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The Soil Erosion Model Guide for Military Land Mangers: Analysis of Erosion Models for Natural and Cultural Resources Applications

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The Soil Erosion Model Guide for Military Land Mangers: Analysis of Erosion Models for Natural and Cultural Resources Applications

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Executive Summary

This report, entitled ***The Soil Erosion Model Guide for Military Land Managers: Analysis of Erosion Models for Natural and Cultural Resources Applications***, is published as part of an ongoing initiative within the Department of Defense (DoD) to evaluate soil erosion prediction methods and technologies for application on military lands. This initiative is intended to support ecosystem management programs and environmental stewardship on military installations controlled by the Armed Services. The overall goal of this initiative is "to determine the best methods to predict soil erosion by wind and water on DoD installations over applicable spatial and temporal scales as a function of both human and natural activities" ***(Evaluation of Technologies for Addressing Factors Related to Soil Erosion on DoD Lands, USACERL Technical Report 97/134, September 1997).***

Twenty-four current soil erosion models were identified by the Tri-Services Natural and Cultural Resources Field Working Group (FWG) as having potential for use by military land managers – the user community. In this study, the twenty-four selected models were reviewed and evaluated against a set of criteria established by the Tri-Services Group. The evaluation is intended to provide the user community with guidance on which models may best support their intended applications related to soil erosion prediction, planning and mitigation.

The report provides an updated assessment of each model, to include the model concepts, constructs and formulation. It also assesses the technical and administrative considerations for each model. Ongoing developments and enhancements for each model are discussed. Finally, the linkage of models to geographic information systems (GIS) and user interfaces, to facilitate data input and analysis is discussed.

Recommendations are made as to which models provide the greatest potential for solving the unique erosion problems found on military lands. While established empirical models, such as the Revised Universal Soil Loss Equation (RUSLE), continue to have useful applications for some purposes, the study recommends that several of the new generation of physically-based, distributed parameter models have the greatest potential for use by DoD land managers. In particular, the Water Erosion Prediction Project (WEPP) model, the CASC2D rainfall-runoff model, and the Simulated of Water Erosion (SIMWE) model, are the most highly developed and supported models within this class of models. Several recommendations are made as to how these models can be revised or enhanced to tailor them for military land use applications. These recommendations provide the foundation for identifying future research initiatives in soil erosion prediction technologies that should be supported by the Department of Defense.

Preface

This document is intended to provide guidance to the Tri-Service CADD/GIS Technology Center on the available soil erosion models for military land managers and their usefulness for natural and cultural resources applications.

The preparation of this report was funded through the Tri-Service CADD/GIS Technology Center (Tri-Service Center) located at the Information Technology Laboratory (ITL), U.S. Army Engineer Waterways Experiment Station (WES) in Vicksburg, Mississippi. The report was prepared under Contract with Colorado State University, Center for Ecological Management of Military Lands. The contract was administered under the direction of the Tri-Services Natural and Cultural Resources Field Working Group (FWG) and the Tri-Services CADD/GIS Technology Center, U.S. Army Waterways Experiment Station

The report was prepared under the direction of Dr. N. Radhakrishnan, Director, ITL, and Mr. Harold Smith, Chief, Tri-Service Center. The Tri-Service Center functions under the guidance and direction of the Executive Steering Group (ESG) composed of Mr. Gary Erickson (Air Force), recent chairman of the group, and composed of Mr. Harold Smith (Center,) Mr. Kisuk Cheung (COE), Mr. Stan Shelton (Army), Mr. Steven Stockton (COE), Dr. Get Moy (Navy), and Mr. Russ Milnes. The goals and objectives of the Tri-Service Center are reviewed and guided by the Executive Working Group (EWG), currently chaired by Mr. M.K. Miles (COE), and composed of Mr. Harold Smith (Center), Mr. Paul Herold (Coast Guard), Mr. Mikeual Perritt (Air Force), Mr. Peter J. Sabo (Army), Mr. Ron Hatwell (COE), Dr. N. Radhakrishnan (COE), Mr. Thomas M. Karst (DLA), Mr. Bobby Bean (Navy), Mr. Gary Biggers (Navy), Mr. Jim Carberry (Navy), Mr. Thomas R. Rutherford (OSD), and Mr. Jim Whittaker (OSD). The principal investigator and author was Dr. William W. Doe III. Co-authors were Mr. David S. Jones and Dr. Steven D. Warrren, both of CEMML.. The technical monitor was Ms. Laurel Gorman, Tri-Services CADD/GIS Technology Center, U.S. Army Waterways Experiment Station, Vicksburg, Mississippi.

The authors acknowledge the contributions of the many U.S. and international scientists and practitioners who have developed and applied the soil erosion models described in this report. Many of these individuals, too many to name individually, were contacted during the course of this study. Their insights and interest in this study are greatly appreciated.

During the publication of this report, Dr. Robert W. Whalin was the Director of WES, and COL. Robin R. Cababa was the Commander.

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1 Introduction

1.1 Background

Soil erosion, by water and wind, is a critical land management problem on those lands controlled by the Department of Defense (DoD). This problem has been well documented in a number of studies (Riggins and Schmitt, 1984; Warren et al., 1991; Doe, 1992).

A previous report, entitled ***Evaluation of Technologies for Addressing Factors Related to Soil Erosion on DoD Lands***, articulated the ecosystem-based management approaches promulgated by DoD and began to define those critical steps, related to soil erosion problems, that must be accomplished to effectively and efficiently implement this management approach *(Evaluation of Technologies for Addressing Factors Related to Soil Erosion on DoD Lands (USACERL Technical Report 97/134, September 1997)*. The report identified the tools and data sources needed to address soil erosion problems, and generally describes the soil erosion modeling environment. It made a number of recommendations to be undertaken by DoD to further identify and implement practices to manage soil erosion problems. These recommendations included DoD participation in refining and applying soil erosion prediction technologies, specifically numerically-based soil erosion models.

Numerous soil erosion models have been developed over the past 50 years, both within the United States and internationally. The current inventory of soil erosion models, used throughout city, county, state and federal agencies, range from the very simplistic to the very complex. Many of these agencies, in cooperation with universities and other research centers, are involved in the further development of these models, for both research and application by land users and managers.

1.2 Objectives

There are currently no established guidelines for use of these models by DoD personnel. As the inventory of soil erosion models has proliferated, the sources of information for their use have become increasingly difficult to synthesize. The DoD land manager who must contend with soil erosion problems, but may have limited experience with modeling, is confronted with a difficult task in identifying and applying the best model for their specific needs.

Therefore, the Department of Defense identified the priority need to develop a technical guide for land managers that would assist them with selecting and applying those soil erosion models which would best fit their decision-making requirements. Rather than begin with the research and development of a new model, it was assumed that existing soil erosion models have great potential for application to military land problems. DoD experts identified twenty-four (24) models in the current inventory that have potential for use by military land managers. Some of these models are well established and have been used by other state and federal land management agencies for decades. Other models within this group are still under development or are being updated to accommodate new technological advances.

The overall objective of this study was: ***to objectively evaluate twenty-four (24) existing soil erosion models against a set of established criteria, and to make recommendations for which of these models have the best potential for assisting military land managers (the model user community) with soil erosion problems on military installations.***

1.3 Approach

A three-phased approach was used in the study. Phase I involved collecting background information, to include published manuals, technical articles and points of contact, on the 24 identified soil erosion models. This process was accomplished through University library sources and Web-based searches. The Internet search resulted in the identification of 35 Web sites, covering 20 of the 24 models, which is provided at ***Appendix A***. A number of model experts were also contacted via e-mail and telephone. A complete listing of agency contacts is provided at ***Appendix B***. The technical references for the models and this report are cited in the References section.

Phase II of the study involved a detailed evaluation of the 24 models against a set of thirteen (13) criteria provided by the DOD Field Working Group committee. Initially, the 24 models were organized into various families (classes) of models to organize the evaluation approach. These model families are described later in this report.

To accomplish Phase II the study team members reviewed the documentation on the models, contacted experts, and completed a summary model fact sheet for each model, which is provided at ***Appendix E***. The fact sheets document the characteristics of the model according to each criteria. Five of the criteria were descriptive in nature. These were:

- Class of Model
- Applications
- Known Limitations
- Assumptions
- Agency Support and Points of Contact

Eight of the criteria were evaluative in nature and included:

- Data Requirements
- Model Results
- Cost and Complexity
- Hardware Requirements

- Geographic Information System (GIS) Integration
- Commercial-off-the-shelf (COTS) Integration
- Graphical User Interfaces (GUI)
- Ease of Use

In addition to providing a written evaluation of each of the criteria, the 24 models were subjectively rated in each of the eight evaluative criteria. An overall rating (summary of the eight criteria scores) was also provided. Rating categories used were: Weak, Fair, Strong and None.

Phase III of the study involved the selection of a subset of eight (8) models from the original 24 models to evaluate their current or future capability to be integrated with Geographic Information Systems (GIS). Since GIS is becoming a readily available technology within DoD, it holds great potential for enhancing the modeling environment on installations. For each of these eight models, work flow diagrams, depicting the data links and processes, were completed. This portion of the study is described fully in later sections of the report.

1.4 Scope

The study was limited to the 24 soil erosion models identified by the Field Working Group. Only water-related soil erosion models were evaluated. The study report will be distributed by the Tri-Services to interested personnel at DoD installations. Additionally, the report will be used by DoD research entities to identify further research investments in these models. The report will serve as a benchmark reference for future DoD and separate Service workshops devoted to identifying strategic research goals in landscape erosion modeling.

2 The Ideal Soil Erosion Model for Military Lands

2.1 Definition of the Erosion Problem

Soil erosion is a natural landscape process of critical concern to many land management agencies. As a geomorphic process, soil erosion can generally be defined as the detachment and transport of in situ (in place) soil particles by two primary natural agents – water (in liquid or ice form) and wind. The consequences of soil erosion are both the removal of soil particles from one location and their subsequent deposition in another location – either on the land surface or in an adjoining watercourse. When moving through or being deposited along a watercourse, the soil particles are referred to as sediment. A single soil particle may undergo multiple cycles of removal and deposition over time spans ranging from a single-event (e.g., hours) to geologic time (e.g., decades or centuries).

A watershed, or basin, is a fundamental landscape unit, the boundaries of which are defined by terrain form and its resulting drainage patterns. Watersheds can be delineated at multiple scales, from a single tributary, stream or creek to a continental-sized area (e.g., the Mississippi River watershed). At all scales, the geometry and terrestrial characteristics of a watershed, and its climatic regime, define the paths and rates of soil erosion caused by water across the landscape. Theoretically, the only way a soil particle can leave a watershed is by physically removing it and transporting it by some human process, or by another natural agent – such as wind or a glacier, across the watershed boundary. The watershed, therefore, is a logical and useful framework for measuring and assessing soil erosion by water.

The naturally occurring soil erosion processes (detachment, transport and deposition) can be accelerated by anthropogenic land use activities. Such activities may include farming, grazing, forest harvesting, mining, road and building construction, and multiple forms of recreation (e.g., hiking, off-road vehicle driving, mountain biking, horseback riding, skiing, etc.). These activities commonly occur across large areas of the landscape over multiple events. Consequently, their impacts are both spatially and temporally distributed, rather than from one single source-point or event. The soil erosion-related effects of these human activities include the loss of fertile topsoil, gullying and non-point source pollution (sedimentation) of watercourses.

Land resource agencies employ soil erosion management practices, often called "best management" practices on a watershed scale, to minimize or mitigate the deleterious effects of associated land uses.. Land management practices, both structural and non-structural, may be employed at various spatial scales, from plot-sized (one acre or less) areas to entire watersheds. Structural measures include the construction of sediment detention berms, settling basins, and the application of gravel or geotextile materials to dirt trails and roads. Non-structural measures include artificial seeding, planting/fertilizing of vegetation, designating off-limits or limited use areas, or limiting the timing (e.g., seasonal, dry, etc.) of certain activities. The objective of land management practices is to minimize the human-induced impacts, while maximizing use (production) of the land for its designated purposes. The success or failure of these practices must be measured against identified management goals or criteria.

2.2 Hypothetical Military Land Use Scenarios

Military training and testing activities, occurring commonly on Department of Defense installations or training/ testing areas, are a unique category of land use, that can significantly increase the frequency and magnitude of soil erosion. The general effects of military activities on the landscape are, in many cases, similar to those caused by other non-military activities, such as agricultural or recreational uses. However, the nature (frequency, magnitude, intensity and duration) of military activities can produce unique impacts, uncharacteristic of other land uses.

Military land use managers must contend with the multiple environmental effects of training and testing activities, while at the same time, ensuring compliance with existing environmental laws and statutes. The general objective of military land management can be stated as follows - - *to optimize use of the land for training and testing activities,* *while ensuring compliance with state and federal laws and the land's long-term sustainability as a resource asset*. It is within this military land management context that the issue of soil erosion modeling must be addressed.

2.2.1 Characterizing DoD Lands

The Department of Defense controls approximately 25 million acres of federal land in the United States, including Alaska and Hawaii. These military lands are divided into hundreds of separate installations, ranging in size from "thousands of acres" to "millions of acres". They are geographically distributed throughout the U.S. with the majority of them located in the southeast, southwest and western states. DoD lands in Alaska exceed 5 million acres. These DoD lands represent diverse ecosystems as shown in Figure __, Distribution of DoD Lands by Ecoregional Province. In many cases the DoD land inventory represents a significant proportion of the federal lands within specific ecological regimes. For example, DoD lands represent the following percentages of total federal landholdings by ecosystem: 38.3% of the Great Plains Steppe and Shrub Province (OK/TX), 24.1% of the Southeastern Mixed Forest Province (VA, NC, SC, GA, AL, MS) 21% of the Yukon Intermontane Plateaus Tayga Province (AK), and 12.7% of the Chihuahuan Semi-desert Province (TX, NM, AZ) (*Conserving Biodiversity on Military Lands*, M. Leslie, et al., The Nature Conservancy, 1996).

This brief description of the physical characteristics of DoD lands suggests that a wide range of landscape processes, associated with different climatic and ecological regimes, occur on these lands. The processes of soil erosion will, likewise, vary considerably. For example, sparsely vegetated, arid lands in the Desert Southwest may experience only episodic rainfall and flood events that impact soil erosion. Rainfall in these regions is more likely to be infrequent, intense and spatially varied – with concomitant impacts on soil erosion processes. Forested landscapes in the Pacific Northwest or Southeastern Coastal Plains may be subjected to high frequency, high volume rainfall-runoff events throughout the year, producing heavy sediment loads in streams and rivers. Soil erosion in the subarctic regions of Alaska may be controlled by freeze-thaw processes and resulting glacial melt during the spring run-off season. **Figure 1** depicts the relative range

of soil erosion expected across these climatic regimes (Brooks et al., 1991). This emphasizes the point that soil erosion (frequency and magnitude) is a highly variable process across the spectrum of military lands.

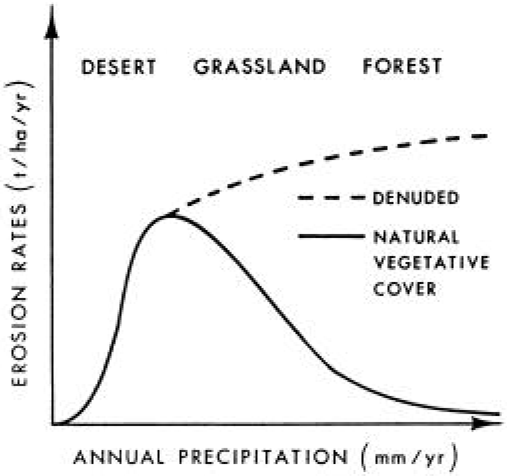

Figure 1. Relationship between erosion rates and annual precipitation for general vegetation cover conditions (from Brooks et al., 1991).

2.2.2 Training and Testing Activities on Military Lands

In defining the context for using and applying soil erosion models by military land managers, it is useful to consider several hypothetical military land use scenarios and their effects on soil erosion. Military land use activities can be generally separated into two categories based upon where they occur on an installation -- the cantonment or on training/testing areas – as shown in **Figure 2** below:

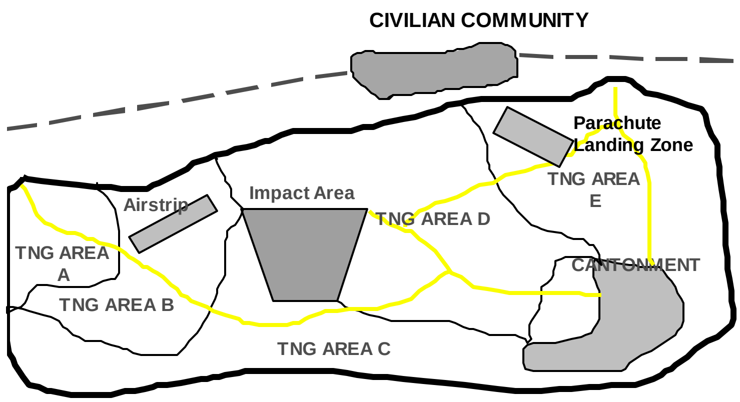

Figure 2. Representation of a military installation and its training areas.

Cantonment areas can be described as the "city" or "community" portion of a military installation. Generally, these areas provide housing for military personnel; buildings, warehouses and parking areas for administrative, supply and maintenance operations; and space for other community functions such as schools, commissaries and recreational activities. Due to the considerable infrastructure and paved areas, soil erosion is generally not considered a significant problem within the cantonment, except where structures such as culverts, bridges, etc, may be undercut or damaged. There is however, concern for non-point source pollution (e.g., suspended sediment) from maintenance areas, parking lots and other locations to adjoining built drainage systems (storm sewers, flood detention basins, etc.) and natural watercourses flowing through the cantonment.

Military activities which occur within training/testing areas are generally more intensive and consequently, considerably more conducive, to causing accelerated soil erosion. Typically, military tactical units, employ soldiers and weapons systems on foot, or by wheeled and tracked vehicles in maneuver warfare scenarios, both with simulated ammunition/munitions or by live-fire. Depending upon the size of units involved, contiguous tracts of land, ranging from several hundred to tens of thousands of acres, may be used at one time. Large-scale maneuver exercises may employ several hundred wheeled and tracked vehicles off-road. These events may occur from several days to several weeks in duration, under all types of weather.

Soil related impacts resulting from these activities include: disturbance and loss of vegetative cover, disturbance and loss of topsoil due to digging fighting positions and tank ditches, deposition of transported soil particles, vertical and lateral compaction and increases in surficial and sub-surface soil bulk density, changes in infiltration rates, rutting from vehicles, formation of rills and gullies and changes in microtopographic features.

Soil erosion not only directly impacts the quality of training lands for tactical use, but it may also produce adverse impacts on related environmental missions, to include the protection of significant habitats and cultural/historical resources. Soil erosion can degrade vegetation used for nesting and survival by endangered species. It can cover or expose sensitive prehistoric or cultural artifacts. Soil or groundwater contamination can occur from fuel and oil spills from individual vehicles, re-fueling sites or field maintenance sites. This contamination can be transported off-site by the movement of soil particles and sediment.

Live-fire exercises take place from established ranges or firing points into impact areas. Impact areas may also be used by tactical aircraft, firing live ordnance in support of ground forces. These impact areas, generally thousands of acres in size, are off-limits and contain numerous duds and unexploded ordnance, posing both a human hazard and the potential for contaminated runoff. Individual weapons firing occurs on small-caliber ranges where targets are arrayed to provide a variety of proficiency ratings. Firing berms and pits associated with these ranges may pose localized soil erosion problems, to include contaminated soil, wetlands and groundwater.

2.2.3 Land Rehabilitation and Soil Erosion Mitigation Practices

The Department of Defense supports a proactive approach towards minimizing and mitigating the undesirable effects of military land use activities. Within the context of soil erosion problems, a variety of land rehabilitation and maintenance practices are employed. These incorporate both structural and non-structural solutions. Examples of structural approaches include the placement of sediment detention structures (reveted berms or dams) along watercourses, construction of paved crossing sites along streams, stabilization of denuded areas using gravel and geo-textile fabrics, bank erosion stabilization using rip-rap or gabions, construction of tactical concealment islands and tree plantings in denuded areas. Non-structural approaches include re-seeding or re-vegetation of damaged areas, temporary withdrawal of lands from use to allow recovery, and designation of limited use areas.

Another real-time mitigation approach, used at some installations, is to stop cross-country vehicle movement during wet (Condition Red) soil conditions, since this is when most rutting and compaction occurs. Such constraints on training are usually at the discretion of the commander, under consultation with range and land management personnel on the training area. Although this management approach can impact the quality of training, it does prevent excessive soil damage in many instances, and minimizes the repair costs for land rehabilitation to the using units.

In addition to planning and implementing soil erosion mitigation techniques, military land managers are concerned with evaluating the relative success of these investments. This approach requires the development of criteria and the documentation of soil, sediment, and vegetation data using a variety of field data and remotely sensed data collection methods.

2.2.4 Terrestrial, Hydrologic and Soil Erosion Data Collection on Military Lands

The majority of military installations have well documented spatial data on the physical attributes of the landscape, to include topography (elevation and slope), soils, vegetation, wetlands, streams and waterbodies, and constructed features such as roads, trails, and engineering structures. This digital data is derived from multiple sources to include maps, field data and remotely sensed imagery (from aerial photography or satellites) and usually maintained in a Geographic Information System (GIS) or Computer-Aided Design (CADD) System. This capability provides an excellent source of data inputs for soil erosion models.

Automated databases, containing information on physical landscape attributes, also exist on many installations. For example, the Army supports the Land Condition-Trend Analysis (LCTA) program, which requires the inventorying and monitoring of vegetative cover and other parameters, through a variety of field-based data collection methods. This data collection is augmented by the use of remotely sensed imagery to classify various categories of landscape, use, and condition. These databases provide another excellent source of input data for models. For example, the LCTA Front-End computer program, operated in Microsoft Access, computes the empirical rates of average annual soil erosion, using the Universal Soil Loss Equation, from each site in the database.

Meteorological and hydrologic data are also collected on military installations through a variety of means and sources. Almost every installation contains at least one weather station, where temperature, precipitation, humidity and wind data are collected and summarized. These weather stations are most commonly associated with airfields and heliports on the installation. In some cases, denser networks of weather stations are located throughout the training/testing areas, operated either by installation personnel or in collaboration with other federal/state agencies, such as the National Weather Service, for flood-forecasting and other purposes. Major watercourses (rivers, streams, creeks) are, in some cases, also equipped with monitoring stations to provide data from gauges on stream velocity, discharge, stage and suspended sediment densities. These stream gauging sites are often monitored through cooperative efforts by the U.S. Geological Survey. Where available, these types of gauge data, are critical inputs to the calibration, validation and simulation of soil erosion models.

2.3 Description and Characteristics of the Ideal Model

Most soil erosion models are developed for specific types of land use activities or application. As their use becomes more universal and accepted in practice, they may be applied to other types of soil erosion issues or problems, albeit with appropriate caution and validation. In developing or selecting a specific soil erosion model for application, the developers and potential users must ask the following questions:

1) Who will use the model?

2) What equipment (computer hardware, software, etc.) is available to run the model and and analyze its results?

3) What is the users' level of technical competency with models?

4) What is the most common scale (space and time) of the application?

5) What level of accuracy and precision is required or desired?

6) How are the results to be interpreted and used?

7) What are the sources and availability of data to support the models?

For example, it makes little sense to invest limited resources into a highly sophisticated model, requiring detailed input data and high-computing capability, if there is no established program to collect data and most users have low-end computer hardware. Similarly, it is not logical to commit resources to a simplistic model with very gross-scale outputs, if detailed, site specific information on soil erosion is required. It is generally recognized that all soil erosion models have limitations, and that none can predict absolutely the amounts of erosion or sediment transport taking place. Nevertheless, if some type of soil erosion modeling is deemed useful and practical to the land management decision-making process, then the questions noted above must be addressed up-front and continuously, during the model development or selection phase.

It is unlikely that any single model can perfectly fit or accomplish all of the applications intended for complex land management decision- making. The best solution may be to identify a suite of erosion models that can be best applied to specific questions or land management problems. Model selection may differ according to the scale of the problem or from one climatic regime to another.

Given these considerations, it is useful to characterize, as best possible, the model selection process for military land managers, using the questions posed above. These constraints and criteria will help to best identify the characteristics of an ideal soil erosion model or suite of models for military land managers.

1) Who will use the model?

Natural resources (conservation) managers and technical staff, Public Works engineers and technical staff, Military training and testing land managers – at the installation and hierarchical command levels of DoD organizations

2) What equipment (computer hardware, software, etc.) is available to run the model and and analyze its results?

IBM-compatible personal computers (486 MhZ and faster processing speeds) and limited UNIX work stations, with standard office software packages (e.g., MicroSoft Office suite) in a Windows-based environment, with some GIS capability (e.g., ArcView), and access to Web-based information/data

3) What is the users' level of technical competency with computers and models?

Generally proficient in the use of computers with limited to no experience in soil erosion modeling

4) What is the most common scale (space and time) of the application?

Site-specific (plot or project scale) applications to landscape-scale watershed applications; single event to long-term predictions (5-20 years) of expected soil erosion rates and locations of sensitivity to soil erosion processes

5) What level of accuracy and precision is required or desired?

Order of magnitude accuracy and high-level of repeatability and replicability

6) How are the results to be interpreted and used?

As a decision–support tool, in plannin, real-time activities and ex-post evaluation; supported and augmented by on-site observations and experience of land managers

7) What are the sources and availability of data to support the models?

Multiple GIS data layers; limited to moderate availability of spatially distributed climatic and hydrologic data

This discussion of constraints and requirements provides a framework for identifying the best soil erosion models for military land managers. While the technology and modeling competency of land managers will undoubtedly improve with future developments and experience, the applications will most likely remain constant. These applications can be classified as either (1) predictive or (2) evaluative.

The predictive applications will be used for both short and long-term planning horizons to provide land managers and land users with an understanding of how military activities may impact soil erosion on their lands internally, as well as consequent trans-boundary impacts. These impacts may include downstream sedimentation and degradation of water quality in streams or air pollution caused by wind-transported materials from an installation site to an off-site community.

Soil erosion modeling can be used in the predictive sense by military land managers to: (Riggins and Schmitt, 1994)

- Calculate the erosion thresholds for a specific watershed, training/testing area or installation-wide
- Calculate expected long-term average annual soil loss for a given parcel of land
- Calculate expected soil loss for an interval (monthly, seasonal or training rotation)
- Calculate expected soil loss from a single storm (rainfall-runoff) event or single military exercise
- Compute sediment yield, either annually or for a single event, from a watershed
- Determine the locations within a watershed or training/testing area that are most sensitive (from a soil erosion perspective) to specific military activities
- Examine potential responses in soil erosion resulting from changes in land use or climatic change

Modeling can be used in an evaluative sense to:

- Measure and compare the effects of implementing soil erosion mitigation practices

- Monitor and evaluate watershed stability and ecological health over time

- Test and evaluate data collection methods and instrumentation

2.4 Agency Development, Technical and Research Support for Erosion Models

Soil erosion models are generally developed for two basic reasons: (1) research and (2) practical application. Research models are not intended, initially, for use in the field. Rather, they are intended to explore the dynamics of soil-water processes and to gain a better scientific understanding of the complex relationships between variables. Such models may be developed for a single component of the soil erosion process (e.g., soil detachment or infiltration) or for multiple components. Once the model serves its purpose it may be discarded or inserted into an existing model framework. Application models are generally developed for specific application(s) with the end user in mind. The components of the model have been generally validated in the field and accepted in practice.

