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CHALLENGES TO WATERSHED MODELING IN FORESTED MOUNTAINOUS ENVIRONMENTS

Kevin Hyde, Scott Woods, John Potyondy*

ABSTRACT: Assessing the effects of management on streamflow and water quality in forested mountainous environments (FMEs) often involves the use of watershed modeling tools and techniques. Numerous models are available for this purpose, but to be useful to watershed managers a model must: 1) accurately predict management impacts, including cumulative watershed effects, 2) have program software that is readily accessible, preferably on the Internet, 3) be user friendly; 4) be well documented, and 5) be legally defendable in terms of the model's scientific basis, its' assumptions and limitations and the error and uncertainty in model output. The USDA Forest Service recently conducted an inventory and review of 25 water and sediment modeling tools to identify those which best meet these criteria. The six highest ranked models were DHSVM, FORest/Delta-Q, R1-WATSED, SEDMODL2, SWAT, and WEPP, all of which met the required criteria for application by Forest Service personnel. While these models represent the state-of-the-art in assessing management effects in FMEs, no one model or combination of models currently meets all of the needs of managers. In order to improve the utility of models for management use, model developers need to provide clearer statements of the intended use of the model, and the model assumptions and caveats. Tools and procedures to assess and report model error and uncertainty must be further developed, along with programs to train managers in their effective use. Managers need to provide monitoring data so that models can be validated under a range of conditions. By working together, managers and model developers can improve our ability to assess and predict the effects of management on soil and water resources within FMEs.

KEY TERMS: watershed modeling; cumulative effects analysis; hydrologic modeling; sediment modeling

INTRODUCTION

Assessing and predicting the impacts of management on soil and water resources in forested mountainous environments (FMEs) often involves the use of models. However, numerous challenges are associated with the use and application of models in FMEs. These challenges can be broadly divided into those associated with model development and with model implementation in the operational and legal framework within which forest management decisions are currently made. With regard to the former, FMEs are extremely complex hydrologic and geomorphic systems with highly variable topography, soils, geology and climate. Management activities and other disturbances such as wildfire lead to a multitude of primary and secondary cause and effect relationships across a range of temporal and spatial scales (MacDonald, 2001). Impacts that overlap in space or time lead to cumulative watershed effects (CWEs), further complicating the task of assessing and predicting management impacts. The relative importance of the different cause and effect relationships varies with climate and geology, so that a model that is calibrated for one location may not work well in another. Finally, since cause and effect relationships often vary with the magnitude and timing of precipitation events, there is an inherent degree of uncertainty that must be recognized and, if possible, quantified in the model output.

In order to reduce the complexity involved in assessing and predicting management effects within FMEs, most models focus on a subset of cause and effect relationships, management activities or environmental resources. For example, SEDMODL2 deals exclusively with the effects of roads on sediment delivery to streams. Similarly, Disturbed:WEPP is used to assess the effects of fire and forest harvest on sediment yield. Further reductions in complexity can be achieved by limiting model predictions to smaller scale landscape elements, such as individual hillslopes or road segments. However, such

* Respectively: Landscape Modeler Hydrologist, METI Corp. for Forest Economics Unit, USDA Forest Service, Rocky Mountain Research Station, 800 E. Beckwith Ave., Missoula MT, 59801, Phone: (406) 329-2137, Fax: (406) 543-2663, kdhyde@fs.fed.us; Program Manager, Stream Systems Technology Center, Watershed, Fish, Wildlife, Air, and Rare Plants Staff, USDA Forest Service, Rocky Mountain Research Station, 2150 Centre Ave, Bldg. A, Suite 368, Fort Collins, CO 80526, Phone (970) 295-5986; jpotyondy@fs.fed.us; Assistant Professor of Watershed Science, College of Forestry and Conservation, University of Montana, Missoula, MT 59812 Phone: (406)243-5257, swoods@forestry.umt.edu.

reductions in complexity are achieved at the expense of reducing the model's ability to assess and predict cumulative impacts across larger geographic areas, which are an increasing area of concern for forest managers. Understanding the capabilities and limitations of each model is a critical aspect of effective model application.

