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Introduction

This chapter presents a synthesis of current computer modeling tools that are, or could be, adopted for use in evaluating the cumulative watershed effects of fuel management. The chapter focuses on runoff, soil erosion and slope stability predictive tools. Readers should refer to chapters on soil erosion and stability for more detailed information on the physical processes involved.

All cumulative watershed effects (CWE) tools are models of natural processes. A “model” is a mathematical or qualitative representation of nature. It includes an understanding of the analysis area including the identification of the important features and processes, such as topography, soil properties, vegetation and climate, as well as their interactions. Models provide answers to the question, “what watershed changes are anticipated as a result of proposed fuel management activities?”

GETTING STARTED

The first step in modeling cumulative watershed effects is to **define the problem(s)** that need to be analyzed. Chapter 14 outlines the qualitative and quantitative questions to be answered in a watershed analysis. Briefly, the manager must define:

- Values of concern (water resource protection, human welfare, wildlife issues, etc.);
- Predictions needed (peak runoff rates, water yield, upland erosion rates, stream sediment delivery rates, etc.);
- The scale of the analysis (e.g. project, watershed, landscape);
- The environmental constraints (e.g. vegetation, climate, topography);

- The temporal context (single event, average annual, return period analysis);
- Requirements of local, state or federal regulatory agencies;
- Organizational constraints (due dates, available resources, computer capabilities, level of analytical and computer skills).

Once the problem is clearly defined, the watershed manager should review current data availability, such as soil surveys, GIS layers, air photo libraries, weather records, past watershed disturbance history and stream flow records for conditions similar to those of the watersheds of concern. If it has not already been done as part of other analyses, the manager should conduct a field survey and develop a set of field notes. Typically, slope lengths and gradients, vegetation conditions, and relevant soil properties (texture, depth, evidence of waterlogging or erosion, water repellency, etc.) are noted. During the field survey, the manager should note current conditions and evidence of past activities contributing to these conditions, such as compaction, or evidence of stunted or unusually lush vegetation, and if appropriate, evidence of past mass movement. A useful reference for this process is Ecosystem Analysis at the Watershed Scale (EAWS): Federal Guidelines for Watershed Analysis (Regional Interagency Executive Committee, 1996).

Impacts of concern

Generally, two public values dominate cumulative watershed effects analyses: impacts on aquatic ecosystems (Chapter 11), and impacts on human resources (e.g. water supplies, structures in flood plains or on alluvial fans, recreation resources).

In some cases, the values at risk or level of public impact may influence the selection of a more or a less sophisticated modeling approach. For example, a high visibility watershed on the edge of a major city may require greater analysis than would a remote watershed adjacent to a wilderness area because the potential risk to offsite values is much greater.

What needs to be predicted

Before choosing a modeling tool, the manager first must identify the specific predictions that are necessary. Typical predictions include upland erosion rates, watershed sediment

delivery rates, peak runoff rates and related attributes such as duration and time to peak, and annual water yields. Predictions may be for average values, or probabilities of exceeding a given value. It is desirable, but not always possible, to use the same model to predict both runoff and erosion. Currently few tools predict both. The WATSED suite of models predicts both, but the erosion and sediment delivery is not linked to the runoff. The WEPP model predicts both runoff and erosion, and the latest version of WEPP (Version 6.2) includes lateral groundwater flow in watershed runoff (Dun et al., 2006). The SWAT and AGNPS models predict both runoff and erosion, but do not link the two on the hillslope. The runoff is used to route eroded sediment through the stream system with these models.

Attributes of Tools

Scales and Frameworks for Analysis

Within the context of this chapter, watershed impacts of management can be evaluated on a project or hillslope scale, or a small (under 100 ha), medium (100 to 500 ha), or large (over 500 ha) watershed scale (Table 1).

For hillslope scale, onsite surveys coupled with soils and contour maps generally provide adequate information for analysis. Analyses are typically carried out with hillslope tools, hillslope by hillslope, and results are compiled in summary tables. Air photos may be particularly beneficial for mass wasting and road erosion analysis at this scale. For mass wasting, photos before and after significant mass wasting events are often compared, and the features of failure sites are linked to other site conditions, such as slope steepness, upslope area, and disturbance history.

For larger area analysis, geographic information systems (GISes) generally are the most effective means to compile, integrate, and synthesize data required to describe the watershed and to run sediment, water and stability modeling tools. Although models vary in their data needs, managers often may access and import publicly available datasets in their GIS (e.g. USGS digital elevations, NRCS soils data, and climate files), generate derivative datasets from elevation models (specifically gradient and aspect data), and delineate watersheds with integrated drainage channels networks. Watershed delineation is especially valuable when first starting a project or for smaller watershed

Table 1. Scales of analysis and dominant processes

| Scale: | Small | Medium | Large |
|-----------------------------------|---|--|--|
| Area | < 100 ha (250 acres) | 100 – 500 ha (250 acres – 2 sq mi) | Over 500 ha (Over 2 sq mi) |
| Dominant Runoff Processes | Surface runoff from rainfall excess or saturated overland flow | Surface and shallow lateral flow | Shallow lateral flow and groundwater processes |
| Dominant Sediment Processes | Rill and interrill erosion; landslides | Rill, ephemeral gully, and gully erosion; landslides and debris flows | Channel erosion and transport processes, large deep-seated landslides |
| Dominant Disturbances | Wildfire; prescribed fire or road surface erosion | Wildfire, stream crossing failure, large runoff events | Large runoff events |

modeling projects where the limited scale of the analysis doesn't warrant use of the more detailed and labor-intensive modeling systems.

Sources of Sediment

There are four sources of sediment associated with fuel management (Table 2): surface erosion from disturbed forest hillsides, runoff and erosion from forest road networks, sediment delivered from mass wasting processes, and sediment from channel bed and bank erosion. Hillside disturbances tend to be ephemeral, lasting one to three years before the hillslope is recovered, whereas roads tend to be a chronic source of sediment, generating sediment every year. Landslides generally generate sediment only during prolonged wet spells when forest hillslopes become saturated, or unusually high runoff-initiated debris flows in upland swales. Hillside and road erosion processes are described in Chapter 5, and channel and mass wasting processes in Chapter 6.

Hillside sources of sediment associated with fuel management are further complicated by wildfire effects. High severity wildfires tend to generate much more sediment than do lower severity prescribed fires or wildfires. The impacts of fuel management on fire severity and frequency are discussed in Chapter 3. In order to fully evaluate the watershed impacts of fuel treatment activities, the manager also must consider the potential for erosion from wildfire. Treatment erosion rates are generally much lower, but will likely occur more frequently than wildfire events. Hence the manager will

Table 2. Sources of sediment in a watershed analysis

| Source | Frequency of Occurrence | Relative Erosion Rate |
|--------------------------------------|-------------------------|-----------------------|
| Hillslopes following wildfire | 20 to 200 years | 100 |
| Landslides | 5 to 10 years | 5 |
| Hillslopes following prescribed fire | 5 to 20 years | 10 |
| Hillsides following thinning | 10 to 40 years | 1 |
| Road networks | Yearly | 2-5 |
| Stream channels | 5 to 10 years | 5-90 |

need to carry out a series of analyses comparing erosion from wildfire at the current forest condition to erosion from fuel treatment and erosion from a wildfire following fuel treatment (Table 2).

Sediment production from both roads and hillslopes is largely dependent on the weather. Wet years will generate more runoff and sediment. If there is a wet year following a hillside treatment, there is a risk of a high level of erosion, whereas there will likely be little to no erosion following fuel treatment in an average to dry year. Roads tend to generate sediment even in dry years, but at a much lower rate.

Routing of sediment through a stream system is also highly weather dependent, with little sediment being routed most years, and most sediment being routed during years with major runoff or flood events. Thus the stream channel serves as a temporary sediment bank, storing sediment from a disturbance for several years to decades as sediment from upland areas is gradually routed through the system. Many of the nation's forests are in areas with steep relief and major differences in climate. Higher elevations tend to have higher precipitation, but a greater amount of that precipitation tends to be snow. Snow melt rates generally are much lower than rainfall rates, and so tend to generate less surface runoff and erosion. Snow hydrology processes also are influenced by the presence of trees, with mature forests holding significant amounts of snow in the canopy, thinned openings and fringes of open areas adjacent to forests being areas of snow accumulation, and large open areas tending to be areas with less snow accumulation. Thus the severity of wildfire, the ephemeral nature of hillside disturbances, the chronic nature of road sediments, the impacts of elevation on climate, the effects of forests on snow hydrology, and the infrequent routing of stream sediments are major challenges to modeling the watershed impacts of fuel management activities.

The ability of various tools to model these attributes will be evaluated in the remainder of this chapter.

Hydrologic Considerations

In addition to consideration of the importance of scale and sources of sediment, there are a number of hydrologic considerations to consider when selecting cumulative watershed effects tools. The first is the nature of the climate. The hydrology may be driven predominantly by thunderstorms, as in the southwestern or eastern U.S., frontal storms as common along the west coast, snowmelt as common in the higher elevations of the Rocky Mountains, or rain-on-snow events as common in the interior Northwest. If climates are dominated by snowmelt, hydrologic tools developed for rainfall dominated climates will not function well. Among these tools are the Universal Soil Loss Equation and NRCS Curve Number technologies.

