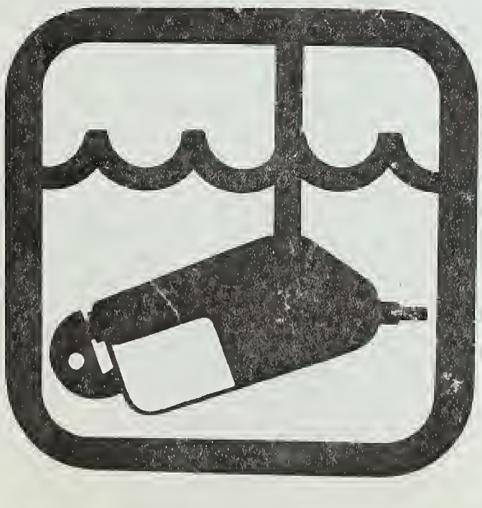
GUIDE FOR PREDICTING SEDIMENT YIELDS FROM FORESTED WATERSHEDS



FOREST SERVICE
U S
DEPARTMENT OF AGRICULTURE

NORTHERN REGION
INTERMOUNTAIN REGION
Soil and Water Management

GUIDE FOR PREDICTING
SEDIMENT YIELDS
FROM
FORESTED WATERSHEDS

U.S. FOREST SERVICE
NORTHERN REGION
INTERMOUNTAIN REGION
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Prepared by a Work Group Comprised of Soil Scientists, Hydrologists, and Watershed Specialists of the Northern and Intermountain Regions and the Intermountain Forest and Range Experiment Station

Document Prepared by and Major Contributions Listed Alphabetically From:
Richard Cline, R-1, Regional Office
Gene Cole, R-4, Boise National Forest
Walt Megahan, Intermountain Experiment Station, Boise
Rick Patten, R-1, Clearwater National Forest
John Potyondy, R-4, Regional Office

A working draft of this document entitled "Guidelines for Predicting Sediment Yields" was previously released in July 1980. This document is essentially the same. Changes made are primarily editorial in nature to clarify and further explain concepts and assumptions.

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EXECUTIVE SUMMARY

A sediment yield prediction procedure has been developed by a work group composed of soil scientists, hydrologists, and watershed specialists of the Northern Region, Intermountain Region, and the Intermountain Forest and Range Experiment Station. The procedure is applicable to the Northern and Intermountain Region's forested watersheds. The procedure was developed principally for watersheds in or generally associated with the Idaho Batholith but the process described has the capability of adaptation to other forested areas. Extrapolation of the numbers given in this guide to areas outside of the Idaho Batholith should be done with extreme care.

The model is applied on watersheds that are stratified using land systems inventory map units. The model produces quantified estimates of sediment yields prior to any management (natural sediment yield) and sediment yields in response to various management scenarios for any number of years. The types of management activities modeled are roading, logging, and fire. The model estimates on-site erosion for a given management activity modifies the amount of erosion according to general land unit characteristics, delivers the eroded material to the stream system, and routes it through the watershed to a critical stream reach where interpretations are made and where monitoring for achievement of planning objectives should take place.

The model simplifies, for analysis, an extremely complex physical system and is developed from a limited data base and scientific knowledge pool. Although it produces specific quantitative values for sediment yield, the results should be treated as rather broad estimates of how real systems may respond. The validity of this model is best when the results are used to compare alternatives, not for predicting specific quantities of sediment yielded. Values produced by this procedure are probably valid for comparisons only where large differences among alternatives are produced.

The model is a conceptual framework which outlines a process and is designed to be supplemented by local data and adapted by individual Forests to better reflect local conditions and observations. As a state-of-the-art effort to predict sediment yield, the procedure will undoubtedly receive close scrutiny. In most instances, better and more precise information and techniques applicable to the level of forest management, as practiced today, are simply not available at this time. Consequently, the procedure will undergo continual change and revision. As more information becomes available from studies such as the Silver and Horse Creek studies, this guide will be revised to incorporate any new data and information.

The authors recognize that every model is subject to misuse. Many models are probably misused because in many cases more appropriate models are not available. Users are often forced to use models outside the range of conditions considered during development simply because the user must have an answer. For this reason, the limitations and assumptions about the model are clearly documented. Users are encouraged to use their technical expertise considerable professional judgment to assure that reasonable use is made of this model. Models are simply tools to assist in decisionmaking, and users ought to test model results against their best technical judgment of what can logically be expected to actually occur on the ground.

INTRODUCTION

It is becoming increasingly apparent that a consistent method for predicting sediment yield from Forest lands, for use in land management planning, is urgently needed to respond to the requirements of the National Forest Management Act (NFMA). The method must reasonably predict changes in sediment yield over time in response to Forest management activities. It should be documentable, portray a consistent logic, and conform to current best estimates of sediment production from research data. It should not be a cut and dried procedure to be followed absolutely without regard to local conditions; however, it should describe, in a conceptual sense, the erosional and sediment-producing processes that actually occur on landscapes. This method provides a basic set of assumptions, procedures, and a quantitative starting point from which to develop locally applicable estimates of natural (undisturbed) sediment production characteristics and response to management activities on a variety of lands. As a state-of-the-art effort to predict sediment yield, the procedure will undergo continual change and revision as new information becomes available. This effort should be thought of as a first approximation attempt to quantify extremely complicated watershed systems.

