the YTC provides the opportunity, facilities, and support for military units, including both active and reserve component forces, to enhance troop readiness and train for mobilization and post-mobilization exercises. In arid/semiarid regions, the potential for extreme spatial and temporal variability in hydrologic conditions during land-based training exercises can directly influence the level of associated environmental impacts from non-point source pollutants such as eroded sediment, petroleum products, and heavy metals. The YTC contains a number of tributaries that flow into 303(d) listed streams, including the Yakima River. Elevated water temperatures and increased sediment loads have contributed to a significant loss of usable habitat for Endangered Species Act (ESA) listed species in large portions of these receiving streams. Estimation of current mobile sediment quantities and sources is a major concern for the YTC, and a high priority concern for DoD lands in general. At the YTC, most erosion (and sediment transport/yield) occurs during extreme events of short duration, often associated with rapid rain-induced snowmelt. Erosion potential can be further enhanced following natural or man-induced range fires.

ADAPTIVE MANAGEMENT FRAMEWORK

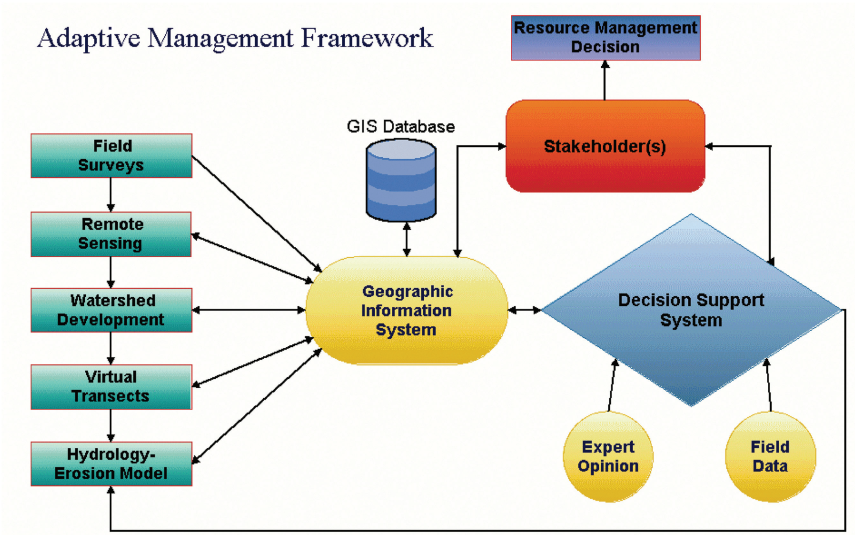
The notion of adaptive management is defined by Walters and Holling (1990) as a systematic and rigorous, scientifically defensible program of learning from the outcomes of management actions, accommodating change, and improving management. The purpose of establishing an Adaptive Management Framework (AMF) is to help provide decision tools that will assist in optimizing design and implementation of operations, management plans and policies in the face of uncertainties. The AMF provides the basis for comprehensive trade-off analyses of multiple interdependent interests including field training operations, watershed assessment, in-stream impact mitigation, habitat restoration, and upstream watershed management practices. The framework is designed to address local, site specific operations and associated effects as well as cumulative processes and effects over a range of scales (e.g., sub-watershed, watershed, basin, etc.).

The ultimate goal of the AMF is not to eliminate process uncertainty but to reduce decision uncertainty. This can only be achieved via a framework that maps actions onto a tradeoff space for a specified set of conditions. For instance, at the YTC, an erosion protection approach may need to be deployed for several years to experience a significant runoff event. Process models can simulate hundreds of years of conditions, but the efficacy of restoration/remediation actions still must be validated with field demonstrations.

While generally advocated, adaptive management has proven difficult to implement. This difficulty is in part due to the lack of readily available, widely implemented tools for resolving critical natural resource management issues. There remains a general need for system tools to "operationalize" the adaptive management process for comprehensive ecosystem management.

The decision tools developed and discussed in this paper are supported by state-of-the-art processes of field surveys, remote-sensing, geospatial modeling, and physically-based hydrologic and erosion modeling, all of which are tightly-integrated into a Geographic Information

FIGURE 2. The Developed Adaptive Management Framework is comprised of a series of base-level building blocks ultimately enabling a stakeholder to query the information database and evaluate resource management scenarios.



System (GIS), thus providing the means for an adaptive management tool usable by stakeholders. Figure 2 provides a graphical overview of the framework processes. The discussion that follows will address these topics.