Watershed managers tasked with assessing the impacts of management on soil and water resources face an additional set of challenges beyond those associated with model development. In order to be useful to managers the model software and documentation should be readily available, preferably via the Internet, at a reasonable cost. Model users are likely to be hydrologists, soil scientists and geomorphologists who, while familiar with the physical processes that the model seeks to simulate, are unlikely to have advanced skills in computer programming. Models should therefore be relatively straightforward to use, preferably with a user-friendly Microsoft Windows style interface. The model documentation should clearly describe the procedures used to represent the various physical processes, such as precipitation, infiltration and surface erosion that drive the cause and effect relationships, and the model assumptions and limitations. Finally, since many management decisions are subject to legal challenges, the model must be legally defendable. Generally this means that the model must be based on sound science, but additional requirements include clear definition of the model's assumptions and limitations, and the range of error and uncertainty in model output. A recent court case involving the USDA Forest Service (US 9th Circuit Court of Appeals, 2004), illustrates the importance of using legally defendable models for management purposes. The case involved a proposed timber sale for which the Forest Service's environmental impact analysis found no significant impact. The court rejected the agency's appeal of a lower court decision that stopped the sale, finding that their cumulative effects analysis was deficient and noting that the agency had failed to use sound scientific methodology. More specifically, the court found that agency reports derived from model use lacked adequate disclosure of model limitations.

In an effort to avoid similar outcomes in the future and to begin to build improved analysis tools, the Northern Region of the USDA Forest Service is engaged in efforts to improve the approach that the agency takes towards using watershed modeling tools for management within FMEs. A committee set up to determine the scope of these efforts concluded that the challenge was not to create new tools, but rather to determine which of the existing array of modeling solutions would best suit, or could be adapted to meet, agency requirements. Prior model inventory reviews (Borah and Bera, 2003; Doe et al., 1999; Jetten et al., 2003; Kalin and Hantush, 2003; Yang et al., 2003) were generally narrowly focused and conducted to satisfy research needs, and they mostly focused on agricultural watersheds, urban settings, or large rivers and reservoir. In addition, these inventories are at least somewhat out of date relative to the rapid advances being made in model research and development. In order to identify the best available modeling tools and techniques for assessing management impacts within FMEs, the Forest Service recently conducted an extensive inventory and review of existing sediment and water modeling tools. This paper presents a summary of the findings of this inventory and review, and provides recommendations for continued improvement of models for use in assessing impacts of management within FMEs.

METHODS

The search for candidate models relied heavily on Internet resources, reflecting the requirement that viable modeling tools and supporting documents must be readily accessible via the Internet. We assumed that prospective model users are trained earth scientists (hydrologist, soil scientist or geomorphologist) with an understanding of the protocols used for watershed assessment and cumulative effects analysis. We further assumed that model users are reasonably computer literate, experienced in Windows and Internet environments, and either possess GIS skills or have access to a qualified GIS specialist. From a practical perspective, we assumed that model users would have limited time, personnel, and budgets and that the data available to build, calibrate, and validate watershed models is limited and highly variable for individual National Forests. Models were evaluated based on the following five criteria:

1. **Intended use:** Was the modeling tool designed for or has it been adapted for use in FMEs and is it applicable for cumulative watershed effects (CWE) analysis?
2. **Accessibility:** Is the computer program and its supporting documents readily available, at minimal or no cost, preferably on-line?
3. **Ease of use:** Does the model have a "user-friendly" interface with data and model build requirements that are reasonably commensurate with the complexity of the area modeled and the questions asked?
4. **Documentation:** Are well-produced user manuals and technical documentation readily available?
5. **Defensibility:** Is the model based on sound, state-of-the-art principles of forest hydrology and geomorphology? Are model assumptions and limitations clearly stated and provided in model documentation? Are model results expressed in terms of probabilities and uncertainty with error analysis incorporated into model functions? Does the model have a substantial publishing record including theory, comparison, and validation?

RESULTS

Over 25 sediment and water modeling tools were identified and reviewed on the basis of the five criteria listed above (Table 1). The following paragraphs describe the six highest ranked models: DHSVM, FORest – Delta Q, R1-WATSED, SEDMODL2, SWAT and WEPP.

DHSVM: Distributed Hydrologic, Soil, Vegetation Model

The Distributed Hydrologic, Soil, Vegetation Model (DHSVM) is a research level, process-based, distributed modeling system designed for integrated modeling of forested hillslopes, watersheds, road and stream networks in mountainous environments. The model was written in command line code and presently has minimal 'user-friendly' interfaces.