The procedure considers both on-site erosion and downstream sediment yield. Uses of these estimates include, but are not limited to, evaluations of on-site productivity, sedimentation of downstream developments, sediment impacts upon fish habitat, and water quality conditions. Because the model relates the effects of land disturbing activities to downstream sediment yield, best management practices can be evaluated to protect water quality conditions.

OBJECTIVES

Specific objectives for the sediment yield model are:

1. To provide a systematic tool to estimate the response of watershed systems with respect to erosion and sediment yields.

2. To develop a process that is conceptually usable at the project level, as well as at the land management planning level.

3. To develop a model capable of estimating sediment yields under natural conditions, present management, and proposed management alternatives.

4. To route predicted sediment yields to a key reach in a watershed system.

STANDARDIZATION

National Forests in the Northern and Intermountain Regions have used a number of techniques to estimate sediment yields from forest lands. Although all of the efforts draw on a common research data base, considerable divergence exists in the procedures, units of measure, and types of erosion compared by the various Forests. This divergence tends to confuse Forest Service land

managers, the public, and even confounds the specialists themselves in attempting to draw meaningful comparisons between two or more Forests, Regions, or areas. The primary goal of this model is to standardize the procedure for predicting sediment yield. A glossary of terms and definitions is included as Appendix A. Agreement has been reached among the Regions to standardize the following aspects of the sediment prediction procedure:

1. Any sediment yield analysis must be done on a watershed basis to be meaningful.

2. Land systems inventory will form the basic units for subdividing watersheds where sediment yield is to be predicted. It is assumed that these units are delineated to reflect predictable slope hydrology and erosional responses.

3. For comparative purposes in planning, erosion and sediment will be expressed as sediment delivered to a stream rather than expressing it as on-site erosion.

4. The standard unit of measure will be tons/square mile/year.

5. Sediment will be expressed as total sediment (bedload plus suspended).

6. Standardized outputs for planning will show sediment yield for three conditions: natural, present, and proposed (with and without various types of mitigation).

LIMITATIONS AND ASSUMPTIONS

Simplifying assumptions have been made in preparing this model. Such assumptions are necessary to address in a manageable manner the complex relationships involved since all possible combinations, factors, and contingencies cannot be covered. The model is intended to be a conceptual framework that attempts to account for the principal controlling variables in the erosion-sediment delivery-routing system in a fundamental way. Most of the data for the model are derived from Idaho Batholith watersheds (range of 0.1 to 2.5 square miles drainage area with an average area of 1.0 square mile). The model contains coefficients for extrapolation to other areas. Users are cautioned that extrapolaton should be done with care. It is intended that Forests adapt the model to local conditions and use local data as the basis for extrapolation wherever it is available. The importance of using better local data, and estimates, if available, in place of supplied values cannot be overemphasized.

Specific assumptions implicit in use of the sediment prediction model are as follows:

1. Sediment yield can be usefully displayed as an expected average annual event although it is subject to considerable variability from year to year and within any single year.

2. Model outputs are primarily intended to indicate trends and to compare management alternatives and secondarily to provide quantified estimates of sediment yield.

3. The variables necessary to drive the model are obtainable from the land systems inventory at the landtype level and equivalent water resource inventories. The land units inventoried must reflect predictable slope hydrology and erosional responses.

4. Slope sediment delivery is defined as the transport of a portion of the eroded material from its source area downslope to a first or higher order stream. For these purposes, a first order stream is defined as any channel with discernible bed and banks.

5. Natural sediment yields of undisturbed watershed systems are derived primarily from streambank erosion of material supplied by creep and mass erosion processes inherent to the system which are independent of surface erosion processes induced by management.

6. Sediment derived from surface erosion should be separated from mass erosion because of differences in sediment delivery.

7. Although the model is conceptually usable at the project level, use of the model at this level requires more refined data and some adaptation of techniques.

CONCEPTUAL BACKGROUND

Available research data which apply to sediment yield in Forest environments are limited. A variety of assumptions concerning parent materials, landscape characteristics, and applicability are required to use these data to estimate sediment yields. The approach taken here is to assume that measurements of sediment yield (measured instream for small watersheds) are the best available for conditions existing on National Forest System lands of the Northern and Intermountain Regions. This data set provides the starting point for the proposed model and the empirical foundation upon which its application rests.

Data which apply directly to field conditions existing in the Northern and Intermountain Regions come primarily from research conducted by W. F. Megahan (Megahan 1974 and 1975; Megahan and Kidd 1972; Megahan and Molitor 1975; Rice Rothacher and Megahan 1972; Platts and Megahan 1975). Supporting and comparative data have been published by Anderson (1975a and b) and Andre and Anderson (1961) for a variety of types of materials in northern California. This literature is useful for developing quantitative estimates of natural sediment yield as well as estimates of sediment yield due to management activities.

There are three alternatives for estimating natural sediment yield. One approach is to use the Universal Soil Loss Equation (USLE) as documented by Wischmeier and Smith (1978), Curtis and Darrach (1977), and Darrach and Curtis (1978). The USLE approach was rejected because most of the conditions required for the use of a surface erosion prediction equation are not applicable on forest lands because most sediment in undisturbed forest

environments is the result of mass erosion processes. The primary objective of the procedure developed here is prediction of instream sediment resulting from land management activities. Site-specific erosion values, as calculated using USLE, are of minor importance in relation to this objective. Given the present supporting data base for USLE and limitations, it was considered inappropriate to use it as a primary source of quantified data for this application. This should not imply that USLE should not be used for calculation of on-site erosion for other applications. Wischmeier and Smith (1978) indicate that the best agreement with USLE occurs when it is applied to slopes of 3 to 18 percent having consistent cropping and management systems represented in the data base used for equation development. Large scale averaging of parameter values, a necessary part of this model, is expected to substantially reduce USLE accuracy. This should not imply that many of the same principles considered important in the USLE model were not applied to the erosion portions of this model.