Land management agencies develop both research and applied models. Research models may be used by only a small contingent of scientists and researchers within an organization, to address complex problems. They may be used by university researchers for basic research in cooperation with an agency. In some cases, a research model may evolve, over time, into an applied one. This evolution may require the agency to provide technical support in the areas of software development, hardware integration and user manual/tutorial development. These latter aspects can require significant personnel and financial resources.

While it is often difficult to assess the long-term intentions of land management agencies in this regard, the level of technical support provided by the agency and their continued commitment to the development of existing soil erosion models is a significant consideration. The best model, without continued updating and improvements to meet changing technology and user expectations, will fail.

3 Model Classification

A model is a representation (physical or conceptual) of reality. Physical models, also referred to as material models, are simpler physical constructs (e.g., metal, wood, concrete) of complex systems that are usually built to a smaller scale than reality, but are assumed to have some properties similar to the prototype system. Computer models, also referred to as formal models, use mathematical representations of reality. (Haan et al., 1982).

3.1 Mathematical Formulation

Computer model formulations can range from very simplistic expressions to very complex, mathematical representations of functions and processes, based upon the observed laws of nature. Models can be subdivided into theoretical (or physically-based) models and empirical models. Empirical models omit the physical laws and express relationships based upon field or laboratory experiments and the data collected from them.

Theoretical models are based upon a set of general laws or theoretical principles. These laws are (1) the conservation of mass (continuity), (2) Newton' s second law of motion (momentum), and (3) the first law of thermodynamics (energy). These equations can be solved analytically or numerically. An analytical solution is one in which the equations are integrated over time and space. A numerical solution uses approximate forms of the governing equations on a finite mesh of points (Maidment, 1991).

Both types of models simplify the physical system. In most cases, even theoretical models contain empirical components. For example, watershed hydrology and soil erosion models are most often hybrid models that include both theoretical and empirical components (Haan et al., 1982). No model can completely and accurately describe the complexities and inter-relationships in nature. However, models can provide a better understanding of natural phenomena (such as transport and deposition of sediment by overland flow) and allow for reasonable prediction and forecasting of events to come. These predictions may be probabilistic or deterministic. If any the model variables are random and have distributions in probability, then the outcomes are probabilistic. If the variables are free from random variation, then the outcomes are deterministic (e.g, for a given set of inputs there is only one possible output) (Haan et al., 1982).

Soil erosion computer models – the type of model discussed in this study -- use mathematical expressions to represent the relationships between various factors and processes occurring on the landscape. These factors generally include meteorologic variables (e.g., precipitation, wind speed), soil properties, vegetative cover, topography, and hydrologic features. The fluvial and geomorphic processes include raindrop impact, soil detachment, overland flow, channel flow, sediment transport and deposition.

3.1.1 Advantages and Disadvantages of Mathematical Formulation

In general, the advantages and disadvantages of empirical versus physically-based modeling, depend upon the intended use and range of application. Empirical models are based upon observed input-output relationships and do not necessarily simulate the actual processes involved. Two variables may appear to be correlated, when in fact, they are not. The user of empirical models must be confident in how these relationships were obtained. Furthermore, empirical relationships should not be applied outside the range of data from which they were obtained. A good example of an empirical soil erosion relationship is the Universal Soil Loss Equation (USLE), and its derivatives, that will be discussed further in this report. The equation is a relatively simple one that is based on a large data set of over 10,000 plot-years of data from natural runoff (rain-induced) plots and 1,000 plot-years of data from simulated rainfall-runoff plots, in agricultural settings (Haan et al., 1982). Although the USLE has been applied extensively for over twenty years, it has been criticized for its use beyond the range and application of the data set, e.g., in different climatic or land use regimes.

Conversely, physically-based models may be applied across multiple landscapes and situations because the mathematical relationships are derived from physical laws, which must be obeyed in all circumstances. These type models also allow the user to better understand cause-effect relationships and to isolate individual components for examination. However, their formulation is generally more complex and their solution may require extensive parameterization and data. Computational difficulties may also be experienced over large landscapes due to variations in scale, grid networks and flows that complicate the mathematical approximations of physically-based equations in the model.

3.2 Model Spatial and Temporal Structure

The landscape and its associated natural processes are inherently heterogeneous in space and dynamic in time. As one moves across the terrain, the in-situ characteristics of slope, vegetation and soil change from one point to the next. Similarly, the magnitude and directional responses of these features, caused by excitation (e.g., rainfall) or perturbations (e.g., human disturbance), is a function of time – that is, time is an independent variable that drives the response.

Models can accommodate the spatial and temporal components of physical systems in various ways. To simplify the parameter inputs and computational requirements, many models ignore the spatial heterogeneity of the landscape and assume homogeneity. These are referred to as lumped parameter models. In these types of models the entire landscape being modeled, or discrete units within the landscape, may be assumed to be the same. Spatially-varied, or distributed, models, on the other hand, attempt to characterize the natural variability of parameter properties and processes. The surface characteristics of landscapes are conveniently defined in this way through the use of spatial data, derived from remotely sensed imagery and digital geographic data in a geographic information system.

Lumped models are usually represented by an ordinary differential equation or a set of linked ordinary differential equations. Distributed models often consist of a set of linked partial differential equations in two or three-dimensions (x, y, z).

Another aspect of spatial structure relates to how the landscape boundaries are represented in the model. For distributed models, there are basically two different ways of representing the landscape: (1) as a series of contiguous grid-cells (raster cells), or (2) as a series of elements. These representations are illustrated below in Figures 3and 4 :

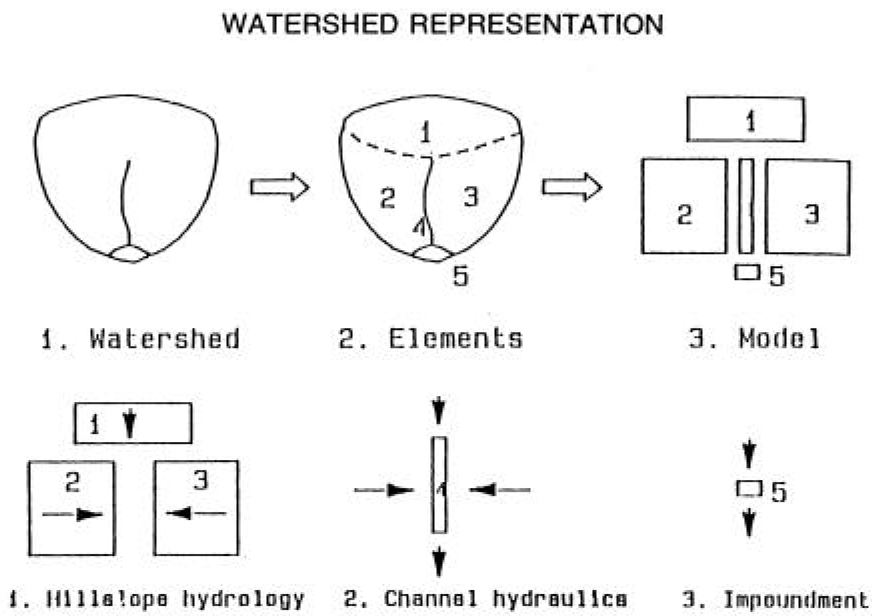

Figure 3. Schematic of watershed represented as elements in a distributed model (from Renard et al., 1995).

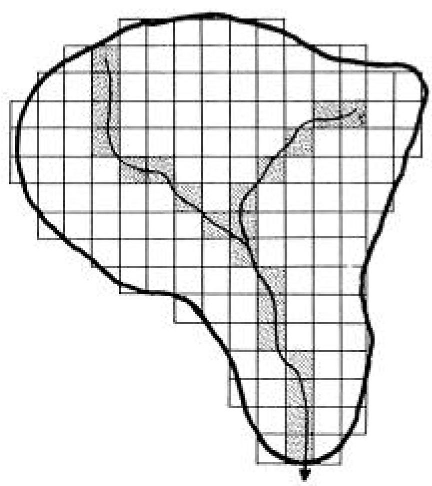

Figure 4. Schematic of watershed represented as raster grid-cells (from Beasley and Huggins, 1991).

Both types of representations have advantages in terms of mathematical formulations and data handling. However, the grid-cell structure greatly facilitates integration with digital data derived from remotely sensed imagery and geographical information systems.

The temporal structure of models is two-fold. The first aspect considers the calendar – e.g., days, weeks, months, years, etc. Single-event models are usually on the shorter end of the time spectrum, while continuous models are generally run for lengthier periods of time. The second aspect of time considers the role of the time factor as a variable in the formulation. Steady-state, or static, models do not concern themselves with the time factor. Dynamic models consider time as an independent variable and can compute the time variability of outputs. This is often accomplished, mathematically, by designating a time-step in the model set-up.

3.2.1 Advantages and Disadvantages of Model Structure

Spatially-varied (distributed) models provide a more realistic approximation of the physical system. In this regard, they are preferable to lumped parameter models. However, tradeoffs must be considered between the accuracy and precision of the model versus the amount of data needed to characterize the system and run the model. Distributed models are notorious for being "data hungry". In some instances the user may be forced, by time and other practical constraints, to estimate or approximate parameter inputs for a spatially-varied model. This approach, to some extent, may negate the distinct advantages of using such a model. The use of a spatial model requires the selection of an appropriate landscape unit or grid-cell size. The user must be aware that the selected scale may directly effect the model outputs – e.g., different outcomes for the same system may be computed.

The choice between single-event or continuous models is largely determined by the user's requirements. Single-event models can provide real-time or near real-time predictions of natural events, such as sediment discharge or yield from a rain storm or snowmelt event, or sand flux from a wind storm. The evaluation of specific frequency events, e.g., the 100-year flood, are well suited to this approach. Single-event models may also be useful in evaluating the superposition of extreme events with specific land-use activities, e.g., a large military maneuver exercise.

Continuous simulation models compute discharge, yield and other process outcomes over larger time periods, for example, weekly, monthly or annually. The outputs of these models represent time integrated estimates. This approach mimics nature in that a large percentage of the erosion on a landscape occurs during a small number of significant events over a long period. Continuous models can simulate a number of years and sum the soil losses over time to obtain average annual estimates of erosion from multiple events (Lal, et al., 1992). These models allow the user to better understand the range of frequencies associated with natural events, e.g., low-flow or high-flow stream discharge events, or to statistically average the outputs to establish long-term planning horizons. In this manner they are of value in evaluating conservation systems wherein conditions change as a function of time (e.g., seasonality or climatically).

A final point to consider in selecting single-event versus continuous modes is the extent to which the user must input parameter values to drive the model. In the single-event mode the user must establish the initial conditions (e.g., soil moisture, surface roughness, canopy cover, etc.) for the model to run. This requires a great deal more knowledge on the part of the user, and can effect the model outputs significantly. In continuous models the initial conditions are not as important since the model adjusts each of the variables over time during the simulation, and therefore the outputs respond to model corrections rather than user input.

3.3 Model Scale of Application

Computer models may be constructed to fit a range of physical scales. The selection of scale often determines which physical processes are most important, and therefore, what must be mathematically coded in the model. In this study, three relative scales were identified for model use: 1) field scale, 2) watershed scale, and 3) landscape or regional scale. Each of these scales can be broadly defined by the size (area) of the physical system domain to be modeled. For purposes of this study the following ranges apply:

Scale	Size of Physical System Domain
Field	< 100 acre (0.4mi2)
Watershed*	100 acre(0.4 mi2) < x < 25,000 acres (100 mi2)
Landscape/Regional	> 25,000 acres (100 mi2)

* NOTE: The term "small watershed" is often used to connote watersheds of size less than 5,000 acres.

3.3.1 Advantages and Disadvantages of Model Scale

The intended application most often dictates the best model scale to be chosen. Some models are specifically designed for a particular scale. Model users must be cautious in extrapolating results from one scale to another. Those processes that are dominant at the smaller scales may not be dominant or significant at larger scales.

The model scale will also directly impact data requirements and the computational power required for processing the data in the model. For example, watershed and regional scale model may require overland flow and channel routing schemes between land units or grid cells.

3.4 Classification of the 24 Erosion Models

In this study, the characteristics of the 24 selected models were identified within four major components to illustrate their commonalities and differences, and to provide a common language for discussing model attributes. These four components were:

- Model Formulation
  1) Empirical
  2) Deterministic (physical or process-based)

- Model Structure (Spatial Variability)
  1) Lumped Parameter
  2) Distributed Parameter

- Temporal Structure (Temporal Variability)
  1) Single-event
  2) Continuous or Long-term average

- Scale of Application
  1) Field scale (plot)
  2) Watershed scale (small to intermediate watersheds)
  3) Landscape/Regional (large watersheds)

Appendix C provides a matrix of model classification according to these components. The model classification by itself does not measure the quality or value of the models to military land managers. Depending upon the application, different model characteristics may be most desirable or applicable.

4 Modeling the Erosion Process

Erosion modeling is based upon our understanding of the physical laws and landscape processes that occur in the natural world. Modeling translates these components into mathematical relationships, either first order principle or empirical, describing the fundamental water erosion processes of ***detachment, transport and deposition***. Numerous scientific textbooks and references describe these processes and modeling constructs. In order to evaluate the pros and cons of various erosion models it is important to understand the key terms and concepts related to soil erosion phenomena. The following discussion is intended to only briefly review these terms and concepts prior to describing how they are used in the respective models.

Erosion by water is induced by the natural occurring events of rainfall or snowmelt, or artificially by irrigation and other types of sprinkler application of water to the surface. Detachment of individual soil particles may occur when water strikes the surface by overcoming the interstitial forces holding the soil particles together. This is commonly referred to as ***rainsplash or raindrop splash***. As the inducing events continue, water infiltrates into the soil at a rate controlled by the intensity of water hitting the surface and the infiltration capacity of the vertical soil profile. The ***infiltration capacity*** is a function of several soil hydraulic characteristics that relate the spacing and bonding of soil particles to each other, and the effects of other micro-surface and sub-surface characteristics.

Water that is not infiltrated begins to pond on the surface. When sufficient depth is achieved at the surface, water flow will begin in the direction of the steepest slope that is unimpeded. This begins the hydrologic process referred to as ***overland flow***, ***or runoff***. Soil particles may be dissolved or suspended in the overland flow, beginning the process of ***sediment transport*** as shown in Figure 5 .

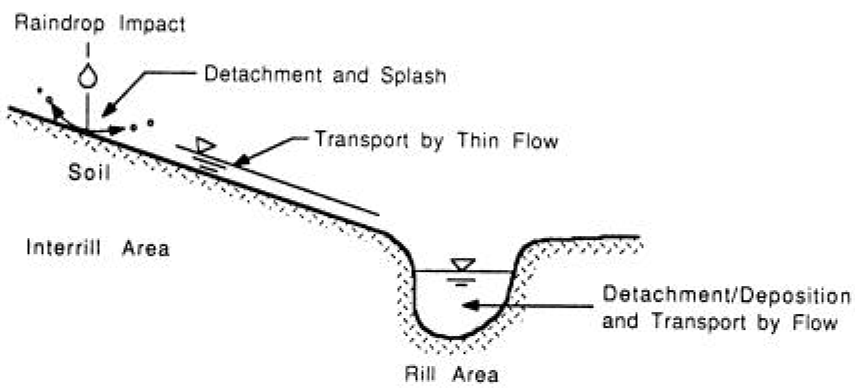

Figure 5. Erosion and transport on inter-rill and rill areas (from Hagen and Foster, 1990).

Watersheds, or catchments, are commonly divided into the upland areas and channels. In the upland areas overland flow is conceptually divided between ***rill flow*** mechanisms and ***inter-rill flow*** mechanisms, which occur on hill slopes. As overland flow converges from various portions of the upland area and becomes more concentrated, it becomes sufficiently erosive to form shallow channels, referred to as ***rills***. Additional soil particles may become detached as water flows through these rills. In the inter-rill areas, runoff occurs as a very thin, broad sheet, sometimes referred to as ***sheet flow***. Both detachment and transport may occur in the rill and inter-rill areas. As erosive power increases, the small rills may converge to form larger surface channels, called ***gulleys***. The rill and inter-rill areas and gulleys are the source areas for water erosion, as shown in

Figure 6 below:

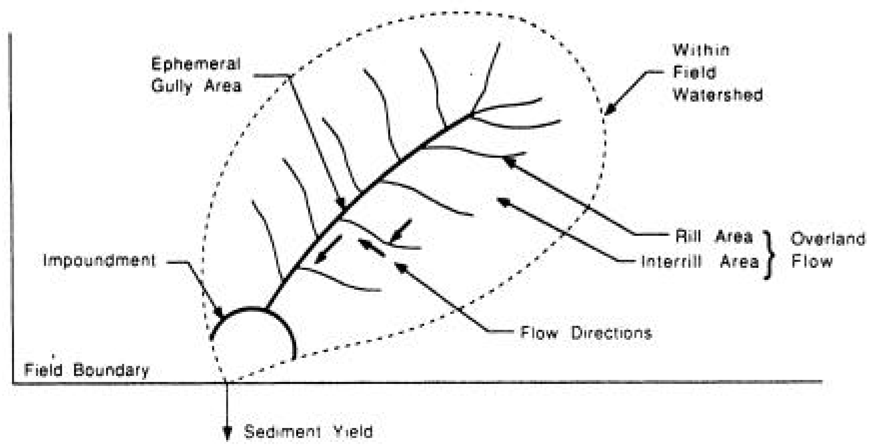

Figure 6. Schematic of rill, inter-rill areas and gulleys on a sub-watershed, or catchment (from Hagen and Foster, 1990).

Eventually, if sufficient water continues down slope it will reach well-defined ***channels***, through which both water and sediment will be carried downstream towards the watershed outlet. If at any point along the water flow path the velocity is decreased (e.g., change in slope), some soil particles may be deposited because the reduced flows cannot carry as much sediment. The ***transport capacity*** is the maximum amount of sediment that a given flow can carry without net deposition occurring. ***Detachment capacity*** and transport capacity are interrelated and it is their interaction that controls the patterns and magnitudes of erosion and deposition. The character of the processes is closely linked to which capacity is the limiting factor. For example, if the detachment capacity of the soil is significantly lower than the transport capacity (e.g., for clayey soils where the inter-particle binding forces are large and resist detachment), than the amount and magnitude of soil ***erosion is limited by the detachment capacity – referred to as the detachment-*** limited case. If on the other hand, the detachment capacity is significantly greater than the transport capacity (e.g., for sandy soils that are easily detached), than the amount and magnitude of soil erosion is limited by the sediment transport capacity of runoff – referred to as the ***sediment transport-limited*** case (Warren, 1998).

The amount of sediment actually leaving a site or watershed is a function of the erosional and depositional processes – both surface and channel – that occur up slope of the discharge point. The amount (mass) of sediment being carried is called the ***sediment load***. The velocity of entrained sediment passing a given point is the ***sediment rate***. When the velocity is multiplied by the cross-sectional area of the channel through which it is passing, a mass rate of transport, called ***sediment discharge*** is computed.

Sediment yield, as shown in Figure 7, is the amount of eroded soil that is delivered to a point in the watershed that is remote from the origin of the detached soil particles. In a watershed, sediment yield includes erosion from slopes, channels and mass wasting (slumping, sliding, falling, etc.), minus the sediment that is deposited after it is eroded, but before it reaches the point of interest (Renard et al., 1997). The sediment yield can be estimated for a given point in a watershed by applying a Sediment Delivery Ratio (SDR). The SDR, usually expressed as a percentage, is the fraction or percentage of gross erosion arriving at a given point, or:

SDR = Ys/ Te, (Brooks et al., 1991)

Where, Ys = sediment yield at a given point
Te = total gross erosion from the watershed upstream of the given point

It is, therefore, the total computed gross soil erosion minus all forms of sediment deposition taking place upstream of the designated point.

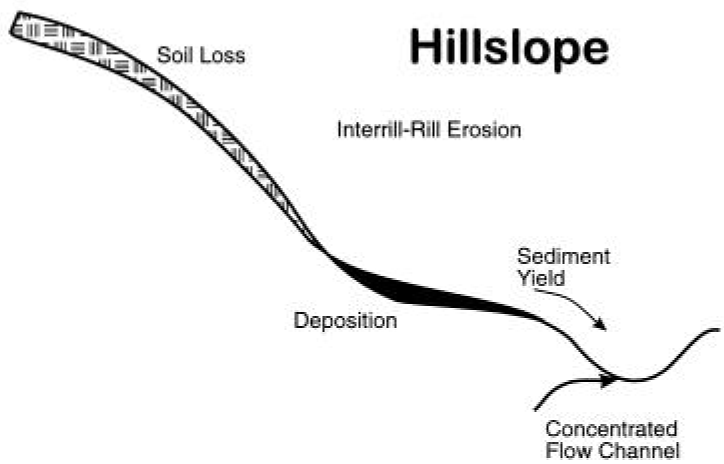

Figure 7. Representation of erosion and deposition from a hill slope to a channel (from Flanagan et al., 1995).

5 Description of the 24 Erosion Models

5.1 Families of Models

To facilitate the evaluation process, the twenty-four models were divided into six families of models. A family of models implies that each model within the family fundamentally uses the same assumptions, equations and model structure in its design. However, individual components of a specific model, as discussed in Section 3.4, within a given family, may be modified or improved upon.

No erosion model is developed without consideration of other models that have gone before it. In many instances, significant components of one model are transferred to another. The new model may be adapted to fit other applications or to fit new technologies. In either case the refinement of older models and the formulation of new models rely on the foundational physical processes of soil erosion and the historical development of modeling efforts.

5.2 The USLE Family of Models

5.2.1 USLE

The Universal Soil Loss Equation (USLE) is the most widely used and accepted empirical soil erosion model. Its development can be traced back to the 1940-50’ s with basic equations developed for sheet and rill erosion, as influenced by slope length, steepness, climate, cropping and management. It was completed and documented in 1965 on the basis of a large body of experimental data from agricultural plots. Over 10,000 plot-years of data from natural rainfall-runoff and 1,000 plot-years of data from simulated rainfall-runoff were used to develop the relationships (Lane, et al., 1992). All of these experiments were conducted in relatively humid locations within the United States, east of the Rocky Mountains.

The development of the USLE was primarily intended to aid erosion control practices on agricultural lands in the United States. With the advent of water quality planning laws and regulations in the early 1970’ s the USLE gained popularity in use. The model has been enhanced over the past thirty years by a number of researchers. It continues to form the basis for numerous conservation planning practices on agricultural lands. It has also been applied internationally.

An exhaustive history of the development of the USLE and its modifications has been published (Renard et al., 1997; Lane et al., 1992; Peterson et al., 1979).

5.2.1.1 Model Principles & Assumptions

The USLE is an empirically derived regression equation that computes the gross average soil loss, A, over a unit area. The gross erosion is that soil loss produced from a combination of sheet, rill, and inter-rill processes. The model does not estimate erosion gully or channel erosion, nor does it compute deposition. It does also not calculate sediment yield – the amount of sediment delivered to a downstream point or watershed outlet. In practice, varying sediment delivery ratios (SDR) have been applied to the gross erosion estimates calculated by USLE to compute sediment yield. The results of these computations are highly variable and represent only a long-term average yield for a given watershed.

The USLE equation computes average soil loss (A) expected over long periods of time (e.g., one year or more). The product is expressed as the multiplication of five factors that affect soil loss, and is given by:

$$A = R\ K\ LS\ C\ P, \text{ where}$$

A = average annual soil loss per unit area
R = rainfall-runoff erosivity factor
K = soil erodibility factor
LS = topographic or slope length/steepness factor
C = cover and cropping-management factor
P = supporting practices (land use) factor

The terms on the right-hand side of this functional relationship are further defined below. R is a factor which accounts for the erosive forces of raindrop impact and the intensity (I) and energy (E) of rainfall events in a particular geographic location. EI values are obtained by multiplying the energy (E) times intensity (I), generally for the 10-year frequency, maximum 30-minute intensity storms recorded from historical data. Isoerodent maps, depicting uniform rainfall-runoff values throughout the United States, have been published by the U.S Department of Agriculture and the National Weather Service.

The K-factor accounts for the influence of in-situ soil properties on soil loss in upland areas. The factor represents an integrated average annual value of the total soil and soil profile reaction to various hydrologic and geomorphic processes, to include soil detachment, transport, localized deposition and infiltration.

The LS factor incorporates the topographic effects of slope length (L) and steepness (S). Slope length is the horizontal distance from the origin of overland flow to the point on the landscape where either (1) the slope gradient changes significantly enough to initiate deposition, or (2) runoff becomes concentrated in a defined channel. Steepness is the percent change in elevation divided by the change in horizontal distance across the slope length, L.

C factor values are determined by surface and sub-surface vegetative effects, to include residue cover, canopy cover, canopy height, surface roughness, and biomass. These sub-factors can reduce the impact of raindrops and slow the movement of water across the landscape. Both the physical effects of agricultural cropping techniques, and their seasonality, are considered.

The P factor accounts for conservation practices used on the landscape to mitigate erosion. These practices include contouring, stripcropping, terracing and sub-surface drainage. If no practices are in place (e.g., natural conditions), then a P-factor value of 1.0 is used.

All of the factors are dimensionless, with the exception of R and K. The variables LS, C and P are expressed as ratios of expected soil loss to experimentally measured loss on "unit plots". A unit plot is defined as "76.2 feet long, with a uniform slope of 9 percent, in continuous fallow, tilled up and down the slope." A C-factor value of .50 means that a particular crop-management system, and its resulting crop/vegetative cover, is 50% (or one half) as erodible as the condition defined by the unit plot.

The units selected for R and K are usually defined in English units such that A, the average annual soil loss, is expressed in "tons per acre per year". For expression in metric units, the values of R and K must be multiplied by a conversion factor. In metric units, A is generally expressed as "kilograms per meter square per year," or "metric tons per hectare per year" (Haan et al., 1992).

The values for all five factors can be derived experimentally, but are most commonly taken from established iso-line(isoerodent) maps, look-up tables or nomographs. Values for K, the soil erodibility factor, are listed by soil series in most official soil surveys published by the Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS). Although individual storm values can be used in the model for R, the USLE should not be used to estimate erosion expected from single rainfall events. Since the model is best used for annual estimates, the R value used should include the cumulative effects of many moderate-sized storms, as well as the effects of occasional severe (high intensity) storms (Singh, 1989).

5.2.1.2 Applications and Limitations of the USLE

The agricultural assumptions and applications underlying the development of USLE are apparent and well documented. It was clearly intended for conservation practices on agricultural lands, where various cropping systems and support practices are applied. The USLE, and its derivatives, have been applied to many other conditions, to include rangelands, forested wildlands, construction sites, surface mine reclamation sites, construction sites, and military training areas. These applications have been debated and criticized to varying degrees. There is clearly the potential for misuse or misinterpretation of the results in these situations (Wischmeier, 1976; Lane et al., 1992). Wischmeier (1976) distinguishes between misinterpretation and misuse. Applying the USLE in new geographic regions or for new purposes is generally not a misuse, but the user should be cautioned about interpreting the results. However, if the factor values in the model cannot be reasonably derived from existing data a misuse is more likely. No matter what the application, soil losses computed by the USLE must be recognized as best estimates, rather than absolute values (Wischmeier, 1976). The USLE has been reported to overestimate soil loss on rangelands.

Applications for which the equation are specifically designed and field tested include: (1) predicting average annual soil movement from a given field plot/slope under specified land use and management conditions, (2) guiding the selection of conservation practices for specific sites, (3) estimating the reduction in soil loss attainable from various changes in cropping systems or management practices, (4) providing local soil loss data to use when discussing erosion control needs and best management practices, and (5) estimating soil losses from construction, rangeland, woodland and recreational areas (Wischmeier, 1976).