Hydrologic analyses of large area flood events may include the development of runoff hydrographs. Specialist tools are available for such analyses, but are generally best done by other agencies, such as the Corp of Engineers, or consultants who have had experience with these tools.

Another hydrologic consideration may be the seasonal or long term distribution of runoff. For example, if there is concern about erosion following a chemical brush control operation in July, the manager may wish to estimate the runoff and erosion risk during a single month, and will need a model that has such a capability. Long term changes in runoff characteristics may be of interest if a long term fuel management plan is envisioned. Such long term changes may have impacts on changing channel morphology if annual peak flows are increased significantly.

It is always a good practice to compare predicted runoff and erosion rates and amounts with values observed in the area. Are the predicted values reasonable compared to monitoring or research studies that have been done in the past for similar conditions?

Environmental Constraints

Some of the currently available predictive models were developed by agricultural researchers focusing on agricultural conditions. This is particularly true for the USLE-based models and the NRCS Curve Number technology. Some of these tools have been

further developed for forest conditions, such as the USLE for southeastern forests (Dissmeyer and Foster, 1981 and 1985). Some tools may not be stable for some common forest conditions, like steep slopes.

If the model is empirically-based, managers need to be careful if adopting a model that was developed for different climates, different vegetations, or different geologic conditions. For example, the WATSED technologies were originally developed with data from Central Idaho. Methods have since been developed to adapt this tool for other areas in the Northern Rockies, but not for forests elsewhere. The Washington Forest Practices (1997) has extended some of the WATSED technology for application in Washington State.

Local Constraints

In some cases, state or local regulations may dictate the model that is selected. For example, the USLE and RUSLE models are considered inappropriate for rangeland conditions (National Cattleman's Beef Assoc., 2003). Numerous city and county codes require that peak runoff rates be predicted by a specific method, generally the Rational method or Curve Number method, or for some specific design storm. There may be guidelines developed by the Forest Service or other agencies for runoff curves based on past experience or observations that can be applied locally, although the manager may wish to adjust the values based on site characteristics. In these cases, the manager will need to provide credible information to support any adjustments made to such guidelines.

Organizational Constraints

As new models or new applications of existing models become available, the manager will likely want to compare the new tools to existing methods or observations to be confident that the model is providing reasonable predictions. Some of these new models may still be under development, in which case the managers may need to work closely with the developers in research organizations or universities to make sure that the model is correctly applied, and the results properly interpreted. As newer models begin to receive more widespread application and acceptance, such collaboration is less critical.

One of the first considerations may be the skills, training and experience of the manager. Has he/she developed the skills on a given tool, or is some training necessary? Is such training available?

Depending on the manager's level of computer expertise, the model interface may be crucial. Models requiring high levels of GIS skills may be acceptable to some specialists, whereas others may have limited GIS modeling experience. Some tools are now available online, but the assumptions associated with the simplified interfaces may not provide the manager with the flexibility needed for some analyses. Some managers may not have a high speed Internet connection, which may limit the use of these models.

The Forest Service provides limited options for a manager for computer hardware. Will the tool run on the manager's current computer system, or on currently available systems? This may be particularly challenging with some of the more sophisticated GIS tools with large computer and disk storage requirements.

Other considerations

There are a number of other attributes that a manager may wish to consider when selecting a tool. Is the model under consideration widely used and accepted by the academic, legal, and environmental community? For example, one of the reasons for a legal decision against the Forest Service was that the model used for the watershed analysis did not predict any variability associated with the estimated means. Another consideration is the availability of the model.

Obtaining the model may be a problem. Is it online or does it require installation from a disk or CD? If it is on a CD, does the manager have the latest version? A few models require registration to proceed with immediate download, and less commonly some tool developers require that the user first register and then wait to be sent a download access password. One tool reviewed, SedMODL2, requests a reasonably modest fee to cover the cost of burning and shipping software on a CD. Once downloaded, many applications are installed through common installation wizards with few if any special configuration requirements. Some installations may require the manager to get permission to install the software. Some models which fall into the research domain, e.g. DHSVM and CASC2D, require the user to compile code and install

special system emulators. These installations may require assistance from computer support specialists.

In order to use a tool, a database must be built. This can be one of the biggest challenges in operating a given tool. Are data readily available to run the model, either from a Forest Service database, or a public source? For example, some of the more sophisticated hydrologic tools require detailed information on soil depths and properties, and properties of bedrock, which may not be readily available. In some cases, a database may need to be reformatted, or certain fields extracted, to obtain the necessary information to run the model.

The input file builder may be as straight forward as choosing from selections on drop-down lists as with the FS WEPP online interface. Many tools, especially those designed as distributed, process-based systems, generally running in a GIS, require large volumes of data from multiple data sources. There is a trend to build interfaces, like GeoWEPP, that guide the user to electronic libraries of public data in order to simplify data acquisition. This approach is especially valuable where users are building models for watersheds for which location-specific data are incomplete or not available. Alternatively, wizards which interactively guide users through each step of the model building process (e.g. DHSVM) provide a framework to ensure that all components are in place for a model run.

The outputs from a given tool should provide the information the manager requires. Some models developed for non-forested conditions may not give the information that the user desires, or may not give it in a satisfactory format. Output files containing more information than a user requires, require additional analysis time in reformatting or synthesizing results.

The documentation is an extremely important part of any tool. In some cases, documentation is readily available online, and includes many illustrations and examples. In other cases, documentation is inadequate, and managers should lobby model developers to provide improved, appropriate documentation if the software seems to be well suited to the manager's needs.

The availability of technical assistance is often important, particularly with more complex models. Some technical assistance may be built into the model, with help

screens incorporated into the interface. In some cases, local or regional experts may be available to provide such assistance. In others, specialists in other agencies, such as the NRCS, Bureau of Reclamation, Army Corp of Engineers, university specialists, federal researchers, or consultants may be available to provide the necessary assistance.

Currently, no single watershed tool meets all these criteria. Managers will have to select from a series of tools those that best meet their needs and organization's abilities. Also, not every CWE analysis requires or merits the complexity possible with some of the currently available tools. New tools with new features and capabilities continue to be developed, and a career as a watershed manager will be one of continued learning and evaluation.

Categories of Models

Cumulative effects models can be categorized into lumped or distributed, conceptual or physically-based, or deterministic or stochastic.

Lumped vs. Distributed Models

Some models assume that an entire watershed is behaving as a single unit, and assume that all of the inputs can be lumped into a single set of variables to describe the entire watershed. The outputs are generated as runoff and/or sediment yield at the watershed outlet. The Rational Peak runoff method and the Curve Number runoff and peak flow models are common examples of lumped models (Ward and Elliot, 1995).

Distributed models allow the user to vary model inputs and site characteristics in space. There can also be interactions between cells, modeling the "runon-runoff" processes common on disturbed forest hillslopes. Hot spots for sediment sources can be identified to focus management, as can environmentally benign areas where management can be more flexible. The GeoWEPP tool is an example of a distributed model using hillslope polygons, and the DHSVM model an example of a distributed model using grids. Many models use combinations of lumping and distributing. For example, soils may be distributed by grid, hillslope topography by polygon, and climate may be lumped for the entire area.

Lumped vs. Distributed Models

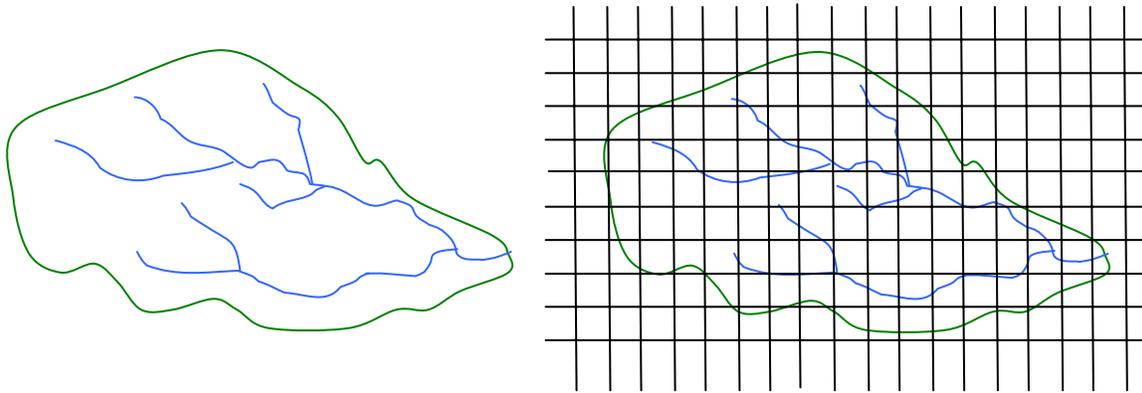


Figure 1. Lumped vs. distributed model. The “lumped” watershed on the left has a single value to describe soil, vegetation, and climate conditions in the entire watershed, whereas the “distributed” watershed on the right may have different values for each grid cell, or in some cases, individual hillslope polygons.

Some form of distributed modeling is essential for estimating sediment detachment and delivery. The data needs, however, may be great, and there may not be adequate information available to describe variations in soil properties including soil depth and surface residue cover. Distributed models are also difficult to calibrate as there are many cells that can be adjusted in order to obtain a reasonable prediction.

A current effort in distributed modeling is to incorporate road networks and their impacts into watershed analysis. This technology has the potential to include the impacts of roads as sources of sediment and runoff, and also to evaluate the effects of roads on fish passage.

