Tools for Analysis

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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, and 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 (CWE) is to define the problems 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 (for example project, watershed, landscape);
- the environmental constraints (for example, vegetation, climate, topography);
- the temporal context (single event, average annual, return period analysis);
- requirements of local, state, or federal regulatory agencies; and
- 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 water logging 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.

Impacts of concern

Generally, two public values dominate cumulative watershed effects analyses: impacts on aquatic ecosystems (Chapter 11), and impacts on human resources (for example, 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 annual water yields, peak runoff rates, and related attributes such as runoff duration and time to peak, upland erosion rates, and watershed sediment delivery rates. 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 are not linked to the runoff. The WEPP model predicts both runoff and erosion, and the more recent versions of WEPP (Version 6.2 or later) include lateral groundwater flow in watershed runoff (Covert and others 2005; Dun and others 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.

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

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 (5 to 40 ha) 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 (GIS) 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 access publicly available datasets in their GIS (for example, USGS digital elevations, NRCS soils data, and climate files), generate derivative datasets from elevation models (such as 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 modeling projects where the limited scale of the analysis does not warrant use of the more detailed and labor-intensive modeling systems. Larger watersheds are frequently divided into small watersheds or hillslope polygons known as hydrologic response units (HRUs) to aid in describing specific areas within a watershed where a given management activity is targeted, such as a thinning operation, or a significant disturbance has occurred, such as a wildfire. One of the challenges in modeling larger watersheds is in linking the HRU runoff and sediment processes to the larger scale (Beighley and others 2005).

Sources of sediment

There are seven typical sources of sediment associated with fuel management (table 2): surface erosion from undisturbed and 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 1 to 3 years before the hillslope is recovered, whereas roads can 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 when there are 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

Table 2. Typical sources of sediment in a watershed analysis.

Source	Frequency of occurrence	Relative erosion amount
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
Undisturbed hillslopes	Yearly	0.1
Road networks	Yearly	2-5
Stream channels	5 to 10 years	5-90

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 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 and thinned openings and fringes of open areas adjacent to forests being areas of snow accumulation. Large open areas may experience less snow accumulation during times of high wind speeds as the wind scours snow from these openings. Open areas with less wind scour could also be areas of high snow accumulation due to less canopy interception. Thus the severity of wildfire, ephemeral nature of hillside disturbances, chronic nature of road sediments, impacts of elevation on climate, effects of forests and wind on snow hydrology, and 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 in the southwestern or eastern United States, frontal storms along the west coast, snowmelt in the higher elevations of the western mountains, or rain-on-snow events 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.

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, 1985). Some tools may not be stable for some common forest conditions, such as steep slopes.

If the model is empirically based, managers need to be careful if adopting a model that was developed for different climates, vegetations, or 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, at one time, the USLE and RUSLE models were considered inappropriate for rangeland conditions (NCBA 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.

Additionally, the computer hardware available to the manager may be inadequate for some models, lacking the memory or speed required for the tool. Older computers may not have the software necessary to run some models, such as recently developed GIS or spreadsheet-based models.

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 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, charges a fee to cover the cost of burning and shipping software on a CD. Once downloaded, many applications are installed through common installation wizards with special computer configuration requirements. Some installations may require the manager to get administrative permission to install the software. Some models that fall into the research domain, such as DHSVM, require the user to compile code and install special system emulators. These installations may require assistance from computer support specialists.

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 from either 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. If online databases are used, it is the user's responsibility to ensure that the data are correct. For example, one online data set contained information from a faulty sensor at a SNOTEL site that was only discovered when the model was not performing as expected.

Many models include file builders to aid in preparing the data for the model. The input file builder may be as straight forward as choosing from selections on drop-down lists, as with the FSWEPP online interface. Many tools, especially those designed as distributed, process-based systems, generally running in a GIS, may require large amounts of data from multiple data sources. There is a trend to build interfaces that guide the user to electronic libraries of public data 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 that interactively guide users through each step of the model building process (for example, 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 in a satisfactory format. Output files containing more information than a user requires may need additional analyses to reformat or synthesize 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 meets 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.