A second approach is to deal with sediment yield delivered to a key stream reach based on available sediment data. This approach provides a quantitative estimate of sediment yield but does not identify the differences in sediment produced by various land units within the watershed nor does it specifically designate the portion of the total sediment yield attributable to land disturbing activities. Because of this limitation, this approach was also rejected.

A third approach is to separate erosional and delivery processes and consider them individually for each land unit. This is the approach chosen for this model because it can be used to estimate sediment yield differences among land units and it can also be used to show sediment yield from alternative management strategies.

The model developed here is intended for forested, mountainous watersheds and does not adequately address erosional processes occurring on rangeland watersheds. USLE models are recommended for estimating on-site surface erosion on rangeland watersheds where overland flow is a significant hydrologic process. Soil erosion nomographs which appear in Tew (1973), Wischmeier et al. (1971), and Wischmeier and Smith (1978), should be helpful. The USLE was not designed to estimate sediment yield, so users taking this approach must estimate deposition and channel-type erosion by other means. The method developed by the Pacific Southwest Interagency Committee (1968) may be appropriate in arid and semi-arid regions as an alternative methodology for directly estimating sediment yield from rangeland watersheds.

The sediment yield model presented in this guide provides a procedure for estimating sediment yield from undisturbed natural watersheds and the additional sediment yield due to management activities. Management-induced sediment is the additional sediment above natural yields resulting from man's activities. It is analyzed separately from that which is derived due to surface erosion processes and that resulting from mass erosion. Natural sediment yield, management-induced sediment from surface erosion, and management-induced mass erosion are then summed to give total sediment yield for any watershed after applying appropriate sediment delivery and routing coefficients.

The sediment yield model operates on a watershed basis. The watershed of interest to planning is delineated and further subdivided by appropriate map units such as landtypes. Natural sediment yield is estimated for each land unit and summed for the entire watershed. The natural sediment yield is then routed to the critical reach, where interpretations are made. Management-induced sediment is estimated for roads, fire, and logging. On-site erosion is calculated for each of these activities for each land unit and the eroded material delivered to the nearest channel. Sediment due to all management activities is summed and then routed to the critical reach. The sediment yield component due to management-induced mass erosion is also estimated where this is considered significant and also routed to the critical reach.

At the critical reach, natural sediment and management-induced sediment (surface and mass erosion) are summed to given an estimate of total sediment yield. The entire analysis is repeated for various management strategies for any number of years so that the natural undisturbed, the present, and the sediment yield from proposed management alternatives can be displayed and compared.

The effects of land disturbing activities are determined as on-site erosion and then delivered to drainages based on slope sediment delivery characteristics of the land. Slope sediment delivery is assumed to be a constant value for any particular type of landscape. It is defined as the proportion of erosion produced in a landscape which is delivered downslope to a first or larger order stream channel. Once in the stream, sediment is routed downstream using an empirical relationship.

Little data is available for estimating slope sediment delivery and what is available is extrapolated from landslide studies (Megahan et al. 1978). Use of sediment delivery concepts are considered important because they provide a mechanism for portraying effects of land disturbing activities as affected by various landtypes and provides the mechanism for delivering sediment to stream channels.

Sediment delivered to streams must next be transported through the stream system to a critical reach where interpretation about the significance of sediment yield is made. There is at present limited capability for evaluating sediment transport. Existing sediment routing formulas are too complex and data intensive for application in Forest planning. Therefore, a more generalized procedure is used. This procedure is a modification of an empirical relation derived by Roehl (1962).

After routing to a critical reach, natural sediment yield and sediment from land disturbing activities are combined as total sediment yield and compared to evaluate management alternatives for the undisturbed natural, present, and proposed management situation. The critical stream reach is the point in the watershed where total sediment yield is assessed in terms of its effects on other resources or resurce values. The analysis can be carried out for any number of years of interest to planning.

Wherever possible, research information is used to generate sediment yield predictions. These sediment yield estimates, based on data for small watersheds, must be extrapolated to relatively larger areas in the planning

process. The effect of extrapolation on reliability is unknown. Although extrapolation results in decreased quantitative reliability, relative trend and difference comparisons remain valid.

PROCEDURE

The sediment yield model proposed here consists of four major parts: (1) natural sediment yield; (2) sediment from surface erosion; (3) sediment from mass erosion; and (4) routing of that sediment to critical stream reaches (Figure 1). Interpretations of model outputs are made at critical reaches to relate sediment yield to resource values.

1. Natural Sediment Yield.

An estimate of natural (undisturbed) sediment yield must be developed to provide a basis for comparison with management-induced sediment yield predictions. The best source of this information is actual long-term real data of sediment yield. Another possible source is data from similar or related watersheds. In most cases, specific measured data will not be available and estimates must be made.

A basic assumption is made that the source of natural sediment is primarily stream channel erosion of banks and stored sediment. The source of supply of this eroded material is assumed to be from natural mass slope erosion processes. (Natural surface erosion and delivery is expected to be insignificant from undisturbed forested watersheds.)