Conceptual vs. Physically-based Models

Conceptual models are based on the physical processes that drive the watershed responses. There is often a heavy reliance on empirical data in these models. They tend to be lumped or only partially distributed. Because of their reliance on observed data, they should not be extrapolated to conditions beyond those that were used in their development. Examples of conceptual models are the Universal Soil Loss Equation (USLE) and the Curve Number technology.

Physically-based models use equations to represent the physical processes that describe the system. These processes may include:

- vegetation growth and senescence,
- impacts of plant community on evapotranspiration, rainfall interception, and soil stability,
- soil water balance and subsurface water movement,
- sediment detachment, transport, and deposition by raindrop splash, shallow overland flow, concentrated rill flow, gullyng, and channel processes, and
- mass failure and debris flow processes.

Input parameters for these models generally are variables that can be measured or derived from measurements of physical or biological processes, such as topography, runoff rates, biomass amounts, and surface cover. Physically-based models generally are more academically acceptable, and generally can be applied to areas other than where the original data that were used for model development were collected. Data needs, however, may exceed what is readily available in areas beyond the sites where the models were originally developed. Examples of physically-based models include the Water Erosion Prediction Project (WEPP) and the DHSVM model.

Deterministic vs. Stochastic Models

A deterministic model will always give the same outputs for the same set of input variables. A stochastic model generally has at least one probabilistic input and will give a result that describes the risk or likelihood of a given prediction. Examples of stochastic models include the climate generator for the WEPP model, or the return period analyses associated with peak runoff events from the Curve Number technology.

Lump-based Runoff Tools

There are two runoff prediction technologies that are generally lump-based: the Rational Peak Flow prediction, and the NRCS Curve Number runoff volume and peak flow prediction (Ward and Elliot, 1995). These technologies are frequently incorporated into other higher level hydrologic models and so a description of each will be given.

Rational Peak Flow

The Rational Peak Flow prediction method is (Schwab et al., 1993):

$$q = 0.0028 C i A \quad (1)$$

| | | | |
|-------|-----|---|---|
| where | q | = | design peak runoff rate (m ³ /s) |
| | C | = | runoff coefficient |
| | i | = | rainfall intensity for the design return period and for a duration equal to the “time of concentration” of the watershed (mm/h) |
| | A | = | area of watershed (ha) |

The runoff coefficient C is a function of vegetation and rainfall intensity (Schwab et al., 1993), and for forests ranges from 0.02 for a rainfall intensity of 25 mm/h to 0.15 for an intensity of 200 mm/h. Users should check with local NRCS or state agency users to determine local values. Some typical values are presented in Table 3. The time of concentration for a given watershed is often estimated by the Kirpich equation (Schwab et al., 1993):

$$T_c = 0.0195 L^{0.77} S^{-0.385} \quad (2)$$

| | | | |
|-------|-------|---|--|
| where | T_c | = | time of concentration (min.) |
| | L | = | distance from watershed divide to watershed outlet (m) |
| | S | = | watershed gradient (m/m) |

When applying the Rational method, the time of concentration is frequently a relatively small number, typically less than 1 hour. To estimate the peak intensity for the desired duration storm, the NOAA Atlas is often consulted (Bonnin et al., 2003). There are Internet sites becoming available that aid the user in determining the intensities of these shorter duration storms (e.g. <http://hdsc.nws.noaa.gov/hdsc/pfds/>). The Rational method is best suited to watersheds under about two square miles. For larger watersheds, other runoff methods are recommended.

Table 3. Typical values for Runoff Coefficient *C* in Rational Equation and descriptions of hydrologic soil groups (Engel et al., 2004)

| Land Use, Crop and Management | Hydrologic Soil Group | | | |
|--|-----------------------|----|----|----|
| | A | B | C | D |
| Cultivated with crop rotations | | | | |
| Row Crops, poor management | 55 | 65 | 70 | 75 |
| Row Crops, conservation mgmt | 50 | 55 | 65 | 70 |
| Small Grains, poor mgmt | 35 | 40 | 45 | 50 |
| Small Grains, conservation mgmt | 20 | 22 | 25 | 30 |
| Meadow | 30 | 35 | 40 | 45 |
| Pasture, permanent with moderate grazing | 10 | 20 | 25 | 30 |
| Woods, permanent, mature, no grazing | 06 | 13 | 16 | 20 |
| Urban residential | | | | |
| 30 percent of area impervious | 30 | 40 | 45 | 50 |
| 70 percent of area impervious | 50 | 60 | 70 | 80 |

Hydrologic Soil Group Descriptions:

A -- Well-drained sand and gravel; high permeability.

B -- Moderate to well-drained; moderately fine to moderately coarse texture; moderate permeability.

C -- Poor to moderately well drained; moderately fine to fine texture; slow permeability.

D -- Poorly drained, clay soils with high swelling potential, permanent high water table, claypan, or shallow soils over nearly impervious layer(s).

Curve Number Runoff Volume and Peak Flow

The Curve Number runoff technology can be used to predict both runoff volume and peak runoff rate (Fangmeier et al., 2005). The Curve Number technology was initially developed from a network of small watersheds covering the entire U.S. Most of these watersheds were in agricultural areas, so data for rangelands and forests was limited. The Soil Conservation Service (SCS), predecessor of the USDA Natural Resource

Conservation Service (NRCS), played a leading role in the development of the research technology (SCS, 1986).

Estimating Total Storm Runoff with Curve Number

The first step in both total runoff and peak flow is to estimate the total runoff depth Q . The Curve Number method uses two foundation equations to estimate Q :

$$Q = \frac{(I - 0.2S)^2}{I + 0.8S} \quad (3)$$

and

$$S = U \left(\frac{1000}{CN} \right) - 10 \quad (4)$$

| | | | |
|-------|------|---|--|
| where | Q | = | runoff depth (mm or in.) |
| | I | = | storm depth (mm or in.) |
| | S | = | maximum potential difference between rainfall and runoff, sometimes referred to as surface storage (mm or in.) |
| | U | = | unit conversion (25.4 mm for metric, 1 in. for English units) |
| | CN | = | NRCS Curve Number for soil and cover condition (see Table 4) |

In watersheds with mixed cover, an area weighted average is generally employed to estimate CN . (Fangmeier et al., 2006).

Estimating Peak Runoff Rates with Curve Number

From the runoff amount Q , peak runoff can be estimated using the methodology developed by the SCS (1986). This manual method has since been incorporated into numerous public and private software programs, several of which are discussed later in this chapter. One method that can be readily adapted to local conditions for applying the

Curve Number technology (Schwab et al., 1996) is to first estimate the time of concentration with the empirical relationship:

Table 4. Some typical curve number values for forested conditions (Goodrich et al., 1005)

| Cover type | Ground Cover (%) | Hydrologic Soil Group (see table 3 for descriptions) | | | |
|----------------------------------|---------------------|---|----|----|----|
| | | A | B | C | D |
| Bare | 0 | 77 | 86 | 91 | 94 |
| Fallow | 5 | 76 | 85 | 90 | 93 |
| Shrubland | 25 | 63 | 77 | 85 | 88 |
| Grassland/Herbacious | 25 | 49 | 69 | 79 | 84 |
| <u>Undisturbed Forests</u> | | | | | |
| Deciduous & Mixed | 50 | 55 | 55 | 75 | 80 |
| Evergreen | 50 | 45 | 66 | 77 | 83 |
| <u>Forest, Low severity fire</u> | | | | | |
| Deciduous & Mixed | 43 | 59 | 60 | 78 | 82 |
| Evergreen | 43 | 49 | 71 | 80 | 85 |
| Shrubland | 21 | 65 | 79 | 86 | 89 |
| <u>Moderate severity fire</u> | | | | | |
| Deciduous & Mixed | 34 | 65 | 65 | 80 | 85 |
| Evergreen | 34 | 55 | 76 | 82 | 88 |
| Shrubland | 17 | 68 | 82 | 88 | 90 |
| <u>High severity fire</u> | | | | | |
| Deciduous & Mixed | 25 | 70 | 71 | 83 | 87 |
| Evergreen | 25 | 60 | 82 | 85 | 90 |
| Shrubland | 12 | 73 | 88 | 91 | 91 |

$$tc = \frac{L^{0.8} \left(\frac{1000}{CN} - 9 \right)^{0.7}}{C s^{0.5}} \quad (5)$$

where tc = time of concentration (hours)
 L = length of watershed (m or ft)

CN = NRCS Curve Number

C = constant (441 for metric, 1140 for English units)

Other methods commonly used to estimate time of concentration generally require the user to estimate the runoff velocity overland and in channels, and the lengths and slopes of the overland area and the channel. Numerous public and proprietary software programs assist in this calculation. Once the time of concentration is estimated, the NRCS has developed a series of curves to estimate peak runoff rate as a function of total storm runoff. There are numerous software programs that have incorporated these curves into the software itself. One relationship between time of concentration, peak runoff rate and total runoff is (Schwab et al., 1996):

$$\log(q) = 2.51 - 0.7 \log(tc) - 0.15 (\log(tc))^2 + 0.071 (\log(tc))^3 \quad (6)$$

where q is peak runoff rate in cubic feet per second per square mile of watershed area per inch of storm runoff. For metric units, multiply this number by 0.0043 to get cubic meters per second per square km of watershed area per mm of storm runoff.