It is unlikely that any watershed tool will meet all of the manager's needs. Managers will have to select from a series of tools 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 (fig. 1). 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 is an example of a distributed model using grid cells. 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. One common approach to distributed modeling is to use hydrologic response units (HRUs) as the smallest unit of discretization. An HRU may be a small watershed or a hillslope polygon, depending on the focus of the analysis (Beighley and others 2005).

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. The benefit of distributed modeling is that more management options can be evaluated. For example, a manager can compare the watershed impacts of thinning only the upper part of hillslopes instead of the entire hillslope or the watershed effects of altering the width of an undisturbed forested buffer along stream channels. Management affects on north-facing slopes can be compared to those on south-facing slopes. In larger watersheds, it may be possible to synchronize or desynchronize hydrographs to obtain desired runoff characteristics. Lumped models would not be as versatile at modeling such spatial variability.

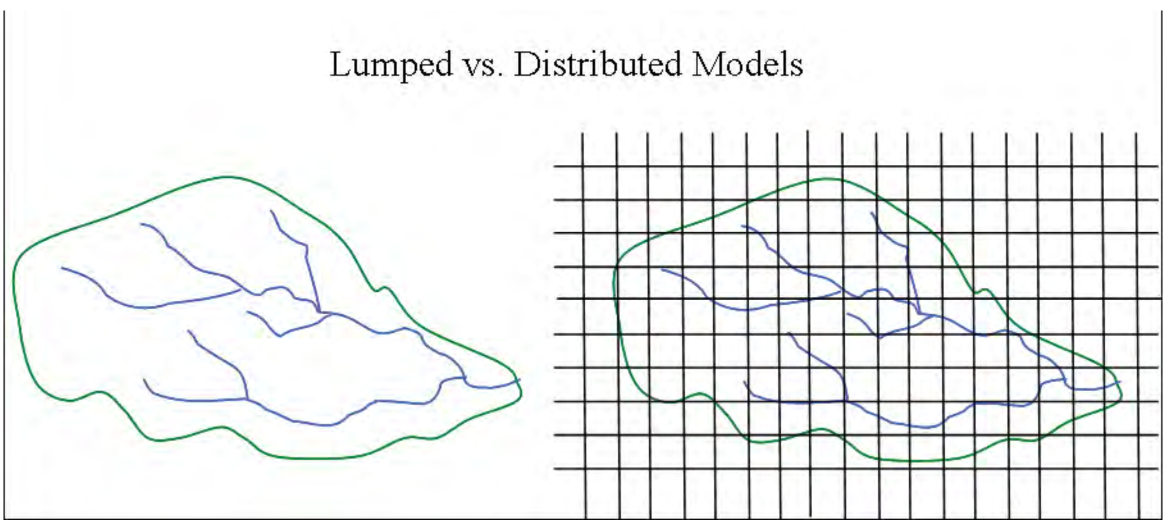

Figure 1. Lumped vs. distributed model. The "lumped" watershed on the left has a single value to describe soil, vegetation, and climate conditions in the entire watershed, whereas the "distributed" watershed on the right may have different values for each grid cell, or in some cases, individual hillslope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

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 (RMRS 2007).

Conceptual vs. Physically Based Models

Conceptual models are based on the physical processes that drive the watershed responses. Physically based models contain mathematical equations and relationships that describe watershed processes. Few models can be labeled as purely conceptual or purely physical, but rather range along a spectrum of complexity from purely conceptual to purely physical. The more conceptual or empirical models require less data, but are less flexible in the application. The more physically based models can often be applied to a greater variety of circumstances, but in order to do this, they will be more computationally intensive and require larger input data sets.

There is often a heavy reliance on empirical data in conceptual 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 processes may include:

- vegetation growth and senescence;
- impacts of plant community on evapotranspiration, rainfall and/or snow 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, gullying, and channel processes; and
- mass failure and debris flow processes.

Input parameters for physically based models are generally 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 are generally more academically acceptable, and can be generally applied to areas other than where the original data 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 a description of each will be given.