FORest-Delta-Q: Forest Erosion Simulation Tools

The Delta-Q module is a fairly straight forward lumped parameter, empirical, GIS-based CWE accounting tool based on curves derived from 26 paired watershed studies throughout the nation. The three erosion models (only 'sediment production' is currently available) use a similar spatial framework with both empirical and process options to simulate erosion outputs.

R1-WATSED: Water and Sediment Yields

R1-WATSED is an empirically-based cumulative watershed effects model designed to model watershed response to multiple management activities and disturbances over time. WATSED is one of many local versions of the R1/R4 Sediment Yield Model (Cline et al. 1981), which also estimates water yield increases. A recently developed Windows based graphical user interface improves ease of model use, assuming sufficient local data exist to build response curves and calibrate outputs.

SEDMOL2: Sedimentation Model

SEDMODL2 is a GIS based road erosion/delivery model designed for FMEs that identifies road segments with a high potential for delivering sediment to streams. Although the model is well documented, ArcInfo interface and data demands for road segments may limit model use.

SWAT: Soil and Water Assessment Tool

The Soil and Water Assessment Tool (SWAT) is a hybrid empirical-process based modeling system designed to model water and sediment fluxes in moderately sized watersheds with varying land uses, soils, vegetation, and management practices over long periods of time. The model was originally developed for agriculture applications, however active research and development programs are improving the model utility in FMEs.

WEPP/FSWEPP/GeoWEPP: The Water Erosion Prediction Project

WEPP is a process-based, quasi-distributed parameter, continuous simulation, erosion prediction modeling tool applicable to hillslope erosion processes (sheet and rill erosion), hydrology, erosion processes, and routing in small watersheds. There is substantial Forest Service investment in web-based interfaces, to adapt original agriculture based design for use in forested mountain environments to model erosion from roads and disturbed areas and to develop a geo-spatial interface (GeoWEPP). Substantial refereed literature exists on validation of the parent WEPP modeling tool.

Table 1. Models identified as part of the inventory and review conducted by USDA Forest Service, Northern Region by the Rocky Mountain Research Station, Forestry Sciences Lab, Missoula.

AGNPS: Agricultural Non-Point Source - USDA, NRCS, Agricultural Research Service
ANSWERS: Runoff and sediment transport model
AQUARIUS: A General Model for Efficient Water Allocations in River Basins
ArcHydro: ArcGIS Watershed Modeling Framework
BASINS: Better Assessment Science Integrating Point and Non-point Sources
CASC2D-Sed: Cascade 2 Dimensional Sediment model
DHSVM: Distributed Hydrologic, Soil, Vegetation Model

GSTARS-W: Generalized Sediment Transport for Alluvial Rivers and Watersheds	
HEC-GeoRAS: Hydrologic Engineering Center – Geospatial River Analysis System	
HEC-HMS: Hydrologic Engineering Center – Geospatial Hydrologic Modeling Extension	
HSPF: Hydrological Simulation Program – Fortran	
KINEROS: Kinematic Runoff and Erosion model	
LISEM: Limburg Soil Erosion Model	
MIKE-BASIN/SHE: Système Hydrologique Européen	
PRMS: Precipitation-Runoff Modeling System	
RHESSys: Regional Hydro-Ecological Simulation System	
SAM Hydraulic Design Package for Channels	
SEDMOL2: Sedimentation Model	
SPARROW: Spatially Referenced Regressions on Watershed Attributes	
SWAT: Soil and Water Assessment Tool	
USLE: Universal Soil Loss Equation and derivatives, RUSLE and MUSLE	
VFSMOD-W: Vegetative Filter Strips Design and Modeling System	
WCS SEDIMENT TOOL: Watershed Characterization System Sediment Tool	
WEPP/FSWEPP/GeoWEPP: The Water Erosion Prediction Project	
WMS-GSSHA: Watershed Modeling System - Gridded Surface Subsurface Hydrologic Analysis	

Table 2 shows a comparison of these six models in terms of how well they fit the selection criteria of 1) appropriateness for the intended use in forested mountain environments (Fit to FME), 2) applicability for cumulative watershed effects analysis (Fit to CWE), 3) accessibility of documentation (Access), 4) ease of use (Ease of Use), 5) availability of well-produced documentation (Documents), and 6) legal defensibility (Defensibility).