Limitations of the Curve Number Method

Recent observations of runoff volumes and rates from forests before and after wildfire have shown that the runoff volume appears to change little, the time of concentration is generally in the magnitude of days for undisturbed forests and minutes to hours for forests following wildfire (Canfield et al., 2005). One analysis suggested that the Curve Number method was not appropriate for forest or rangeland watersheds, and managers would be better off estimating runoff as a fraction of precipitation based on field observations (Springer and Hawkins, 2005). For thinned or prescribed fire conditions, the time of concentration is likely to be longer than would normally be estimated for overland flow as most of the runoff is from subsurface lateral flow. In the past, watershed managers often reduced the curve number to reduce peak flow rate estimates from forests compared to non-forested areas rather than increase the time of concentration values. This area warrants further research.

USLE-Based Tools

In the period from 1945 until 1965, a method of estimating soil erosion based on statistical analyses of field plot data from small plots located in many states was developed, which resulted in the Universal Soil Loss Equation (Wischmeier and Smith, 1978). The USLE was parameterized for some forest hillslope conditions for intensive forest management practices in the southeastern U.S. (Dissmeyer and Foster, 1981). A revised version of the USLE (RUSLE) was later developed as a computer application (Renard et al., 1997). When predicting erosion, RUSLE allows more detailed consideration of management practices, rangeland, seasonal variation in soil properties and topography than does the USLE. In 2005, RUSLE2 was released as an application for the PC Windows operating system (Foster and Toy, 2003). The basic form of the USLE/RUSLE models is:

$$A = R K L S C P \quad (7)$$

| | | | |
|-------|-----|---|--|
| where | A | = | average annual soil loss (tons/acre/year or tons/acre/y) |
| | R | = | rainfall and runoff erosivity factor for a geographic location |
| | K | = | soil erodibility factor |
| | L | = | slope length factor |
| | S | = | slope steepness factor |
| | C | = | cover management factor |
| | P | = | conservation practice factor |

The A , R , and K factors are different for English units and metric units. To avoid confusion, this chapter will use all English units. Metric units for these three variables can be found in Fangmeier et al. (2006). The other factors have no units. The L and S factors are used in some other models, including the WATSED cumulative effects model (USFS, 1990).

USLE Factors

R Factor

The R factor is based on the rainfall intensity and energy for a given location (Renard et al., 1997). Figure 2 is the “isoerodent” map for the western U.S. in English units, providing an estimate of the R factor. The west coast and eastern U.S. maps, as well as other methods for estimating R , can be found in Renard et al. (1997). The R factor is best suited for climates where runoff and erosion is dominated by large storms, and not snow melt.

K Factor

The K factor generally is estimated from soil properties. The equation developed for agricultural soils is:

$$K = \frac{[2.1 \times 10^{-4}(12 - OM)M^{1.14} + 3.25(s - 2) + 2.5(p - 3)]}{100} \quad (8)$$

| | | | |
|-------|------|---|--|
| where | K | = | Soil erodibility (English units) |
| | OM | = | Organic matter (percent) |
| | M | = | Particle size fraction in soil between 0.001 and 0.1 mm, or percent silt plus percent fine sand (percent) |
| | s | = | Subsoil structure class: 1 – very fine granular 2 – fine granular 3 – med or coarse granular 4 – blocky, platy or massive |
| | p | = | Permeability class: 1 – rapid 2 – moderate to rapid 3 – moderate 4 – slow to moderate 5 – slow 5 – very slow |

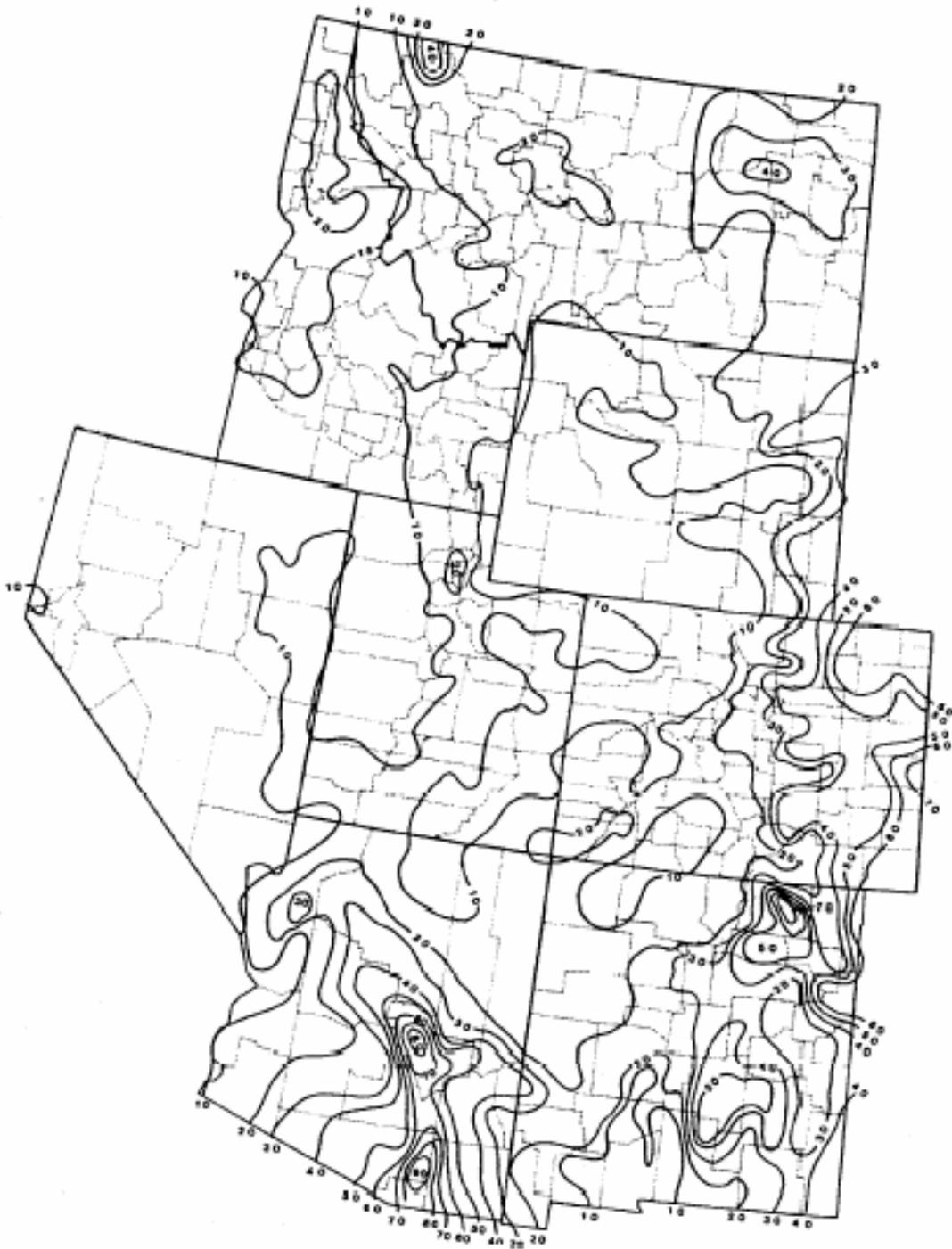


Figure 2. Isoerodent map of R factor values for the western U.S. (Renard et al., 1997)

In forest environments, soil erodibility has been found to be a function not only of soil properties, as assumed in the USLE technologies, but also the vegetation condition.

Vegetation condition in the USLE technologies is addressed in the C factor. Because of this interaction, users should be cautious when applying the USLE to forest conditions to ensure that compatible C and K factors are used. It is not advisable to obtain a K factor estimate from one source and a C factor estimate from another.

L and S Factors

The topographic factors, L and S , adjust the predicted erosion rates to give greater erosion rates on longer and/or steeper slopes, when compared to the USLE “standard” slope steepness of 9 percent and length of 22 m. These factors address the increasing rill erosion rates as more runoff accumulates with longer slopes, and the hydraulic shear in runoff increases on steeper slopes. The methods for estimating L and S factors were modified in RUSLE, and it is advisable to use the RUSLE/RUSLE2 method for estimating these topographic factors rather than the USLE method.

The RUSLE L factor can be calculated as

$$L = \left(\frac{l}{72.6} \right)^b \quad (9)$$

where L = slope length factor

l = slope length in ft

b = dimensionless exponent

For conditions where rill and interrill erosion are about equal on a 9 percent, 22-m long slope

$$b = \frac{\sin \theta}{\sin \theta + 0.269 (\sin \theta)^{0.8} + 0.05} \quad (10)$$

where θ = field slope angle = $\tan^{-1}(S)$

S = slope steepness (ft/ft)

For most conditions where rill erosion is greater than interrill erosion (such as soils with a large silt or fine sand content), b should be increased up to 75 percent. Where rill erosion is less than interrill erosion (on short slopes or low gradient soils with ridge

tillage, or soils generating little runoff), b should be decreased as much as 50 percent. RUSLE2 makes this calculation internally.

The S factor depends on the length and steepness category of the slope. For slopes less than 15 ft long

$$S = 3.0 (\sin\theta)^{0.8} + 0.56 \quad (11a)$$

For slopes greater than 15 ft long and steepness less than 9 percent

$$S = 10.8 \sin\theta + 0.03 \quad (11b)$$

For slopes greater than 15 ft long and steepness greater than or equal to 9 percent

$$S = 16.8 \sin\theta - 0.50 \quad (11c)$$

For the USLE, the slope length is measured from the point where soil erosion begins (usually near the top of the ridge) to the outlet channel or a point downslope where deposition begins. RUSLE also considers non-uniform concave or convex slopes. RUSLE2 considers the entire hillslope, including areas of deposition.