A variety of modifications have been made to the USLE equation to refine its application on rangelands and forested lands. Most of the rangeland modifications are implemented in the Revised USLE (RUSLE), discussed in Section 5.2.3. The major concerns for application to forested lands are that for most forest practices, the irregular pattern of soil disturbance and the interruption of surface flow paths by debris and forest litter will cause USLE estimates to be too high (Hewlett, 1982). A vegetation management (VM) factor has been developed for forested lands, to replace the traditional C and P factors in the model. The VM factor accounts for canopy cover effects; effects of low-growing vegetative cover, mulch, and litter; and land use effects (Brooks, et al., 1991).

The most common and practical use of the USLE as a conservation management tool is to compare computed erosion rates for a given area, with a set of proposed land use practices, to published values of acceptable soil loss tolerances, expressed as T. T values have been published by soil series for the majority of soil types found in the United States. They are based largely on professional judgment and range from 1 –5 tons per acre per year. Therefore, if the computed soil loss rate, A, using the USLE is 4 tons/acre/year, and the T value is 2 tons/acre/year, the erosion rate exceeds acceptable thresholds by a factor of 2, or 200 % (4/2 x 100). This ratio (A/T) of computed soil loss to acceptable soil loss tolerances is called the Erosion Status (ES). Another expression using these two terms is called the Erodibility Index (EI). The EI ratio expresses the inherent erodibility of a site, assuming that the only factor impacted by human activities is the C-factor. By substituting T for A in the USLE, the EI is computed as: EI = (R K LS P)/T. The computed value can be used as a metric to determine if the land is highly erodible.

The application of USLE described above, using the ES and EI ratios, was used on military lands at Fort Hood, Texas to derive a management map showing the values of ES and EI across the landscape (Warren et al., 1989). Using multiple spatial data bases for soils, vegetation and elevation they derived the appropriate USLE factors for each 50-meter grid cell, across the entire 250,000 acre installation. They assumed that no significant agricultural or conservation support practices were in place and used a value of 1.0 for P throughout the calculations. The authors suggest that this approach has a wide range of applications to military land managers, to include: 1) providing land condition inventories, 2) determining carrying capacity and training loads for particular areas within the installation, 3) demarcating administrative area and off-limits boundaries, 4) identifying potential areas for land rehabilitation, and 5) criteria for evaluating future land acquisitions. A similar approach, using GIS-derived factor values, was used to compute gross erosion on a large watershed within the U.S. Army Pinon Canyon Maneuver Site in eastern Colorado (Harrison and Doe, 1997).

As discussed previously, the USLE should not be used to compute sediment yield, except for estimates of long-term average yields across a given watershed. In this manner the sediment yield is generally estimated by applying one of several analytical Sediment Delivery Ratios (SDR), used as a lumped accounting of sediment load changes below a specific point in the watershed, or at the outlet. Harrison and Doe (1997) applied this technique to USLE computations on a study watershed in the U.S. Army Pinon Canyon

Maneuver Site, Colorado. They computed the total gross expected soil loss, in tons, across a 31,000 acre watershed by multiplying a spatially weighted USLE rate by the watershed area. They then applied three different SDR' s ranging from 9.7% to 46 % (e.g., 9.7 – 46% of eroded soil leaves the watershed). Their calculations showed that the resulting sediment yields were within the same order of magnitude as the average annual sediment load measured by the U.S. Geological Survey at the watershed outlet during a four-year period.

The general effects of military operations, particularly large-scale mechanized maneuvers, on the landscape have been well documented. These impacts include compaction of the soil (both laterally and vertically in the soil profile), loss of vegetative cover and changes in micro-relief (surface roughness). Under most circumstances, these perturbations decrease infiltration, increase overland flow and cause rills and gullies to form. These impacts can be indirectly associated with changes in the C and K factors of the USLE. In the Pinon Canyon Maneuver Site study, experimental results obtained from tracked vehicle impacts tests and Land Condition-Trend Analysis (LCTA) plots were used to adjust parameter values based upon changes in bulk density and loss of vegetative cover (Harrison and Doe, 1997). The undisturbed C-factor values for each grid-cell in disturbed portions of the watershed were uniformly increased by 50% based upon the plot data. K-factor values, for the same disturbed areas, were uniformly increased 12.5% based upon the vehicle field tests. A comparison of undisturbed versus disturbed erosion estimates was made for those areas impacted by maneuvers, with an expected increase in the overall gross erosion (tons/acre/year).

5.2.2 MUSLE

The USLE was modified in 1975 to predict sediment yield for individual storm events (Williams, 1975). The R-factor (rainfall-runoff) in the equation was replaced with a runoff factor, based upon the assumption that runoff is the best single indicator of sediment yield. This approach was tested on eighteen of watersheds ranging in size from 132 to 4,380 acres in size, with data from over 700 individual storm events (Williams, 1975). Several different forms of the runoff factor were evaluated using the data and the equations were optimized to achieve the best results. The equation that best fit the data was:

$$S = 95\ (Q \times q_p)^{0.56} \times K \times LS \times C \times P, \text{ where}$$

S = Sediment yield in tons
Q = volume of storm runoff in acre-feet
Q_p = peak flow rate in cubic feet per second

This equation accounted for 92 percent of the variation measured in sediment yield, and was generally more accurate for the larger storm events.

5.2.2.1 Applications and Limitations

Although the modified USLE proved to be a fairly accurate sediment yield predictor it is important to take caution with applying this equation on any wide basis. The optimum values of the coefficients in the equation may need to be adapted for other small watersheds. It is also inappropriate to apply the equation to watersheds exceeding 5,000 acres in size. Finally, the MUSLE only provides an estimate of total sediment yield, rather than the yield of individual particle classes (e.g., sand, silt and clay). It provides no information on how sediment yield is distributed over time during a runoff event and should not be used where soil detachment is the controlling factor in sediment yield.

In order to apply MUSLE the user must have hydrologic data available from individual storm events, to include volume of runoff and peak flow. This information is typically derived from a storm hydrograph, which depicts the time-varying changes in stream flow over time at a designated downstream point. The hydrograph can be constructed from gauge data captured during the actual storm event, or be estimated from historical data using rainfall-runoff curves.

5.2.3 RUSLE

Since the USLE was formally developed and published a number of studies and data collection were undertaken by researchers to improve its noted deficiencies. These improvements were initiated under the USDA concept of the Revised Universal Soil Loss Equation (RUSLE) in 1985, and completed with publication of the RUSLE Handbook in 1997 (Renard et al., 1997). The RUSLE maintains the same basic six - factor structure as the original USLE. However, all of the equations used to derive the factors have been modified and enhanced to account for a variety of field conditions. Procedures for computing each factor from basic data have also been developed for cases where published values are not readily available. Finally, the procedures and factor values have been computerized into a variety of automated programs and routines to assist the user with selecting parameter values and performing the RUSLE computations (Renard et al., 1997).

The RUSLE essentially replaces the USLE as the preferred empirical equation for computing average gross erosion rates across landscapes. The developing agency, USDA-ARS and the authors contend that RUSLE will provide erosion technology for use in addressing problems being proposed in the last decade of the 20th century or until new modeling technologies become available (Renard et al., 1997).

The following provides a general summary of the improvements and enhancements made to the original USLE by RUSLE (Renard et al., 1997). The R (rainfall-runoff erosivity factor) database has been expanded for the western United States to account for the more time and spatially variant rainfall patterns found in those geographic regions. Additionally,equivalent R-factor values have been computed for snow-melt induced runoff events. In many cases, the R values for Western states have increased 100% - 700 % from their original values. The K (soil erodibility factor) has a time-variant component that accounts for the seasonal effects of freeze-thaw in cold regions. This is an important process to account for since freeze-thaw actions cause soil fluffing, which can make individual soil particles highly susceptible to detachment and transport. Equations for estimating the value of K from particle size data have also been included. For the LS (length-slope topographic factor), additional algorithms have been developed which significantly decrease computed soil loss on slopes greater than 20%. Additionally, for non-uniform slopes, equations based upon the convexity or the concavity of the slope are incorporated, since the shape of the slope can significantly effect the amount of erosion (e.g., erosion is generally greater on convex slopes). The C (cover management factor) computations have been altered to include the incorporation of five sub-factors: prior land use, surface cover, crop canopy, surface roughness and soil moisture. P (support practice) factors have been expanded to consider conditions for rangelands, contouring, stripcropping, and terracing. The developers note, however, that the P-factor remains the least well defined of all the factors (Renard et al. ,1997; Lane et al., 1992). A detailed explanation of the factors and their derivations is available in the USDA-ARS guide to conservation planning with RUSLE (Renard et al., 1997).

5.2.3.1 Applications & Limitations

The improvements made by RUSLE make the USLE-based erosion prediction model generally more applicable across a wider range of landscapes, both geographically and scale-wise. The effect of RUSLE on USLE soil erosion estimates will vary by location. Although a total generalization cannot be made, RUSLE estimates of gross soil erosion have been found in many cases to be less than those computed using USLE (Lal et al., 1994; Jones et al., 1996). The automated capabilities using the RUSLE software facilitate data input and parameter selection. The software is available through USDA-ARS or can be down loaded from their Internet Web site (see ***Appendix A***).

The selection of appropriate parameter and sub-parameter equations and values in RUSLE requires some knowledge of the landscape to which it is to be applied. While there are only five factors in the RUSLE equation, there is significant effort involved in identifying sub-factor conditions. One of the most common misconceptions with inexperienced users of RUSLE is that you simply have to look up five values in a table and compute the soil loss. The model is much more sophisticated than this. The enhancements made to RUSLE may be viewed as a disadvantage from the standpoint that the additional sub-factors require more data to make them useful. If this data is not readily available the user may be required to make estimates based upon professional judgment, which can lead to inconsistency in the application. It is therefore essential that some time of vegetation monitoring plots be established to collect the necessary data for the computations. Without this ground-truthed data the calculations become relatively meaningless, or at best may provide very misleading results.

The RUSLE has been applied to estimates of soil erosion on military lands. A case study was applied to the U.S. Army Yakima Training Center (YTC) in the state of Washington (Jones et al., 1996). The authors found that the soil loss estimates on a number of land condition-trend analysis) LCTA) plots were significantly less (50% or more) than USLE estimates for the same plots. These computed differences were attributed to several of the sub-factors in the C-factor component of the equation. C values in RUSLE were 65% smaller than their corresponding USLE values. Additionally, the authors note that some assumptions about sub-factor values were made that could influence the results.

RUSLE estimates were also compared to calculated USLE estimates for the U.S. Army Pinon Canyon Maneuver Site, Colorado (Harrison and Doe, 1997). In their comparison, the authors kept all the factor values constant, except for R and C. The R-factor was determined from the updated isoerodent maps and decreased from a value of 100 to a value of 40. The C-factor was computed at the grid-cell scale using data derived from Land Condition-Trend Analysis (LCTA) plots. The C-factor values using RUSLE were generally lower than those computed by USLE, ranging from 100-700% smaller than their corresponding USLE values. Although this trend in values has been reported in other studies the high degree of variation reinforces the potential problems associated with lack of field data to determine parameter sub-values.

RUSLE has also been used to compute historical erosion rates at Fort Leonard Wood, MO (Albertson, 1998). The author modified the C and P factors in the equation to account for the changes in land use covering a 200-year time period from pre-settlement (in 1800) to the year 2000.

5.2.4 USPED

The limitations of the USLE model and its derivatives, the MUSLE and RUSLE, have been outlined in the preceding sections. In particular, these empirical equations can be used only to estimate gross erosion, and lack any capability to compute deposition along hill slopes, depressions, valleys or in channels. Similarly, these equations represent a soil detachment capacity-limited case in that the erosion estimates are based on rainfall intensity and raindrop impact on the surface, as expressed by the R factor.

The influence of terrain on erosion is represented by the topographic factor, LS, which assumes a uniform slope angle and length along the path of water flow. Improvements to the LS factor equations in RUSLE accommodate irregular slopes by incorporating the amount of hill slope convexity and concavity. Studies have shown that convex slopes may increase erosion by 30% or more as compared to uniform slopes of the same steepness as the average steepness of the convex slope.(Renard et al., 1992). The LS factor can be derived from Digital Elevation Model (DEM) data using standard slope algorithms. However, both the USLE and RUSLE only consider erosion along the computed flow lines, usually along the x and y axes and diagonals, and ignore convergence or divergence of water flows from other directions. Deposition is not considered or computed in these equations.

The limitations in USLE/RUSLE noted above often result in high estimates of erosion, because depositional areas, such as micro-depressions and valleys, are not typically excluded from the computations. This makes the application of these equations highly suspect in complex terrain. The Unit Stream Power-based Erosion/Depositon (USPED) model is intended to improve upon these inherent deficiencies by using high accuracy interpolation techniques for adequate terrain representation (Mitasova et al., 1996).The USPED uses a dimensionless index of sediment transport capacity, T, and a topographic index, E, representing the change in transport capacity in the direction of flow, to estimate the spatial distribution of both erosion and deposition. The parameter, T, is derived from the general form of the sediment transport equation for unit stream power theory, describing the effects of terrain on soil erosion. The upslope contributing area is used as measure of water flux into a given location, or grid-cell. The index, E, is positive for areas with topographic potential for deposition and negative for areas with erosion potential. These components of the USPED model are combined with the other factors in the USLE/RUSLE formulations to compute erosion and deposition patterns across a complex landscape.

The USPED is intended for use where the topographic component of USLE/RUSLE-based erosion models are derived from Digital Elevation Model (DEM) data in the form of grid-cells. The tracing of flows from one cell to adjoining cells is often complicated because of data resolution and accuracy, and because “data pits” may trap the flow lines and cause numerical inconsistencies (Mitasova et al, 1996). In USPED updated spline and smoothing techniques are used with the DEM data for reducing data artifacts and for reinterpolating the data to a higher resolution. Several of these routines have been incorporated into the GRASS GIS system.

5.2.4.1 Applications & Limitations

The USPED model has been tested on several landscapes using different elevation data sets (range of elevation values and resolution) (Mitasova et al., 1996). One application was for a small field-scale area (500 m by 500 m) in central Illinois using digitized contours, derived from 10-foot contours on a 1:24,000 scale topographic map of the region. The model results were very satisfactory as compared to those results derived from the USLE LS formulations. The USLE formulation predicted high erosion potential at the lower, concave parts of hill slopes, where deposition is usually observed. Similarly, the USLE predicts relatively low erosion in areas with convergent water flow, where higher rates would be expected. The USPED estimates were much more consistent with slope and energy characteristics of the landscape.

The model was also applied to a military training area within the U.S. Army Yakima Training Center (YTC) in eastern Washington state. The standard 30-meter resolution Digital Elevation Model (DEM) data, available through the U.S. Geological Survey, was used in this analysis. Due to the relatively low resolution of the data and the complex terrain there were significant systematic errors in deriving the topographic indices. This limitation prevented accurate results from being obtained for erosion/deposition estimates and therefore, only the topographic sediment transport capacity index for each grid-cell was computed (Mitasova et al., 1996).

The USPED model was applied to another military installation, Camp Shelby, Mississippi, with more promising results. The purpose of the analysis was to provide a planning tool for proposed changes in military land use, specifically, an increase in tracked vehicle maneuvers. In the study 5-meter resolution data was created from digitized contours. The erosion/deposition index was computed for both the undisturbed condition and the proposed intensive land use. The spatial analysis, using USPED, allowed the planners to identify areas least susceptible to erosion and to make recommendations for mitigation measures in areas of high erosion and deposition (Mitasova and Brown, 1996).

The use and applications for USPED have been enhanced through the use of scientific visualization tools integrated with GIS. These tools can be used to illustrate dynamic landscape phenomena and processes, such as erosion and transport, in three-dimensional form. Research studies are currently ongoing to apply these techniques to USPED and other terrain-dependent soil erosion models.

5.2.5 EPIC

The Erosion-Productivity Impact Calculator (EPIC) is an empirical, continuous simulation model designed to assess the effects of soil erosion on soil productivity. The model is designed for application on field sized areas up to 250 acres on homogeneous landscapes. Although it was designed to estimate the long-term relationships (1 –4,000 years) between soil erosion and soil productivity, the model has been adapted to include simulation of pesticide and nutrient transport across fields. Various agricultural management practices can be tested in the model to determine their effects on nitrate, phosphorous, pesticides and sediment (Sharpley et al., 1990).

The model includes a weather generator which provides values for rainfall and other meteorological parameters based upon long-term weather records. The hydrologic component of the model includes surface runoff, return flow, percolation, evapotranspiration, lateral subsurface flow and snow melt.

Soil loss is computed by the USLE/RUSLE equations. Sediment yield estimates can be computed using the Modified USLE (MUSLE). The model does not calculate sediment transport or deposition.

5.2.5.1 Applications & Limitations

The EPIC model has been used for a variety of agricultural applications to include drought assessment on crops, global climate change analysis and farm level planning. The advantage of using EPIC is its capability to simulate, using the synthetic weather generator, a large number of scenarios which can be used as a decision support tool for soil management practices.

5.2.6 APEX

The Agricultural Policy/Environmental eXtender (APEX) model is an improvement of the EPIC model, which incorporates a routing scheme between subareas or fields for sediment deposition, nutrient and pesticide transport and subsurface flow. It can be applied to larger areas than the EPIC model, for example, whole farms or small watersheds. Each sub-area or field is assumed to be homogeneous.

The hydrologic and sediment components of the model are similar to EPIC. APEX can route surface runoff and related contaminants between components of the landscape as either concentrated, channelized or overland flow

5.2.6.1 Applications & Limitations

The APEX model is capable of simulating a variety of cropping variables and management practices. These include different crop characteristics, plant populations, dates of planting and harvest, timing of fertilization and irrigation and tillage.

APEX can also be used to simulate the impacts of cropping systems on water quality. The model has been used in both the United States and Europe to assess the impacts of best management practices on pollutant loadings to surface water bodies and ground water.

5.2.7 ALMANAC

The ALMANAC model is a derivative of both the EPIC and APEX models that is used t predict the effects of agricultural management decisions on crop production for field sized areas. The model incorporates both a water erosion and wind erosion component.

5.2.7.1 Applications & Limitations

The primary applications of ALMANAC relate to plant competition and crop growth over long periods of time. The model can be used to assess weed competition effects on crop yield, optimization of planting densities and success of planting various hybrid crops.

5.2.8 AGNPS

The Agricultural Nonpoint Source Pollution (AGNPS) model is a physically-based, distributed, single-event model designed to simulate sediment and nutrient transport from agricultural watersheds, and evaluate the corresponding water quality. The model was developed by the Agricultural Research Service (ARS) of USDA in 1980 and has been continuously improved upon. The most recent version of the model, Version 4.03, was completed in 1994, and its additional features are well documented (Young et al., 1994). More recently, a joint venture between ARS and the Natural Resources Conservation Service (NRCS), entitled AGNPS 98, was initiated to add a continuous simulation capability to the model and integrate it with several other computer programs.

AGNPS is designed to be applied primarily at the watershed scale, ranging from sizes of ten acres to 50,000 acres. In the model the landscape is represented by a series of grid-cells, or elements. Each grid cell is assumed to be homogeneous with respect to the physical characteristics it represents. This aspect of the model makes it particularly compatible with raster geographic information systems (GIS).

AGNPS has three major components including hydrology, soil erosion and nutrient pollution. The runoff volume and peak flow rate are derived for specific precipitation events using the Soil Conservation Service (SCS) Curve Number (CN) parameter. The CN is determined empirically based upon type of land use, soil type and hydrologic soil condition and is a measure of the runoff potential of an area. Curve Number tables and nomographs are readily available. Approximately 4,000 soil types have been classified into Hydrologic Soil Groups (HSG) for this purpose (Haan et al., 1994). Basic equations using total accumulated rainfall and the CN compute the runoff volume for the storm. The peak runoff rate is then estimated using an empirical relationship using the runoff volume and other characteristics of the watershed. A similar approach is used in the CREAMS model.

Upland erosion in each grid cell is computed using a modified form of the Universal Soil Loss Equation, relating factors for storm energy, soil erodibility, topography, cover and management, and supporting conservation practices. Additionally, a factor to adjust for slope shape within the cell is incorporated into the equation. The soil loss is computed for each cell and then subdivided into five particle size classes. Detached sediment is then routed from cell to cell as a function of slope between adjoining cells. The routing equation is derived from the steady-state continuity equation, accounting for deposition and sediment transport capacity within the system. Streambank and gully erosion are estimated as point sources of sediment and added to the upland sediment estimates. The effective sediment is ultimately transported to the watershed outlet (Young et al., 1989).

The nutrient pollution or chemical transport component of AGNPS is adapted from the CREAMS model. It estimates the transport of nitrogen (N), phosphorous (P) and chemical oxygen demand (COD) throughout the watershed. Chemical transport calculations are divided into soluble and sediment adsorbed phases. These processes are affected by nutrient levels in rainfall, fertilization and leaching. (Young et al., 1989).

5.2.8.1 Applications & Limitations

The AGNPS model has been used within several states to evaluate pollution in runoff and degradation of water quality resulting from agricultural land management practices (Young et al., 1989). Specifically, it has been used to:

- Prioritize watersheds for potential severity of water quality problems
- Identify critical areas within a watershed that are contributing to downstream pollution
- Evaluate effects of alternative management practices

One of the major advantages of AGNPS is that it can identify critical areas within a watershed where excessive erosion and runoff is occurring. This model output information can be used as a decision support tool for government agencies in cooperation with local land users. Once the critical areas are identified, appropriate best management practices (BMP) can be identified and implemented. These BMPs can be tested as scenarios within the model before they are implemented to estimate the expected improvements in sediment yield and water quality (Young et al., 1989).

As previously discussed, the AGNPS model is particularly well suited to integration with GIS, both from a data input and data output analysis perspective. A GRASS(GIS) – AGNPS interface has been developed and is discussed later in this report. The interface greatly facilitates the derivation of the 22 input parameters need to run the model. The use of Digital Elevation Model (DEM) data to derive topographic inputs is an example of this approach (Srinivasan et al., 1994). A number of visualization tools linked to GIS have also been developed to analyze the model simulation outputs, either at the grid-cell level or for the entire watershed.

5.2.9 CREAMS

CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) is a field-scale (less than 100 acres in size) model that predicts runoff, erosion and transport from agricultural areas. The model was developed in 1980 as a tool to evaluate the effects of various agricultural practices on pollutants in surface runoff and in soil water below the root zone, in response to off-site water quality concerns (Lane et al., 1992).

The model can operate in both single storm-event mode or in a long-term average (continuous) mode. The continuous mode is the intended mode of operation and can predict long-term averages from 2-50 years.

Although the CREAMS model uses various aspects of the USLE/RUSLE equation to compute, for instance, interrill erosion by raindrop impact, it differs radically from the USLE/RUSLE empirical formulations in that it uses a process-based approach to calculate the various components of erosion and route sediment across the field. The CREAMS model, unlike USLE/RUSLE, accounts for gully erosion and deposition across the channel and landscape profiles. In this regard, CREAMS represents a major technological advance in expressing soil loss as a process-based phenomenon, including erosion, transport and deposition.

The CREAMS model represents the hydrologic component of the field system using three elements – overland flow planes, channels and impoundments. The field is assumed to be uniform in soil composition, topography (slope) and land use (agricultural practices). An important aspect of the CREAMS model is that it accounts for sediment aggregation of individual soil particles. This is important because clay particles often form in aggregates and attract chemical pollutants. They therefore become critical in computing contaminant loads associated with sediment transport and deposition.

In the CREAMS overland flow component, erosion is computed as sheet and rill erosion, on a variety of concave or convex profiles. Interrill erosion is computed separately using the USLE formulation. Since runoff often concentrates in a few major channels before leaving a farm field, erosion and deposition within the channel system is important to include in the model formulation. Channel bank erosion caused by scour between the channel sidewalls and moving water is computed based upon relationships between critical shear stresses in the soil and the flow hydraulics produced by the channel geometry (Lane et al., 1992). The model also accounts for backwater effects along the edges of the field where oftentimes runoff is slowed down by dense vegetation, causing deposition along the boundary. The effects of impoundment terraces used to drain runoff are also accounted for.

5.2.9.1 Applications & Limitations

The CREAMS model is intended primarily to evaluate sediment yield from established agricultural fields. Its major advantages are that it is process-based, and therefore measures both erosion and deposition across the landscape profile. The user is therefore able to identify where in the field system major erosion and deposition rates are occurring (Lane et al., 1992). The model is also useful for evaluating the pollution potential (e.g., the transport of undesirable chemicals) from a field. This has obvious applications for evaluating compliance with water quality standards off-site. The model computes an enrichment ratio based upon soil surface area, that can be summed with the calculated sediment yield, to provide a metric for pollution potential of the sediment itself (Lane et al., 1992).

Several aspects of the CREAMS model are appropriate solely for agricultural applications. For example, there is a plant nutrient submodel that accounts for various chemical process within the soil profile to compute nitrate leaching. These would appear to have limited application on military lands.

The major limitation of the model is that it is applicable only to field-sized applications, although some applications have been used on areas up to 1000 acres in size. There is no grid-cell capability that also limits its applications across larger landscapes. The assumption of uniformity within the model' s components is not well suited to non-agricultural applications.

Model input requirements to run the CREAMS model are extensive and are detailed in the User' s Manual (Knisel, et al., 1980). The user must define a number of physical features within the study area, to include soil hydraulic, slope, and channel characteristics. Additionally, daily rainfall amounts from gauging stations are needed to compute rainfall-runoff Curve Numbers (CN). Peak runoff rates must also be derived using regression equations based upon the relationship between runoff volume and watershed characteristics.

5.2.10 SWRRB

The Simulator for Water Resources in Rural Basins (SWRRB) model is a physically-based, continuous erosion model designed to simulate water and sediment yield from watersheds. It was developed by the USDA-ARS to provide a tool for predicting the effects of land use in rural areas. The model contains components of both the USLE and CREAMS models. Sediment yield is based upon the Modified USLE (MUSLE) equation.

The model contains five major components: weather, hydrology, sedimentation, nutrient transport and pesticide transport.

5.2.10.1 Applications & Limitations

5.2.11 SPUR

The Simulation of Production and Utilization of Rangelands (SPUR) model is a comprehensive rangeland simulation model developed to simulate the effects of various grazing and livestock practices on semi-arid grassland and shrubland areas. Both a field-scale (grazing unit) and watershed scale (up to 6,000 acres) are available.

SPUR' s model structure is the same as SWRRB, except that it contains an animal and economic components to assess the effects of land degradation on livestock production and profit.

5.2.11.1 Applications & Limitations

The applications of SPUR are primarily for grazing and livestock management.

5.2.12 SWAT

The Soil and Water Assessment Tool (SWAT) is a derivative of the SWRRB model that can be applied to larger watershed and more complex landscapes. It uses a grid-cell characterization of the landscape to represent the spatial variability across large watersheds or regions.

The SWAT model has been integrated with the GRASS GIS system. A variety of hydrologic tools in GRASS are used to generate the input maps for the model.

5.2.12.1 Applications & Limitations

SWAT has been applied to a large military installation at Fort Hood, Texas. The model was used to study sediment and nutrient contamination of a large reservoir on the installation. The upstream impacts of training and testing were contributing to increased loading of the reservoir, used for flood control and water supply. The researchers were interested in evaluating the effects of grass filter strips, as best management practices, within several of the watersheds feeding the reservoir. A watershed map of the installation was created from digital topographic data.Water sample data was used to calibrate the model. The results of these simulations are still pending.