The starting point for the natural sediment yield component of the model (Figure 2) is the value 25 tons of sediment per square mile per year (Table 1). This value is for landscapes developed under the influence of water erosion on granitic slopes with gradients near 60 percent. Values are in terms of sediment delivered to streams and were measured in streams using sediment traps estimated to be 80 percent efficient. The range of 10 to 100 tons/square mile/year is an estimate of reasonable variance from the normal value on steeper and less steep landscapes. The range is thought to be generally valid for forested landscapes in the interior west. (Megahan, personal communication.)

Table 1--Sediment yield estimates for granitic landscapes

Type of Landscape	Average Sediment Rate Tons per Square Mile Per Year
High sediment producing areas (4 x "normal")	100
"Normal" sediment producing areas	25
Low sediment producing areas (0.4 x "normal")	10

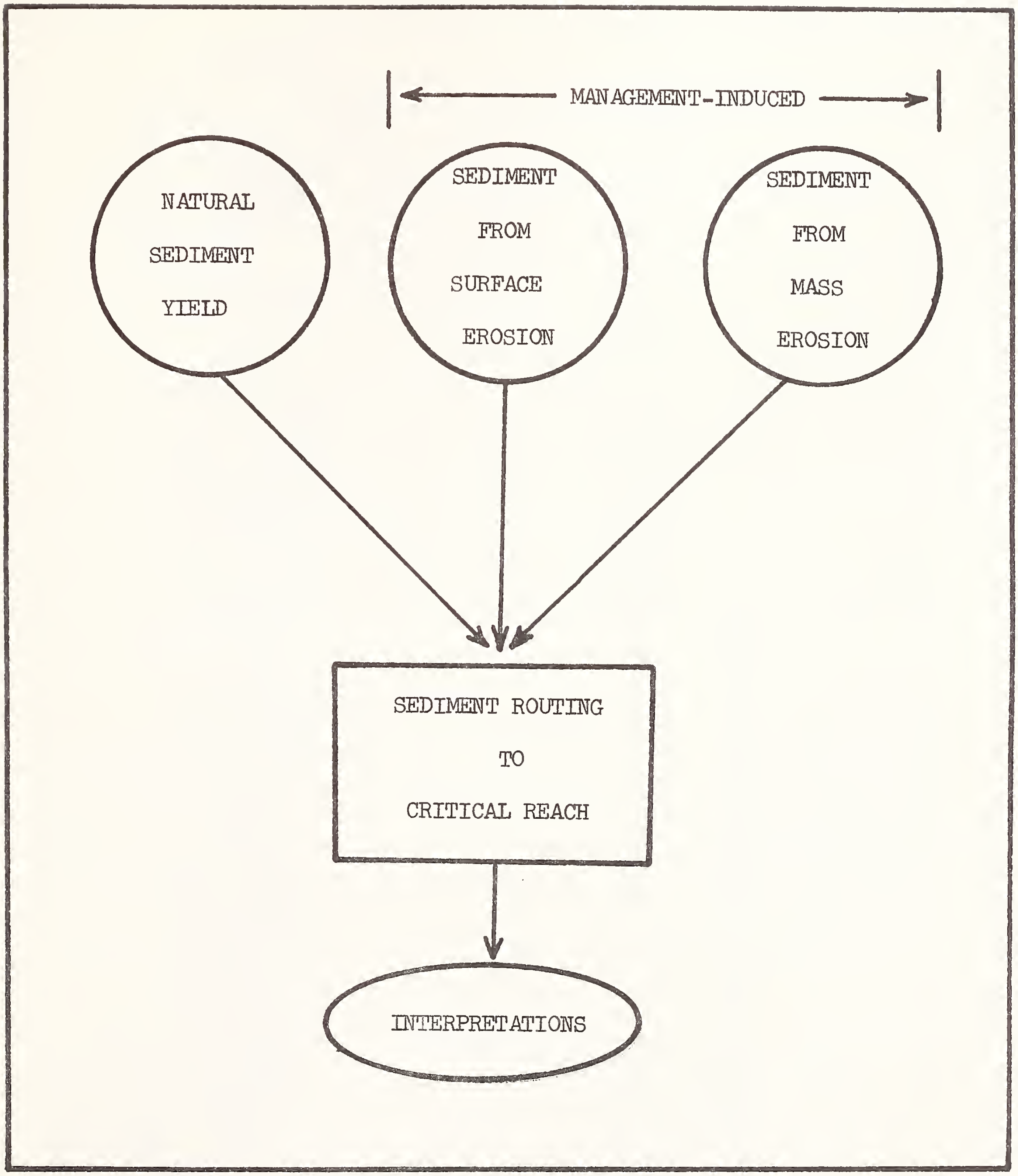

Figure 1: Generalized diagram of sediment yield model components.