C Factor

The C factor is the cover management factor, sometimes referred to as the cropping factor. This factor was originally developed to allow users to specify the cover condition for every two-week period in a rotation. A rotation may last for several years, and an extended calculation is necessary (Ward and Elliot, 1995). The RUSLE technologies frequently add subfactors to the estimate of C , further complicating this critical calculation. This methodology was developed in order to consider the surface condition during any two week period in relation to the climate during that same period. In forest and rangeland conditions, however, it is much more appropriate to think of the term as cover management, and to consider C as constant for the entire year. Runoff and soil erosion are dominated by ground cover, and when using USLE technology, it is important to make sure the correct term is selected. Wischmeier and Smith (1978) developed a set of C factors for forest and rangeland conditions that were a function of canopy height and cover, and ground cover. For forest management activities in the southeastern U.S., Dissmeyer and Foster (1981) expanded the Wischmeier set to include site preparation tillage practices common in the Southeast. As tillage generally is not

Table 5. USLE *C* factors for forest conditions (Wischmeier and Smith, 1978)

| Percent of area covered by canopy of trees and undergrowth | Percent of area covered by duff at least 50 mm (2 in.) | <i>C</i> Factor |
|---|---|-----------------|
| 100 – 75 | 100 – 90 | 0.0001 – 0.001 |
| 70 – 45 | 85 – 70 | 0.002 – 0.004 |
| 40 – 20 | 70 – 40 | 0.003 – 0.009 |

Table 6. USLE *C* factors for burning (Wischmeier and Smith, 1978)

| Ground Cover (Percent) | Soil Condition | |
|---------------------------|-------------------|--------------|
| | Excellent to Good | Fair to Poor |
| 10 | 0.23 – 0.24 | 0.26 – 0.36 |
| 20 | 0.19 | 0.21 – 0.27 |
| 40 | 0.14 | 0.15 – 0.17 |
| 60 | 0.08 – 0.09 | 0.10 – 0.11 |
| 80 | 0.04 – 0.05 | 0.05 – 0.06 |

associated with fuel management, but ground cover disturbance is, the Wischmeier and Smith (1978) *C* factors are presented in Table 5 for forested conditions, and Table 6 for burning. The RUSLE1 technology can calculate a *C* factor internally from a fixed cover condition, and a similar “permanent vegetation” option is available in RUSLE2.

Recent Variations on the USLE

In the RUSLE2 technology, sediment delivery across buffers is predicted as a function of runoff estimated by the Curve Number method. The *C* factor in RUSLE is based on a weighted average of vegetation cover throughout a growing cycle, and takes into account prior land use, canopy cover, surface cover, surface roughness, and soil water content.

Some variations of the USLE have been developed to make erosion estimates for individual storms. This may be done by considering the *R* factor for an individual storm, or with the MUSLE technology described below.

The factors in RUSLE generally have been developed from and validated by research studies on tilled agricultural soils. There has been some rangeland research with

RUSLE that has developed *C* factors based on surface cover, and which give reasonable erosion predictions for rangeland hillslopes (Elliot, 2001). Applications of RUSLE to disturbed forest hillsides and roads has been limited.

MUSLE

The modified USLE (MUSLE) replaces the *R* factor with the product of rainfall amount and runoff amount to predict soil erosion for a single storm. Most applications of the MUSLE technology use Curve Number to estimate the runoff. The other USLE factors (*K*, *L*, *S*, *C*, and *P*) remain unchanged for MUSLE applications. Because MUSLE is relatively easy to program, it has been incorporated into numerous soil erosion models in recent years. Its limitations are similar to those of the two technologies that drive it.

AGNPS, AnnAGNPS: Agricultural Non-Point Source

The AGNPS erosion model is a distributed parameter tool for moderate to small sized agricultural watersheds. AGNPS and its newer iteration, AnnAGNPS, are well established, actively supported, production-ready tools. AGNPS modeled a single event, simulating a pulse of outputs from an individual storm. AnnAGNPS extends the modeling into continuous, annual outputs. The system is driven by three core technologies: erosion modeled by RUSLE, hydrology by the SCS Curve Number method, and sediment/contaminant transport using CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems). Additional AGNPS modules include a channel network evolution model (CCHEID) and stream corridor model (CONCEPTS), components which emphasize the condition of water within stream channels. Snowmelt is not modeled. Both versions run within GIS shells and are challenging to apply. AGNPS is fundamentally an agricultural tool with limited expected utility in forested mountainous environments.

SWAT: Soil and Water Assessment Tool

The SWAT modeling tool predicts the impact of land management practices upon water, sediment, and chemical yields in large, complex watersheds. SWAT is a distributed model with linked modules using both process and empirical logic. Key climate and

vegetation simulations are process driven while the core hydrology and sediment modeling includes use of an enhanced SCS Curve Number approach to estimate runoff volume, and USLE and MUSLE technologies to estimate soil erosion. SWAT has a long development history, strong institutional commitment, and a substantial publishing record based upon worldwide application. Comprehensive documentation and ease of access, download, and installation permit users to efficiently load and execute the SWAT tool. SWATAV launches through a stable ArcView 3.x interface. A forthcoming release is expected to function in Arc 8-9.x. Although originally developed for agricultural applications, the developers have demonstrated a commitment to improving mountain hydrology including implementing advances in topographically driven snowmelt processes.

SWAT is a user-friendly, if complex, modeling system which could be a valuable tool for CWE analysis. The existing system requires addition of more refined forest practice definitions. One of the big challenges when applying SWAT to forested watersheds is that SWAT currently estimates all runoff with Curve Number technology. Generally, users will calibrate the Curve Number for SWAT for a given watershed from observations from a nearby watershed. As most forest runoff is dominated by lateral flow, and many by snowmelt hydrology, this will be a major limitation to applying SWAT for steep forested watersheds.

Rule-Based Tools

R1-WATSED and derivatives – Water and Sediment Yields

The USDA Forest Service, Region 1 WATSED program is a cumulative watershed effects tool designed to model watershed response to multiple management activities and disturbances over time. It estimates and tracks changes in annual water and sediment yields, mean monthly flows, delivery of total sediment to a defined stream reach, and relative annual changes to sediment delivery within the stream network. WATSED models vegetation and hydrologic recovery, past and assumed future activities,

background erosion from hillslopes, and surface and mass erosion from activities including roads.

WATSED is an empirical model driven by locally derived and calibrated coefficients, and recovery response curves. The model assigns lumped parameters to each land area modeled (landtype units within watersheds) using a linked table structure. Currently there is no GIS interface, but prototypes are under development. Changes to vegetation cover are modeled and expressed as Equivalent Clearcut Areas (ECAs). A Windows interface guides the user through all stages of the model application. A tool to link WATSED with Region 1 databases is near completion. WATSED spawned several derivatives, each customized for conditions within a given national forest, including LoloSED, NezSED, and BoiSED for Lolo, Nez Perce, and Boise National Forests, respectively.

State Variants of WATSED

Several states, Washington and Idaho in particular, have developed state-specific lookup tables to apply to the WATSED technology. Examples are Washington Forest Practices and Idaho Cumulative Watershed Effects tools. A computer application of the Washington Forest Practices called WARSEM has been developed for Washington State.

SEDMODL2

SEDMODL2 is a GIS-based road erosion and sediment delivery model designed to identify road segments with a high potential for delivering sediment to streams. The model is based on empirical relationships developed by the Washington State Forest Practices manual. SEDMODL2 estimates annual background sediment and sediment production by individual road segments, locates road/stream intersections, and estimates delivery of road sediment to streams. Developers provide core climate data for several western states and optional base geology data for Washington, Oregon, and Idaho. For most of the variables which define each road segment, users may choose default values or define attributes with locally available data. SEDMODL2 has an interactive Windows interface and well-written documentation.

Delta-Q and FOREST (FOREst Erosion Simulation Tools)

Delta-Q and FOREST are a suite of Cumulative Watershed Effects tools that will be completed in 2007. A partial version that does not include in-stream routing is currently available for download. These tools are intended to provide managers with estimates of relative cumulative changes in forested watershed responses due to multiple management activities over time. Development of these tools is in part driven by the intent to move beyond the basic Equivalent Clearcut Area (ECA) approach commonly used within USDA Forest Service Region 5. The general structure uses GIS-based, 2-dimensional spatial representations as an organizing shell to calculate cumulative impacts and watershed recovery across multiple treatment areas. Delta-Q uses an empirical approach driven by curves developed from 26 paired watershed datasets to model changes to water yields from disturbed forested areas. FOREST predicts changes to sediment regimes from hillslopes and roads in three integrated tools that calculate sediment production, delivery and, eventually, in-stream routing. Hillslope calculations are based on user-provided data defining hillslope erosion response and recovery rates. Hillslope delivery to streams uses database files derived using the WEPP model; the database files are included in the FOREST distribution package and instructions are included so that the user also can use WEPP to customize a file for his or her own region. Sediment changes from roads are calculated using one of three user-chosen methods: one of two empirical equations or via look-up tables provided with the core model or provided by the user. The look-up tables may incorporate local knowledge or may be developed using an outside program such as WEPP:Road. Road delivery to streams is a simple “cookie-cutter” routine that allows all sediment within a certain distance of the stream to be delivered based on an empirical relationship between percent connectivity and mean annual precipitation (Coe, 2006).