Rational Peak Flow

The Rational Peak Flow prediction method is (Schwab and others 1993):

$$q = 0.0028\ C\ i\ A \tag{1}$$

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 and others 1993) and for forests, ranges from 6 to 20 (table 3). 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 and others 1993):

$$T_c = \frac{L^{0.77}}{3077 s^{0.385}} \tag{2}$$

where
T_c = time of concentration (h)
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 Precipitation-Frequency Atlas is often consulted (Bonnin and others 2003). There are Internet sites available that aid the user in determining the intensities of these shorter duration storms for many states (http://hdsc.nws.noaa.gov/hdsc/pfds/). The Rational method is best suited to watersheds under about 2 mi^2. For larger watersheds, other runoff methods are recommended. One of the reasons the runoff coefficient is so small for forest watersheds is that much of the runoff is shallow subsurface lateral flow or groundwater, rather than surface runoff, so peak rates are less than would occur on agricultural sites of similar area.

Table 3. Typical values for Runoff Coefficient *C* in Rational Equation and descriptions of hydrologic soil groups (Engel and others 2009).

	Hydrologic Soil Group			
Land Use, crop and management	**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 and others 2006). The Curve Number technology was initially developed from a network of small watersheds covering the entire United States. Most of these watersheds were in agricultural areas, so data for rangelands and forests was limited. The USDA Natural Resource Conservation Service (NRCS) played a leading role in the development of the research technology.

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:

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

and

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

where Q = runoff depth (mm or inch)
I = storm depth (mm or inch)
S = maximum potential difference between rainfall and runoff, sometimes referred to as surface storage (mm or inch)
U = unit conversion (25.4 mm for metric, 1 inch 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 the curve number (Fangmeier and others 2006).

Table 4. Some typical Curve Number values for forested conditions (Goodrich and others 2005).

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
Undisturbed Forests					
Deciduous & Mixed	50	55	55	75	80
Evergreen	50	45	66	77	83
Forest, Low severity fire					
Deciduous & Mixed	43	59	60	78	82
Evergreen	43	49	71	80	85
Shrubland	21	65	79	86	89
Moderate severity fire					
Deciduous & Mixed	34	65	65	80	85
Evergreen	34	55	76	82	88
Shrubland	17	68	82	88	90
High severity fire					
Deciduous & Mixed	25	70	71	83	87
Evergreen	25	60	82	85	90
Shrubland	12	73	88	91	91

Estimating peak runoff rates with curve number

From the runoff amount Q, peak runoff can be estimated using the methodology developed by the NRCS (2002). 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 and others 1996) is to first estimate the time of concentration with the empirical relationship:

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

where Tc = time of concentration (hours)

L = length of watershed (m or ft)

CN = NRCS Curve Number

C = constant 441 for metric, 1,140 for English units)

s = average watershed gradient (m/m or ft/ft)

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 and others 1996):

$$\log(q) = 2.51 - 0.7 \log(Tc) - 0.15\,(\log(Tc))^2 + 0.071\,(\log(Tc))^3 \tag{6}$$

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 and others 2005). One analysis suggested that the Curve Number method was not appropriate for forest or rangeland watersheds, and a better estimate of runoff is 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 for non-forest conditions 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 (USLE) (Wischmeier and Smith 1978). The USLE was parameterized for some forest hillslope conditions for intensive forest management practices in the southeastern United States (Dissmeyer and Foster 1981). A revised version of the USLE (RUSLE) was later developed as a computer application (Renard and others 1997). When predicting erosion, RUSLE allows a 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 Windows operating system (Foster and Toy 2003). The basic form of the USLE/RUSLE models is:

$$A = R\,K\,L\,S\,C\,P \tag{7}$$

where
- A = average annual soil loss (tonnes/ha/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 and metric units. To avoid confusion, this chapter will use all English units. Metric units for these three variables can be found in Fangmeier and others (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 and others 1997). Figure 2 is the "isoerodent" map for the western United States in English units, providing an estimate of the R factor. The west coast and eastern United States maps, as well as other methods for estimating R, can be found in Renard and others (1997). The R factor is best suited for climates where runoff and erosion are dominated by large storms, not snow melt, whereas much of the area in figure 2 is dominated by snow process, making these areas problematic for USLE applications.