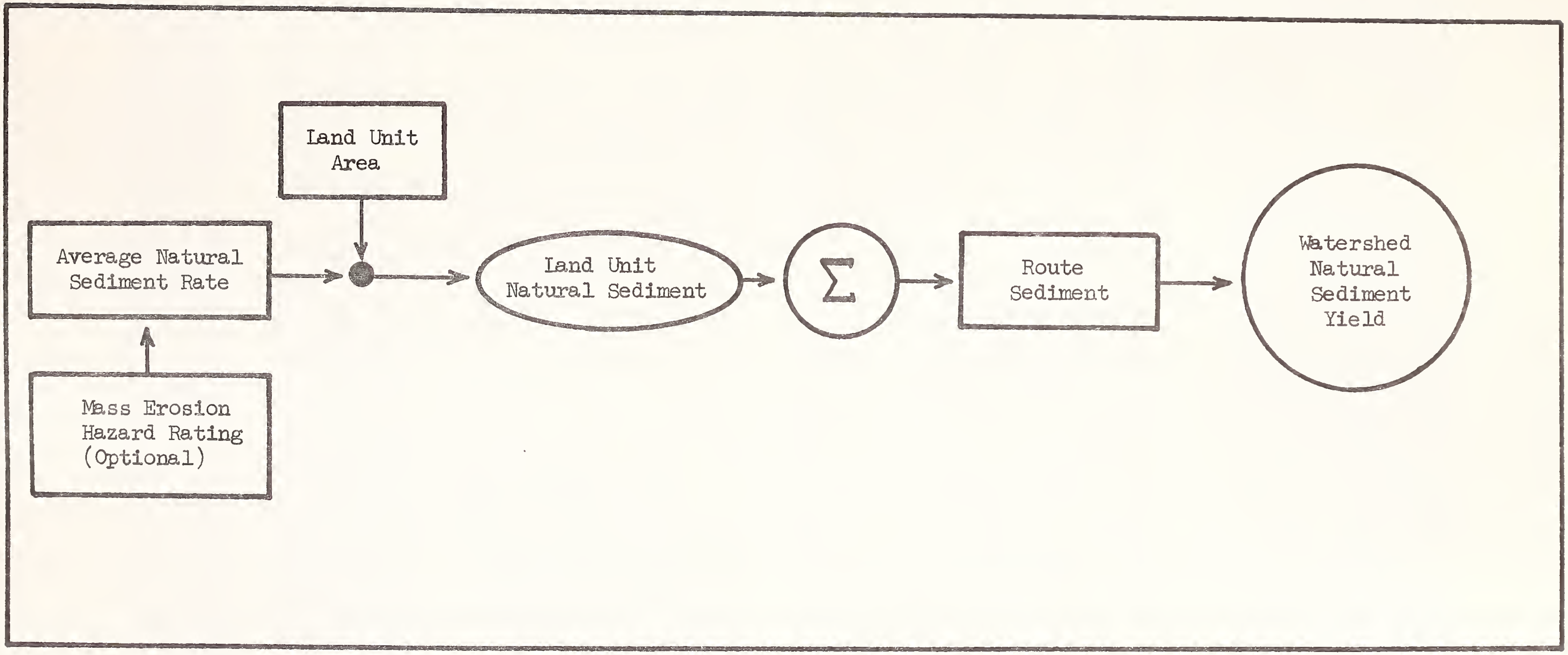

Figure 2: Process flow chart - Natural Sediment Yield.

Watersheds from which this data was measured ranged in size from 0.1 to 2.5 square miles with an average drainage area near 1.0 square mile. Landtypes found within these watersheds are predominantly strongly dissected mountain slope land, as described by the Boise National Forest Land Systems Inventory (Wendt 1973). See Appendix B for descriptions of these landtypes. Extrapolations should use these descriptions as a reference for applying the 25 tons per square mile per year value to local map units. Since natural surface erosion is considered insignificant, the variation in natural sediment yield is assumed attributable to differences in mass erosion hazards and delivery differences.

Forest personnel are encouraged to identify the landtype on their Forest with similar characteristics for extrapolation to identify the landtype which would be equivalent to the average natural sediment rate of 25 tons/square mile/year. Those who feel confident in extrapolating base sediment for other landtypes on their Forest, based on data or other defensible techniques, are encouraged to use their local expertise to do so. Where this is done, the process or procedure used should be fully documented. A procedure is proposed for extrapolation to other landtypes where better estimates are not available. In lieu of the proposed procedure for estimating the average natural sediment rate for individual land units, some Forests may feel more comfortable using USLE or other approaches for this purpose if surface erosion is significant for the area under consideration. It should be noted that most USLE factors will have to be adjusted for the geographic area under consideration. On-site erosion estimates generated by methods other than those developed in this guide (e.g., USLE) will have to have sediment delivery ratios applied to them to express erosion as sediment for later comparison.

In order to express the variability of natural sediment yields, a functional relationship relating mass erosion hazards to average natural sediment rates is proposed. Since natural surface erosion is assumed insignificant, land units with high mass erosion hazards are assumed to have high sediment yields. Hazard ratings are qualitative, relative interpretations of land units within a watershed. Guidance for the development of mass erosion hazard ratings and explanations of site characteristics to consider can be found in WRENSS[1]--Chapter 5, Soil Mass Movement. A copy of this chapter is included as Appendix C. Most Forests already have mass hazard erosion ratings available as part of the land systems inventory. To use the procedure described here, mass erosion hazard ratings will have to be developed for each land unit using the rating procedure given in Chapter 5 of WRENSS.

For the purposes of developing hazard ratings, soil mass movement is classified into two major types: debris avalanches-debris flows and slump-earthflows. A hazard rating of the natural hazard of each type of mass movement is provided in WRENSS (Appendix C-Tables V.5 and V.7). The relative importance of each type of soil mass movement must be evaluated for the area of model application and the appropriate mass erosion hazard rating used.

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[1] U.S. Forest Service. 1980. An approach to water resource evaluation non-point sources-silviculture (WRENSS), a procedural handbook. U.S. Environmental Protection Agency, Athens, Georgia, EPA-600/8-80-012, August 1980 (available from National Tech. Information Service, Springfield, VA 22161).