METHODS

The collection and processing of data required to develop the adaptive management framework are conducted in the context of hillslope hydrology and erosion models. These models are based on both physical and biological processes which establish a linkage between training operations, remediation or other management measures, and relevant endpoint impacts including soil surfaces, vegetation, receiving streams, etc. A series of methods were established which provide the basis for the adaptive management framework.

Field Surveys

Field data on representative hillslopes distributed across the YTC were collected in 2003, 2004, and 2005. Data were collected to represent three broad classes of land use: (1) rangeland, (2) unimproved roads, and (3) firebreak roads (see Figure 3). Within each of these three classes, data were collected to represent a range of land use intensity and soil types. The soil types included what are generally considered "rocky soils" and "non-rocky soils" depending on the degree of their rock, cobble, and gravel content. A total of 577 segments from hillslope transects were collected and supported remote-sensing and modeling efforts.

Remote-Sensing

Remotely-sensed imagery plays a key role in the erosion determination process, allowing field-calibrated estimations of vegetation canopy cover, ground surface cover, unimproved roads, and fire breaks as well as providing a consistent approach to characterize and monitor changes in bare soils and vegetative canopy cover throughout the YTC. High resolution (~2.5 m) multi-spectral data from the QuickBird sensor, moderate resolution (10 m) data from the SPOT sensor, field data, and digital terrain data were used to develop a relationship between pixel response and ground/canopy cover conditions (see Figure 4).

FIGURE 3. Field data was collected on three broad land use types: (1) rangeland, (2) unimproved roads, and (3) firebreak roads.

FIGURE 4. Percent vegetation canopy cover derived from SPOT 10-meter Resolution Multi-Spectral Imagery. Notice the low canopy linear features in the zoom window representing unimproved road (running East-West) and a firebreak (running Northwest-Southeast).

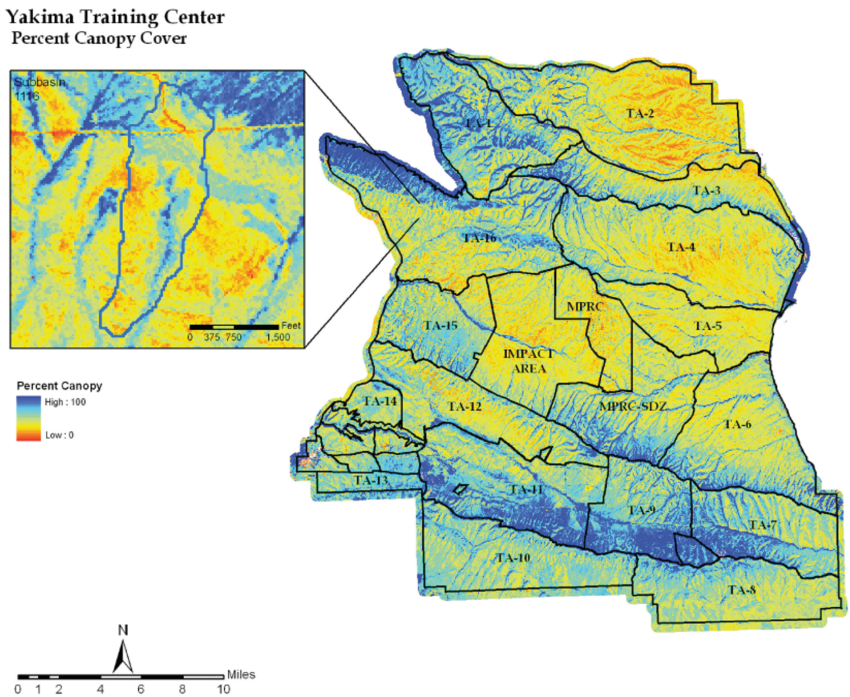


Image analysis quantified landscape-level characteristics in several steps: (1) identification and analysis of vegetative and soil indices that best reflect relative quantities of vegetative cover and bare soils, (2) use of these data sets from sequential imagery to detect significant increases or decreases in bare soils as a result of training activities, and (3) application of sophisticated change-detection methods including textural analyses and linear spectral un-mixing techniques to optimize the detection and characterization of biotic signatures. The image analysis results are used as input parameters for geospatial modeling in which topographically simulated field transects, referred to as "virtual transects," are constructed to derive all necessary input data for the hydrologic and erosion modeling. These models quantify the magnitude and spatial distribution of surface water run off, soil erosion, and sediment loading to streams.