K factor

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

$$K = \frac{\left[2.1\times10^{-4}(12-OM)M^{1.14} + 3.25(s-2) + 2.5(p-3)\right]}{100} \tag{8}$$

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

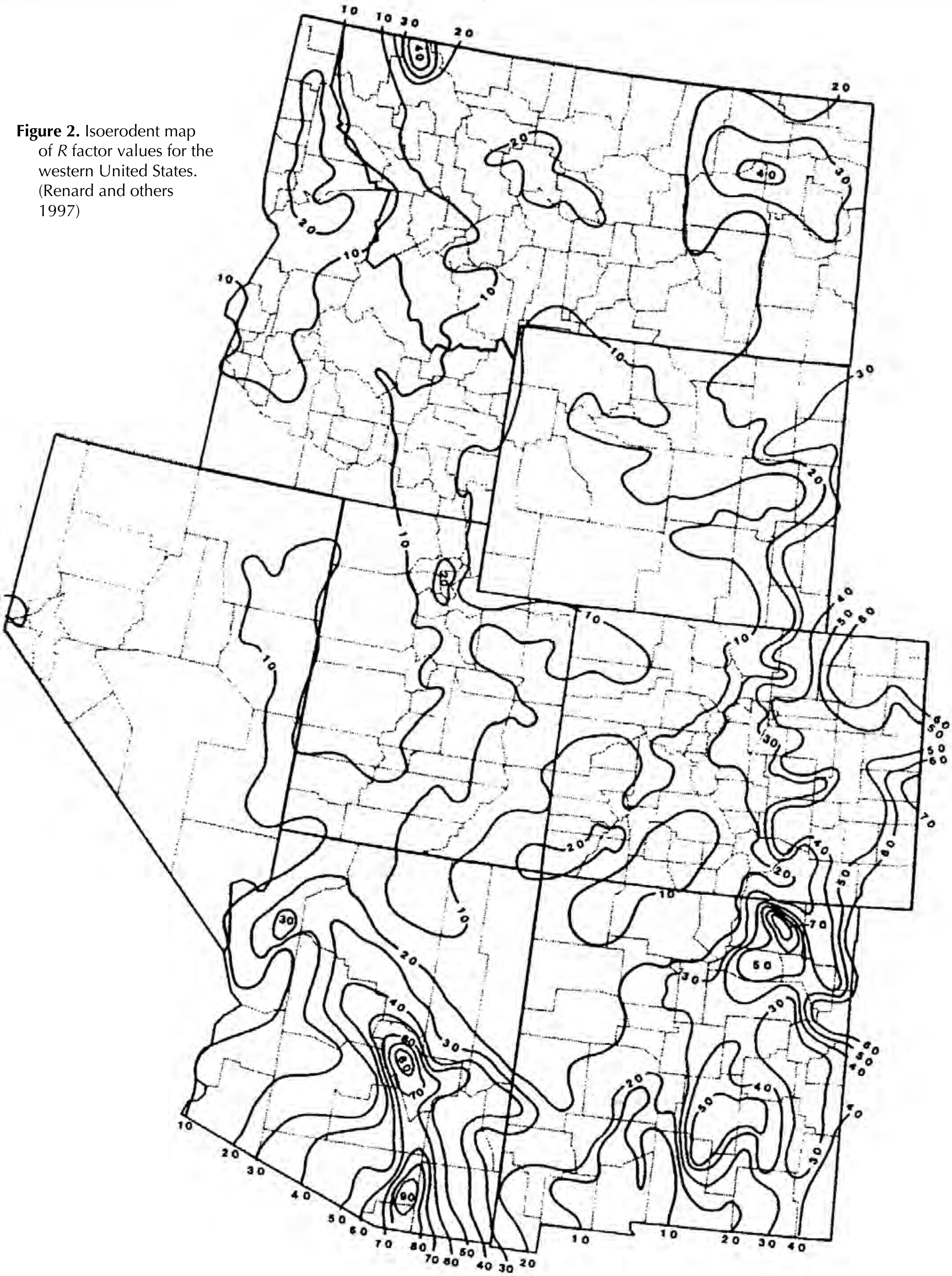

Figure 2. Isoerodent map of *R* factor values for the western United States. (Renard and others 1997)

In forest environments, soil erodibility has been found to be a function of not only soil properties, as assumed in the USLE technologies, but 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 72.6 ft (22 m). In many mountainous conditions, the lengths and steepness values are greater than intended for the *L* and *S* factors. 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:

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

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, 72.6-ft long slope

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

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), *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:

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

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

$$S = 10.8 \sin\theta + 0.03 \tag{11b}$$

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

$$S = 16.8 \sin\theta - 0.50 \tag{11c}$$

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 2-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 2-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 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 ensure that 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 United States, Dissmeyer and Foster (1981) expanded the Wischmeier set to include site preparation tillage practices common in the Southeast. Because tillage is not generally 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.