A relationship betweeen mass erosion hazard ratings (valid for either debris avalanches-debris flows or slump-earthflows) and the average natural sediment rate has been developed (Figure 3). The reference landtype to which the value 25 tons per square mile per year applies has a hazard rating of 33 using the rating procedure for determining natural hazard of debris avalanche-debris flow failures in WRENSS. Minimum and maximum possible hazard rating end points were equated to the range of average annual sediment rates (10 to 100 tons/square mile/year, respectively) and a curvilinear line graphically fitted between these points. Once hazard ratings are developed for each land unit, one simply enters the graph in Figure 3 to obtain an estimate of the average natural sediment rate for that land unit. Application of this procedure to all land units will provide an array of values defining the range of average natural sediment rates.

The following steps outline the overall procedure for estimating average natural sediment yield (see Figure 2):

Step 1. Delineate the watershed of interest above the critical reach.

Step 2. Overlay the watershed with land units (landtypes).

Step 3. Determine the average natural sediment rate by one of the following methods.

(a) Extrapolate using local data and local expertise, or

(b) Determine mass erosion hazard ratings as given in WRENSS-Chapter 5 and obtain average natural sediment rate using the graph in Figure 3.

(c) Use USLE or other technique for estimating on-site erosion and apply a slope sediment delivery ratio.

Step 4. Multiply the average natural sediment rate by the land unit area to obtain the land unit natural sediment.

Step 5. Repeat Step 3 and 4 for each land unit, sum the sediment from all land units and convert to T/mi^2/yr to obtain a weighted average for the watershed.

Step 6. Route sediment to critical reach. (Procedure to be discussed in subsequent section.)

2. Sediment From Surface Erosion

Surface erosion in a natural (undisturbed) forested watershed is insignificant. Surface erosion, however, becomes an important sediment producing process on lands disturbed by man's activities. In addition, transport of surface eroded material from slopes to channels is a fluvial process rather than a gravitational process. For these two reasons, sediment derived from management-induced surface erosion and sediment derived from management induced mass erosion are treated as separate and independant processes.

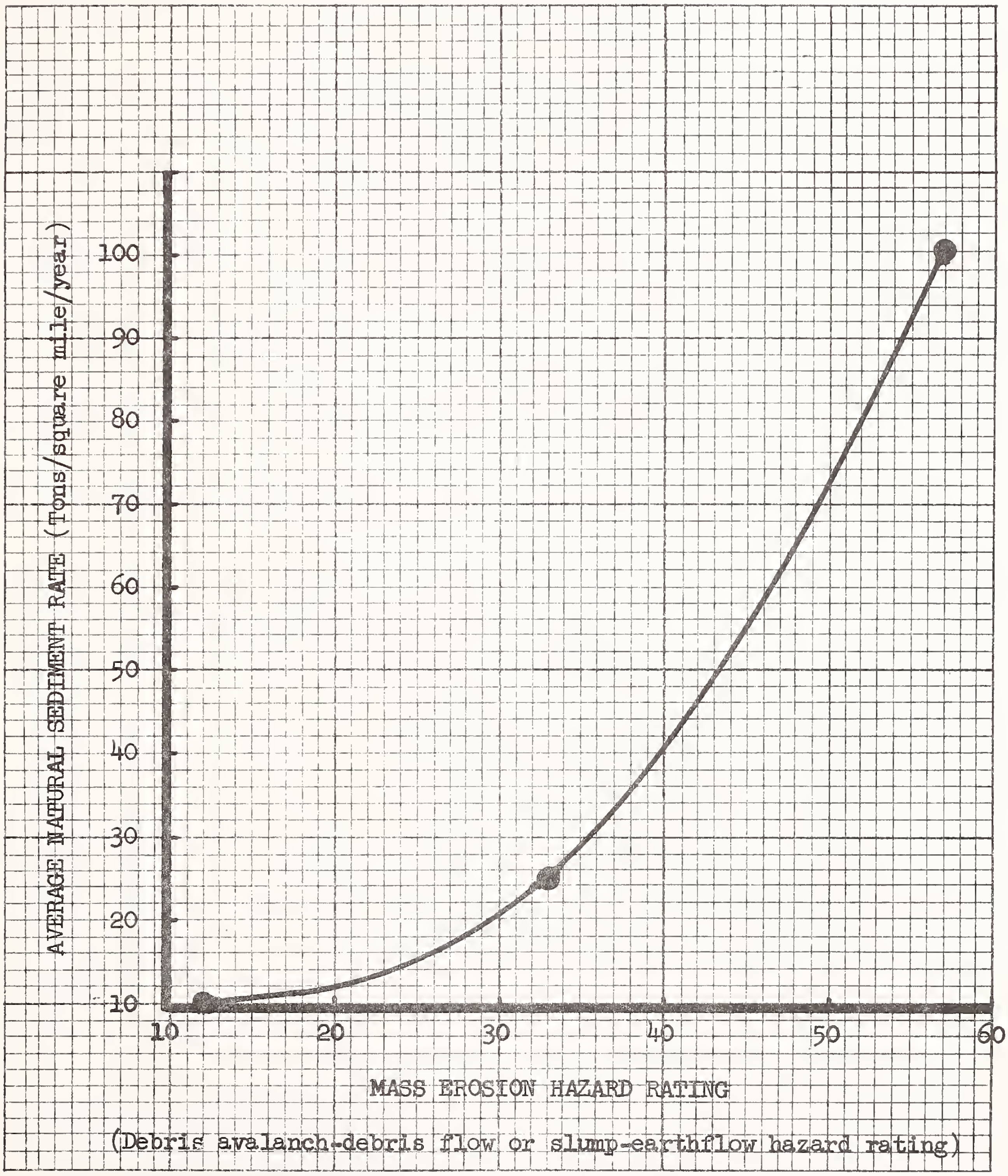

Figure 3: Average natural sediment rate as a function of natural mass erosion hazard rating.