GEOSPATIAL MODELING

Watershed Development

To provide a multi-scale-capable adaptive management tool, all modeling work was developed in a manner to use the smallest logical unit area that was defined as a first-order watershed. This philosophy provides the end-user the ability to combine and link specific areas to assess resource management needs as deemed necessary. The first-order watersheds were developed using United States Geological Survey (USGS) 10-meter Digital Elevation Models (DEM) and the commonly-used Deterministic-8 (D8) method for extracting flow paths and watershed boundaries (O'Callaghan and Mark, 1984). Field-survey data and GIS-based upslope drainage area analysis determined that an average drainage area of 2600 m^2 provided the establishment of concentrated flow at the YTC. The watershed processing resulted in 3,469 first-order watersheds with an average basin size of 4200 m^2 (see Figure 5).

Virtual Transect Model

A GIS-based virtual transect model was developed allowing for the estimation of soil erosion conditions on a first-order watershed scale. The intent of the "virtual transect" is to spatially model overland flow paths and collect various data along these paths, just as is observed and performed in the field. A single virtual transect is divided into segments based on changes in slope with a minimum segment length of 1.5-times the DEM resolution. The segments essentially allow a virtual transect to collect detailed data along its route. The derived virtual transect model data includes percent vegetative canopy cover, percent ground surface cover, soil type, soil texture, slope steepness, segment length, accumulated length, majority land use for the segment, azimuth, long-term mean precipitation, and long-term mean temperature. A spatial validation of data results from the virtual transect model and field-determined flow paths show a high-degree of agreement (see Figure 6).

The conditions determined by the virtual transect model provide parameter inputs to the hydrology and erosion models and allow for a consistent approach for determining sediment yield parameters at multiple scales (single sub-basin to entire site). This modeling effort thus represents a heretofore unavailable methodology for using remote-sensing and geospatial technology to parameterize distributed hydrology and soil erosion models.

FIGURE 5. A Total of 3,469 first-order sub-basins were developed as a base for multi-scale sediment yield analysis.