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.)	C 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	Soil condition: 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

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 Modified USLE (MUSLE) technology described below.

The factors in RUSLE have generally been developed from, and validated by, research studies on tilled agricultural soils. Some rangeland research with RUSLE developed *C* factors based on surface cover, which give reasonable erosion predictions for rangeland hillslopes (Elliot 2001). Applications of RUSLE to disturbed forest hillsides and roads have 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 (Bingner and others 2007; Suttles and others 2003). AGNPS and its newer iteration, AnnAGNPS, are well established, actively supported, production-ready tools. AGNPS models a single event, simulating a pulse of sediment 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 NRCS 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 that 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 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 (Arnold and others 1998; Di Luzio and others 2002, 2004). 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 NRCS 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. 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 that 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 (USFS 1990). 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). The ECA concept was developed in the 1970s as a method for estimating the change in runoff amounts and peak flows associated with a forest practice. It assumes, for example, that 2 acres of partially cut forest will have the same affect on water yield as 1 acre of clearcut forest. As a forest regrows, the ECA is reduced (Ager and Clifton 2005). WATSED has a Windows interface to guide the user through all stages of the model application. 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 (Dubé and McCalmon 2004). 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 that 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 complementary Cumulative Watershed Effects tools. These tools are intended to provide managers with estimates of relative cumulative changes in forested watershed responses due to multiple management activities over time (MacDonald and others 2004). Development of these tools is in part driven by the intent to move beyond the basic Equivalent Clearcut Area (ECA) approach. The general structure uses GIS-based, two-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 can also 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 based on an empirical relationship between percent connectivity and mean annual precipitation.

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. The empirical approach of Delta-Q could limit applicability where the area of concern is distant from one of the 26 experimental sites and 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 (Watershed Analysis Risk Management Framework)

WARMF 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 and 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 a small watershed (up to about 2 mi^2). 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 2,600 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 to match a specific site. Additional climate data can be downloaded from an online web site (http://forest.moscowfsl.wsu.edu/fswepp/) that has a 4-km (2.5-mile) grid of monthly precipitation values for the continental United States This site 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 (table 7). The Forest Service suite of interfaces (FS WEPP) is available for forested hillslope applications (Elliot 2004), and the ARS interfaces have a greater emphasis on agricultural or rangeland conditions.

WEPP FuMe is specifically designed to support fuel management activities. It carries out 12 runs from a single set of inputs. These runs include nine hillslope scenarios: undisturbed forest; low, moderate, and high impact thinning; low, moderate, and high impact prescribed fire; and low and high intensity wildfire. Additionally, there are three road runs for low, moderate, and high levels of traffic. The output page provides tables and a narrative of the results of those runs in the context of fuel management activities to assist the user in synthesizing the results.

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 less than 2 mi^2 if users desire to consider predictions of peak runoff rates.

At the WEPP hillslope scale, only surface runoff is considered, whereas both surface runoff and subsurface lateral flow are considered when modeling watersheds. More than 90 percent of the runoff from many steep forested watersheds is from shallow lateral flow or groundwater flow (Conroy and others 2006; Covert and others 2005; Dun and others 2006; Zhang 2006).

Table 7. Online WEPP interfaces.

Name	Location	Features
WEPP:Road	http://forest.moscowfsl.wsu.edu/fswepp/	Road erosion and sediment delivery from individual segments
WEPP:Road Batch	http://forest.moscowfsl.wsu.edu/fswepp/	Multiple road segments for a given soil and climate
Disturbed WEPP hillslopes	http://forest.moscowfsl.wsu.edu/fswepp/	Disturbed forest and rangeland
WEPP FuME	http://forest.moscowfsl.wsu.edu/fswepp/	Multiple WEPP runs to support fuel management planning
ERMiT	http://forest.moscowfsl.wsu.edu/fswepp/	Post wildfire sediment delivery and mitigation analysis
WEPP Web Interface	http://milford.nserl.purdue.edu/	Agriculture and rangeland erosion, detailed graphics
WEPP CAT	http://typhoon.tucson.ars.ag.gov/weppcat/index.php	Ag, and range Climate Assessment Tool including buffers

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 are generally well defined. For natural watersheds, users should use the GeoWEPP technology to build watersheds.