Delta-Q and FOREST provide easy to use, straight-forward, and simple approaches to assessing relative cumulative change. The user must adjust basic response settings for local conditions and knowledge. The empirical approach of Delta-Q could limit applicability where the area of concern is distant from one of the 26 experimental sites and where there is insufficient basis to determine which experimental site most closely matches the area of concern. In FOREST, model calculations for activity areas

and roads are not linked. The spatial interface provides a convenient and efficient means to assess possible changes.

WARMF

The WARMF model was developed under the sponsorship of the Electric Power Research Institute to aid in TMDL analysis. It is a lumped parameter GIS model that uses USLE-based erosion prediction, and Curve Number technology for surface runoff. WARMF includes groundwater flow and estimates nutrient and bacterial loads. Because of its lumped nature, it does not lend itself to project scale management. It also has the limitations of the USLE and Curve Number technologies for forest conditions. It is one of the few models available that addresses nutrients and bacterial loads.

(<http://www.epa.gov/ATHENS/wwqtsc/html/warmf.html>)

Physically-Based Tools

Physically-based models predict runoff and/or soil erosion from equations that generally describe the processes that are occurring, such as infiltration, runoff, subsurface water flow, and soil detachment, transport, and deposition.

WEPP

The Water Erosion Prediction Project (WEPP) model is an interagency physically-based hydrology and soil erosion model (Flanagan and Livingston, 1995). It can be run for individual hillslopes, or for small watershed (up to about 2 sq mi.). The WEPP technology includes a Windows interface, a GIS interface, several online interfaces, and a stand alone executable program with text file input and output files that can be incorporated into other applications. Most applications of WEPP include databases of soils, climates, and vegetation descriptors.

CLIGEN

The CLIGEN weather generator and database of statistics from more than 2600 weather stations is part of the WEPP technology. Within the WEPP Windows interface is a feature to allow users to alter the statistics for the climate they have selected. Additional

climate data can be downloaded from the Rock:Clime web site which has a 4-km (2.5-mile) grid of monthly precipitation values for the continental U.S. The Rock:Clime interface also allows a user to modify temperature and precipitation data if local records are available.

WEPP Hillslope Version

The Hillslope version of WEPP predicts runoff, onsite erosion, and offsite sediment delivery for a hillslope. Interfaces have been developed to run this version from either Windows or over the Internet.

WEPP Windows

The WEPP Windows hillslope interface predicts erosion from single hillslopes, or from lists of hillslopes in project mode. Users may alter any of the hundreds of input variables required to run WEPP. This is a highly flexible interface, but users seldom have all of the inputs necessary to build input files. Templates are included in the interface for a wide range of forest conditions, including those needed for cumulative watershed effects of fuel management.

Internet Suite of Tools

Both the Forest Service and the Agricultural Research Service have developed Internet interfaces for the WEPP model. The Forest Service suite of interfaces (FS WEPP) is available for forested hillslope applications. They include WEPP:Road, WEPP:Road Batch, Disturbed WEPP, ERMiT, and WEPP FuMe (Elliot, 2004) (<http://forest.moscowfsl.wsu.edu/fsw pepp/>).

WEPP FuMe is specifically designed to support fuel management activities. It carries out twelve runs from a single set of inputs, and provides tables and a narrative of the results of those runs in the context of fuel management activities.

WEPP Watershed Models

WEPP Windows contains a watershed option. WEPP Watershed combines hillslopes, channels, and instream structures such as check dams, which it calls “impoundments.”

The current version predicts peak flow using a variation of the rational equation, which limits the size of a watershed to under one or two square miles.

The runoff predicted from the WEPP technology was based on surface runoff only, but the 2006 release incorporated subsurface lateral flow from the hillslopes into the stream channels. Well over 90 percent of the runoff from many steep forested watersheds is from shallow lateral flow or groundwater flow (Conroy et al., 2006; Covert, 2003; Dun et al., 2006; Zhang, 2005).

WEPP Watershed Windows Interface

The WEPP Watershed Windows interface is difficult to use but it allows the user to alter all of the variables necessary to run a watershed analysis, including properties of channels and impoundments. Building a watershed within WEPP Windows is an arduous task for large landscapes. It is best suited to modeling engineered sites, such as ski slopes, parking lots, or agricultural terraces, where dimensions and grades of hillslope planes and channels generally are well defined. For natural watersheds, users should use the GeoWEPP technology to build watersheds.

GeoWEPP

GeoWEPP is a GIS wizard which builds files to run WEPP Watershed on either ArcView or Arc 9.x platforms. Topographic analysis tools build the slope files for both hillslope polygons and channels from a DEM. The same soil, climate, and management databases that are used by WEPP Windows are used by GeoWEPP. Generally, input files are created, edited, and tested in WEPP Windows so they can be accessed by GeoWEPP.

Currently, Forest Service users may need to do some GIS data manipulation to format the DEM files, but work is ongoing to make this unnecessary. GeoWEPP can also read text files that describe the soil or vegetation in each grid cell, which may enhance its application for interpreting GIS maps of fuel management activities within a watershed.

DHSVM: Distributed Hydrology, Soil, and Vegetation Model

DHSVM is a distributed, physically-based hydrologic tool that operates in a GIS. Recently it has incorporated sediment detachment and transport as a function of surface runoff. It was developed at the University of Washington in conjunction with the USDA

Table 7. Summary of currently available watershed management tools.

| Tool Name | Predicts | Empirical / Process | Status |
|------------------|-------------------------------|---------------------|------------------|
| AGNPS | Runoff and Erosion | Emp | Production |
| Delta-Q / FOREST | Runoff and Erosion | Emp | Production/ Beta |
| DHSVM | Runoff | Process | Research |
| Rational | Runoff | Emp | Production |
| SCS Curve Number | Runoff | Emp | Production |
| SedMODL2 | Runoff and Erosion from roads | Emp | Production |
| SWAT | Runoff and Erosion | Emp | Production |
| WARMF | Runoff and Erosion | Emp | Production |
| WATSED | Runoff and Erosion | Emp | Production |
| WEPP | Runoff and Erosion | Process | Production |

Forest Service, Pacific Northwest Research Station. DHSVM was specifically designed to address complex hydrologic interactions and variability due to climate and topography. DHSVM models hydrologic processes within vegetation; surface and subsurface flow; management activities; road networks incorporated into hillslope and stream channel connections; saturation induced mass wasting and redistribution; hillslope erosion driven by saturation excess runoff and rainfall and leaf drip detachment; road surface erosion including integration with road side ditches and culverts; sediment delivery to stream networks; routing through channels; water discharge accounting for contributions from overland and subsurface flows; and sediment deposition, storage and transport within stream channels based upon channel geometry, water flux, and particle sizes of delivered debris.

DHSVM is primarily a research tool relying on an understanding of GIS command line code. A data assembly wizard assists with preparing input information. With further development, DHSVM could provide support for a comprehensive CWE

analysis. Access further information on-line at:
<http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/>.

Summary of Watershed Tools

Table 7 provides a summary of currently available tools that have been applied to watershed analysis. All of these tools can be run within a GIS framework, some more easily than others. Most tools are based on the empirical USLE/Curve Number technologies, with the exception of WEPP and DHSVM. The main differences among the empirical models is the spatial detail allowed in the hillslope description, and how the sediment is routed through the stream system. There are also differences in the availability of databases for forest cumulative watershed effects, and other support that is available for the model. Currently, WEPP has the best database for modeling cumulative watershed effects. The empirical technologies have somewhat easier interfaces to use, but do not correctly model the dominant forest hydrologic and erosion processes.

Other Modeling Tools Available

These systems are considered separately because they are, to date, experimental research tools, because they are commercial, or because, while they are developed and popular among the water and sediment modeling community, intended uses vary significantly from CWE applications. With many of these models, additional training or consultants are needed before applying the model.

Hydrologic Engineering Centers (HEC) Tools

The HEC tools were developed by the Army Corps of Engineers. HEC-HMS, Hydrologic Modeling System, simulates rainfall-runoff responses and flow accumulation and routing through watersheds. HEC-RAS, River Analysis System, models open channel flow through watershed scale stream and river networks. Future versions of HEC-RAS are expected to model sediment and contaminant transport. HEC-ResSim models flow regimes in regulated river systems. In general, the HEC-series tools are thoroughly documented with well-written user manuals. For completed HEC modules, ArcView 3.x interfaces provide step-by-step assistance with model build, execution, data

analysis, and graphic display. Through partnership with The Nature Conservancy, HEC-EFM, Ecological Functions Model, proposes to model ecological responses to alternative flow regimes. For more information on HEC tools access <http://www.hec.usace.army.mil>

TauDEM: Terrain Analysis Using Digital Elevation Models

The TauDEM toolset incorporates multiple DEM and terrain analysis functions. Terrain data are extracted from a DEM through interactive dropdown menus. Specialized terrain analysis functions include calculation of slope/area ratio, flow distance to streams, downslope influence, decaying accumulation, concentration limited and transported limits accumulation, and upslope dependence. TauDEM was developed by engineers at Utah State University. It is available as a toolbar plugin to both Environmental Systems Research Institute, Inc. (ESRI) ArcGIS (8.x and 9.0) and MapWindow, a free GIS data viewer developed at Utah State University. For software and information access <http://hydrology.neng.usu.edu/taudem/>. This site provides a download link and detailed documentation of TauDEM operation, theory, interpretation, and supporting literature.