5.2.13 HUMUS

The Hydrologic Unit Model for the United States (HUMUS) is derivative of the SWAT model that is used on a large basin scale (10,000 km2) to model surface and sub-surface water quality and quantity. It is considered applicable to national and regional scale concerns.

5.2.13.1 Applications & Limitations

The HUMUS model was tested on the Lower Colorado River basin and will be used in a national assessment of water quality under the Resource Assessment Act.

5.2.14 GLEAMS

The Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model was developed as an extension of the CREAMS model (see Section 5.2.9) to evaluate the impact of agricultural management practices on potential pesticide and nutrient leaching (vertical flux) within, through, and below the root zone. The model, like CREAMS, also estimates surface runoff and sediment losses from field-sized areass. GLEAMS is a physically-based, continuous simulation model. Although it was originally developed for field-scale analysis its capabilities have been extended to larger watershed areas using geographic information systems (GIS).

The GLEAMS model has four major components: hydrology, erosion/sediment yield, pesticide transport and nutrients. A large number of hydrologic inputs are required to include precipitation, water balance parameters (e.g., water uptake by crops, potential evapotranspiration), and soil hydraulic factors (e.g., saturated hydraulic conductivity). The model functions on a daily time-step basis and uses a modified Curve-Number (CN) procedure derived from soil hydrologic properties. The Curve Number estimates the maximum available storage in the soil and excess water is then computed as surface runoff (Knisel, 1993).

As in the CREAMS model, the landscape is characterized by a combination of overland flow, channel and impoundment elements. Each element is considered to have homogeneous characteristics (soils, rainfall, land use, etc.) and the appropriate input parameters (slope, width, length, etc.) must be identified for each. Soil detachment and sediment transport occur as both rill and inter-rill processes and are mathematically routed into concentrated flows in channels. Deposition, by particle size, occurs where sediment transport capacity is exceeded and resulting sediment yield from the field area is computed.

The most significant component of GLEAMS is the plant nutrient component which simulates the plant nutrients of phosphorous and nitrogen. The component of the model mathematically defines the major processes and transformations of nitrogen and phosphorous, and considers surface and sub-surface pathways to estimate loadings (concentrations) at the edge of fields and at the bottom of the root zone (Knisel, 1993). The complete nitrogen and phosphorous cycling process between the atmosphere, vegetation and soil profile is represented. It includes land application of animal waste as well as inorganic fertilizers. These chemicals may be adsorbed onto sediment and transported across the surface or into adjoining watercourses.

All of the components of GLEAMS require extensive parameter selection and data inputs. This process is facilitated by a variety of parameter editors and help screens which allow the selection of default values or user specified values.

5.2.14.1 Applications & Limitations

Applications of GLEAMS range from the simple to complex. The model can provide estimates of the impacts of various agricultural management systems on chemical transport of pollutants. Various application rates for fertilizers, methods and timing of application can be tested to reduce root zone leaching. Typical uses include:

- Providing estimates of historical pollutant loadings from known or assumed field conditions and agricultural activities.
- Providing estimates of pollutant loadings with application of various conservation strategies, to rank their effectiveness in reducing the impact of sediment, nutrients or pesticide contamination.
- Tracking the fate and movement of agricultural chemicals to evaluate the type of chemicals, application rate or timing of application as it impacts pollutant loading in surface runoff or leached water.

The GLEAMS model has been used as a component of automated pesticide risk screening analysis for counties and agricultural districts, called the National Agricultural Pesticide Risk Analysis (NAPRA) program. The model computes the estimated pesticide loss from below the root zone or at the edge of a field. A risk assessment score is then provided based upon Environmental Protection Agency drinking water standards.

Although GLEAMS was developed for field-scale applications its capabilities have been extended to larger areas (e.g., watersheds) through the use of geographical information systems. For example, the model was used in a study on agricultural soils in the alluvial plain of the Chiana River in Italy (Garnier et al., 1998). The authors used GLEAMS to assess the environmental sustainability of animal waste disposal in the region. The model was used initially on 2.5-acre sample areas. It was then expanded for application using 400-meter sized grid cells – defined as land units – containing homogeneous physical and land use properties. They used 40 years of data to compute the annual average values of leachate and leached nitrate, and the nitrate concentration in the leachate. They also used the model to evaluate the carrying capacity of soils, defined as the total amount of nitrogen that can be applied on a particular area in one year without unacceptable losses in groundwater quality.

One of the noted deficiencies of the model was the inability to update soil parameters based upon land use induced impacts, during the simulation (Garnier, et al., 1998). The model was not able to consider that animal waste fertilizer improves the hydrologic performance of soils by improving soil structure and decreasing leaching. The authors note that model outputs should be considered as a “rough evaluation” of system behavior. These limitations have consequences for evaluating military land use as well, since the movement of wheeled and tracked vehicles across the surface can alter soil physical properties, either positively or negatively, with respect to structure, infiltration, and surface ponding.

The GLEAMS model is most applicable to military activities that are concerned with pollutant leaching and transport due to contamination. Both nitrogen fixation and phosphorous loadings may be impacted by the degradation and decomposition of ammunition and ordnance in impact areas or on firing ranges.

5.2.15 CASC2D

The CASC2D (acronym for 2-dimensional, cascading run-off) model is a physically-based, distributed (2-dimensional) rainfall-runoff model that can be applied to a variety of watersheds with varying land use components. The model was initially developed in the early 1990’s at Colorado State University as a research tool to examine the spatial and temporal effects of watershed parameter and rainfall variability on watershed response (Julien and Saghafian, 1991; Doe, 1992). The model was initially integrated with the GRASS GIS system for data inputs and analysis of simulation outputs (Doe, 1992; Doe and Saghafian, 1992). Additional capabilities, to include an upland erosion and sediment routing routine (CASC2D-SED) have been developed (Johnson, 1998). The model has also been fully integrated within GRASS and incorporated into the Watershed Modeling System(WMS), developed by Brigham Young University, to facilitate raster data input and analysis using a suite of GIS and visualization tools (Mitasova et al., 1995).

CASC2D is a grid-cell based model which represents the spatial variability of the landscape at a user-specified resolution, generally between 30 – 300 meters. It can also accommodate spatially and temporally varied rainfall inputs from rain gauge data collected in the watershed. The point rainfall data is spatially distributed using an inverse-squared algorithm function from the gauge location. The spatially distributed components of CASC2D make it particularly compatible with raster data inputs from GIS data layers, remote sensing and weather radar-derived rainfall rates (Ogden, 1992).

There are two major components within the CASC2D model – a hydrologic component and an upland erosion component. The hydrologic component includes the Green and Ampt formulation for infiltration, a two-dimensional (x,y) solution of the diffusive wave form of the continuity equations for overland flow, and a one-dimensional solution of the diffusive wave formulation for channel routing (Ogden and Saghafian, 1997). Model computations are performed for each grid cell at a user specified time step, usually between 5-30 seconds. Within each grid-cell representing the landscape, soil hydraulic parameters (hydraulic conductivity, soil moisture) control the vertical movement of rainfall into the soil profile. As infiltration capacity is exceeded in the cell, the remaining surface depth of water is routed in two orthogonal directions to adjoining cells, according to the water surface slope, as shown in Figure 8:

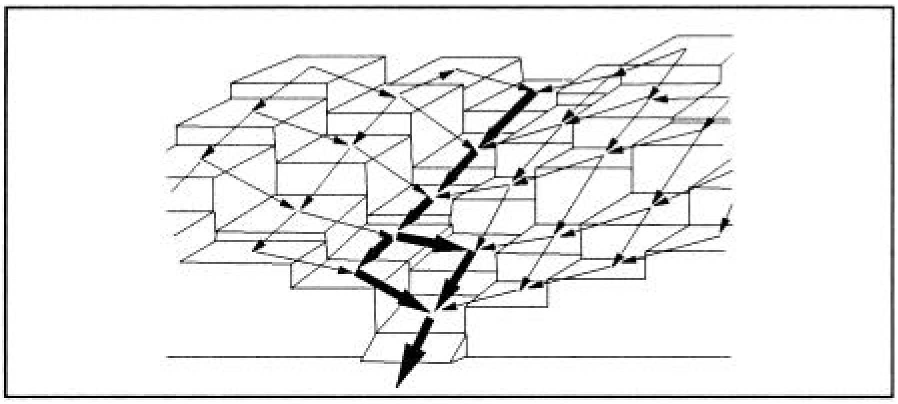

Figure 8. Conceptual schematic of CASC2D overland flow (from Julien and Saghafian, 1991).

Manning' s resistance equation, representing surface roughness and slope, is used to calculate overland flow velocities. The water is then either absorbed, if the infiltration capacity of the receiving cell is not exceeded, or routed to the next cell. Runoff which reaches a designated channel cell is routed through the channel network to the watershed outlet (Doe et al., 1997).

Within the soil erosion component (CASC2D-SED) sediment discharge from a rainfall event is computed for each grid cell using a modified form of the Kilinc-Richardson equation, which is an empirically based formulation derived from flume experiments with simulated rainfall. The erosion routine computes available sediment amounts by three different particle size classes (sand, silt, clay). The calculated amount is multiplied by an erosivity factor (K), a cover and management factor (C), and a conservation practices factor (P), derived from the USLE formulation. Based upon the trap efficiency within a grid cell, material is either suspended or deposited in each grid cell, and the residual is transported to adjoining cells. When transported sediment reaches a channel element the smaller particles are routed as suspended load, and the sand is routed as bed load (Johnson, 1997).

One of the major advantages of the CASC2D model is its dynamic visualization capability. Model simulations can be viewed interactively on the computer screen, which allow the user to better understand the internal watershed dynamics. Multiple windows appear when the simulation begins depicting a variety of hydrologic and erosion processes at grid-cell level of resolution. As the simulation progresses, the grid cells change color according to their respective values. Model outputs for a variety of parameters can be examined for any time during the simulation, or summarized in graphical form over the length of the entire event. Additionally, the model' s inherent compatibility with GIS allow for spatially distributed outputs to be easily analyzed.

The modular structure of CASC2D facilitates the additional of new routines and components. Ongoing developments include a continuous simulation model which relies on the Penman-Montieth evapotranspiration (ET) estimation method to compute the evolution of soil moisture content between precipitation events (Ogden and Senarath, 1997). Other improvements include updated channel routing schemes to accommodate in-stream hydraulic structures (bridge crossings, culverts, detention basins)

5.2.15.1 Applications & Limitations

CASC2D has been tested on variety of watersheds within the United States. It was initially applied to small, semi-arid watershed in Idaho to examine hydrologic response due to spatially varied infiltration. Subsequent testing of the model was performed on a 32,000-acre watershed in a grassland, semi-arid environment of southeastern Colorado, using a 300-meter grid cell resolution (Doe, 1992). These initial tests indicated that the model replicated measured hydrograph data from the respective watersheds with good accuracy.

Subsequent testing of the model was performed on several watersheds in humid and semi-arid environments, using grid-cell scales of 50 to 100 meters. The sedimentation component of the model was tested initially on a small watershed in Mississippi using a 400-meter grid-cell size (Johnson, 1998). A comparison of the sediment yield parameters with measured data showed that the model computed upland erosion within acceptable ranges.

CASC2D has been applied to military landscapes, specifically to simulate the impacts of mechanized military maneuvers on watershed response (Doe, 1992: Doe et al., 1997). The concept of a "maneuvershed" is used to define the hydrologic boundaries of a natural watershed within a military maneuver area (Doe, 1992). Within a maneuvershed, land disturbance is spatially distributed according to the pattern of military activities. The movement of wheeled and tracked vehicles directly impacts the soil and vegetation properties of the landscape, inducing changes in infiltration, surface runoff and sediment transport in response to rainfall events. Using data collected from tracked vehicle impact studies these impacts can be quantified and simulated at the grid-cell level in CASC2D. For example, soil hydraulic conductivity and vegetative cover values can be reduced in the input files and various land use scenarios can be tested. These simulations provide the user with both a visual and quantitative depiction of how landscape processes may change when perturbed. The studies at the U.S. Army Pinon Canyon Maneuver Site in Colorado focused on changes in surface runoff and stream flow, without accounting for erosion and sediment flux. However, the addition of the CASC2D-SED routine allows for changes in sediment distribution to be analyzed in the same manner.

5.3 The MULTSED/ARMSED Family of Models

5.3.1 MULTSED

The Multiple Watershed Storm Water and Sediment Runoff Simulation (MULTSED) model is a physically-based, distributed, single event model which computes runoff and erosion from watersheds (Wenzel and Melching, 1987). The model was developed in the late 1970’ s at Colorado State University and was the precursor for many of the next generation of physically-based models, such as KINEROS and EUROSEM.

MULTSED represents the landscape using three different types of units: (1) two-plane subwatersheds which simulate the upper portion of the watershed, (2) channel units which simulate downstream channel segments, and (3) single plane units, which represent lateral discharge into channel units. The model user must design these units based upon the topography of the given watershed.

The hydrologic component of MULTSED incorporates rainfall, infiltration and overland flow. Rainfall data from individual storm events is input in time increments (every five minutes) for the length of the storm. Uniform rainfall can also be applied. Water runoff is computed for each of the model units by subtracting water removed due to interception by vegetation canopy and water infiltrated into the soil. Infiltration is computed using the Green and Ampt equation, as a function of antecedent soil moisture and hydraulic conductivity.

The sediment component of the model computes sediment yield for the watershed by comparing the potential sediment supply with the sediment transport capacity (Wenzel and Melching, 1987). Detachment of soil particles is modeled as raindrop detachment, overland flow detachment and channel flow detachment. The available sediment, by particle size, is computed for each subwatershed or plane unit, and then routed to the channel units.

5.3.1.1 Applications & Limitations

MULTSED requires that the model user specify various soil detachment coefficients. These coefficients are best determined using calibration methods to achieve a “best fit” for the model. This process can be complicated and time consuming. It also requires that storm discharge and sediment yield data be available to perform the calibration. Caution must be used in transferring parameter values from one watershed to another.

The model was tested on two small watersheds, one in a semi-arid rangeland environment in Arizona and the other in an agricultural sub-watershed of Iowa. Both of these watersheds had been extensively studied and extensive data on flows and sediment yield were available for calibration. Generally, the hydrographs representing water flows to the outlet were a good fit to measured data, and the sediment yields were overestimated.

5.3.2 ARMSED

The Army Multiple Watershed Storm Water and Sediment Runoff (ARMSED) model is an Army tailored adaptation of the MULTSED model (Riggins et al., 1987). It, like MULTSED, is intended for simulation of single-storm events on spatially varied watersheds.

5.3.2.1 Applications & Limitations

The ARMSED model was tested on a 40.5 acre rangeland watershed in New Mexico. The model was tested for three specific cases: (1) a design storm event with no field data, (2) a measured rainfall event with no field data, and (3) a measured rainfall using detailed data from field investigations (Riggins et al., 1987). The tests showed that incorporating field data to derive parameter values does not necessarily improve the model results. The measured rainfall event simulations greatly overestimated the measured peak discharge. The use of field-derived parameter values almost doubled the sediment yield when compared to parameter estimates using published tables and nomographs. This amplifies the problem of collecting accurate data in the field, particularly with regards to infiltration data where the high degree of spatial variability can greatly effect field measurements.

5.4 The WEPP Family of Models

5.4.1 Model Principles & Assumptions

The Water Erosion Prediction Project (WEPP) represents the culmination of several decades of research, field studies and model development by the U.S Department of Agriculture and its subordinate organizations, primarily the Agricultural Research Service (ARS) and the Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS). WEPP model development began in 1985 and was fully documented and implemented in 1995. WEPP is intended to replace the USLE/MUSLE/RUSLE models and expand the capabilities for erosion prediction in a variety of landscapes and settings. WEPP also contains features and components that have been derived from or similar to other accepted erosion models, to include USLE, CREAMS, EPIC, SWRRB, ANSWERS and AGNPS. The model can be applied to crop land, pasture land, range land, forested land, and lands disturbed by construction and mining. The model has had only limited testing on military lands but several studies are ongoing.

5.4.2 WEPP

WEPP is a process-based, distributed parameter, and continuous simulation erosion prediction model. It uses a daily time step in the computations for continuous simulation. A single storm event option is also available. The model is initiated by climatic inputs derived from multiple meteorological variables measured at weather stations throughout the United States. Processes within the model include erosion, sediment transport and deposition across the landscape and in channels. Sediment is routed in the model through the overland and channel networks via a sediment transport equation. Deposition in impoundments is also considered.

WEPP has two different versions - - profile/hillslope and watershed. The landscape is represented by overland flow elements, each of which is considered to have homogeneous characteristics. The hillslope version is directly imbedded in the watershed version, which estimates sediment delivery to channels from one or more profiles within a watershed.

WEPP simulates erosion by rainfall, snow melt or irrigation water application to the surface.Soil erosion in WEPP is represented either by 1) soil particle detachment by raindrop impact and transport by sheet flow across inter-rill areas, or 2) soil particle detachment, transport and deposition by concentrated flows in rills or channels. Along a hillslope both rill and inter-rill erosion and deposition are calculated. On inter-rill areas soil detachment is induced by raindrop impact, which is then transported by shallow sheet flow to rill channels. Overland flow routing is computed by kinematic wave approximations to the continuity equation (conservation of mass). Sediment detachment in rills is induced by the hydraulic shear of water flow against the side walls of the rill. Net detachment occurs when the hydraulic shear stress of flow exceeds the critical shear stress of the soil and when sediment load in the rill is less than the sediment transport capacity. Net deposition occurs when the sediment load in the flow exceeds the sediment transport capacity (Flanagan and Nearing, 1995). The same relationships between load and transport capacity are applied to movement of sediment in channels.

The hydrologic component of WEPP incorporates infiltration, overland flow and channel flow. The model uses the Green-Ampt infiltration equation to compute the amount of water moving into the surface profile under the established antecedent conditions, prior to a rainfall event. Rainfall excess is computed as the difference between the rainfall rate and the infiltration capacity of the soil. This excess water is then routed across the surface using kinematic wave solutions to the continuity equation for overland flow. In the watershed version, the water is then routed into channels and the peak runoff rate is computed using two different methods. After the channel runoff volume has been computed, channel water balance calculations are performed.

In addition to the erosion and hydrologic components described above, WEPP contains model components for climate/weather generation, winter processes, plant growth and residue decomposition, water balance in the soil profile, soil parameters and watershed impoundment (Flanagan and Nearing, 1995). Meteorological inputs are derived from a weather generator scheme using data collected at established weather stations across the United States. The variables that are generated include mean daily precipitation, daily maximum and minimum temperature, mean daily solar radiation, and mean daily wind direction and speed. The precipitation, temperature and radiation data are used to simulate frost and thaw development in the soil, snowfall and snowmelt.

Since plant cover is an essential component of this process the model calculates daily plant growth and the decomposition and accumulation of residue and litter. A number of plant growth characteristics, to include canopy cover, biomass, leaf index, residue and litter cover, are incorporated. Different growth rates and patterns are established for crop land or rangeland environments. The water balance component of WEPP maintains a continuous balance of soil moisture within the soil root zone on a daily basis, using information generated by the weather, infiltration and plant components of the model.The hydrologic and erosion components of the WEPP are closely related to in-situ soil properties, to include roughness, hydraulic conductivity, bulk density and the effects of tillage. Erodibility factors are derived from a combination of these variables. The impoundment component computes the trapping of sediment by outflow structures, such as terraces, farm ponds and check dams. It performs a mass balance of inflows, storage and outflows for these impoundments. The outputs of this model component include 1) peak outflow rate and volume leaving the impoundment, 2) peak sediment concentration and yield by particle size classes, and 3) median particle sized diameters for each particle size class (Flanagan and Nearing, 1995).

5.4.2.1 Applications & Limitations

The WEPP model computes spatial and temporal distributions -- where and when -- of soil loss and deposition across a hillslope or in a watershed. WEPP can be used for a variety of applications in both crop land and rangeland environments. Numerous field validations on field scale plots and watersheds are ongoing. It is anticipated that further refinements to the model will continue to increase its applicability and usefulness.

Comparisons between WEPP and USLE/RUSLE predictions and measured data have been documented for limited case studies on hillslopes (Boardman and Favis-Mortlock, 1998). The authors found yearly soil loss and average annual soil loss results from all three models to be very close to measured data, although all outputs exhibited large standard deviations.

Studies using WEPP on rangelands have shown that the model can quantify the erosion impacts of various land use alternatives, such as stocking rates for cattle. Because the model explicitly accounts for plant growth, both naturally or from reseeding, changes in surface cover induced by grazing are readily calculated. The resulting changes in sediment concentration and delivery can be readily observed for various stocking rates, allowing managers to determine feasible strategies to remain within acceptable soil loss tolerances (Laflen et al., 1994). The model is also very useful in determining locations along a hillslope or within a watershed where soil detachment is most likely to occur. These determinations facilitate the implementation of soil erosion mitigation methods at these points.

Preliminary studies are underway to apply WEPP modeling on military lands. One of the major limitations of such application is the ability to model the types of impacts on soil and vegetative properties caused by cross-country military vehicle movement and other military activities. It has been suggested that these limitations will not be difficult to overcome and that it may require customized programming of the user interface (Price et al., 1997).

One of the most important features of WEPP is the user interface that has been developed to assist with inputting the numerous data files required to run the model. Supporting expert systems and default databases for many regions in the United States simplify the input process. The interface also allows the user to select from amongst several graphical output modes. WEPP is also being incorporated into the Modular Soil Erosion System (MOSES), which is a combined graphical interface that will facilitate several ARS erosion models, to include RUSLE.

The WEPP model, in its current form, does not facilitate integration with raster-based (grid-cell) GIS, which is a limiting factor for its use by military land managers.

5.4.3 SIMWE

The SIMulation of Water Erosion (SIMWE) model, like WEPP and CASC2D, represents a new advancement of physically-based, process erosion models, integrated with emerging technologies, that enhances the understanding of spatially and temporally distributed landscape phenomena. The SIMWE model is a watershed and landscape scale model which uses Monte Carlo stochastic (probabilistic) methods and bivariate functions to solve and simulate the first order principle equations of continuity and momentum (Mitasova et al., 1996). It is a grid-cell model that uses Digital Elevation Model (DEM) data and spatially distributed GIS data layers as inputs to the model. SIMWE is currently used as a research tool to demonstrate new techniques and technologies related to process-based soil erosion modeling and provides strong motivation for incorporating these developments into other established models, such as WEPP.

SIMWE is based upon the solution of the continuity equation, which describes the flow of sediment over the landscape. This solution is a function of steady state water flow, soil detachment and transport capacities and landscape surface properties (e.g., soil type, roughness and vegetative cover) (Mitas et al., 1997). Many of these parameters are derived from the WEPP User' s manual. Two-dimensional (x,y) shallow water flow is mathematically solved by a form of the continuity equation (conservation of mass) and a diffusive wave approximation of the conservation of momentum equation. The diffusive term in the diffusive wave formulation is modified and solved using stochastic Monte Carlo techniques.

Sediment transport is mathematically solved in the model based upon a closed form of the continuity of sediment mass equation, using Monte Carlo methods. These stochastic techniques enable the equations to be solved for more complex cases, such as landscape discontinuities in slope or cover (Mitasova et al., 1996). SIMWE extends the capabilities of other process-based models, such as WEPP, by representing sediment flow as a 2-D (bivariate) function, rather than a 1-D construct. It is therefore particularly well suited to simulating these processes in complex terrain.

The SIMWE model has been linked to a variety of dynamic (animated) cartography visualization tools that display erosional and depositional surfaces in 3-D space (Mitas et al. 1997). Advanced GIS tools are used to support the processing, analysis and visualization. These visualization tools can be used to illustrate different methods of solution, the influence or sensitivity of certain modeling parameters, the comparison of model results with field data and simulation of scenarios using improved conservation methods (Mitas et al., 1997).

5.4.3.1 Applications & Limitations

The SIMWE model has been used primarily as a research and data exploration tool to advance concepts in soil erosion modeling and visualization, particularly within the realm of Digital Elevation Model (DEM) and GIS data.

The model has been applied to an experimental farm in Germany where high erosion problems were identified during large rainfall events under bare cover conditions. The model was used to simulate the design and placement of erosion protection measures, principally grass cover, with promising results. The model has also been tested on a larger size landscape within the same region of Germany. The model has also been used to simulate water flow and erosional processes for terrain with structures, such as terraces and ponds, or when other terrain discontinuities exist.

One of the limitations of process-based models, is that large, complex landscapes, such as those encompassed by military installations, are much more complex and diverse than traditional agricultural settings, where landscape features are more uniform. Extensive spatial data sets must be incorporated and discontinuities in the data must be dealt with. SIMWE holds great promise for alleviating some of these limitations, and for allowing visualization of erosion and deposition across these complex landscapes in 3-D.

5.5 The ANSWERS Family of Models

5.5.1 Model Principles & Assumptions

The Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) model was one of the first distributed parameter models to be developed for predicting watershed response to various land use practices. ANSWERS is a distributed, physically-based, event-oriented model that was originally developed in 1976 to simulate the the response of agricultural watersheds to singe rainfall events. Its primary use is to plan and evaluate strategies for the control of nonpoint source pollution from intensively cropped areas (Smolen et al., 1983).

ANSWERS characterizes the landscape as a series of elements, or square grids. The size of each grid is dependent upon the availability of input data. Typically, the grid size is determined by the availability of Digital Elevation Model (DEM) data to characterize the slope and aspect. In addition to these topographic variables, other grid cell variables representing soil properties, crop properties, surface configuration, conservation practices and channel characteristics, must be defined by the user. The model uses the C and P factors from the Universal Soil Loss Equation (USLE).

Since it is a physically-based, deterministic model, the hydraulic response of each grid element is computed using solutions to the continuity equation, which expresses time sensitive relationships between inflows, storage and outflows from one grid cell to its adjacent neighbors. The spatial and temporal variability of rainfall events are simulated from input data with time increments of one minute. Physically-based mathematical relationships are used to describe interception, infiltration, surface retention, drainage, overland flow, channel flow and subsurface flow (De Roo et al., 1989). Each element acts as an overland flow plane with a specified slope and direction (x,y) of steepest descent. As infiltration excess and ponding occurs in each element it is routed as overland flow using Manning' s equation. When water and sediment reach an element with a channel they are transported to the outlet.

The soil erosion component of the model computes soil detachment by raindrop impact, transport and detachment by overland flow and deposition, where sediment load exceeds transport capacity. The detachment formulations use equations derived by Meyer and Wishcmeier, relating several USLE factors to include K, C and P.

Various output options allow the user to view composite or spatially distributed results from simulations. Statistics on the amount of soil removed or deposited in each element are computed during the simulation. Sediment eroded in one element may or may not reach the channel system or outlet if it is deposited in a downslope element. In this manner, specific locations within the watershed can be analyzed for their representation as sources or sinks of sediment. Grid-cell maps can be displayed showing the predicted soil loss or deposition for each element or these maps can be converted to contour maps depicting various amounts of sediment across the watershed.

An updated version of the ANSWERS model computes sediment loss and deposition by particle size class. A new project, ANSWERS 2000, is also underway to further refine and update the model.

5.5.2 Applications & Limitations

One of the major advantages of the ANSWERS model is that it can be used to test various land use scenarios and erosion control methods within a watershed. This approach was used on a 100-acre watershed in the Netherlands with a variety of cropping and conservation practices (De Roo et al., 1989). Rainfall events of different magnitudes were simulated to test watershed response under normal and extreme conditions. From these simulations graphs depicting soil loss in tons/hectare were derived for various recurrence intervals (e.g., 1-, 5-, 10-, 25-, 50-, 100-years) under different management scenarios. A similar approach was used on a small, 25-acre field catchment used for grazing in Queensland, Australia (Connolly et al., 1997). Measured and simulated rainfall data were used to evaluate the effects of surface conditions, particularly vegetative cover.