GeoWEPP. GeoWEPP is a GIS wizard that 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 Digital Elevation Model (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. 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 prepares the data with the aid of a GIS and then runs the model using command line codes in a Unix interface. 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 Forest Service, Pacific Northwest Research Station. DHSVM was specifically designed to address complex hydrologic interactions and variability due to climate and topography. It was originally developed to assess changes in flow resulting from logging at relatively large scales. DHSVM (Version 3) 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 and UNIX 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/.

SMR: Soil Moisture Routing Model

SMR is a physically based distributed hydrologic model that uses simple "map calculation" commands within grid-based GIS software packages (in other words Arc/INFO, GRASS) to represent the hydrology of a landscape. The model, originally developed at Cornell University (Brooks and others 2007; Frankenberger and others 1999; Johnson and others 2003), was designed as a simple management tool to simulate spatially distributed soil water, surface runoff, subsurface lateral flow, and streamflow using publicly available data and requiring minimal calibration. Since the program uses commands inherent in nearly all available GIS software packages, the source code is a very simple batch file or script file (only a few pages long) that is easy to read and modify. Although the model does not include many of the complex algorithms in the DHSVM model, such as variability in aerodynamic and canopy resistance within multiple layers of the canopy and corrections for atmospheric stability to calculate evapotranspiration, the fundamental hydrologic mechanisms used to route subsurface lateral flow and generate saturation-excess runoff are very similar to those in the DHSVM model. Despite these simplifications, the model has been shown to provide good agreement with distributed soil moisture, perched water tables, and snow water equivalent measurements as well as stream flow and spatial surface runoff patterns. The model has been used in agricultural dominated watersheds to identify critical management zones associated with nutrient and pathogen transport. In forestry, SMR applications have helped to identify landslide susceptibility (Gorsevski and others 2006b) and quantify the effects of climate change on regional water supply and streamflow (Mehta and others 2004). Further information is available at: http://soilandwater.bee.cornell.edu/Research/smdr/index.html.

Summary of Watershed Tools

Table 8 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 are 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.

Table 8. Summary of currently available watershed modeling tools.

Tool name	Predicts	Empirical / process	Status
AGNPS	Runoff and erosion	Emp	Production
Delta-Q / FOREST	Runoff and erosion	Emp	Production/Beta
DHSVM and SMR	Runoff	Process	Research
Rational	Runoff	Emp	Production
NRCS 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

Other Modeling Tools Available

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

NetMap

NetMap is an integrated suite of numerical models and analysis tools created for three purposes: (1) to develop regional scale terrain databases in support of watershed science and resource management, (2) to automate numerous kinds of watershed analyses keying on environmental variability for diversifying resource management options, and (3) to improve tools and skills for interpreting watershed-level controls on aquatic systems, including natural disturbance. Hillslope attributes, such as erosion potential, sediment supply, road density, forest age, and fire risk, are aggregated down to the channel habitat scale (20 to 200 m), allowing unique overlap analyses, and they are accumulated downstream in networks revealing patterns across multiple scales. Watershed attributes are aggregated up to subbasin scales (approximately 10,000 ha), allowing comparative analyses across large watersheds and landscapes. Approximately 25 automated tools address erosion risk, habitat indices, channel classification, habitat core areas, habitat diversity, and sediment and wood supply, among others. Search functions target overlaps between specific hillslope and channel conditions and between roads and landslide or debris flow potential. To facilitate its use, NetMap contains hyperlinked users' manuals and reference materials, including a library of 50 watershed parameters. NetMap provides decision support for forestry, restoration, monitoring, conservation, and regulation (Benda and others 2007). NetMap approaches watershed analysis by stream segment reach rather than from DEM grids as in AGNPS and DHSVM or from hillslope polygons as in SWAT and WEPP. Its original intent was to aid in evaluating impacts of land management on aquatic ecosystems, but it also shows considerable potential to aid in cumulative watershed effects for other watershed services. The 2007 version does not predict absolute amounts of hillslope erosion, but rather estimates the erosion risk from hillslopes associated with each channel segment. NetMap is not a public domain package, so to apply it, the managers need to obtain the program and the necessary watershed information from the developers (http://www.earthsystems.net/).