Significant sources of sediment due to management activities considered by this model are roads, fire, and logging (Figure 4). Erosion rates for other man-caused sediment producing activities must be developed by the user. Data for this effort comes primarily from research conducted by W. F. Megahan (Megahan 1974 and 1975; Megahan and Kidd 1972; Megahan and Molitor 1975; Rice, Rothacher, and Megahan 1972; Platts and Megahan 1975) supplemented by data from Anderson (1975a and b) and Andre and Anderson (1961). The values developed represent the amount of additional sediment produced due to surface erosion resulting from management activities.

The model for management-induced surface erosion is based on research data that suggests a basic soil loss rate associated with roads, fire, and logging, which are reduced as a function of time since the activity took place. The erosion rates in the model are modified by the dominant controlling variables on the land unit on which they occur, the magnitude of the activity, specific characteristics of the activity, and possible mitigation factors. Slope sediment delivery is estimated as a function of land unit characteristics to route eroded material from its source to the stream system.

A comparison of erosion for materials derived from a variety of rock types is provided by Andre and Anderson (1961) and appears in Table 2.

Table 2 - Mean surface aggregation ratio and derived geologic erosion factors for soils from different rock types in California.

Rock Type	Mean Surface Aggregation Ratio	Coefficient of Variation (Percent)	Geologic Erosion Factor
Acid igneous (granitic)	118	35	1.0
Basic igneous	49	53	.42
Serpentine	41	44	.35
Miscellaneous metamorphic	46	50	.39
Schist	89	67	.75
Hard sediments	61	18	.52
Soft sediments	78	83	.66
Alluvium	124	88	1.05

These authors related erosion to the mean surface aggregation ratio of surface soils. Another article by Anderson (1975b) portrays surface aggregation ratios for granitic rock ranging from 149 to 71, hence the value 118 from the 1961 article seems reasonable as a basis for comparison. Coefficients of variation are included to provide a perspective on data reliability. This is particularly important in variable materials like alluvium where one standard deviation is 88 percent of the mean value of the original data. The geologic erosion factor is obtained by dividing the mean surface aggregation ratio of soils from each rock type by 118.

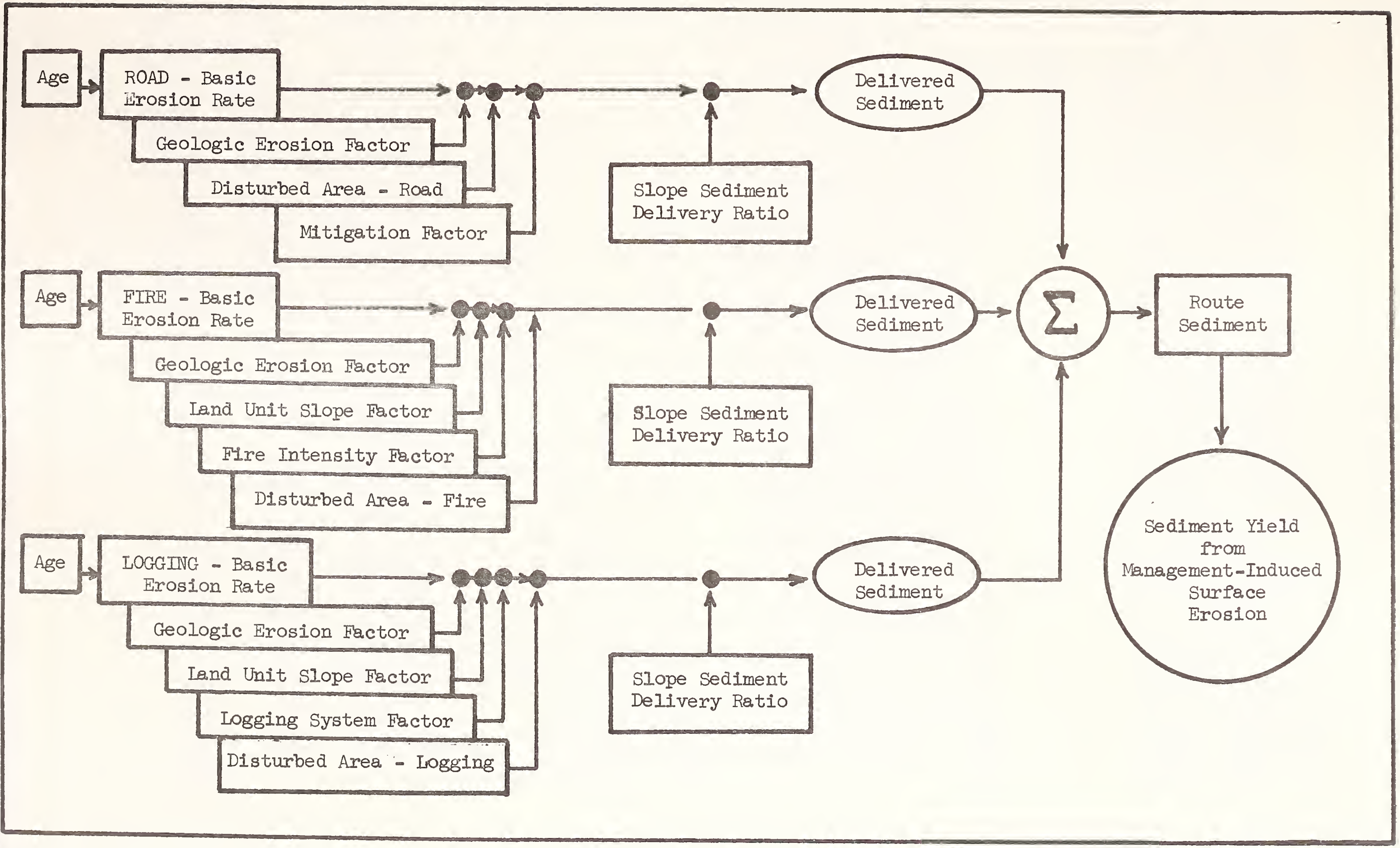

Figure 4: Process Flow Chart - Sediment Yield from Management-Induced Surface Erosion.