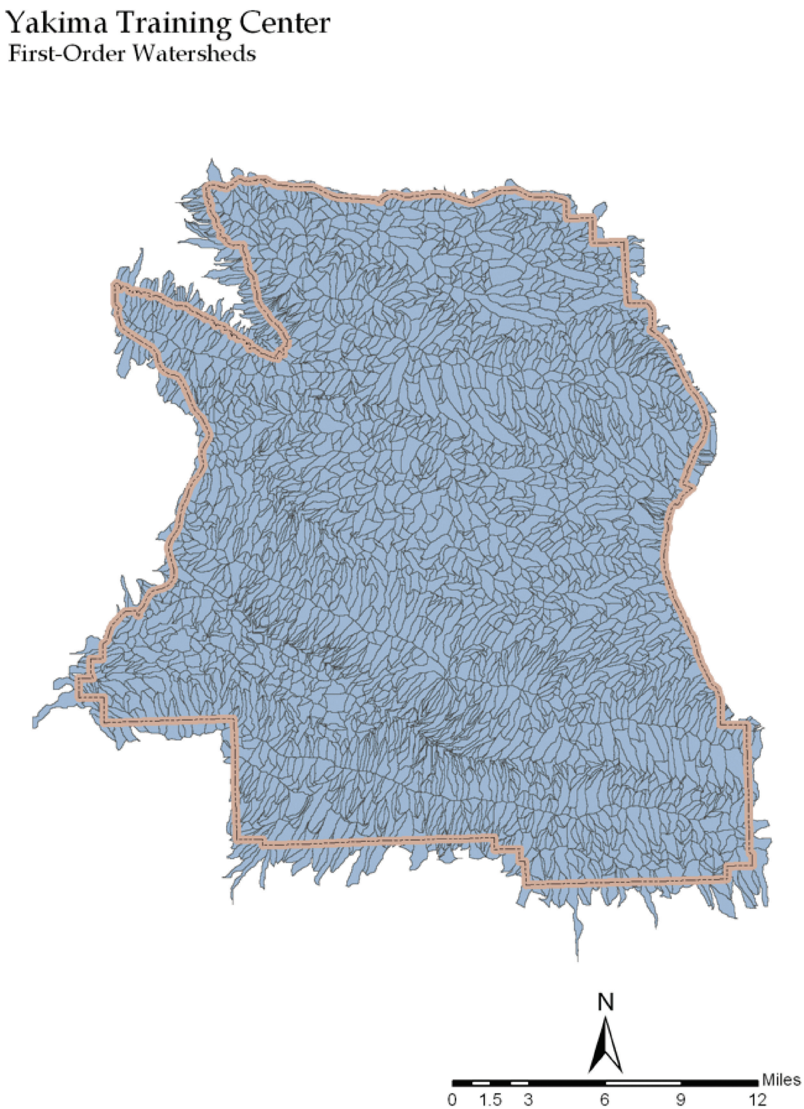
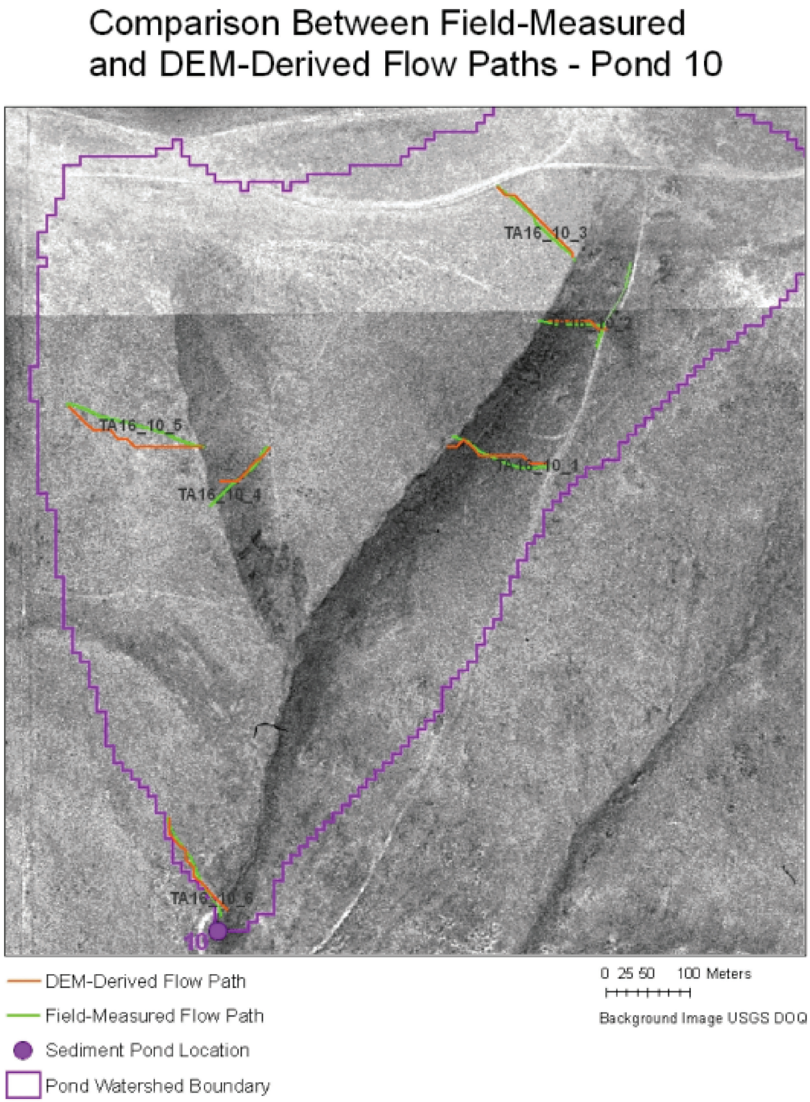


FIGURE 6. A spatial comparison of field measured flow paths and flow paths derived from the virtual transect model.



DISTRIBUTED HYDROLOGIC AND EROSION MODELS

The hydrologic and erosion modeling efforts conducted directly address the need to quantify erosion rates and sediment loading under alternative land uses, and subsequently provide the critical information needed for the adaptive management framework. The complex topography, meteorology, vegetation, soils, and land use patterns at the YTC dictate the use of spatially distributed models to capture critical variability in runoff/erosion processes. The episodic nature of surface runoff and erosion in semi-arid locations such as the YTC limits the opportunity for calibration, favoring physically-based models with a limited number of input parameters. Two distributed, physically based models of intermediate complexity were linked; the Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al., 1994; Stork et al., 1998; Wigmosta et al., 2002) is used to simulate runoff production and the Hillslope Erosion Model (HEM) (Lane et al., 1995; Lane et al., 2001) is used to estimate erosion and sediment yield. The coupled DHSVM-HEM models provide the desired simplicity as well as the capability for continuous annual simulation and thus simulation of the more difficult winter processes.

GIS-BASED ADAPTIVE MANAGEMENT DECISION SUPPORT SYSTEM

A GIS-based decision support interface is being developed to allow YTC personnel and stakeholders the ability to evaluate soil erosion conditions in response to training and remediation activities throughout the site. A GIS-based development platform was chosen as an efficient and cost-effective solution as the source data already exists in a GIS database and the YTC public works department (land manager) is versed in using GIS software. In addition, working with and visualizing the data in a spatial context increases the value of communication and comprehension by the stakeholders. The GIS framework will utilize and link to components outside of the GIS system creating a cohesive, functional, and easy-to-use decision environment. The DHSVM-HEM model input data and results are linked to the GIS database through a unique sub-basin identifier quantifying the actual mean soil erosion rates to compare with regulatory requirements, water quality criteria, etc.