All of the models satisfy the first criteria – applicability in forested mountain environments. The DHSVM, R1-WATSED and SEDMODL2 are more highly ranked because they were specifically developed for forested mountain environments, whereas FORest, SWAT, and WEPP have been adapted to forested settings. The DHSVM model is the highest ranked for CWE assessment because it is a truly spatially distributed model. FORest, R1-WATSED, SWAT, and WEPP are readily accessible via the internet. In contrast, SEDMODL2 and DHSVM were developed by a non-governmental organization and a research unit, respectively, that have less of a mandate to disseminate free information to the public. As expected, the research level DHSVM model can be difficult to use because of the absence of a user-friendly graphical user interface in the present version. However, the model developer envisions working with Forest Service watershed managers to produce a streamlined, less data intensive, decision support version of the model. Users of the FORest model must have sufficient experience and local data to adjust curves to local conditions. Both DHSVM and R1-WATSED lack extensive documentation, whereas SWAT has comprehensive documentation for each component of the model.

Table 2. Comparison of models by primary selection criteria. Five stars (*****) indicates that the model meets the criteria in almost all respects; one star (*) indicates that the model poorly meets to criteria. The ratings have a relatively narrow range at the high end of the rating scale because the table consists only of the top six models of the 25 examined by the review.

Model	Fit to FME	Fit to CWE	Access	Ease of Use	Documents	Defensibility
DHSVM	*****	*****	**	*	*	***
FORest	****	***	*****	***	****	***
R1-WATSED	*****	***	*****	***	**	***
SEDMODL2	*****	***	***	****	****	***
SWAT	****	****	*****	****	*****	****
WEPP	****	****	*****	****	****	***

All of the models are based on reasonably sound science and so achieve a moderate level of legal defensibility. Of the six models, SWAT is the most highly ranked for this criteria largely because it has been so widely used and because it has been certified in for use in federal courts, albeit in applications east of the Rocky Mountains. The most recent version of SWAT incorporates routines for auto-calibration, sensitivity analysis, and error and uncertainty analysis that further improve the overall defensibility of the model results. Only one of the models, SEDMODL2 offered a clear statement of assumptions and limitations. Purpose statements were readily located, but these alone are insufficient to defend model use.

DISCUSSION

The six models described here represent the state-of-the-art in modeling tools for application to management issues within FMEs. However, no one model meets all of the requirements for managers engaged in assessing the effects of management within FMEs. Management questions and analysis needs vary in complexity and scale, and so managers should expect to tailor model selection to the task at hand. It is expected that substantial thought and discussion will be required to decide just what this modeling "tool kit" should look like and how it will function. We propose that the best way forward is for agencies to agree on a limited number of models and then to support the development and refinement of these models for use within FMEs. This will also help to guard against problems associated with locally derived models which often lack scientific review and may therefore be difficult to defend and support when legally challenged. Finally, the development of corporate resource information databases and GIS analysis applications argues for the development of standardized data inputs to run suites of models efficiently.

Model defensibility remains a major concern for managers engaged in assessing the impact of management on soil and water resources within FMEs. Errors will always be inherent in all modeling solutions (Beven, 2006), some reducible and others wholly irreducible (van der Sluijs, 2002). Therefore regardless of how fine a tool kit can be constructed, managers will always need tools, methods, and guidance to adequately express the assumptions, limitations, and caveats of modeling systems when used in the legal arena. The first hurdle is to acquire clear statements of system assumption and limitations, ideally from model developers. If not them, through a research led effort specifically designed to decipher model documentation. Error and uncertainty in model output is still relatively poorly defined, but that which is understood must be effectively transferred from the research arena to managers. Another critical component of defensibility as pointed out by the Iron Honey case is data currency. Support for consistent data collection programs needs to be reemphasized and revitalized. A further concern with establishing legal defensibility of models lies in model validation – comparison of model predictions with observations other than those used for model calibration. Managers need to monitor management impacts over appropriate spatial and temporal scales, thus providing data sets for model validation and refinement.

In summary, the challenge of developing a responsible and effective modeling strategy has been treated as a two part problem, acquiring appropriate modeling tools and collecting quality data for model calibration and validation. Three more components must be added. First, standards for documenting intended uses, assumptions, and caveats must be developed and enforced. Second, tools and procedures to assess and report model error and uncertainty must be further developed along with programs to train managers in their effective use. Finally, managers need to provide model developers with the data needed for model validation and refinement. Meeting these challenges requires a clear, unified vision and commitment of resources from researchers and managers, but the result will be better predictions of management impacts and improved resource management.

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