Annual runoff and peak discharges from the catchment decreased significantly when vegetative cover was increased by destocking of animals and revegetation.

As with many distributed models, one of the limitations of ANSWERS is that the user must provide parameter inputs for rainfall and other landscape characteristics. Some of these inputs, such as slope and aspect, can be facilitated by the use of Digital Elevation Model (DEM) data in a geographic information system. However, other inputs, such as soil hydraulic measurements and surface roughness characteristics, must be collected from field data. Sensitivity studies of the various parameters have shown that model results are highly sensitive to the parameter values for infiltration, soil moisture content and surface roughness (De Roo et al., 1989). Significant errors can result from improper parameter values.

Another consideration in using ANSWERS, as with other distributed models, is the effect of selecting a given grid-cell size to characterize the watershed. In the Netherlands study, results from a distributed (4,275 grid cells) case versus a lumped parameter (20 cells) case were compared. The distributed case computed total runoff as 46 percent higher and soil loss as 36 percent higher (De Roo et al., 1989).

5.6 The KINEROS Family of Models

5.6.1 KINEROS

The KINematic Runoff and EROSion (KINEROS) model is a physically-based, distributed model that simulates water runoff and sediment transport across small watersheds from single rainfall events. The kinematic component of the model is related to the mathematical solution of the equations of continuity and momentum using the kinematic wave approximation. While these solutions do not preserve all of the properties of the more complex equations, they have been shown to be excellent approximations for most overland flow conditions (Woolhiser et al., 1990). In KINEROS these equations are solved implicitly using a finite difference methods.

In KINEROS the landscape is represented as a series of interconnected elements -- planes and channels. Each element has unique characteristics with regards to slope and its physical soil and land cover properties, which are specified by the model user as input files. The elements are connected in a cascading sequence from the upland portions of the watershed to the outlet. The general approach is to divide a given watershed into a branching system of channels with plane elements contributing lateral flow to downstream channel elements or to the upper end of first order channel elements. Runoff generated by rainfall events is routed over each plane and through the channel system to the outlet. Similarly, soil is eroded from each plane and either deposited or routed through the system.

Rainfall inputs may be uniform across the entire landscape or spatially varied. Rainfall rates are reduced by an interception depth, which is a function of vegetative cover. The residual rainfall is allowed to infiltrate into the soil as a function of the rainfall rate and infiltration capacity of the soil, which is related to several soil hydraulic properties. This process is solved numerically for each time step. Excess rainfall which is not infiltrated is ponded until depths are sufficient to generate overland flow. Overland flow is computed using a one-dimensional form of the continuity equation, solved using the kinematic approximation. Manning' s resistance equation is used to modify flows across the surface as a function of slope and a resistance parameter. Water flow in channels is computed in the same fashion.

KINEROS simulates the movement of eroded soil by treating erosion by raindrop impact and detachment separately from erosion caused by flowing water. A sediment mass balance approach is used to compute available sediment. Several different mathematical relationships can be used to compute sediment transport capacity. The sediment mass balance is solved mathematically for each time step. When transport capacity is exceeded soil particles are deposited at the settling velocity rate. Routing of sediment through reservoirs and ponds can also be accommodated with appropriate equations for particle settling (Woolhiser et al., 1990).

Developments are ongoing to enhance the initial version of KINEROS with visual and graphical components. This KINEROS2 version will incorporate a choice of erosion transport schemes by the user and compute sediment concentrations in time at selected points along the surface profiles (Woolhiser, personal communication).

5.6.1.1 Applications & Limitations

The KINEROS model has been tested on watersheds in a variety of landscape and climatic regimes to include the Walnut Gulch experimental watershed in Arizona and several European watersheds (R. Smith, personal communication). For the latter tests it was compared with several other models for use in global change research and performed well (R. Smith, personal communication).

5.7 European Models

The family of European models represents those models that have undergone their primary development and testing outside of the United States. This association is merely for convenience and is not intended to imply that these models are all related in some fundamental way. Rather, they have been more commonly used in landscapes and scenarios found prevalently in Europe.

5.7.1 EUROSEM

The European Soil Erosion Model (EUROSEM) is a dynamic, physically-based, distributed erosion model designed to predict erosion, deposition, sediment transport and sediment yield for individual storm events on field sized catchments and watersheds. The development of EUROSEM was begun in the late 1980' s by a consortium of European scientists as a parallel development to other physically-based models, such as CREAMS, ANSWERS and WEPP, which were being developed in the United States (Morgan, 1994).

EUROSEM uses a dynamic, rather than a steady-state approach, to modeling erosional processes. It is designed to operate for successive one-minute time steps within a rainfall event. EUROSEM uses the runoff generator and water and sediment routing routines from KINEROS.

EUROSEM employs the same land characterization features as KINEROS – representing the landscape as a series of interlinked elements. These elements are either uniform slope planes or channels. Each element is assumed to have uniform characteristics such as slope, soils and landcover. Each natural slope plane is represented by a rectangle whose length is equal to the average flow path of the element and whose area is equal to that of the element. The elements are arranged in a natural cascading sequence to enable correct routing of water and sediment over the land surface (Morgan et al., 1998). The characteristics and sequencing must be set-up in the model initialization files prior to executing the model.

The model uses a mass balance (continuity) equation to determine the amount of water and sediment flowing across a given element. Rainfall depths from successive time periods in the storm are used to calculate rainfall intensity and volume. After interception by vegetation and surface depression storage is accounted for the excess rainfall is represented as throughfall to the surface. Based upon the soil hydraulic properties, overland flow is generated as infiltration-excess. The solution to the runoff equation is accomplished via Manning' s equation for overland flow, based upon depth of flow and hydraulic resistance of the surface. Hydrological outputs of the model include total runoff and a storm hydrograph.

Soil particle detachment by raindrop impact is computed for each time step as a function of the kinetic energy of the rainfall at the surface, the detachability of the soil and the surface water depth. Soil detachment by runoff is modeled by a general equation as a function of the difference between sediment concentration in the flow at capacity and the actual sediment concentration. The unit stream power function, also used in USPED, is used to model sediment transport capacity in rills. A different equation is used to model inter-rill flow. When the concentration of flow exceeds the sediment transport capacity, net deposition occurs as a function of the settling velocity of transported particles. The mass balance equation is numerically solved to obtain the net rate of erosion and the sediment discharge rate (volume per time) for each time step at selected points or nodes along a slope plane. Model outputs for erosion include total soil loss and a storm sediment graph (amount of sediment per time) for each surface element. This provides useful data to analyze the timing of peak runoff and sediment delivery to various parts of the watershed (Morgan et al., 1998).

5.7.1.1 Applications & Limitations

EUROSEM has been applied to both agricultural and non-agricultural areas at the plot (field) scale for validation of the results with actual measurements. Twenty-nine plot erosion events were simulated on farm plots in Great Britain. In general, EUROSEM outputs over predicted. The peak values of sediment discharge were well correlated but the timing of the sediment was displaced by several minutes (Quinton, 1998). Several potential sources of error were noted. Validation of the model was also performed on non-agricultural plots in the Mediterranean region (Albaladejo et al., 1998). EUROSEM over predicted the runoff volume and soil loss for these plots. High model sensitivity to soil surface characteristics (e.g., roughness) was reported.

The structure of EUROSEM facilitates user changes to input parameters, which can then be used to evaluate various conservation measures – both agronomic and mechanical. This includes the effects of terracing, tillage practices and vegetative buffer strips. To illustrate these applications simulations were conducted on a hypothetical field, containing both vegetated and non-vegetated segments. Different slope plane elements represented these various landscape features. The simulations provided estimates of how grass strips of various dimensions might reduce soil loss (Rickson, 1998).

5.7.2 SHE

The Systeme Hydrologique Europeen (SHE) model is a physically-based, distributed model that underwent development in the late 1970' s as part of a coordinated European initiative to develop improved models for rainfall-runoff processes in response to a wide range of water resources and land use applications in watersheds. The model framework incorporates all aspects of the hydrologic cycle, to include rainfall, evapotranspiration, interception , snowmelt, overland flow, channel flow and saturated (sub-surface) flow. The spatial distribution of watershed characteristics is represented in the model by an orthogonal grid network in the horizontal and in the vertical, by a column of horizontal layers (Abbott et al., 1986a).

The model uses mass balance principles and mathematical approximations of first principle equations (continuity and momentum) to move water through the physical system. Meteorological input data and vegetation parameters simulate the total evapotranspiration and net rainfall resulting from interception, drainage and evaporation. Residual water is used in the calculation of soil moisture changes in the upper soil profile. The overland and channel flow component use topography, channel shape and flow resistance across the surface to route water across the landscape towards the watershed outlet. Mathematical approximations are used to solve the 2-D continuity and momentum equations. Channel flow is solved in 1-D. Water movement through the soil profile is computed using a one-dimensional equation relating soil hydraulic parameters. Lateral movement through the saturated zone is characterized as a one-layer, unconfined aquifer. Snowmelt inputs are modeled using energy and mass balance relationships (Abbott et al., 1986b).

More recently, an erosion and sediment yield component (SHESED) and contaminant transport component (SHETRAN) have been adapted to the SHE model. SHESED simulates soil erosion by raindrop impact, leaf drip and sheet overland flow. Eroded material is transported across the landscape via overland flow. Erosion in channels is modeled as bed erosion. The sediment routing routine is not limited for fine sediments but a sediment transport capacity is used for coarser material (Wicks and Bathurst, 1996).

5.7.2.1 Applications & Limitations

The SHESED component of SHE was applied to two small agricultural catchments, 10-15 acres in size, in Iowa. The results accurately predicted the measured variations in sediment yield. The model was also applied in a riverine setting on a watercourse in Wyoming for a 37-day period. The model demonstrated good reproduction of observed sediment discharge magnitudes, but some variation in the timing of the sediment peak (Wicks and Bathurst, 1996). The SHETRAN component was applied to a 200 acre basin in France, characterized by badlands topography. Both a lumped parameter approach and a distributed parameter approach using 5 meter-resolution data were tested. Simulation results were compared with bulk measured sediment yields of suspended sediments. The simulation outputs compared more favorably at the annual scale, than at the event scale ((Bathurst et al., 1998).

5.7.3 SEMMED

The Soil Erosion Model for MEDiterranean Areas (SEMMED) is a semi-empirical, long-term average, distributed model intended for regional landscape applications. The model characterizes the terrain using Digital Elevation Model (DEM) data and uses multi-temporal satellite remotely sensed imagery to account for vegetation properties and soil moisture. SEMMED was developed specifically for application in the Mediterranean regions of Europe (de Jong and Riezebos, 1997).

SEMMED has a modular structure that incorporates a water component and a sediment component. The mathematical formulations are derived from both empirical models, such as USLE, and physically-based equations for sediment transport capacity. The model estimates yearly soil-loss through both rainfall splash detachment and sediment transport over the surface. Mean annual rainfall is used to compute the energy for splash detachment and the volume of runoff, using an R-factor equation similar to that used in the USLE. Soil moisture capacity is derived from several soil and land cover parameters, to include bulk density, top soil rooting depth and potential evapotranspiration. The amount of overland flow is a function of the soil moisture storage and rainfall.

Soil detachment by rainfall is based upon empirical relationships between rainfall energy and interception by vegetative cover. The USLE C-factor is used to account for effects of crop cover. Excess rainfall becomes overland flow, which is drained down slope using a routing algorithm with the DEM. A potential cumulative overland flow map is generated. This map is combined (using GIS overlay techniques) with the other factor maps to generate a distributed transport capacity map (deJong and Riezebos, 1997).

5.7.3.1 Applications & Limitations

SEMMED has been implemented on several international projects in France and Italy on landscapes ranging from 100 km2 (25,000 acres) to 4200 km2 (1,000,000 acres). Multi-spectral and multi-temporal satellite imagery was used along with 1:250,000 scale topographic maps to derive a spatial database for the model. Rainfall data from a 26-year period was collected from 430 recording stations to derive the rainfall inputs. The model was used to develop a qualitative risk assessment map of soil erosion. The computed values of soil erosion were well correlated with sediment deposition data taken from two large reservoirs inside the catchment areas. The patterns of erosion identified from the model were also consistent with degraded areas delineated from the remotely sensed imagery. These studies constituted some of the first applications of semi-empirical soil erosion modeling on very large watershed areas (regional scale).

Accuracy assessments of model results were performed using error propagation techniques (de Jong and Riezebos, 1997). The assessment indicated that soil loss predictions were highly variable. It is likely that the model is under predicting soil loss because it does not take into account soil detachment by overland flow.

6 Evaluation of the 24 Erosion Models

The twenty-four models were evaluated qualitatively against eight criteria established by the study sponsors. For each model a qualitative rating was assigned separately for each criteria, and an overall assessment rating was assigned. The results of this evaluation are presented in ***Appendix D***. The ratings are subjective in nature and intended to provide the reader with a general comparability of the models. The ratings were based upon information derived from the models' technical documentation manuals, users' manuals, Web site information and technical reports. The models were not tested interactively with data sets for this study. More detailed information pertaining to each of the models and the respective criteria are summarized in the Model Fact Sheets at ***Appendix E***.

6.1 Evaluative Criteria

The eight evaluative criteria and a brief definition of them are provided below:

1) <u>Data Requirements</u>: The types, quantity and format of data inputs required to execute the model
2) <u>Model Results</u>: The types, quantity and format of data outputs derived from model simulations
3) <u>Cost and Complexity</u>: The availability and cost (public domain or purchase) of the model software, its setup and initialization requirements, and sophistication of its model structure
4) <u>Hardware/System Requirements</u>: Computer hardware (e.g., processors, random access memory (RAM), storage space, etc.) and configurations required to efficiently operate the model

5) <u>Geographic Information System (GIS) Integration</u>: The compatibility and capability of the model to be linked with GIS software for both data input and data output
6) <u>Commercial-off-the-shelf Integration (COTS)</u>: The compatibility and capability of the model to be linked with other commercial software (e.g, Microsoft Excel or Access) to facilitate data input or data analysis
7) <u>Graphical User Interface (GUI) Configuration</u>: The function and content of interfaces designed within the model or external to the model to facilitate or visualize data inputs or analysis
8) <u>Ease of Use</u>: The relative level of difficulty for a novice field user to acquire, setup and run the model with a particular data set

6.2 Qualitative Ratings

Appendix D provides a summary of the twenty-four erosion models evaluated against the eight criteria established in Section 6.1. Three qualitative ratings were used in the evaluation scheme, based upon the degree to which the model' s attributes would satisfy the model user community - - defined in this report as installation or field-level managers or technicians. These ratings are defined below:

Excellent: Easily satisfies user standards, capabilities or information needs

Fair: Minimally satisfies user standards, capabilities or information needs

Poor: Fails to satisfy user standards, capabilities or information needs (either because the criteria is excessive in terms of user knowledge or cost, or because it does not exist at all)

All of the criteria are assumed to have equal weighting in the matrix.

7 Integration of GIS with Erosion Models

7.1 Conceptual Framework

To be effective, erosion prediction technologies and models must be usable by technicians and managers at the field level (Lal et al., 1992). Within the Department of Defense this applies to environmental/conservation specialists and land managers at individual installations. Models must be coupled with database generation capabilities, geographic information systems, graphical user interfaces and visualization tools in an integrated system that facilitates the user' s needs for analysis and understanding of soil erosion related problems. This conceptual framework for a GIS can be illustrated as shown in Figures 9 and 10 below:

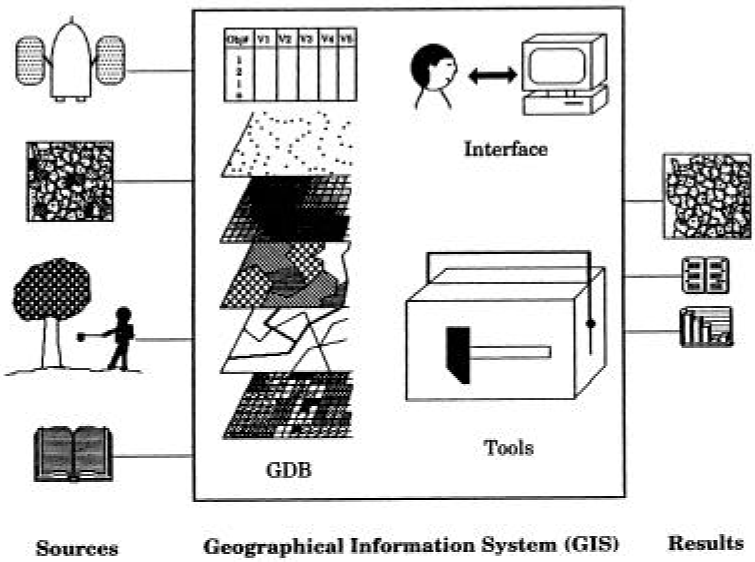

Figure 9. Major components of a GIS, showing data sources (inputs)), GIS tools and interfaces for spatial data processing and data outputs (from Singh and Fiorentino, 1996).

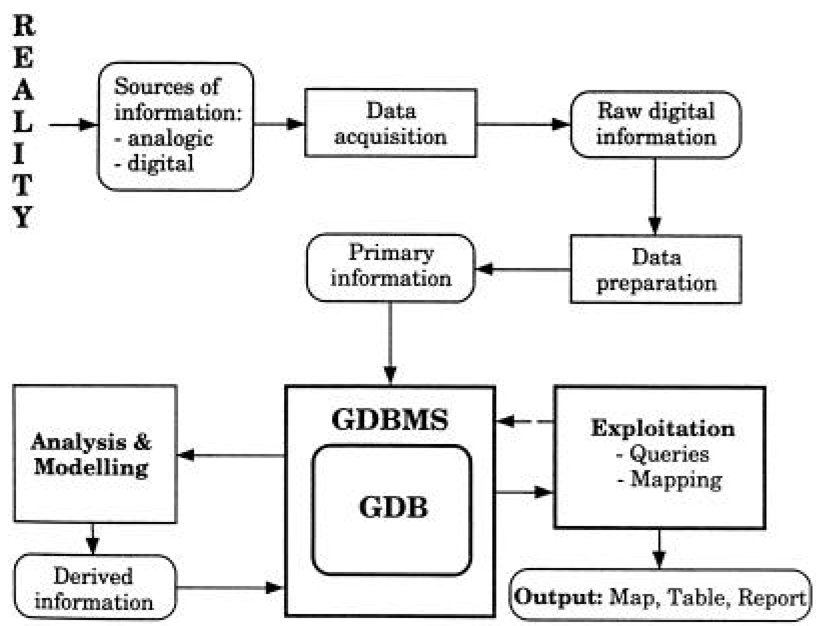

Figure 1 . GIS and geographical data base (GDB) management system (MS) externally linked to a model (from Singh and Fiorentino, 1996).

7.1.1 Description and Advantages of Using GIS

Geographical information systems (GIS) are automated tools for capturing, storing, viewing and performing analyses of spatially distributed data (Singh and Fiorentino, 1996). Numerous GIS architectures and software have been developed over the last twenty years to the point that they are now an essential component and decision support tool for most landscape related problems. Generally, most GIS systems are capable of handling and merging digital data in a variety of formats (e.g., raster or vector), scales and geodetic projections.

The development and proliferation of spatially-distributed environmental models, to include soil erosion models, has paralleled the advances in GIS technology. As the scale and complexities of these models have increased, scientists and practitioners have found GIS to be a useful technique for coping with the vast numbers of data and the spatial relationships between data from disparate sources (Singh and Fiorentino). To a large extent the fields of study within the hydrological sciences, to include soil erosion prediction and management, have led the way in linking spatial models to distributed geographic data in GIS.

The linkage between GIS technology and erosion models can range from loosely coupled to tightly coupled arrangements, as shown in Figure 11 below (Stuart and Stocks, 1993):

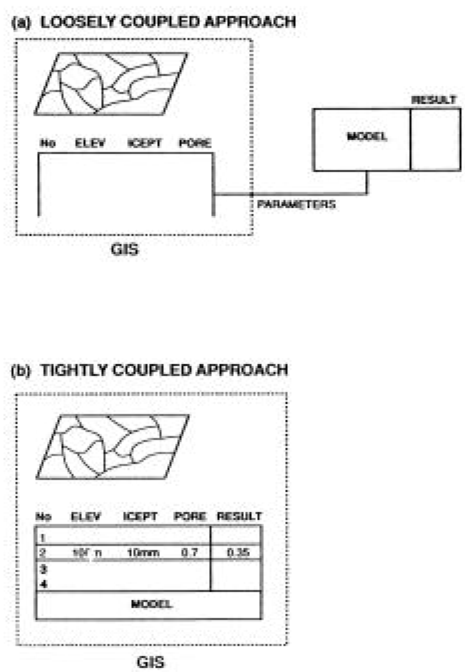

Figure 11. Two alternative ways of linking a model to a GIS: (a) loosely coupled, and (b) tightly coupled (from Stuart and Stocks, 1993).

The linkage, or coupling, of soil erosion models with GIS technology can be further categorized into four levels of integration, from loosely coupled to tightly coupled (Mitasova et al., 1995). These levels of conjuctive use are:

1. Development of spatial data structures to be used by a distributed model: this is commonly referred to as a "poor man's GIS", whereby the use of GIS software is not explicit, but the data development and structure parallels that found in most GIS architectures

2. Model input/output processing using a GIS: this approach has been commonly used to develop spatial input files for specific parameters of a model, to perform output analysis of model simulations and for some 2-D or 3-D visualization using standard GIS software routines. In these linkages the GIS system (software and hardware) is often used separately from the model and files must be transferred back and forth externally between the GIS and the model

3. Linkage of a model and a GIS through a user interface: this approach is more technologically sophisticated than those approaches in (1) and (2), in that the model user is typically working in one computer environment, with an interface that seamlessly moves spatial data between the GIS environment and the modeling environment. These types of linkages are often referred to as spatial decision-support systems

4. Full integration of a model within a GIS: this represents a full integration such that the model actually adopts the spatial data structure of the GIS. There are no conversion routines necessary to translate data between the GIS and the model and the model is completely expressed in terms of the GIS command structure.

In category 1 the GIS is a sub-component of the model, whereas in category 4, the opposite is true. In categories 2 and 3 the model and GIS are separate components (e.g., they have their own operating system, data structure and architecture).

Most of the current integration of soil erosion models with GIS is consistent with categories 2 and 3. Examples of category 2 type linkages have existed for over ten years. More recently, advances in computer processing speed, Internet digital data access and system integration software have spawned several category 3 type linkages. Category 4 type linkages remain problematic because of the lack of an efficient temporal dimension in most GIS systems. The main advantage of this type of integration is that each process in the model can be represented by one simple GIS command (one or two lines of computer source code), which greatly simplifies model modification, maintenance and reusabilty (Singh and Fiorentino,1996).

The advantages of using a GIS with distributed erosion models are quite obvious from the perspective of spatial data handling. For example, one of the major data inputs required for these models is Digital Elevation Model (DEM) data to represent the landscape topography. Using the DEM, GIS can compute altitudes, slope and aspect at various grid-cell sizes. Other distributed data layers can be derived from point field-based measurements using geostatistical interpolation techniques, or from digitized soil and land use maps. These data layers can be aggregated or disaggregated to varying spatial scales depending on the users' needs (Singh and Fiorentino, 1996).

Other advantages of using GIS with models include 1) producing multiple modified input maps to simulate different land use scenarios and conservation planning methods, and 2) displaying output maps showing the time variation of spatial erosion and deposition processes. The ability to test and simulate multiple scenarios is one of the primary purposes served by erosion modeling. Using map overlay and map mathematical routines various data layers can be combined to create input maps that represent various scenarios. The ability to combine various multiple parameters and output files into display maps greatly enhances the analysis of model simulations and allows the user to identify critical areas within the landscape that are sensitive to change. These advantages are conceptually illustrated in Figure 12 below:

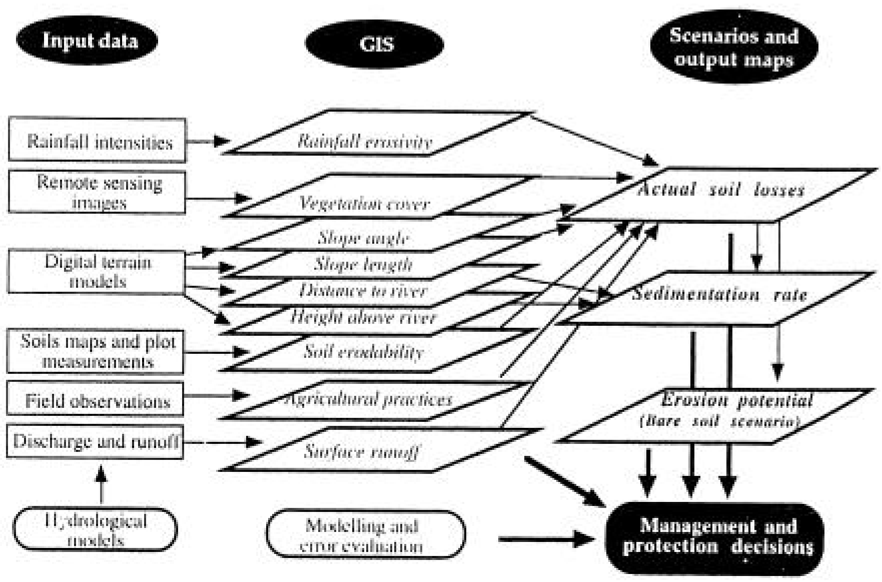

Figure 12. Conceptual structure and information flow in GIS-based erosion model (from Bonn et al., 1997).

7.2 Selection and Evaluation of the 8 Models with GIS linkages

Many of the models evaluated in this study were identified as having some capability for GIS linkage and graphical user interface. Eight of these models were selected for further analysis because they have best developed this capability. The eight models are: AGNPS, ANSWERS, CASC2D, EPIC, SIMWE, USLE/RUSLE, USPED and WEPP. The GIS capabilities and linkages for these eight models were evaluated both descriptively and by the use of schematics, with application examples illustrated where appropriate.

7.2.1 General Schematic of GIS Workflow Processes

A GIS workflow process, as shown in Figure 13, consists of four basic steps: 1) problem definition, 2) data input, 3) data manipulation and analysis, and 4) data output (Nyerges, 1991).

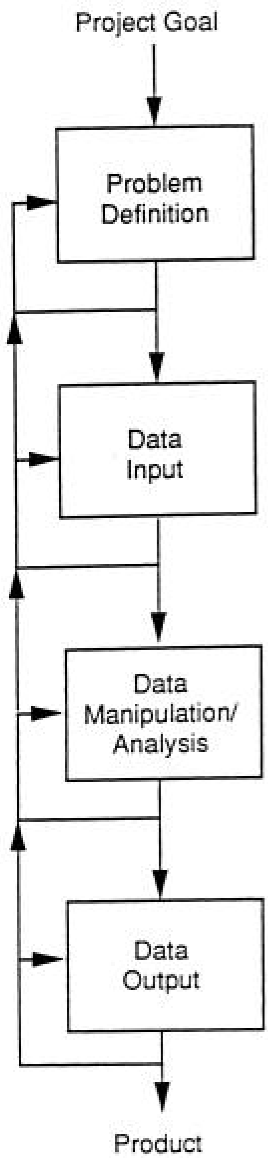

Figure 13. GIS-model integration as a workflow process (from Nyerges, 1991).