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 a partnership with The Nature Conservancy, HEC-EFM, Ecological Functions Model, proposes to model changes in flow characteristics during the year so that users can evaluate the ecological responses to alternative flow regimes. For more information on HEC tools access go to http://www.hec.usace.army.mil.

GRAIP: Geomorphic Road Analysis and Inventory Package

GRAIP is a data collection and analysis process and a set of tools for evaluating the impacts of roads on forested watersheds (RMRS 2007). GRAIP combines a road inventory methodology with a GIS analysis tool set to predict sediment production and delivery, risk of mass wasting from gullies and landslides, and ease of fish passage where roads cross streams. For further information on the status of this tool go to: http://www.fs.fed.us/GRAIP/index.shtml.

ArcHydro: GIS for Water Resources

ArcHydro was designed as an organizing framework with which to generate integrated watershed systems linked to relational databases that then port data to and from watershed modeling tools (ESRI 2002; Maidment and Djokic 2000). It functions as a toolbar plugin in ESRI Arc 8 to 9.x. Required terrain data are extracted from a DEM. Channel segments of a 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/.

Methods of Slope Stability Analysis

Introduction

Landslides may be considered at a variety of spatial scales during analyses of the watershed effects of fuel 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 also assess 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 is greater than 1, in other words, 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.

The most simple limit equilibrium formulation, and one that works well on many mountainous hillslopes, is the "infinite slope" analysis (fig. 3). Here, the assumption is made that the failure along which sliding occurs, the failure surface, is planar and generally parallel to the ground surface. This failure surface is often understood to be at the soil/bedrock contact, as rock mechanical shear strength is normally much greater than that of soil. It is further assumed that the slope is infinitely long, hence the "infinite slope" nomenclature, and homogeneous. This means that any single small element of

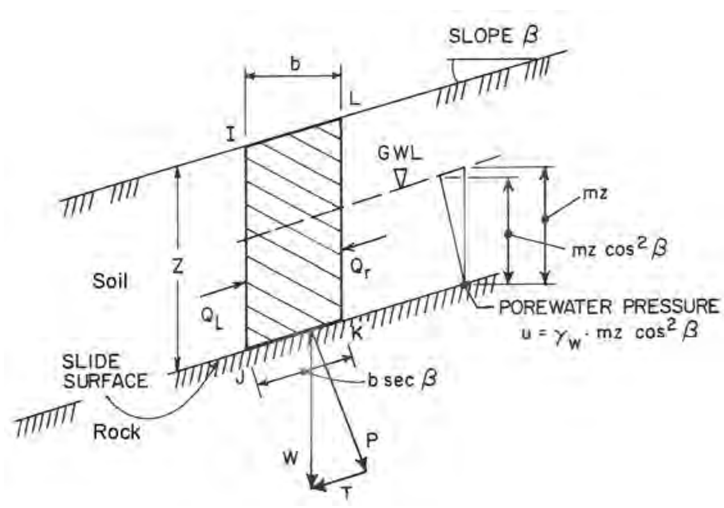

Figure 3. Forces involved in a limit equilibrium infinite slope stability analysis.

the slope can be analyzed and the stability of that element will be the same as that of the whole slope. It also means that the force acting on the upslope face of the element will be exactly balanced by the force acting on the downslope face. A further very important assumption is that forces acting parallel to the topographic contours (cross-slope forces) can be ignored. So, the analysis is purely two-dimensional and involves only the balance of forces along the failure surface on the bottom of the analyzed slope element that is normally oriented directly down the line of steepest descent on the slope (fig. 3). If a further simplifying assumption is made that the groundwater is unconfined and flowing parallel to the slope, the FOS can be calculated as:

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

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
ø = 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 values 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.

Fuel 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. In soils that are high in silt, the "apparent" soil cohesion c_s can be high because of internal water tension at low water content. If fuel management results in reduced evapotranspiration, then it is possible that pore water pressure could increase and the apparent cohesion decrease, leading to a reduced FOS.