RSAM: Road Sediment Analysis Model – under development

RSAM is a suite of GIS-based watershed tools that are under development. RSAM tools are designed to analyze the impacts of forest road networks on stream systems relative to sediment production, mass wasting risk, and fish passage barriers (Prasad et al., 2005). These tools are products of a project between Utah State University and the USDA Forest Service. The watershed model workspace is built within the ESRI ArcMap GIS using TauDEM. The model offers three specific capabilities: modeling sediment delivery to streams from forest road erosion using a modified USLE-derived approach; road terrain stability through extension of the Stability Index Mapping (SINMAP) functions; and impacts of fish passage barriers on habitat continuity (development of this last capability pending). For further information on the status of this tool contact Dr. Charlie Luce (cluce@fs.fed.us).

GTARS-W: Generalized Sediment Transport for Alluvial Rivers and Watersheds – under development

GTARS-W, the newest version to the Bureau of Reclamation GSTAR river engineering modeling series, is intended to add hillslope erosion and sediment transport processes to existing channel/river/reservoir routing schemes. It will use the unit stream power approach and dynamic simulation of suspended sediment concentrations to account for sheet, rill, and gully erosion. It is a physically-based, process-oriented, semi-distributed model built with arbitrarily sized and shaped Watershed Elements. Watershed Element cells may be adjusted to most effectively account for variations within the modeled watershed. GSTAR is currently under development. Existing GSTAR tools and other information are available at <http://www.usbr.gov/pmts/sediment/model/gstars/>.

Basin1 Extension for ArcView 3.x

The Basin1 extension delineates drainage basins with descriptive and associated channel networks described by either the Strahler or Shreve stream-ordering methods. The application requires the Spatial Analyst extension. The resulting stream network and drainage areas are not integrated. Each drainage area or basin is created as an individual file. If the goal is to build a watershed model divided into sub-watersheds, the user must delineate and merge sub-basins into a master analysis unit. Basin1 was developed by the Department of Water Affairs & Forestry, Pretoria, South Africa and is publicly available for download at the ESRI ArcScripts site.

Archydro: GIS for Water Resources

Archydro was designed as an organizing framework with which to generate integrated watershed systems linked to relational databases which then port data to and from watershed modeling tools. It functions as a toolbar plugin in ESRI Arc 8-9.x. Required terrain data are extracted from a DEM. Channel segments of network system are linked to drainage areas through node architecture. Nodes associate all watershed metrics into a personal geodatabase structure. XML programming language then links the geodatabase to external modeling systems. Archydro was developed by the Center for Research in Water Resources (CRWR) of the University of Texas at Austin, and ESRI. Software and

documentation are available at <http://www.crwr.utexas.edu/giswr/>. This site includes access to general documentation including a Portable Document Format version of ArcHydro text, a training exercise, links to software download and on-line support.

CASC2D-Sed: Cascade 2 Dimensional Sediment Model

CASC2D-Sed is a research-grade, process-driven, single-event, distributed, raster-based tool. It models hillslope hydrology and erosion and delivery and routing of water and sediment through a channel network. Sediment delivery is a function of predicted runoff. This data-intensive tool was originally developed at Colorado State University with funding by the Army Research Office (ARO) for the Army Corps of Engineers. Earlier versions were written as extensions to the public-domain GRASS GIS systems. The most recent developments are run user-compiled, command line code. Further information may be obtained from http://www.engr.colostate.edu/~pierre/ce_old/Projects/CASC2D-Rosalia/Index.htm

USGS MMS: Modular Modeling System

The Modular Modeling System (MSS) is a framework to build custom modeling solutions from a library of compatible, open source modeling modules. MMS was developed by the US Geological Survey through the Precipitation-Runoff Modeling Project. It is based on the premise that there is no universal modeling solution and by extension that each modeling problem requires a unique set of integrated modeling tools. From the developers' perspective, "This concept requires that we change the question of 'Which model is most appropriate for a specific set of criteria?' to 'What combination of process conceptualizations is most appropriate?'" (Leavesley et al., 2002). The open source modular approach allows updated or new modeling components to be added as hydrologic modeling technology advances.

The MMS platform currently runs in the Windows environment via the Cygwin Unix emulator (Windows and Linux shells are in development to replace the need for the Cygwin interface). Through the core interface the user chooses and couples individual modules and runs the integrated system. MMS tools are accessed to construct a GIS-

based watershed system, integrate required datasets, run parameter estimation procedures, create user defined simulations and analysis, conduct sensitivity analysis, export results for visualization in a GIS, and other functions. While management applications are mentioned, the complexity of the system suggests practical application will be challenging. (http://www.brr.cr.usgs.gov/projects/SW_precip_runoff/mms/)

SIAM: Sediment Impact Analysis Method

The Bureau of Reclamation developed SIAM as a spatially explicit tool to conduct a geomorphic evaluation of sediment dynamics and sediment movement through drainage networks. Sediments are routed through a channel network from source to sink through simulation of bedload and washload transport processes and associated changes to channel morphology. SIAM functions over short- and long-term timeframes to model potential channel adjustments to changes in flow and sediment regimes. The tool is expected to be applied in large basins with multiple tributaries to analyze stability trends, link sediment sources to downstream impacts, develop and evaluate management options, and to integrate management and analysis of sediments with other watershed goals. Currently in beta release, SIAM is expected to be incorporated into future releases of the Army Corps of Engineers HEC-RAS software. More information is available at <http://www.usbr.gov/pmts/sediment/model/siam>.

Methods of Slope Stability Analysis

Introduction

Landslides may be considered at a variety of spatial scales during analyses of the watershed effects of fuels management. At one extreme, the general hazard of slope failure is studied over a large, relatively homogeneous portion of a landscape. In this case, the analysis applies to the entire polygon and predicts only general susceptibility to landslides, rather than the likelihood of a particular mass failure. At the other extreme, the stability of a particular portion of a single hillslope may be investigated and analyzed intensely. The techniques of stability analysis change considerably over this range of scales. Traditionally, stability analyses concern evaluating the likelihood that a slide or

slides will happen. However, regardless of the spatial scale of investigation, there are several other important considerations beyond simple landslide occurrence that can affect the choice of stability analysis method. Is it necessary to appraise also the size, specific location, timing, frequency, velocity, or travel distance of slides? Do predictions need to be made in absolute or relative terms?

The following is a brief review of a complex subject and all those unfamiliar with this subject are strongly encouraged to seek technical assistance from experts within and outside the agency before attempting to analyze the mass stability of hillslopes.

Analysis of individual landslides or single hillslopes

This subject is a well-established core component of the field of geotechnical engineering. In general terms, an analysis is made by calculating both the available static forces resisting sliding and the static forces causing sliding. The ratio of resisting to sliding forces describes the “Factor of Safety” (FOS) against sliding and theoretically a slope will not fail if the $FOS > 1$, i.e. the shear strength available is greater than the strength required to just barely maintain stability. This method is sometimes called a limit equilibrium slope stability analysis as it concerns conditions in the slope when the balance of forces is just at the limit of equilibrium.

soil

rock

$$FOS = \frac{c_s + c_r + (\gamma z \cos^2 \beta - \gamma_w m_z \cos^2 \beta) \tan \phi}{\gamma z \sin \beta \cos \beta} \quad (12)$$

where

- c_s = soil cohesion
- c_r = root cohesion
- γ = soil unit weight = ρg
where ρ = soil bulk density and g = gravitational acceleration
- γ_w = water unit weight
- m_z = vertical distance from the failure surface to the groundwater surface
- z = vertical soil depth
- β = slope angle
- ϕ = angle of shearing resistance of soil (soil “friction angle”)

Of these variables, the FOS is most sensitive to c_s , c_r , m_z , z , and β and effort should be concentrated on their definition while reasonable assumptions can often be made about the others without introducing undue uncertainty. Equation 12 is the basis for almost all mechanistic techniques of slope stability analysis that are currently used at any scale of investigation of mountainous hillslopes.

Fuels management potentially affects two parameters in Equation 12: c_r and m_z . The first is due to changes in the three-dimensional spacing, size, and strength of roots in a hillslope. The second is a result of changes in the groundwater conditions that may arise from variations in the water use by vegetation on the slope. These effects are discussed in Chapter 6.

Very simple analyses like that above can be computed quickly on a hand-held calculator. However, computerized analyses also have been developed to evaluate many more complicated slope conditions including those with non-planar failure surfaces, confined groundwater situations with excess pore water pressure, variable soil properties, pseudo-static forces from earthquakes, and surcharge loads from concentrated masses on the ground surface. When the assumptions of an infinite slope are relaxed, automated searches can be made for the minimum FOS for any size of landslide on a slope profile.

These techniques are discussed in great detail in many references such as Graham (1984), Nash (1987) and Duncan (1996).