Spreadsheet-Based Decision Support System

A Spreadsheet Implemented Multi-objective Decision Support System (SIMDSS), adapted from an early standalone USDA-ARS prototype called WQDSS, has been developed and will be incorporated into the GIS-based adaptive management framework (Yakowitz,1992). The SIMDSS utilizes a spreadsheet environment to evaluate multiple-criteria alternative weighting into an easy-to-understand format for the end-user by providing summary statistics, graphs, and a familiar spreadsheet environment to facilitate various management scenarios. Data supporting SIMDSS can come from various sources including simulation models, measured data, and/or expert opinion to quantify decision criteria (Lawrence et al., 1997); SIMDSS provides this flexibility by utilizing a scoring function which converts numerical values into a dimensionless quantity. This built-in capability enables system users to mesh data from differing sources to arrive at the best possible decisions.

User Interface

The GIS-based framework provides the core operating function to execute and compare various alternatives in a spatial context, store data in spatial and tabular databases, execute hydrology and erosion models, link and feed SIMDSS, and provide the user with comprehensive analyses. The framework is being developed within Environmental Systems Research Institute's (ESRI) ArcGIS® 9.1 software suite. The use of the Python scripting language and Visual Basic® used within the ArcObjects® component model provides the core development platform. The goal in this effort is to provide a customized user environment that is clear, easy-to-use, adaptable, and can be put into use with about one-half day of training. A careful design implementation of the system has been developed and is described herein. The overall system can be reduced to three broad functions (1) review and spatial selection, (2) land use effects analysis, and (3) remediation effects analysis. The analysis procedure has the ability to provide multi-scaled analysis, ranging from a single sub-basin to the entire YTC. This GIS framework provides site managers a valuable, quantitative, and defensible decision support tool to assess soil erosion in response to training and/or remediation activities.

Review and Spatial Selection

The review and spatial selection process provides two functions. First, it allows the user to become familiar with their area of interest by reviewing available data such as topography, drainage networks, climate data (long-term precipitation and long-term temperature), soils, vegetation, soil erosion potential, cadastral data (boundaries), and other relevant data. The second function provides the user the ability to interactively select the areas they are interested in analyzing. The minimum element for selection is based on a first-order sub-basin; however the maximum element can be scaled up to all sub-basins within the YTC.

Land Use Effects Analysis

The land use effects analysis gives the user an opportunity to assign a state of land use intensity at the sub-basin scale. A 4×4 matrix is presented to specifically select the level of activity occurring at each land use type. There are four levels of intensity that can be used: (1) no effect, (2) low, (3) medium, and (4) high. The DHSVM-HEM model is linked and data is returned to the GIS database. Basic geospatial processing calculates the net change in sediment yield between pre-training or base condition and post-training conditions. The resulting data provides a visual opportunity to review the pre- and post sediment yield results in a spatial and graphed context. As a final step, data is stored and linked to populate the SIMDSS where the various land use effect alternatives can be weighed.

Remediation Effects Analysis

The remediation effect analysis provides a method to evaluate and review alternative land activities as related to sediment yield. The process is somewhat similar to that of the land use effect analysis in terms of applying one of four levels of effectiveness to an activity based on land use type. The four levels of effectiveness can be defined in basic categories of (1) poor (2) fair, (3) good, and (4) excellent. Each level of effectiveness is applied to the primary land use categories as have been defined previously. As with the land use effect analysis, once the user-selected parameters are defined, the DHSVM-HEM databases are accessed and model results are retrieved, area-weighted to the sub-basin, and final results are populated to the GIS database. The sediment-yield results are viewed spatially as (1) post-training condition, (2) remediation condition, and (3) net change. The resulting analysis is stored and linked to the SIMDSS for completion of the decision support process.

CONCLUSIONS

This paper presents a GIS-based decision support framework that provides the YTC stakeholders the ability to plan for training activities and map the erosion potential response in a system designed to be easy-to-use and provides meaningful results to help formulate the decision making process. The presented methods, tools, and designs provide a new and unique ability to incorporate a multi-modal system incorporating field data, remote-sensing, geospatial modeling, hydrologic and erosion modeling, and a decision support system linked by a GIS-based user interface. The system works to articulate the multi-objective tradeoffs of management alternatives based on stakeholder decision criteria that allow for a defensible method of evaluating alternatives for YTC site management needs.

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