Very simple analyses like that above can be quickly computed 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 can also 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 can also 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 can either 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 fuel 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:

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

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 ø

Equation 13 is derived from Equation 16 in Casadei and Dietrich (2003), which 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 that mobilize into debris flows will move at rates on the order of m/s to tens of m/s. In the Oregon Coast Ranges, it has been empirically found that shallow land slides (soil thickness 1 m or less) (Dietrich and others 2007) tend to stop when the slope angle in the runout zone declines to less than 3.5^o or when a tributary transporting a debris flow intersects a receiving channel at an angle greater than 70^o (Benda and Cundy 1990).

Thus far, the discussion has focused on planar failures. In some cases, rotational failures can occur. These are more common on uneven terrain or where the surface is underlain by uneven bedrock leading to pockets of elevated soil water. Roads frequently are subject to rotational failures. These types of failures are more difficult to analyze, and generally require iterative solutions. Computer programs such as XSTABL (Sharma 1994) have been developed to assist for these conditions.

Earth flows may be another source of sediment movement, accelerated by increased soil water contents as previously discussed. Their analysis, however, is best carried out by geotech specialist as there are no readily available tools for such soil displacement.

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 air photos 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 air photos 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 and others 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 air photos 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. In many cases, the inventory data are used to calibrate, and validate, the other predictive methods (McClelland and others 1999).

GIS multi-factor overlay approaches

An extension of the simple inventory is to map the variables that could reasonably affect slope stability, in other words, the parameters in Equation 12. 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 discriminate analyses, logistic regression, or Bayesian belief models (Carrara and others 1991; Dai and Lee 2001; Gorsevski and others 2006a; Gritzner and others 2001)

These GIS-based analyses are relatively simple to conduct if suitable factor maps are available for the pertinent parameters. 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, or if management, fires, or other changes in land use occur that change the vegetation community and thus the root cohesion. GIS analyses do not generally predict landslide size, timing, frequency, 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 cannot evaluate landslide size (Gorsevski and others 2006b; Montgomery and Dietrich's SHALSTAB model (1994); Ward and others 1982).

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 and a temporal dimension. Pack and others (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. In their model Stability Mapping Index (SINMAP), they then calculate a probability of failure rather than an FOS. Gorsevski and others (2006b) 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 in their Distributed Shallow Landslide Analysis Model (dSLAM). This model uses either an event-based rainfall record or theoretical distributions from Monte Carlo simulations to predict the pore water pressure, and thus computes 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. In their Level one Stability Analysis model (LISA), Hammond and others (1992) also employed a Monte Carlo analysis with probability density functions for all parameters in Equation 12. Rather than calculating the probability of failure directly on the pixels in a DEM, LISA first stratifies the landscape into homogeneous units and then evaluates the probability of failure 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 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 are inherently less stable. Cut slopes also frequently intercept shallow groundwater and can concentrate this water in places that will cause landslides. Normally, groundwater concentrations will occur where road fill is thickest—across the corridors of small unchanneled valleys and hollows. 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 and others (1975). In this approach, landforms are mapped in detail using a combination of air photo interpretation and field work, and then process domains, including those of landslides, are interpreted from the morphologic maps. By doing this, a qualitative assessment of local or regional landslide hazard can be produced. Future remote sensing will likely incorporate LiDAR capabilities into evaluating road stability (Kwak and others 2005).

Quantitative deterministic analyses, most often based on the infinite slope equation, can also be done over entire road corridors. A recent example is that of Borga and others (2004) who used the SHALSTAB model with an adaptation of the groundwater component to accommodate the interception and rerouting of groundwater by a road network. A similar approach is used by Prasad and others (2005) 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 or data set to see whether reasonable values are still predicted (Conroy and others 2006; Elliot and Foltz 2001; Elliot and others 1991). Many models require some form of calibration as part of the application. For example, many of the WEPP vegetation files require calibration for local weather conditions to ensure that predicted amounts of canopy and ground cover are correct. The SWAT model is generally calibrated for runoff for current conditions before evaluating alternative management activities. Many research papers have been published on model validation, but 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? If not, the user may need to consider some additional calibration or add some qualifying comments in the report associated with the modeling activity. If a given tool does not appear to be performing in a satisfactory manner, it may be useful to contact the group supporting that model to ensure the model is being used correctly and to determine if the model is appropriate for the given conditions.

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