7.2.2 Selected Model Schematics

Selected examples of model-GIS integration are provided below. While not all inclusive they provide useful examples of the architecture for the types of linkages described earlier.

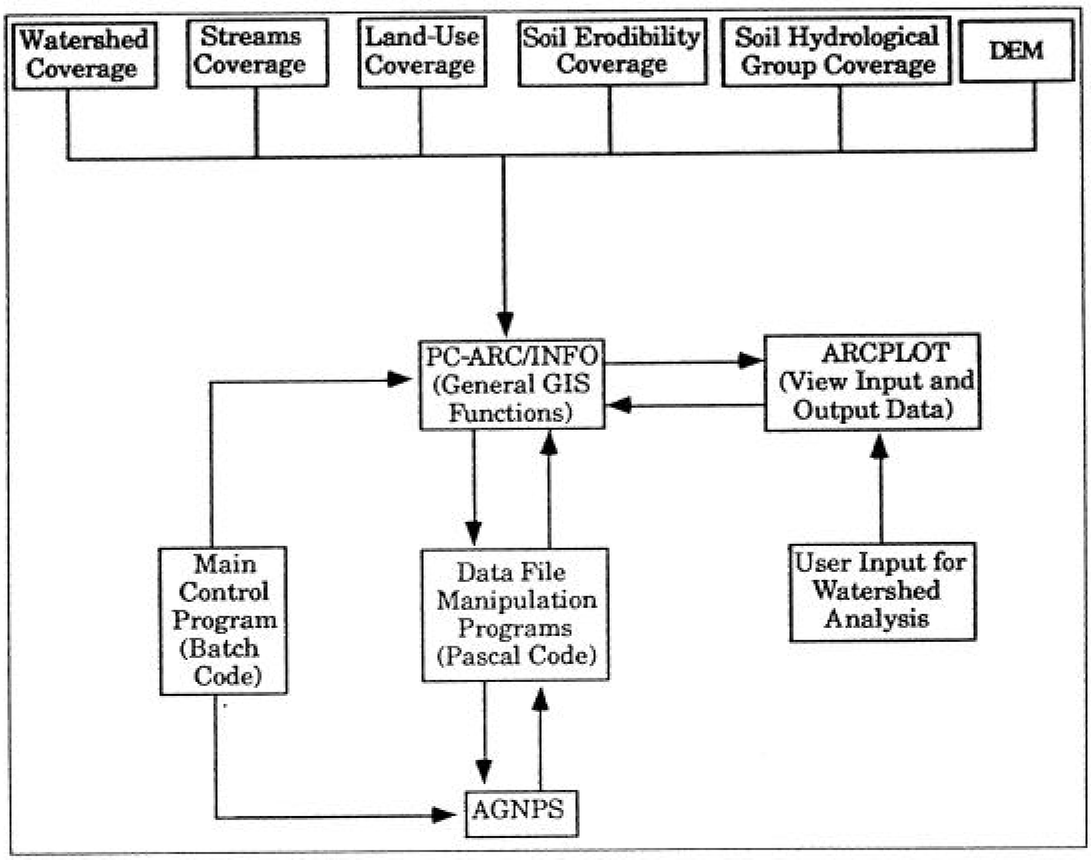

Figure 14. Workflow process and schematic for AGNPS-GIS integration (from Jankowski and Haddock, 1996).

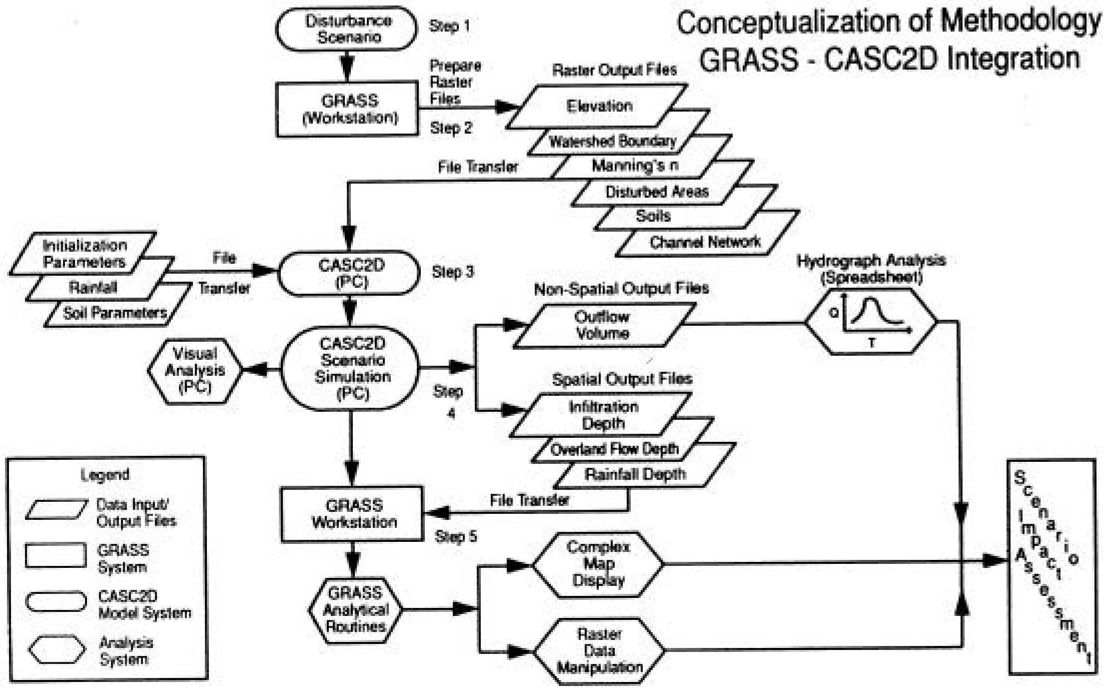

Figure 15. Workflow process schematic for CASC2D-GIS integration (from Doe et al., 1996).

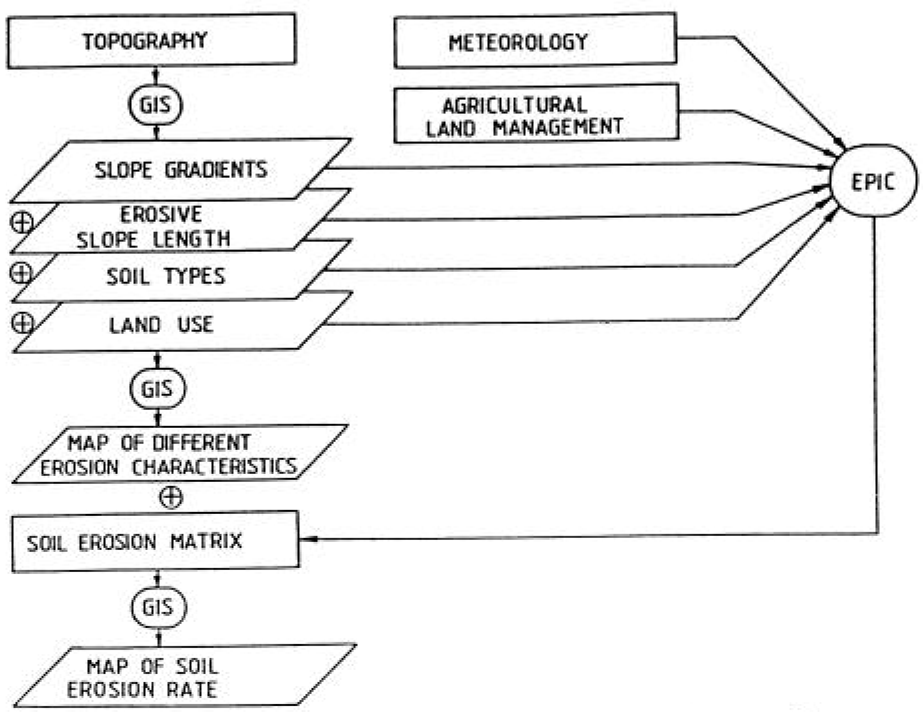

Figure 16. Workflow process integration for EPIC-GIS integration (from Klaghofer et al., 1993).

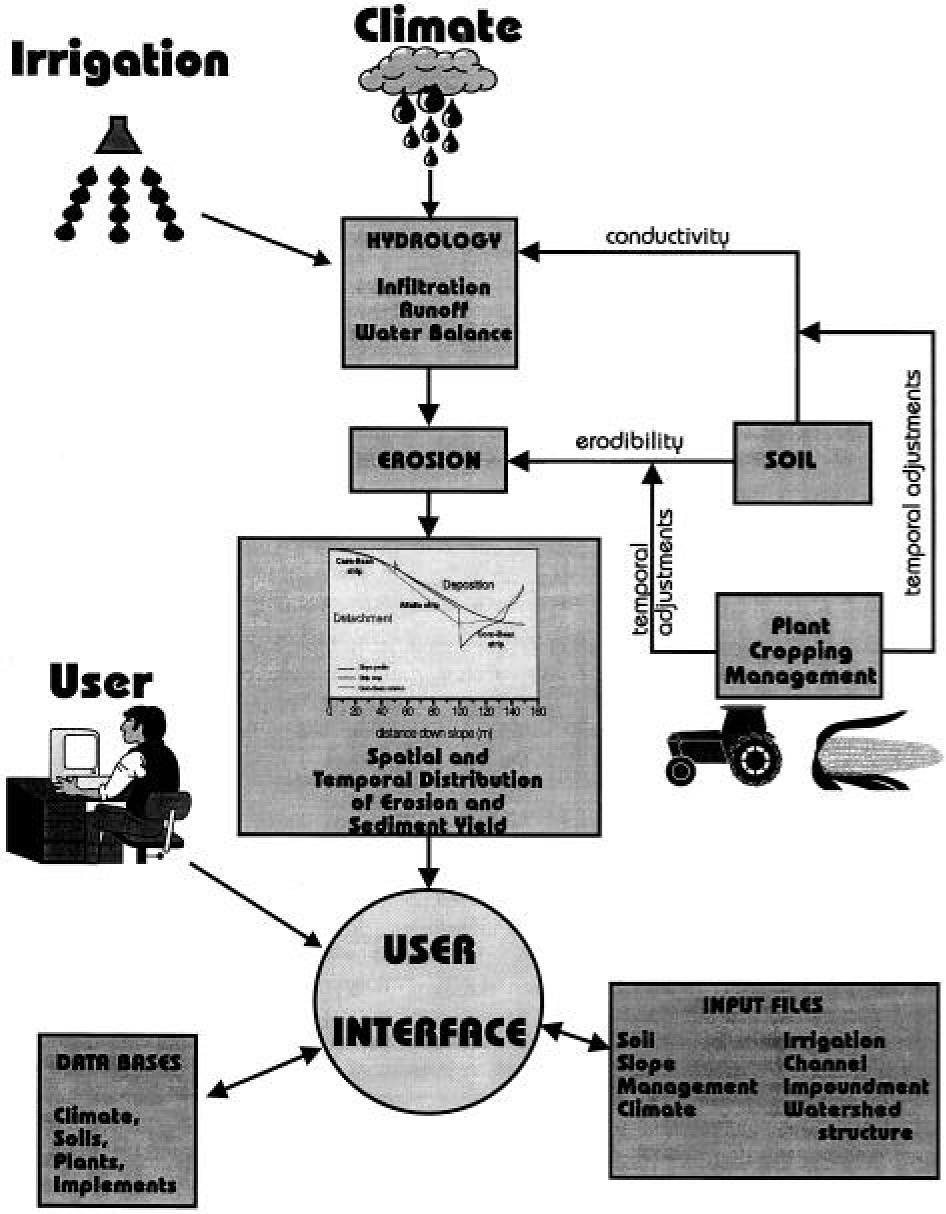

Figure 17. Workflow process for WEPP-User Interface (from Renard et al., 1995).

8 Conclusions and Recommendations

8.1 Best Models for Current Use

As shown in Appendix D each of the twenty-four erosion models have been subjectively rated according to nine criteria, and an overall evaluative rating has been assigned. Based upon the ratings provided in the matrix, as well as the applications and limitations of each model described in this report, the following models are recommended for consideration and use by military land managers (NOTE: models listed alphabetically):

- AGNPS (single-event and continuous)
- CASC2D (single-event)
- RUSLE (long-term average)
- USPED (long-term average)

Although not rated as high as the four models shown above, both SIMWE (single-event model) and WEPP (continuous model) are recognized as having components and characteristics that have excellent potential for military land use applications. Of these six models, five of them (less WEPP) are based upon a grid-cell characterization of the landscape, and are therefore, inherently compatible with geographic information systems (GIS). WEPP is a based upon a series of elemental planes Three of the models – CASC2D, USPED and SIMWE – have excellent capabilities for dynamic visualization of the model simulations, as illustrated in Figures 18-20 below:

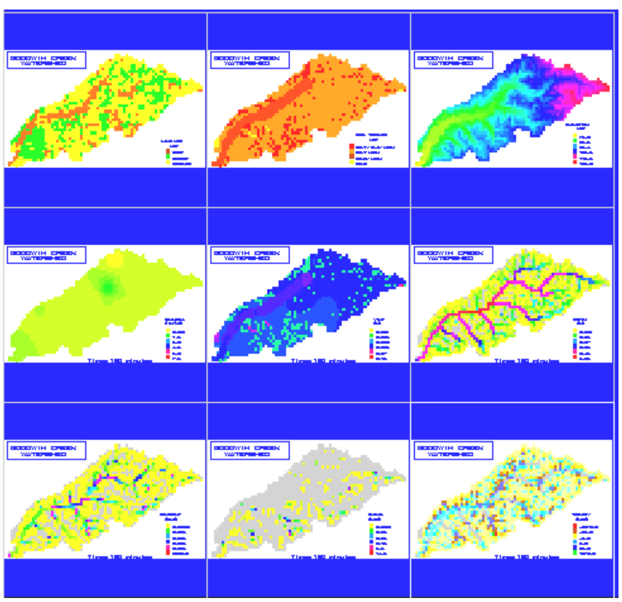

Figure 18. Dynamic simulation view of CASC2D for a watershed showing distribution of input parameters (top row), hydrologic processes (middle row) and erosion/depositional processes (bottom row) (from Johnson, et al., 1997).

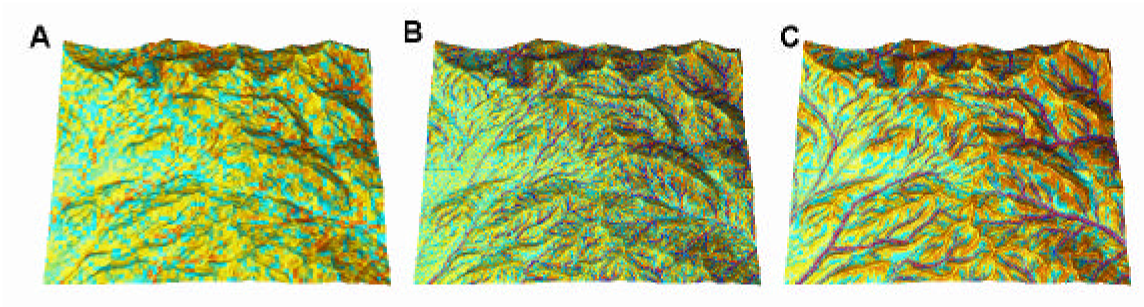

Figure 19. 3-D representation of topographic potential for net erosion and deposition as predicted by USPED using DEM resolutions of 90 (A), 30 (B) and 10 (C) meters (from Warren, 1998).

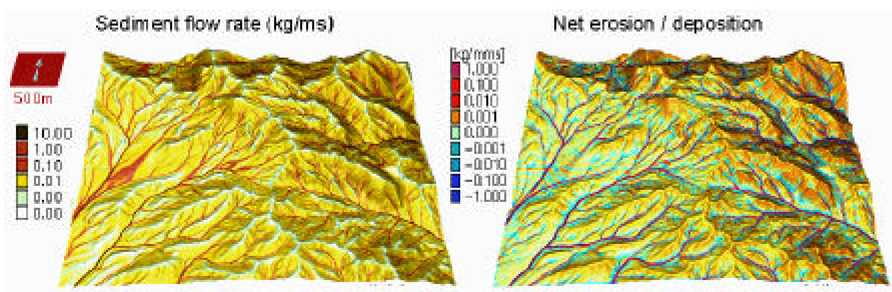

Figure 20. 3-D visualization of sediment flow rates and net erosion/deposition as predicted by SIMWE using a 30-m resolution DEM (from Warren, 1998).

This aspect of erosion modeling is considered to have significance to practitioners, who may be less familiar with model structure and formulations, but can easily visualize and compare model results with their field-based observations.

Many other models had some criteria that were independently rated as excellent. However, the overall assessment of the other models was that, in their current configuration, they were not well suited for military land applications.

8.2 Future Research and DoD Supported Development of Erosion Models

During the conduct of this study a number of potential areas for programmatic support and future research by Department of Defense agencies were identified that would enhance the use and application of existing erosion prediction technologies by military land managers. These areas include:

1. Development of a comprehensive spatial and parameter database for a typical military training area, to include historical rainfall, stream flow and sediment flow

data, that could be tested with various erosion models for parameter calibration and results verification.

2. Programmatic support for automated and manual data collection within military training areas, with emphasis on soil hydraulic parameters, meteorological variables, stream flow and sediment discharge in watercourses.

3. Integration of data collected from military land use impacts, such as tracked vehicle impact studies, with erosion input model parameters and modification of land use factors to fit military type activities.

4. Characterization of the spatial distribution, frequency and intensity of military land use activities.

5. Adoption of enhanced visualization techniques for dynamic simulation and model output assessment.

8.3 Beyond 2000 – The Land Manager and Soil Erosion Modeling

Soil erosion problems will continue to present military land managers with significant challenges in the 21^{st} century. Technological advances in military weaponry and equipment, and the corresponding expansion of the battlefield, will demand more space for military training and testing to ensure readiness. This trend will expose more land to potential degradation from training and testing activities. Some Department of Defense installations have already reached near critical thresholds for sustainability of their soil resources. Careful planning and management will be required to ensure the long-term viability of these resources to meet mission requirements.

Currently, soil erosion modeling is used only sparingly on military lands. Modeling cannot replace practical knowledge and experience of the land and the land user. However, erosion prediction technology, in the form of integrated, automated and user-friendly erosion models, has great potential to enhance the understanding of the impacts of military activities on landscape processes. Many of the models and related tools described in this report, with some refinements, can be implemented rapidly as practical tools to assist military land managers in mitigating these impacts.

9 References

Abbott, M.B. et al. (1986a). *An Introduction to the European Hydrological System – Systeme Hydrologique Europeen, SHE, 1: History and Philosophy of a Physically-based, Distributed Modelling System*, Journal of Hydrology, Volume 87, 1986, pp. 45-59.

Abbott, M.B. et al. (1986b). *An Introduction to the European Hydrological System – Systeme Hydrologique Europeen, SHE,2: Structure of a Physically-based, Distributed Modelling System*, Journal of Hydrology, Volume 87, 1986, pp. 61-77.

Albaladejo, J. et al. (1998). *EUROSEM: Preliminary Validation on Non-agricultural Soils*, in Modelling Soil Erosion by Water (J. Boardman and D. Favis-Mortlock, eds.), Proceedings of the NATO Advanced Research Workshop, September 11-14, 1995, Springer-Verlag, Berlin, pp. 314-325.

Albertson, P. E. (1998). *Geomorphic Development of Fort Leonard Wood, Missouri*, Ph.D. dissertation, University of Missouri-Rolla, Rolla, Missouri, 1998, 155 p.

Bathurst, J.C. et al. (1998). *Modelling badlands erosion with SHETRAN at Draix, southeast France,* in Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes, IAHS Publication No. 249, pp. 129-136.

Bonn, F., J. Megier and A.A. For a (1997). Remote sensing assisted spatialization of soil erosion models within a GIS for land degradation quantification: Expectations, errors and beyond, Remote Sensing ' 96 (Spiteri, ed.), Balkema, Rotterdam, pp. 191-197.

Brooks, K.N. et al. (1991). *Hydrology and the Management of Watersheds*, Iowa State University Press, Ames, IA, 392 pp.

Boardman, John and David Favis-Mortlock (1998). *Modelling soil erosion by water*, Proceedings, NATO Advanced Research Workshop on Global Change: Modelling Soil Erosion by Water, University of Oxford, 11-14 September 1995, NATO ASI Series, Volume 55, Springer-Verlag, Berlin, Germany, 527 pp.

Connolly, R.D. et al. (1997). *Distributed parameter hydrology model (ANSWERS) applied to a range of catchment scales using rainfall simulator data*, Journal of Hydrology, Vol. 201, Issue 1-4, December 1997, pp. 311-328.

De Jong, S.M. and H.T. Riezebos (1997). *SEMMED: A distributed approach to soil erosion modeling,* in Proceedings Remote Sensing ' 96: Integrated Applications for Risk Assessment and Disaster Prevention for the Mediterranean, 20-23 May 1996, A.A. Balkema Publishers, A. Spiteri (ed.), Rotterdam, 1997.

De Roo, A.P.J., L. Hazelhoff and P.A. Burrough (1989). *Soil Erosion Modelling Using ANSWERS and Geographical Information Systems*, Earth Surface Processes and Landforms, Vol. 14, pp. 517-532.

Doe, W.W. (1992). *Simulation of the Spatial and Temporal Effects of Army Maneuvers on Watershed Response*, Ph.D. dissertation, Department of Civil Engineering, Colorado State University, Fort Collins, CO, 1992, 301 pp.

Doe, W. and B. Saghafian (1992). *Spatial and temporal effects of Army maneuvers on watershed response: The integration of GRASS and a 2-D hydrologic model*, Proceedings, 7th Annual GRASS GIS User' s Conference, Denver, CO, National Park Service Technical Report NPS/NRGISD/NRTR-93/13, August 1993, pp. 91-105.

Doe, W.W., B. Saghafian and P.Y. Julien (1996). *Land-Use Impact on Watershed Response: The Integration of Two-Dimensional Hydrological Modelling and Geographical Information Systems*, Hydrological Processes, Vol. 10, 1996, pp.1503-1511.

Doe, W.W., P.Y. Julien and F.L. Ogden (1997). *Maneuversheds and Watersheds: Modeling the Hydrologic Effects of Mechanized Training on Military Lands*, Proceedings, American Water Resources Association Summer Symposium on Water Resources Education, Training, and Practice: Opportunities for the Next Century, June 29-July 3, 1997, Keystone Resort, CO, pp. 767-776.

Flanagan, D.C. and M.A. Nearing (1995). *USDA-Water Erosion Prediction Project (WEPP) – Technical Documentation*, National Soil Erosion Research Laboratory, Report No. 10, USDA-ARS-MWA, West Lafayette, IN, 1995.

Garnier, Monica et al. (1998). *Integrated Use of GLEAMS and GIS to Prevent Groundwater Pollution Caused by Agricultural Disposal of Animal Waste*, Environmental Management, Vol. 22, No. 5, pp. 747-756.

Goodchild, M.F. et al. (1996). *GIS and Environmental Modeling: Progress and Research Issues*, GIS World Books, GIS World, Inc., Fort Collins, CO, 486 pp.

Haan, C.T., H.P. Johnson and D.L. Brakensiek (1982). *Hydrologic Modeling of Small Watersheds*, American Society of Agricultural Engineers Monograph No. 5, ASAE, St. Joseph, MI, 379 pp.

Haan, C.T., B.J. Barfield and J.C. Hayes (1994). *Design Hydrology and Sedimentology for Small Catchments*, Academic Press, San Diego, California, 1994, 588 pp.

Hadley, R.F. and E.D. Ongley (1989). *Sediment and the Environment*, Proceedings, International Symposium, 17-18 May 1989, Baltimore, MD, International Association of Hydrological Sciences (IAHS) Publication No. 184, 218 pp.

Hadley, R.F. and T. Mizuyama (1993). *Sediment Problems: Strategies for Monitoring, Prediction and Control*, Proceedings, International Symposium, 19-21 July 1993, Yokohama, Japan, International Association of Hydrological Sciences (IAHS) Publication No. 217, 284 pp.

Hagen, L.J. and G. R. Foster (1990). Soil Erosion Prediction Technology, in Proceedings, Soil Erosion and Productivity Workshop (W.E. Larson et al., eds.), University of Minnesota Press, Saint Paul, MN, pp. 117-135.

Harrison, J.S. and W.W. Doe (1997). *Erosion Modeling in Pinon Canyon Maneuver Site Using the Universal Soil Loss Equation and the GIS System-GRASS*, TPS 97-21, Center for Ecological Management of Military Lands, Colorado State University, December 1997, 47 pp.

Hewlett, John D. (1982). *Principles of Forest Hydrology*, University of Georgia Press, 1982, 183 pp.

Jankowski, P. and G. Haddock (1996). *Integrated Nonpoint Source Pollution Modeling System*, in GIS and Environmental Modeling: Progress and Research Issues (M. Goodchild et al., eds.), GIS World Books, Fort Collins, CO, pp. 209-211.

Johnson, B.E. (1997). *Development of a Storm Event Based Two-Dimensional Upland Erosion Model*, Ph.D. dissertation, Department of Civil Engineering, Colorado State University, Spring 1997.

Johnson, B.E., P.Y. Julien and D.K. Molnar (1997). *Advances in Soil Erosion Modeling on Goodwin Creek Watershed*, Proceedings, Conference on Management of Landscapes Disturbed by Channel Incision, May 20-22, 1997, Oxford, MS.

Julien, P.Y.and B. Saghafian (1991). *A Two-Dimensional Watershed Rainfall-Runoff Model: CASC2D User's Manual*, Colorado State University Report CER90-91PYJ-BS-12, March 1991, 66 pp.

Julien, P.Y., B. Saghafian and F.L. Ogden (1995). *Raster-Based Hydrologic Modeling of Spatially-varied Surface Runoff*, Water Resources Bulletin, AWRA, Vol. 31, No.3, pp. 523-536.

Knisel, W.G., editor (1993). *GLEAMS, Version 2.10*, University of Georgia Coastal Plain Experiment Station, Biological and Agricultural Engineering, UGA-CPES-BAED Publication No. 5, November 1993, 182 pp.

Knisel, W.G., editor (1980). *CREAMS: A Field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems*, USDA, Conservation Research Report No. 26, 640 pp.

Laflen, J.M., D. Flanagan, J. Ascough, M.Weltz and J. Stone (1994). *The WEPP Model and Its Applicability for Predicting Erosion on Rangelands*, in Variability of Rangeland Water Erosion Processes, Soil Science Society of America Special Publication 38, Madison, WI, 1994.

Jones, D.S. et al. (1996). *Calculating Revised Universal Soil Loss Equation (RUSLE) Estimates on Department of Defense Lands: A Review of RUSLE Factors and U.S. Army LCTA Data Gaps*, CEMML TPS 96-8, Center for Ecological Management of Military Lands, Colorado State University, Fort Collins, CO, 9 pp.

Klaghofer, E., W. Birnbaum and W. Summer (1993). *Linking sediment and nutrient export models with a geographic information system*, in HydroGIS 93: Application of GIS in Hydrology and Water Resources, IAHS Publication No. 211, 1993, pp.501-506.

Klaghofer, W.S. and W. Zhang (1998). *Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes*, Proceedings, International Symposium, 13-17 July 1998, Vienna, Austria, International Association of Hydrological Sciences (IAHS) Publication No. 249, 445 pp.

Kovar, K. and H.P. Nachtnebel (1993). *Application of Geographic Information Systems in Hydrology and Water Resources Management*, Proceedings, International Symposium, 19-22 April 1993, Vienna, Austria, International Association of Hydrological Sciences (IAHS) Publication No. 211, 693 pp.