Equation 12 can be used to predict in absolute terms the FOS of an individual slide at a particular location. As we will see later, it also can be implemented in a GIS format to map the spatial variability in FOS, either in an absolute or relative sense. If this analysis predicts a landslide at a particular location, it also can be used to evaluate the timing and frequency of such sliding, although this is not easy. Examination of Equation 12 shows that the only parameter that naturally varies strongly in time is the pore water pressure (through the variable m_z). This parameter normally fluctuates in response to temporal patterns of precipitation, snow-melt, or rain-on-snow. Changes in m_z in response to variations in moisture input to the hillslope either can be established through empirical correlations or by groundwater modeling. If the temporal pattern of other parameters, such as the root cohesion, is known, then again the timing and frequency of sliding can be objectively evaluated by repeating the analysis of Equation 12 for those changed conditions.

In its two-dimensional form, the simple limit equilibrium stability analysis does not predict landslide size: the analyzed element can be of any length along the slope profile. Slide size is quite important as it strongly influences other results, such as the slide travel distance and the amount of debris likely to be carried into a stream. If the infinite slope analysis is extended to three dimensions, then size can be estimated. Currently the great majority of stability analyses, even computer-based techniques, are two-dimensional, although there is now a moderate amount of research to develop three-dimensional analysis techniques. This is an issue of particular importance to fuels management as the reinforcement from tree roots is truly three-dimensional (cross slope and up/down slope as well as vertical). A change in a forest canopy that increases or reduces root reinforcement logically should affect not only the location, but the size of landslides.

If the infinite slope equation is cast in terms of a balance of total forces, it is possible to predict the lateral dimensions of a slide according to:

$$\frac{\gamma z \sin \beta \cos \beta - c_b - (\gamma z - \gamma_w m_z) \cos^2 \beta \tan \phi}{z((w + q)c_l + 2\overline{\sigma'_{ho}} \tan \phi)} = \frac{1}{w} \quad (13)$$

- where
- c_b = soil + root cohesion on the base of the slide
 - c_l = soil + root cohesion on the sides and head of the slide
 - w = the width of the slide (cross slope width)
 - q = the ratio of landslide width/downslope length
 - $\overline{\sigma'_{ho}}$ = depth-averaged frictional resistance on the sides of the slides
 - $= \frac{K_o}{2} (\gamma z - \gamma_w m_z) \cos \phi$
 - K_o = at rest earth pressure coefficient = $1 - \sin \phi$

Equation 13 is a rederivation of Equation 16 from Casadei and Dietrich (2003) that includes the lateral soil friction as well as lateral soil and root cohesion.

While predictions of the FOS of some specific location, or the width of a slide at a site, are relatively straight forward, estimates of slide velocity and travel distance are difficult. This is an area of very active research, but the prevailing advice at the present time is to assume that shallow slides which mobilize into debris flows will move at rates on the order of meters/second to tens of meters/second. In the Oregon Coast Ranges it has been found empirically that they tend to stop when the slope angle in the runout zone declines to $<3.5^\circ$ or when a tributary transporting a debris flow intersects a receiving channel at an angle $>70^\circ$ (Benda and Cundy, 1990).

Slide hazard assessment over broad areas

Landslide inventories

It is commonly observed that landslides often happen in places where they have occurred in the past. Thus, a relatively simple inventory of past landslides may have some predictive power about future events. Slide inventories over broad areas are normally conducted by stereoscopic examination of airphotos with some limited ground verification of results. These inventories often simply identify slide locations, but occasionally they are expanded to also map landslide types, sizes, and runout distances. If

airphotos of multiple ages are available, the time of occurrence and recent state of activity can sometimes be estimated. Inventories can be quantified by calculating the spatial variation in landslide density to produce what is called a landslide isopleth map (Wright et al., 1974). The advantage of photo-based inventories is that they are relatively inexpensive and can survey large areas rather quickly. It is very difficult, however, to determine the size of landslides from airphotos and often little is learned of the site conditions that caused sliding. Furthermore, if current or future slope conditions are outside those represented by the photographic record of landslides, erroneous predictions of existing or future hazard may be produced. Still, this is an extremely useful technique and normally a slide inventory map is developed, even if other analysis techniques are employed, and the inventory data are used to calibrate, and, one hopes, validate, the other methods.

GIS multi-factor overlay approaches

An extension of the simple inventory is to also map the variables that could reasonably affect slope stability, i.e. the parameters in Equation 12. Then in a GIS environment these parameter maps are overlaid and examined for combinations of parameters that exist at mapped landslide sites. By identifying the same combinations of parameters at other locations, a map of future landslide susceptibility or hazard is produced that is based on correlations of slope, aspect, vegetation, geologic materials and geologic structure with past landslides. In more sophisticated models, the correlations are evaluated statistically using discriminant analyses, logistic regression, or Bayesian belief models (e.g. Carrara et al., 1991; Dai and Lee, 2001; Gritzner, 2001; Gorsevski et al, 2006b)

These GIS-based analyses are relatively simple to conduct, if suitable factor maps are available for the pertinent parameters. However, again the assumption is that future conditions will be within the range represented by the existing record of landslides. This supposition may be in error if the regional climate changes dramatically, or if management or fires, etc., significantly change the vegetation canopy and thus the root cohesion. GIS analyses also do not directly predict landslide size, timing or frequency, or velocity or runout distance.

Deterministic engineering style analyses

In this approach, mechanistic analyses of the type shown in Equation 12 are performed over large areas represented in a GIS. The result is a distributed, physically based model that can predict local slope stability in absolute or relative terms. The great advantages are that the technique is objective and can predict location, timing and frequency of slides. It is also possible to conduct sensitivity analyses and predict landscape response to changes in environmental conditions from natural and human causes. These conditions may be completely outside the range of those represented in the history of observable landslides in an area. For example, it is possible to investigate the effects of forest thinning or complete removal on slope stability. At present, almost all models of this type employ the two-dimensional infinite slope analysis (Equation 12) and so cannot evaluate landslide size (Ward, 1982; Montgomery and Dietrich, 1994; [SHALSTAB model]; Gorsevski et al., 2006a).

A distinct disadvantage of this approach is that the full list of parameters in Equation 12 must be characterized over large areas. Some, such as soil depth and pore water pressure, are very difficult to predict; pore water pressure in particular is a problem because it varies in four dimensions, three spatial as well as in time. Pack et al. (1998) attempted to resolve the problems of parameter uncertainty by describing the probability distribution function (assuming a uniform probability density function) of some parameters, rather than using single valued parameters. They then calculate a probability of failure rather than a FOS in their model SINMAP. Gorsevski et al. (2006a) used a stochastic weather generator and a soil water balance model in a GIS approach to predict areas of instability. Wu and Sidle (1995) noted that rainfall is a stochastic parameter and their model dSLAM uses either an event-based rainfall record or theoretical distributions from Monte Carlo simulations to predict the pore water pressure, and thus they can compute either FOS or probability of failure. dSLAM also incorporates the time rate of decay of root strength after tree death and the rate of site vegetation regrowth, although still only in a two-dimensional model. Hammond et al. (1992) also employed a Monte Carlo analysis with probability density functions for all parameters in Equation 12 in their model LISA. Rather than calculating the probability of failure directly on the pixels in a DEM, LISA first stratifies the landscape into homogeneous units and then the

probability of failure is evaluated for each stratum using a Monte Carlo scheme. This is a subtle but important difference and in the LISA model a high probability of failure for a stratum gives no information about where in a polygon a particular bad combination of conditions might exist that would lead to a higher probability of failure. The assumption is that the polygon is homogeneous and the probability of failure is equal throughout.

As discussed before, all distributed mechanistic models require calibration and validation against local landslide information in a slide inventory map.

Analysis of slope stability along roads

Depending on the terrain that is traversed and the style of construction, roads can have a variety of effects on slope stability. Cut and fill slopes are normally steeper than local undisturbed terrain, and so inherently less stable. Cut slopes also frequently intercept shallow groundwater and can concentrate this water in places that will cause landslides. Road fill is often thicker where the corridor crosses small unchanneled valleys and hollows. These are sites where there is normally a concentration of groundwater and disruption of groundwater flow by the overlying fill can cause elevated pore water pressures and fillslope failure. Mountain roads are sometimes damaged when they cross landslides that are so large they are relatively unaffected by the road, yet the road is a victim when the slides move.

The stability of a road corridor can be considered at a variety of spatial scales, ranging again from individual slides to the general mass stability of an entire road. Individual slides are analyzed using methods such as those introduced previously. At broader scales of investigation, mapping techniques have been developed that can be described as qualitative engineering geomorphology analyses. This method of “reading the landscape” from a geomorphic perspective over time scales well beyond human experience is described in a series of papers published mostly in the *Quarterly Journal of Engineering Geology*. Perhaps the first of these is the pioneering work by Brunsden et al. (1975). In this approach, landforms are mapped in detail using a combination of airphoto interpretation and field work and then process domains, including those of landslides, are interpreted from the morphologic maps. In this way a qualitative assessment of local or regional landslide hazard can be produced.

Quantitative deterministic analyses, most often based on the infinite slope equation, also can be done over entire road corridors. A recent example is that of Borga et al. (2004), who used the SHALSTAB model with adaptation of the groundwater component to accommodate the interception and rerouting of groundwater by a road network. A similar approach is used by Prasad et al. (in press) who employ a modified version of the SINMAP probabilistic stability analysis as part of the Road Sediment Analysis Model (RSAM).

Model Calibration and Validation

Calibration is the process of determining input variables so that the model generates satisfactory predictions. Validation is using a calibrated model on a different site to see whether reasonable values are still predicted (e.g. Conroy 2005, Chapter 6).

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