Lal, R. (1994). *Soil Erosion Research Methods*, 2d edition, St. Lucie Press, Delray Beach, FL, 340 pp.

Lane, L.J. et al. (1992*). Development and Application of Modern Soil Erosion Prediction Technology – The USDA Experience,* Australian Journal of Soil Research, Vol. 30, pp. 893-912.

Maidment, D.R. (1996). Environmental Modeling with GIS, in GIS and Environmental Modeling: Progress and Research Issues (M. Goodchild et al., eds.), GIS World Books, Fort Collins, CO, pp. 315-323.

Mitas, L., W.M. Brown and H. Mitasova (1997). *Role of Dynamic Cartography in Simulations of Landscape Process Based on Mulitvariate Fields*, Computers & Geosciences, Vol. 23, No. 4, pp. 437-446.

Mitas, L. and H. Mitasova (1998). *Distributed soil erosion simulation for effective erosion prevention*, Water Resources Research, Vol. 34, No. 3, pp. 505-516.

Mitasova, H. et al. (1996). *Modelling topographic potential for erosion and deposition using GIS*, International Journal of Geographical Information Systems, Vol. 10, No. 5, pp. 629-641.

Mitasova, H., W. Brown, D. Johnston and L. Mitas (1996). *GIS Tools for Erosion/Deposition Modeling and Multidimensional Visualization, Part II: Unit Stream Power-Based Erosion/Deposition Modeling, and Enhanced Dynamic Visualization*, Contract Report, U.S. Army Construction Engineering Research Laboratories, Champaign, IL, August 1996, 39 pp.

Mitasova, H., L. Mitas, W.M. Brown and D. Johnston (1996). *Multidimensional Soil Erosion/Deposition Modeling, Part III: Process based erosion simulation*, Contract Report, U.S. Army Construction Engineering Research Laboratories, Champaign, IL, December 1996, 28 pp.

Morgan, R.P.C., J.N. Quinton and R.J. Rickson (1993). *EUROSEM: A User Guide, Version 2*, Silsoe College, Cranfield University, United Kingdom, 96 pp.

Morgan, R.P.C. (1994). *The European Soil Erosion Model: An Update on Its Structure and Research Base*, in Rickson, R.J. (ed.), Conserving Soil Resources: European Perspectives, CAB International, Wallingford, Oxfordshire, pp. 287-299.

Morgan, R.P.C. et al. (1998). *The EUROSEM Model,* in Modelling Soil Erosion by Water (J. Boardman and D. Favis-Mortlock, eds.), Proceedings of the NATO Advanced Research Workshop, September 11-14, 1995, Springer-Verlag, Berlin, pp. 389-398.

Nyerges, T.L. (1991). *GIS for Environmental Modelers: An Overview*, Proceedings, First International Conference on Integrating GIS and Environmental Modeling, Boulder, CO, 1991, pp. 1-14.

Ogden, F.L. (1992). *Two-Dimensional Runoff Modeling with Weather Radar Data*, Ph.D. dissertation, Department of Civil Engineering, Colorado State University, 1992.

Ogden, F.L. and B. Saghafian (1997). *Green & Ampt Infiltration with Redistribution*, Journal of Irrigation and Drainage Engineering, American Society of Civil Engineers, 123 (5), pp. 386-393.

Ogden, F.L. and S.U.S. Senarath (1997). *Continuous Distributed Parameter Hydrologic Modeling with CASC2D*, Proceedings, XXVII Congress, International Association of Hydraulic Research, San Francisco, CA, August 1997.

Osterkamp, W.R. and T.J. Toy (1997). *Geomorphic considerations for erosion prediction*, Environmental Geology 29 (3/4), February 1997, pp. 152-157.

Peterson, A.E. and J.B. Swan (1979). *Universal Soil Loss Equation: Past, Present and Future*, Soil Science Society of America Special Publication No. 8, Madison, WI, 53 pp.

Price, D.L. et al. (1997). *Evaluation of Technologies for Addressing Factors Related to Soil Erosion on DoD Lands*, USACERL Technical Report 97/134, U.S. Army Corps of Engineers Construction Engineering Research Laboratories, September 1997, 100 pp.

Quinton, J.N. (1998). *Validation of Physically Based Erosion Models, with Particular Reference to EUROSEM*, in Modelling Soil Erosion by Water (J. Boardman and D. Favis-Mortlock, eds.), Proceedings of the NATO Advanced Research Workshop, September 11-14, 1995, Springer-Verlag, Berlin, pp. 300-313.

Renard, K.G. et al. (1997). *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)*, U.S. Department of Agriculture, Agriculture Handbook No. 703, 404 pp.

Rickson, R.J. (1998). *Potential Applications of the European Soil Erosion Model (EUROSEM) for Evaluating Soil Conservation Measures*, in Modelling Soil Erosion by Water (J. Boardman and D. Favis-Mortlock, eds.), Proceedings of the NATO Advanced Research Workshop, September 11-14, 1995, Springer-Verlag, Berlin, pp. 326-335.

Riggins, R.E. and L.J.Schmitt (1984). *Development of Prediction Techniques for Soil Loss and Sediment Transport at Army Training Areas*, USACERL Interim Report N-181, U.S. Army Construction Engineering Research Laboratories, Champaign, IL, 36 pp.

Riggins, R.E., T.J. Ward and W. Hodge (1989). *ARMSED, A Runoff and Sediment Yield Model for Army Training Land Watershed Management, Volume I: Parameter Estimation Guide and Volume II: Program Documentation*, U.S. Army Construction Engineering Laboratory ADP Report N-89/12, August 1989, 68 pp. and 95 pp.

Saghafian, B. (1996). Implementation of a Distributed Hydrologic Model within GRASS, in GIS and Environmental Modeling: Progress and Research Issues (M. Goodchild et al., eds.), GIS World Books, Fort Collins, CO, pp. 205-208.

Sharpley, A.N. and J.R. Williams (1990). *EPIC – Erosion/Productivity Impact Calculator: Model Documentation*, USDA-ARS Technical Bulletin No. 1768, 235 pp.

Singh, V.P. (1989). *Hydrologic Systems: Volume II (Watershed Modeling)*, Prentice Hall, Englewood Cliffs, NJ, 1989, 320 pp.

Singh, V.J. and M. Fiorentino (eds.) (1996). *Geographical Information Systems in Hydrology*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 443 pp.

Smolen, M.D. (1983). *Hydrologic/Water Quality Models for Agriculture and Forestry*, USDA-Agricultural Research Service, Southern Cooperative Series Bulletin No. 291, June 1983, 104 pp.

Srinivasan, R. et al. (1994). *The Impact of GIS-derived Topographic Attributes on the Simulation of Erosion Using AGNPS*, Applied Engineering in Agriculture, American Society of Agricultural Engineers, Vol. 10 (4), pp. 561-566.

Stuart, N. and C. Stocks (1993). *Hydrological modelling within GIS: an integrated approach*, Proceedings, HydroGIS 93: Application of GIS in Hydrology and Water Resources, IAHS Publication No. 211, 1993, pp. 319-329.

Summer, W., E. Klaghofer and W. Zhang, ed.(1998). *Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes*, International Association of Hydrological Sciences, IAHS Publication No. 249, 1998, 453 pp.

Warren, S.D. et al. (1991). *An Erosion-Based Land Classification System for Military Installations*, USACERL Technical Manuscript N-91/05, U.S. Army Construction Engineering Research Laboratories, Champaign, IL, 12 pp.

Warren, S.D. (1998). *Digital Terrain Modeling and Distributed Soil Erosion Simulation/Measurement for Minimizing Environmental Impacts of Military Training (DRAFT)*, U.S. Army Corps of Engineers Construction Engineering Research Laboratories, Interim Report 99, November 1998, 33 pp.

Weltz, M.A. et al. (1998). *Influence of abiotic and biotic factors in measuring and modeling soil erosion on rangelands: State of knowledge*, Journal of Range Management, Vol. 51, September 1998, pp. 482-495.

Wenzel, H.G. and Melching, C.S. (1987). An Evaluation of the MULTSED Simulation Model to Predict Sediment Yield, U.S. Army Construction Engineering Research Laboratory Report N087/27, September 1987, 87 pp.

Wicks, J.M. and J.C. Bathurst (1996). *SHESED: a physically based, distributed erosion and sediment yield component for the SHE hydrological modelling system*, Journal of Hydrology, Volume 175, Issue 1-4, February 1996, pp. 213-238.

Williams, Jimmy R. (1975). *Sediment-yield prediction with Universal Equation using runoff energy factor, Proceedings of the Sediment-Yield Workshop on Present and Prospective Technology for Predicting Sediment Yields and Sources*, USDA Sedimentation Laboratory, Oxford, MS, November 1972, USDA-ARS Report ARS-S-40, pp. 245-252.

Woolhiser, D.A., R.E. Smith and D.C. Goodrich (1990). *KINEROS, A Kinematic Runoff and Erosion Model: Documentation and User Manual*, U.S. Department of Agriculture, Agricultural Research Service, ARS-77, 130 pp.

Young, R.A. et al. (1989). *AGNPS: A nonpoint-source pollution model or evaluating agricultural watersheds*, Journal of Soil and Water Conservation, March-April 1989, pp. 168-173.

Young, R.A., C.A. Onstad, D.D. Bosch and W.P. Anderson (1994). *AGricultural Non-Point Source Pollution Model, Version 4.03, User's Guide*, USDA-ARS North Central Soil Conservation Research Laboratory, Morris, MN, July 1994.

9.1 *Appendix A: Internet Web-site References*

Web Reference List – Erosion Models

MODEL NAME	WEB REFERENCE
AGNPS	Http://dino.wiz.uni-kassel.de/model_db/mdb/agnps.html
	Http://www.wcc.nrcs.usda.gov/water/factsheets/agnps.html
	Http://pasture.ecn.purdue.edu/~aggrass/models/agnps/Index.html
	Http://www.infolink.morris.mn.us/~lwink/products/agnps.htm
	Http://www.sedlab.olemiss.edu/AGNPS98.html
ALMANAC	Http://arsserv0.tamu.edu/nrsu/almafact.htm
ANSWERS	Http://pasture.ecn.purdue.edu/~aggrass/models/answers/
APEX	Http://arsserv0.tamu.edu/nrsu/apexfact.htm
CASC2D	Http://www.eng2.uconn.edu/~ogden/pdf/casc_man.pdf
	Http://www.eng2.uconn.edu/~ogden/pdf/casc2_desc.pdf
CREAMS	Http://dino.wiz.uni-kassel.de/model_db/mdb/creams.html
EPIC	Http://www.wcc.nrcs.usda.gov/water/factsheets/epic.html
	Http://arsserv0.tamu.edu/nrsu/epicfact.htm
EUROSEM	Http://www.silsoe.cranfield.ac.uk/eurosem/eurosem.htm
GLEAMS	Http://arsserv0.tamu.edu/nrsu/glmsfact.htm
	Http://www.wcc.nrcs.usda.gov/water/factsheets/gleams.html
HUMUS	Http://brcsun15.tamu.edu/humus/
KINEROS	Http://Dino.wiz.uni-kassel.de/model_db/mdb/kineros.html
RUSLE	Http://www.itc.nrcs.usda.gov/focs/RUSLE/
SEMMED	Http://www.frw.ruu.nl/fg/demon.html
SIMWE	Http://www2.gis.uiuc.edu:2280/modviz/
	Http://www2.gis.uiuc.edu:2280/modviz/reports/cerl97/rep97.html
SPUR	Http://juniper.tamu.edu/taes/rlem/spur.htm
SWAT	Http://www.brc.tamus.edu/swat/downloads/dos.html
	Http://arsserv0.tamu.edu/nrsu/swatfact.htm
	Http://www.brc.tamus.edu/swat/
	Http://www.brc.tamus.edu/swatgrass/index.html
SWRRB	Http://arsserv0.tamu.edu/nrsu/swrbfact.htm
	Http://www.wcc.nrcs.usda.gov/water/factsheets/swrrbwq.html
USLE	Http://www.bae.ncsu.edu/bae/research/jep_models/lsuwand/www/USLE.html
USPED	Http://www2.gis.uiuc.edu:2280/modviz/reports/cerl97/rep97.html
WEPP	Http://soils.ecn.purdue.edu/~wepp/weppdocs.html
	Http://soils.ecn.purdue.edu/~wepphtml/wepp/wepptut/main.html
GU – INTERFACES (GUI)	
MOSES	Http://soils.ecn.purdue.edu/~wepp/moses.html
WMS	Http://www.bossintl.com.hk/html/wms_tech_info.html
	Http://www.ecgl.byu.edu/software/wms/download/pc.html

9.2 Appendix B: Institutional/Agency Support and Points-of-Contact

SOFTWARE/APPLICATIONS	GIS SOFTWARE/INTERFACE
AGNPS (Agricultural Nonpoint Source Pollution Model) USDA-ARS National Sedimentation Laboratory 598 McElroy Drive P. O. Box 1157 Oxford, MS 38655 - 1157 (601) 232-2900 Dr. Robert Young USDA-ARS, North Central Research Lab Morris, MN 56267 (612) 589-3411	AGNPS-GRASS interface has been completed POC: Dr. Bernie Engel University of Purdue engleb@ecn.purdue.edu
ALMANAC (Agricultural Land Management Alternatives w/ Numerical Assessment Criteria) USDA-ARS Grassland Soil and Water Research Laboratory 808 E. Blackland Rd. Temple, TX 76502 And Texas Agriculture Experiment Station (TAES), Texas A&M University Jim R. Kiniry, Research Agronomist (ARS) (254) 770-6506 kiniry@brcsun0.tamu.edu Jimmy Williams, Hydraulic Engineer (TAES) (254) 770-6508 Deborah Spanel, Biological Technician – plants (TAES) (254) 770-6515 Paul Dyke, Agricultural Economist (TAES) (254) 770-6612 Verel Benson, Agricultural Economist (NRCS) (254) 770-6630	

ANSWERS (Areal Nonpoint Source Watershed Environmental Response Simulation) North Carolina State University David B. Beasley, Ph.D., P.E. Professor and Head Biological and Agricultural Engineering North Carolina State University Raleigh, NC 27695-7625 Phone: (919) 515-2694 FAX (919) 515-6772 david_beasley@ncsu.edu Dr. Theo A. Dillaha Biological Systems Engineering Dept. Virginia Polytechnic Institute Blacksburg, VA 24061-0303 Phone: (540) 231-6813 FAX: (540) 231-3199 dillaha@vt.edu	ANSWERS-GRASS interface completed in GRASS version 4.1 POC: Dr. Bernie Engel University of Purdue engleb@ecn.purdue.edu
APEX (Agricultural Policy Environmental Extender) USDA-ARS Grassland Soil and Water Research Laboratory 808 E. Blackland Rd. Temple, TX 76502 And Texas Agriculture Experiment Station (TAES), Texas A&M University Jimmy Williams, Hydraulic Engineer (TAES) (254) 770-6508 Verel Benson, Agricultural Economist (NRCS) (254) 770-6630 Avery Meinardus, Computer Assistant (TAES) (254) 770-6637	

ARMSED (Army Multiple Watershed Storm Water and Sediment Runoff Model) Developed by the U.S. Army Construction Engineering Research Laboratory, Champaign, Illinois Mr. Robert E. Riggins, USACERL Champaign, IL 1-880-USA-CERL There is no current supporting agency and few to no users of the ARMSED program. Originally derived from MULTSED.	
CASC2D (Cascade Two-Dimensional Rainfall-Runoff Model) Developed by Colorado State University (Dept. of Civil Engineering) and currently adopted by USAWES for Army/DoD use Dr. Pierre Y. Julien, Dept. of Civil Engineering Colorado State University (970) 491-8450 E-mail: pierre@lance.colostate.edu Dr. B. E. Johnson U.S. Army Waterways Experiment Station, Coastal and Hydraulics Laboratory Vicksburg,MS (601)-634-3693 E-mail: billy.e.johnson@wes01.usace.army.mil Dr. Fred Ogden Dept. of Civil and Environmental Engineering University of Connecticut, Storrs, CT (860)-486-2771 E-mail: ogden@eng2.uconn.edu	CASC2D is incorporated into the Watershed Modeling System (WMS), a GUI developed by Brigham Young University and transferred for use to USAWES. Army/DoD users may use WMS free of charge. POC is Mr. Jeff Jorgenson, USAWES. WMS development and maintenance is provided by BYU under contract. Christopher M. Smemoe WMS Software Manager 300 CB BYU Provo UT 84602 E-mail: smemoe@byu.edu Fax: (801) 378-2478

CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) Dr. Wayne Skaggs, Professor North Carolina State University Dept. of Biological and Agricultural Engineering Box 7625 Raleigh, NC 27695 (919) 515-6739 E-mail: skaggs@eos.ncsu.edu	
EPIC (Erosion Productivity Impact Calculator) USDA-ARS Grassland Soil and Water Research Laboratory 808 E. Blackland Rd. Temple, TX 76502 And Texas Agriculture Experiment Station (TAES), Texas A&M University epic@brcsun0.tamu.edu http:// epic@brcsun0.tamu.edu/epic Jimmy Williams, Research Scientist/Hydraulic Engineer (TAES) (254) 770-6508 Verel Benson, Agricultural Economist (NRCS) (254) 770-6630 Avery Meinardus, Programmer (TAES) (254) 770-6637 Ray Griggs, Agricultural Engineer/ Associate Res. Scientist (TAES) (254) 770-6631	

EUROSEM (European Soil Erosion Model) Dr. Roy Morgan, Professor of Soil Erosion Control School of Agriculture, Food & Environment Cranfield University Silsoe, Bedfordshire MK45 4DT, United Kingdom +44 (0) 1525 863059 E-mail: http://www.silsoe.cranfield.ac.uk/people/rmorgan.htm	
GLEAMS USDA-ARS Grassland Soil and Water Research Laboratory 808 E. Blackland Rd. Temple, TX 76502 And Texas Agriculture Experiment Station (TAES), Texas A&M University Kevin King, Hydraulic Engineer (ARS) (254) 770-6616 Walter Knisel (developer/retired), Hydraulic Engineer (ARS) (912) 386-3889 Ralph Leonard (retired), Soil Scientist (ARS) (912) 386-3462 Frank Davis, Computer Specialist (ARS) (912) 386-3462 Ray Griggs, Agricultural Engineer (TAES) (254) 770-6631	GLEAMS-GRASS interface under development POC: Dr. Bernie Engel University of Purdue engleb@ecn.purdue.edu

HUMUS (Hydrologic Unit Model for the United States) USDA-ARS Grassland Soil and Water Research Laboratory 808 E. Blackland Rd. Temple, TX 76502 And Texas Agriculture Experiment Station (TAES), Texas A&M University Hailing Wang, Research Associate (254) 770-6608 Fax: (254) 770-6561 wang@brcsun0.tamu.edu Raghavan Srinivasan, Associate Professor (254) 770-6670 FAX: (254) 770-6561 srin@brcsun0.tamu.edu	
KINEROS (Kinematic Runoff and Erosion Model) U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) Southwest Watershed Research Center 2000 E. Allen Rd Tucson, Arizona (520) 670-6481 U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) Water Management Research Unit Fort Collins, Colorado Roger E. Smith, Research Hydraulic Engineer (WMRU) (970) 491-8263 roger@lily.aerc.colostate.edu David C. Goodrich, Research Hydraulic Engineer (SWRC) (520) 670-6380 Ext. 16	

MULTSED (Multiple Watershed Runoff and Sediment Model) Dr. Daryl B. Simons, (developer) Professor Emeritus Department of Civil Engineering Colorado State University Fort Collins, Colorado 80523 (970) 482-4051 Dr. Tim Ward Dept. of Civil Engineering University of New Mexico Albuquerque,NM	
MUSLE (Modified Universal Soil Loss Equation) Primary Support Institution/Agency: USDA-ARS National Sedimentation Laboratory 598 McElroy Drive P. O. Box 1157 Oxford, MS 38655 - 1157 (601) 232-2900 George Foster, Project Leader (601) 232-2940 foster@sedlab.olemiss.edu	
RUSLE (Revised Universal Soil Loss Equation) Primary Support Institution/Agency: USDA-ARS National Sedimentation Laboratory 598 McElroy Drive P. O. Box 1157 Oxford, MS 38655 - 1157 (601) 232-2900 George Foster, Project Leader (601) 232-2940 foster@sedlab.olemiss.edu	Raster GIS inputs (GRASS, ARCINFO) compatible with model use for large watersheds POC: Dr. Steve Warren Center for Ecological Management of Military Lands Colorado State University E-mail: swarren@cemml.colostate.edu Dr. William Doe Center for Ecological Management of Military Lands Colorado State University E-mail: bdoe@cemml.colostate.edu

SEMMED (Soil Erosion Model for Mediterranean Areas) Dr. Steven M. de Jong Department of Physical Geography P.O. Box 80115, 3508 TC Utrecht, The Netherlands E-mail: s.dejong@frw.ruu.nl	
SHE (Systeme Hydrologique European) Dr. D.E. Storm Dept. of Biosystems & Agricultural Engineering Oklahoma State University Stillwater, OK 74078-6016 (405) 744-8422 E-mail: dstorm@okstate.edu	
SIMWE (Simulated Water Erosion) Geographic Modeling and Systems Laboratory (GMSL) Department of Geography 220 Davenport Hall University of Illinois at Urbana-Champaign Urbana, IL 61801 Lubos Mitas National Center for Supercomputing Applications University of Illinois at Urbana-Champaign Urbana, IL 61801 (217) 244-1971 lmitas@ncsa.uiuc.edu Helena Mitasova (GMSL) (217) 333-4735 helena@gis.uiuc.edu William M. Brown (GMSL) (217) 333-5077 brown@gis.uiuc.edu	Dynamic 2D-3D simulations using Digital Elevation Model (DEM) and GIS raster data layers POC: Dr. Steve Warren Center for Ecological Management of Military Lands Colorado State University E-mail: swarren@cemml.colostate.edu

SPUR (Simulation of Production and Utilization of Rangelands) Northwest Watershed Research Center USDA Agricultural Research Service Northwest Watershed Research Center 800 Park Blvd., Plaza IV, Suite 105 Boise, ID 83712-7716 (208) 422-0700 Operator SPUR/SPUR2.4 J. K. Foy, Texas Agricultural Experiment Station P. O. Box 1658, Vernon, TX 76385 (817) 552-9941 Ext. 250 j-foy@tamu.edu J. D. Hanson, USDA-ARS-NPA, Great Plains Systems Research Unit P. O. Drawer E, 301 S. Howes St. Ft. Collins, CO 80522 (970) 490-8324 jon@gpsr.colostate.edu W. R. Teague, Texas Agricultural Experiment Station P. O. Box 1658, Vernon, TX 76385 (817) 552-9941 Ext. 235 r-teague@tamu.edu SPUR-2000 Fred Pierson, Hydrologist (NWRC) (208) 422-0720 fpierson@nwrc.ars.pn.usbr.gov Ken Spaeth, Hydrologist (NRCS) (208) 422-0729 kspaeth@nwrc.ars.pn.usbr.gov Dee Carlson, Support Scientist (University of Idaho at Boise) (208) 422-0718 dcarlson@nwrc.ars.pn.usbr.gov	

<table>
<tr><td>SWAT
(Soil and Water Assessment Tool)

Primary Support Institution/Agency:

USDA-ARS
Grassland Soil and Water Research Laboratory
808 E. Blackland Rd.
Temple, TX 76502

Jeffrey G. Arnold, Agricultural Engineer
USDA-ARS
808 East Blackland Rd.
Temple, TX 76502
arnold@brcsun0.tamu.edu
(254)770-6502

R. Srinivasan
srin@brcsun0.tamu.edu
(254)770-6670</td><td>SWAT-GRASS inteface under development.

POC:
R. Srinivasan
srin@brcsun0.tamu.edu
(254)770-6670</td></tr>
<tr><td>SWRRB(WQ)
(Simulator for Water Resources in Rural Basins – Water Quality)

Primary Support Institution/Agency:

USDA-ARS
Grassland Soil and Water Research Laboratory
808 E. Blackland Rd.
Temple, TX 76502
and
Texas Agriculture Experiment Station (TAES), Texas A&M University

Jeffrey G. Arnold, Agricultural Engineer
USDA-ARS
808 East Blackland Rd.
Temple, TX 76502
arnold@brcsun0.tamu.edu
(254)770-6502

Jimmy Williams, Hydraulic Engineer (TAES)
(254) 770-6508</td><td></td></tr>
</table>

USLE (Universal Soil Loss Equation) Primary Support Institution/Agency: Agricultural Research Service USDA Dr. John M. Laflen 2150 Pammel Drive Iowa State University Ames, IA 50011 (515) 294-8327 E-mail: laflen@ecn.purdue.edu	Raster-based GIS inputs (GRASS, ARCINFO) are compatible with model
USPED (Unit Stream Power Erosion and Deposition Model) Geographic Modeling and Systems Laboratory (GMSL) Department of Geography 220 Davenport Hall University of Illinois at Urbana-Champaign Urbana, IL 61801 Lubos Mitas National Center for Supercomputing Applications University of Illinois at Urbana-Champaign Urbana, IL 61801 (217) 244-1971 lmitas@ncsa.uiuc.edu Helena Mitasova (GMSL) (217) 333-4735 helena@gis.uiuc.edu William M. Brown (GMSL) (217) 333-5077 brown@gis.uiuc.edu D. Johnston (GMSL)	GRASS-derived inputs for 3-D simulation capability; currently under development through SERDP POC: Dr. Steve Warren Center for Ecological Management of Military Lands Colorado State University E-mail: swarren@cemml.colostate.edu

WEPP (Water Erosion Prediction Project) WEPP Technical Support USDA-ARS National Soil Erosion Research Laboratory (NSERL) 1196 Bldg. SOIL West Lafayette, IN 47907-1196 Phone: (317) 494-8673 email: wepp@ecn.purdue.edu http://soils.ecn.purdue.edu:20002/~wepp/nserl.html Dennis Flanagan, Agricultural Engineer (765) 494-7748 flanagan@ecn.purdue.edu John Laflen, WEPP Leader USDA- ARS The National Soil Tilth Laboratory 2150 Pammel Drive, ISU Ames, Iowa 50011 (515) 294-8327 aflen@ecn.purdue.edu Stanley Livingston, Soil Scientist (317) 494-2946 living@ecn.purdue.edu Charles Meyer, Systems Analyst (765) 494-8695 meyerc@ecn.purdue.edu	BETA Test Version of WEPP Windows 95/NT interface has been developed for model version 98.4 that provides GIS-like inputs (not raster cells)

9.3 Appendix C: Matrix of Classification (MSExcel File)

9.4 Appendix D: Matrix of Model Evaluation (MSExcel File)

9.5 Appendix E: Erosion Model Fact Sheets

FACT SHEETS COMPLETED FOR:

AGNPS
ANSWERS
CASC2D
CREAMS
GLEAMS
MUSLE
RUSLE
SIMWE
USLE
USPED
WEPP

FACT SHEETS TO BE COMPLETED FOR:

APEX
ALMANAC
ARMSED
EPIC
EUROSEM
HUMUS
KINEROS
MULTSED
SEMMED
SHE
SPUR
SWAT
SWRRB

APPENDIX E:
Erosion Model Fact Sheet and Evaluation

Model Name: Agricultural Non-Point Source Pollution Model (AGNPS)

Descriptive Criteria

1. Classification of Model:
- Physically-based
- Distributed (grid-cell)
- Single-event
- Watershed scale (10 – 50,000 acres in size)

2. Applications of Model:
- Agricultural watersheds
- Estimate soil loss and deposition across the landscape
- Estimate nitrogen, phosphorous and chemical oxygen demand transport
- Determine locations of critical areas that contribute to sediment and pollutants
- Evaluate effects of alternative agricultural land management practices

3. Known Limitations:
- Resolution of grid-cell data may effect output values
- Continuous simulation under development

4. Assumptions:
- Uses lumped parameter approach for rainfall (total accumulation) – does not accommodate non-uniform rainfall events
- Grid-cells have uniform characteristics
- Uses USLE/RUSLE formulation to compute soil loss in upland areas
- Curve Number (CN) approach used to calculate rainfall excess for runoff

5. **Agency Support and Points of Contact**:

AGNPS 98:	AGNPS Version 4.03
USDA-ARS	USDA-ARS
National Sedimentation Laboratory	North Central Soil Conservation Lab
598 McElroy Drive	Morris, MN 56267
P. O. Box 1157	Dr. Robert Young
Oxford, MS 38655 - 1157	(612) 589-3411
(601) 232-2900	

Model Name: AGNPS

Evaluative Criteria

1. <u>Data Requirements:</u>

- 22 input parameters
- Landscape topography from Digital Elevation Model (DEM) data, to include user defined grid-cell size
- SCS Curve Number
- USLE/RUSLE factors
- Surface roughness
- Channel characteristics

2. <u>Model Results:</u>

- Outputs for each cell or entire watershed
- Runoff volume
- Erosion and deposition totals
- Sediment totals and yield
- Sediment concentrations and particle sizes
- Nitrogen, phosphorous and chemical oxygen demand totals and concentrations

3. <u>Cost and Complexity:</u>

- Installation on hard drive requires some familiarity with set-up and configuration files
- Well documented
- GIS integration greatly enhances model use and data analysis
- Moderately difficult to use

4. <u>Hardware/System Requirements:</u>

- IBM-compatible personal computer
- MS-DOS Version 3.0 or later
- 3 Mb of hard disk space
- An 80286 (286) or later processor
- Graphics adapter and monitor (CGA minimum)
- GIS system (preferred)

5. Geographic Information System (GIS) Integration:

- Model interface with GRASS has been developed
- 8 basic GIS data layers required to derive input files
- Excellent integration with GIS

6. Commercial-off-the-shelf Integration:

- None

7. Graphical User Interface (GUI) Configuration:

- Output interface program developed for visualization of data
- Graphical output display options include:
  - Soil loss
  - Nutrients movement
  - Runoff movement
- Allows different scenarios to be compared
- Spatially distributed maps of outputs can be produced

8. Ease of Use:

- Limited knowledge of GIS required to run model
- Moderate number of parameters required
- Well documented
- Fairly simple for a physically-based model

APPENDIX E:
Erosion Model Fact Sheet and Evaluation

Model Name: Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS)

Descriptive Criteria

1. Classification of Model:

- Physical, process-based
- Distributed parameter
- Single event
- Field or watershed scale

2. Applications of Model:

- Agricultural land use
- Evaluate impact of various conservation management practices
- Evaluate effects of different rainfall scenarios in combination with different land use and conservation management practices
- Delineate "hot spots" of erosion and deposition within the landscape

3. Known Limitations:

- Gully and channel erosion processes are not explicitly defined
- Highly sensitive to some parameter input values, particularly soil hydraulic parameters, soil moisture and surface roughness
- Grid-cell size may effect results
- Single-storm (rainfall) event applications only – no snowmelt

4. Assumptions:

- Landscape characterized as grid-cells, each containing uniform properties
- Manning's equation used to compute excess rainfall (runoff)

5. **Agency Support and Points of Contact:**

David B. Beasley, Ph.D., P.E.	Dr. Theo Dillaha
Professor and Head	Associate Professor
Biological and Agricultural Engineering	Biological Systems Engr. Dept.
North Carolina State University	Virginia Polytechnic Institute
Raleigh, NC 27695-7625	Blacksburg, VA 24061-0303
Phone: (919) 515-2694	Phone: (540) 231-6813
FAX (919) 515-6772	FAX: (540) 231-3199
david_beasley@ncsu.edu	dillaha@vt.edu

Model Name: ANSWERS

Evaluative Criteria

1. **<u>Data Requirements:</u>**

- Distributed rainfall from gauge data (1-minute interval)
- Landscape topography (slope, aspect)
- Soil hydraulic properties (to include USLE K-factor)
- C and P USLE Factors
- Surface roughness parameters

2. <u>Model Results:</u>

- Spatially distributed soil loss and deposition from a rainfall event
- Soil loss for various time recurrence intervals
- Particle sized distribution of eroded sediment

3. <u>Cost and Complexity:</u>

- Public domain
- Requires spatial data files (GIS)
- Requires significant soils data – some lookup tables available
- Moderately complex modeling
- Moderately easy to use

4. <u>Hardware/System Requirements:</u>

- IBM-compatible personal computer
- GIS data handling capability

Model Name: ANSWERS

5. Geographic Information System (GIS) Integration:

- Linkage with GRASS under development

6. Commercial-off-the-shelf Integration:

- None

7. **Graphical User Interface (GUI) Configuration:**

- None

8. Ease of Use:

- Requires some familiarity with input parameters
- Fairly well documented
- Moderately difficult to use

APPENDIX E:
Erosion Model Fact Sheet and Evaluation

Model Name: CASC2D

Descriptive Criteria

1. Classification of Model:
- Physically-based, two-dimensional (distributed)
- Single-event based, with continuous simulation option
- Watershed scale
- Grid-cell representation of landscape
- Rainfall-runoff, channel routing and erosion/deposition

2. Applications of Model:
- Simulate multiple land-use scenarios and impacts on watershed response
- Simulate spatially distributed, non-uniform rainfall events
- Utilize weather radar to excite physical system and initiate rainfall-runoff
- Analyze effects of military land use activities, such as mechanized maneuver impacts

3. Known Limitations:
- Requires rainfall data and stream flow data for calibration and validation
- Requires sediment yield data for verification of model results
- Grid-cell size effects model outputs
- Model is sensitive to soil moisture and other soil hydraulic parameters

4. Assumptions:
- Soil profile and water content are uniform in vertical profile
- Grid-cells have homogeneous characteristics

5. **Agency Support and Points of Contact**:
Dr. Pierre Y. Julien, Dept. of Civil Engineering, Colorado State University
(970) 491-8450 E-mail:pierre@lance.colostate.edu

Dr. B. E. Johnson
Coastal and Hydraulics Laboratory
U.S. Army Waterways Experiment Station, Vicksburg, MS
(601)-634-3693 E-mail: billy.e.johnson@wes01.usace.army.mil

Dr. Fred Ogden
Dept. of Civil and Environmental Engineering
University of Connecticut, Storrs, CT
(860)-486-2771 E-mail: ogden@eng2.uconn.edu

Model Name: CASC2D

Evaluative Criteria

1. **<u>Data Requirements:</u>**

- Uniform or distributed rainfall data
- Digital Elevation Model (DEM) data w/specified grid-cell size
- Watershed boundary delineation
- Soil hydraulic parameters (hydraulic conductivity, soil moisture)
- Surface roughness
- K, C and P USLE parameters
- Channel network and characteristics

<u>2. Model Results:</u>

- Spatially disributed output maps and graphs of multiple parameters
- Event hydrographs
- Sediment discharge and yield

<u>3. Cost and Complexity:</u>

- Public domain
- Significant number of spatial data inputs
- Some calibration required for parameters
- Moderately difficult to setup and initialize model for simulation

<u>4. Hardware/System Requirements:</u>

- IBM-compatible personal computer or UNIX workstation
- 200 MHz processing speed or higher
- Microsoft Windows 95 or higher
- 32 MB RAM

Model Name: CASC2D

5. Geographic Information System (GIS) Integration:

- Fully integrated with GRASS GIS system
- Very compatible with raster-based GIS inputs

6. Commercial-off-the-shelf Integration:

- None

7. Graphical User Interface (GUI) Configuration:

- Integrated with the Watershed Modeling System (WMS) to facilitate data file input and output analysis
- Dynamic visualization routines during model simulation

8. Ease of Use:

- Difficult to set up model and initialize files
- Sensitive to time step and other initialization parameters
- Input is facilitated through WMS and GIS integration

APPENDIX E:
Erosion Model Fact Sheet and Evaluation

Model Name: CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems)

Descriptive Criteria

1. Classification of Model:
- Physically-based (deterministic)
- Lumped-parameter
- Single-event or continuous (preferred)
- Field scale only

2. Applications of Model:
- Determine effects of various agricultural practices on pollutant transport and sediment yield from fields
- Evaluate pollution potential of an agricultural field
- Downstream compliance for water quality
- Computes erosion and deposition
- Computes sheet, rill, inter-rill and channel erosion

3. Known Limitations:
- Limited to field scale sized areas

4. Assumptions:
- Pollutants are attracted to aggregates of clay-sized particles
- Physical system is characterized as a combination of flow planes, channels and impoundments
- Single land-use, homogeneous soils, spatially uniform rainfall

5. **Agency Support and Points of Contact**:

Dr. Wayne Skaggs, Professor
North Carolina State University
Dept. of Biological and Agricultural Engineering
Box 7625
Raleigh, NC 27695
(919) 515-6739
E-mail: skaggs@eos.ncsu.edu

Model Name: CREAMS

Evaluative Criteria

1. **Data Requirements:**

- Multiple inputs characterizing the physical system
- Soil hydraulic parameters
- Daily rainfall amounts
- Soil Conservation Service Curve Numbers (CN)
- Must be input by data card files

2. Model Results:

- Sensitive to parameter inputs for particular locations
- Sediment yield (tons)
- Enrichment ratio (soil surface area potential for pollution)

3. Cost and Complexity:

- Public domain
- Difficult to input parameters

4. Hardware/System Requirements:

- DOS or UNIX operating system
- Software written in FORTRAN

Model Name: CREAMS

5. Geographic Information System (GIS) Integration:

- None

6. Commercial-off-the-shelf Integration:

- None

7. **Graphical User Interface (GUI) Configuration:**

- None

8. Ease of Use:

- Very difficult to use
- Input files are done by cards (old computer technology)

APPENDIX E:
Erosion Model Fact Sheet and Evaluation

Model Name: Groundwater Loading Effects of Agricultural Management Systems (GLEAMS)

Descriptive Criteria

1. Classification of Model:
- Physically-based
- Field scale application
- Continuous simulation (annual or multi-annual)
- Lumped parameter (assumes homogeneous properties for each land unit)

2. Applications of Model:
- Evaluate agricultural management practices and their impacts on pollutant/pesticide loading both below the root zone and at the edge of fields, particularly nitrogen and phosphorous
- Estimates of historical pollutant loadings from animal waste disposal and other practices
- Fate and movement of agricultural chemicals (pesticides)
- Effects of farm level management decisions on water quality

3. Known Limitations:
- Field-scale, but can be applied to larger areas using GIS
- Does not update soil parameters during simulation
-

4. Assumptions:
- Modified USLE used for erosion and sediment loss/yield
- Homogeneous characteristics for field or land unit
- All channels in field are naturally eroded

5. **Agency Support and Points of Contact**:

USDA-ARS
Grassland Soil and Water Research Laboratory
808 E. Blackland Rd.
Temple, TX 76502
And
Texas Agriculture Experiment Station (TAES), Texas A&M University
Kevin King, Hydraulic Engineer (ARS)
(254) 770-6616

Model Name: GLEAMS

Evaluative Criteria

1. **Data Requirements:**

- Multiple parameter inputs for climate, hydrology, soils and agricultural practices
- 110 single parameters or groups of parameters
- Data intensive

2. **Model Results:**

- Annual or long-term averages of sediment loss, yield and pollutant loadings
- Tabular format

3. **Cost and Complexity:**

- Public domain software (Version 2.10) – executable program and data help files
- Multiple input parameters require knowledge of physical properties
- Moderately complex to develop initial input files

4. **Hardware/System Requirements:**

- Operates in DOS environment on IBM compatible personal computer
- FORTRAN source code for micro-computer version
- Printer with 132-character record length capability

5. **Geographic Information System (GIS) Integration:**

- Has been integrated with GRASS and IDRISI to derive land units for larger areas
- GRASS-GLEAMS interface under development
- ARC-INFO application developed for accessing database in GLEAMS input format

6. **Commercial-off-the-shelf Integration:**

- None

7. **Graphical User Interface (GUI) Configuration:**

- User help files and parameter data files available

8. **Ease of Use:**

- Difficult to determine values for multiple parameters
- Difficult to set-up and initialize
- Use is greatly facilitated by GIS

APPENDIX E:
Erosion Model Fact Sheet and Evaluation

Model Name: Modified Univeral Soil Loss Equation (MUSLE)

Descriptive Criteria

1. <u>Classification of Model:</u>

- Empirical
- Lumped parameter or distributed (grid-cell)
- Single-event
- Field or watershed scale

2. <u>Applications of Model</u>:

- Predict gross sediment yield (tons) from individual storm events

3. <u>Known Limitations</u>:

- Equation based upon limited watersheds (size and geographic distribution)
- Coefficients may need to be modified for other watersheds
- Does not calculate yield by individual particle class sizes (sand, silt, clay)

<u>4. Assumptions:</u>

- Sediment yield is hydrologically a function of volume of storm runoff and peak flow

5. <u>Agency Support and Points of Contact</u>:

USDA-ARS
National Sedimentation Laboratory
598 McElroy Drive
P. O. Box 1157
Oxford, MS 38655 - 1157
(601) 232-2900

Dr. Matt Romkens, Project Leader
(601) 232-2940
E-mail: romkens@sedlab.olemiss.edu

Model Name:

Evaluative Criteria

1. Data Requirements:

- Requires input values for 4 factors:
  K – Soil Erodibility
  LS – Slope Length and Steepness
  C – Cover and Cropping Management
  P – Conservation Support Practices
- Values obtained from tables, maps and nomographs
- Requires rainfall event data obtained from historical records and rainfall-runoff hydrographs

2. Model Results:

- Expressed as sediment yield (tons)
- Can be compared to actual measurements from sediment/stream gauges installed at point of interest

3. Cost and Complexity:

- Public domain
- Requires collection and calibration of rainfall data
- Low cost, moderate complexity

4. Hardware/System Requirements:

- No computer requirements
- Computations can be performed with a calculator

Model Name: Modified Universal Soil Loss Equation

5. **Geographic Information System (GIS) Integration:**

- None

6. **Commercial-off-the-shelf Integration:**

- None

7. **Graphical User Interface (GUI) Configuration:**

- None

8. **Ease of Use:**

- Moderately easy to use (if rainfall data and runoff relationships available)

APPENDIX E:
Erosion Model Fact Sheet and Evaluation

Model Name: Revised Universal Soil Loss Equation (RUSLE)

Descriptive Criteria

1. <u>Classification of Model:</u>

- Empirical (same as USLE model)
- Lumped parameter or distributed (grid-cell)
- Long-term average
- Field or watershed scale

2. <u>Applications of Model</u>:

- Estimate long-term average gross soil erosion on agricultural or range lands
- Improved version of USLE for regions in western United States
- Guide selection of conservation practices
- Evaluate reduction in soil loss from management practices
- Compare estimates to acceptable soil loss tolerances/thresholds
- Determine carrying capacity on military lands
- Identify areas susceptible to erosion or for rehabilitation

3. <u>Known Limitations</u>:

- Computes only gross average soil erosion from sheet, rill and inter-rill processes
- Does not estimate gully or channel erosion
- Does not estimate deposition
- Does not route sediment across the landscape or estimate sediment yield

4. **<u>Assumptions:</u>**

- Erosion is a function of five physical and land-use factors
- Spatial uniformity of all factors within specified land units

5. **<u>Agency Support and Points of Contact</u>**:

USDA-Agricultural Research Service (ARS)
National Sedimentation Laboratory
598 McElroy Drive
P. O. Box 1157
Oxford, MS 38655 - 1157
(601) 232-2900

George Foster, Project Leader
(601) 232-2940
E-mail: foster@sedlab.olemiss.edu

Model Name: Revised Universal Soil Loss Equation (RUSLE)

Evaluative Criteria

1. Data Requirements:

- Requires input values for five factors:
  - R – Rainfall-Runoff Erosivity
  - K – Soil Erodibility
  - LS – Slope Length and Steepness
  - C – Cover and Cropping Management
  - P – Conservation Support Practices
- Sub-factor values must be determined for several parameters using field-based data

2. Model Results:

- Generally expressed as A in tons/acre/year for given land unit
- A can be divided by soil loss tolerance (T) to compute Erosion Status (ES), which provides measure of acceptability for current land conditions

3. Cost and Complexity:

- Public domain
- Determination of sub-factor criteria and values requires user knowledge
- Parameter value selection facilitated by automated User' s Guide
- Low cost, moderate complexity

4. Hardware/System Requirements:

- Desktop personal computer (486 or higher processing speed)
- Software package runs in DOS or UNIX on IBM-compatible machines
- Requires 640 kilobytes of RAM memory

5. Geographic Information System (GIS) Integration:

- Can be spatially applied across large areas using GIS data layers
- Applicable to all raster GIS software
- Several examples of GIS integration on military lands

6. Commercial-off-the-shelf Integration:

- None

7. Graphical User Interface (GUI) Configuration:

- RUSLE Software program provides DOS-based interface for parameter value selection

8. Ease of Use:

- Sub-factor parameter values may be difficult to determine
- User software facilitates parameter selection
- Moderately easy to use for most geographic areas (where parameter values have been predetermined)

APPENDIX E:
Erosion Model Fact Sheet and Evaluation

Model Name: SIMulation of Water Erosion (SIMWE)

Descriptive Criteria

1. <u>Classification of Model:</u>
- Physically-based, process model
- Spatially-distributed (grid-cell, 2D) using Digital Elevation Model (DEM) data
- Field or watershed scale
- Single-storm events
- Uses stochastic (probabilistic) techniques to solve first-principle equations of continuity and momentum

2. <u>Applications of Model</u>:
- Computes distributed erosion and deposition across the landscape at grid-cell resolution
- Applicable for complex terrain with discontinuities in surface profiles
- Simulates steady state water flow across the surface
- Simulate effects of alternative land-use scenarios or conservation planning methods

3. <u>Known Limitations</u>:
- Requires high resolution DEM data
- Limited validation with field measurements
- Does not incorporate channel flow or transport (overland flow only)

4. <u>Assumptions:</u>
- Erosion is sediment capacity transport limited
- Monte Carlo stochastic methods used to solve continuity equations

5. **<u>Agency Support and Points of Contact</u>**:

Geographic Modeling and Systems Laboratory (GMSL)
Department of Geography
220 Davenport Hall
University of Illinois at Urbana-Champaign
Urbana, IL 61801

Helena Mitasova (GMSL)	Lubos Mitas
(217) 333-4735	(217) 244-1971
helena@gis.uiuc.edu	lmitas@ncsa.uiuc.edu

Model Name: SIMWE

Evaluative Criteria

1. Data Requirements:

- Digital Elevation Model (DEM) data
- Rainfall data (uniform rate)
- Surface roughness parameters
- Soil erodibility parameters (from USLE)
- Vegetation parameters (from USLE)

2. Model Results:

- Spatially distributed net erosion and deposition
- Rates of erosion and deposition
- Sediment flow rates
- Steady state water depths
- Dynamic visualization tools available to display results in 3-D

3. Cost and Complexity:

- Requires use of DEM data and GIS routines
- High resolution data requires high-end computer processing capability
- No User' s Manual currently available – to be developed

4. Hardware/System Requirements:

- High end (Pentium) processor for PC or workstation
- Color graphics capability

5. Geographic Information System (GIS) Integration:

- GIS routines in GRASS facilitate data inputs for terrain characterization

6. Commercial-off-the-shelf Integration:

- None

7. Graphical User Interface (GUI) Configuration:

- Compatible with dynamic visualization tools for 3-D depiction of processes and outputs

8. Ease of Use:

- Not yet developed for public domain use
- Requires some familiarity with DEM data and GIS routines
- Excellent visualization enhances understanding of model simulation and results

APPENDIX E:
Erosion Model Fact Sheet and Evaluation

Model Name: Universal Soil Loss Equation (USLE)

Descriptive Criteria

1. Classification of Model:
- Empirical
- Lumped parameter or distributed (grid-cell)
- Long-term average (steady state)
- Field or watershed scale

2. Applications of Model:
- Estimate long-term average (e.g., annual) gross soil erosion on agricultural lands
- Guide selection of conservation practices
- Evaluate reduction in soil loss from management practices
- Compare estimates to acceptable soil loss tolerances/thresholds
- Determine carrying capacity on military lands
- Identify erosion sensitive areas or areas for rehabilitation

3. Known Limitations:
- Computes only gross average soil erosion from sheet, rill and inter-rill processes
- Does not estimate gully or channel erosion
- Does not estimate deposition
- Does not estimate sediment yield
- Most applicable to agricultural areas in eastern half of United States

4. Assumptions:
- Erosion is a function of five physical and land-use factors
- Spatial and temporal uniformity of all factors within specified land units

5. **Agency Support and Points of Contact**:

Agricultural Research Service
U.S. Department of Agriculture
Dr. John M. Laflen
2150 Pammel Drive
Iowa State University
Ames, IA 50011
(515) 294-8327
E-mail: laflen@ecn.purdue.edu

Model Name: Universal Soil Loss Equation

Evaluative Criteria

1. Data Requirements:

- Requires input values for 5 factors:
  R – Rainfall-Runoff Erosivity
  K – Soil Erodibility
  LS – Slope Length and Steepness
  C – Cover and Cropping Management
  P – Conservation Support Practices

- Values readily obtained from tables, maps and nomographs

2. Model Results:

- Generally expressed as A in tons/acre/year for given land unit
- A can be divided by soil loss tolerance (T) to compute Erosion Status (ES), which provides measure of acceptability for current land conditions

3. Cost and Complexity:

- Public domain
- Selection of parameter values is straight-forward
- Low cost, low complexity

4. Hardware/System Requirements:

- No computer requirements
- Can be calculated manually or with a calculator

5. **<u>Geographic Information System (GIS) Integration:</u>**

- Can be spatially applied across large areas using GIS data layers
- Basic GIS layers (elevation, vegetation, soil) can be reclassified to obtain values for input parameters
- Applicable to all raster GIS software
- Several examples of GIS integration on military lands

6. **Commercial-off-the-shelf Integration:**

- None

7. **Graphical User Interface (GUI) Configuration:**

- None

8. **Ease of Use:**

- Simple multiplication of factors
- Parameter values readily obtained from published sources
- Very easy to use

APPENDIX D:
Erosion Model Fact Sheet and Evaluation

Model Name: Unit Stream Power-based Erosion/Deposition (USPED) Model

Descriptive Criteria

1. Classification of Model:

- Empirical (modification to USLE)
- Unit stream power theory used to compute sediment transport capacity
- Grid-cell based (using Digital Elevation Model data)
- Routing of sediment using terrain/slope algorithms
- Field or watershed scale

2. Applications of Model:

- Computes distributed long-term average soil erosion and deposition
- Predict areas of high soil loss and sediment deposition
- Planning tool to assess changes in land use scenarios
- Has been applied to several military installations

3. Known Limitations:

- Most suitable for complex terrain (non-uniform hill slopes)
- Highly dependent upon resolution of digital elevation data
- Has undergone limited validation of results

4. Assumptions:

- Must compute directional derivatives of unit stream power index using terrain slope
- Elevation data is accurate representation of landscape

5. **Agency Support and Points of Contact:**

Geographic Modeling and Systems Laboratory (GMSL)
Department of Geography
220 Davenport Hall
University of Illinois at Urbana-Champaign
Urbana, IL 61801

Helena Mitasova (GMSL)	Lubos Mitas
(217) 333-4735	(217) 244-1971
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Model Name: USPED

Evaluative Criteria

1. Data Requirements:

- USLE/RUSLE factors for R, K, C and P
- GIS data layers for factors
- High resolution Digital Elevation Model (DEM) data

2. Model Results:

- Net average erosion and deposition at grid-cell scale
- Maps of distributed erosion and deposition

3. Cost and Complexity:

- Requires DEM data
- Some familiarity with GIS routines required
- Factor values readily available from USLE data tables
- Still in research application mode – not fully fielded
- Relatively simple to use

4. Hardware/System Requirements:

- GIS system (workstation) required

Model Name: USPED

5. Geographic Information System (GIS) Integration:

- Required GIS to model terrain
- GRASS GIS routines available for DEM smoothing and reinterpolation

6. Commercial-off-the-shelf Integration:

- None

7. Graphical User Interface (GUI) Configuration:

- Several dynamic visualization tools have been integrated to enhance model results analysis in 3-D

8. Ease of Use:

- User's Manual under development
- Requires some experience with DEM and GIS routines
- Moderately difficult to use

APPENDIX D:
Erosion Model Fact Sheet and Evaluation

Model Name: Water Erosion Prediction Project (WEPP)

Descriptive Criteria

1. Classification of Model:
- Physical, process-based
- Distributed parameter
- Continuous simulation (single event optional)
- Field (hill slope) or watershed scale
- Represents current state of available erosion prediction technologies

2. Applications of Model:
- Calculate spatial and temporal distribution of erosion and deposition across a landscape
- Applicable to a wide variety crop land and range land settings
- Used as a conservation planning tool to determine where specific conservation/soil erosion mitigation strategies should be implemented
- Determine the effects and management thresholds associated with various land uses and land use intensities
- Compute sediment yield for a field or watershed

3. Known Limitations:
- Only applicable to areas where Hortonian overland flow dominates (e.g., rainfall rates exceed infiltration capacity, subsurface flows are negligible)

4. Assumptions:
- Landscape characterized as overland flow planes, hill slopes, channels and impoundments
- Kinematic wave approximation of continuity equations

5. **Agency Support and Points of Contact**:
USDA- ARS
The National Soil Tilth Laboratory
2150 Pammel Drive, ISU
Ames, Iowa 50011
(515) 294-8327
John Laflen, WEPP Leader E-mail: laflen@ecn.purdue.edu
USDA-ARS
National Soil Erosion Research Laboratory (NSERL)
1196 Bldg. SOIL
West Lafayette, IN 47907-1196
Phone: (317) 494-8673

Model Name: WEPP

Evaluative Criteria

1. Data Requirements:

- Climate/weather input files (Climate Generator)
- Soil infiltration parameters
- Overland flow hydraulic parameters (surface roughness, slope length, soil texture)
- Percolation and soil evaporation parameters
- Plant growth and residue characteristics
- Cropping practices
- Soil properties (roughness, bulk density, hydraulic conductivity)
- Channel and impoundment characteristics

2. Model Results:

- Sediment yield from a field or watershed
- Spatial and temporal distribution of erosion and deposition

3. Cost and Complexity:

- Public domain
- Model and data files available from Internet
- Multiple input files
- Significant learning curve for user
- Very complex modeling and difficult to use initially

4. Hardware/System Requirements:

- MS DOS 5.0 or higher operating system environment
- IBM-compatible personal computer with minimum of 16 MB RAM

5. Geographic Information System (GIS) Integration:

- None

6. Commercial-off-the-shelf Integration:

- None

7. Graphical User Interface (GUI) Configuration:

- WEPP Version 95.7 User Interface module for input files and databases
- Climate generator
- Two graphical output modes can be selected – 1) distribution of erosion and deposition on a slope, 2) plotting up to 6 landscape variables

8. Ease of Use:

- Requires some training to use effectively
- Moderately difficult to use

LAST PAGE OF DRAFT REPORT

APPENDIX C: MS EXCEL FILE

APPENDIX D: MS EXCEL FILE