Geologic erosion factors in Table 2 are used as coefficients to modify basic erosion rates for areas underlain by bedrock other than granitics. As an example, a geologic erosion factor of 0.39 would be applied to Belt Supergroup rocks of northern Idaho which are classified as miscellaneous hard metamorphic rocks. Similar extrapolations are made for all activities occurring on bedrocks other than granitics to adjust basic erosion rates to specific sites by multiplying by the appropriate geologic erosion factor. It should be noted that the values in Table 2 are not all inclusive of the possible bedrock types that may be encountered.

a. Management Effects

(1) Roads

Roads in the Idaho Batholith are assumed to have basic erosion rates (Table 3) based on sediment data from a "standard" maintained 16-foot native material road with ditch (Megahan 1974 and personal communication). Basic road erosion rates are modified by the geologic erosion factor and multiplied by the disturbed area of the road prism segment. The road prism used in this context is the total area disturbed including subgrade, cut and fill slopes, ditches, berms, turnouts, and any other constructed features when present. Tables of geometry for low standard roads (Megahan 1976) are helpful to determine total area disturbed. The total area disturbed factor generally adequately handles deviations from the 16-foot standard road which involves changes in road width. It also handles deviations resulting from roads located on various side slopes.

Table 3 - Basic erosion rates for standard practices in tons per square mile per year.

	Year						
Practice	1	2	3	4	5	6	6+
Roads 1/	67,500	18,000	5,000	5,000	5,000	5,000	5,000
Fire 2/	550	120	25	5	0	0	0
Logging 3/	340	180	140	90	40	20	0

1/ Road area includes horizontal distance from toe of fill to top of cut. Standard 16-foot road assumed to have sustained 5-7 percent grade, balanced construction, insloped with ditch, native surface, and cross drains at 500-foot spacing constructed in granitic materials on a 50 percent side slope and is annually maintained.

2/ Standard fire is assumed to have burned at high intensity and consumed at least 40 percent of standing vegetation. Side slope is assumed to be approximately 45 percent.

3/ Standard logging system is clearcut with tractor yarding. Temporary roads and skid trails are assumed cross ditched and seeded as part of standard logging practice.

Roads to be considered include all system roads in the watershed and any major constructed temporary road system. Nonspecified roads and skid trails internal to logging units are considered as part of logging effects discussed in the next section and should not be duplicated here.

Basic erosion rates for roads were derived from Megahan's data (unpublished) and distributed over time in accordance with the shape of logarithmic functions (Anderson, 1975b). Megahan's data indicates initial road sediment yield from small watersheds in the Idaho Batholith averaged 54,000 tons per square mile per year. Sediment delivery on these small watersheds was assumed near 100 percent, and sediment traps were estimated to be 80 percent efficient. Dividing 54,000 by trap efficiency (0.8) yields the starting value of 67,500 in table 3. The estimated time to return to a stable value of 5,000 tons per square mile per year in 3 years forms the other end point.

Mitigation measures are applied to basic road erosion rates in the form of a percentage reduction depending upon the intensity of measures applied. Reductions in erosion due to mitigation measures are presented in Table 4.

Reduction in erosion in Table 4 for vegetative mitigation measures are derived from research in the Idaho Batholith (Megahan and Kidd, 1972) with additional factors for physical mitigation measures estimated to serve as approximations of expected erosion reduction. These values are intended as guidelines for areas where local data is not available. They are highly variable and judgment and common sense should be used in their application. Mitigation is assumed to be applied promptly before the first year's sediment is produced.

Table 4 - Suggested erosion reduction percentages for various mitigation measures.

Mitigation Measures	Percent Reduction in Erosion (Percent)
Vegetative measures	
Seed and fertilizer application	25
Plant ponderosa pine, seed, and fertilize	28
Wood chip mulch, seed, and fertilize	37
Straw mulch, seed, and fertilize	43
Netting in aspen blanket, seed, and fertilize	56
Asphalt and mulch	57
Mulch and net, seed, and fertilize	58
Sod	60
Physical measures	
Road tread surfaced	20-25
Road grade 5% or less	2
Rip-rap fill	50
Road partially closed (no maintenance)	75
Road permanently closed (obliterated)	95
Buffer strips along water course[1]	10-15
Filter windrows (slash or baled straw) at bottom of fill slope	35-40

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[1] As specified in Packer, P. E. and G. F. Christensen (1964).

If this assumption cannot be reasonably made, mitigation factors should be adjusted accordingly. Road closure mitigation measures are applied beginning with the erosional season after roads are closed.

Mitigation can generally be summed with the limitation that mitigation measures can only reduce a maximum of 80 percent of the erosion with the exception of roads that are to be obliterated where 95% of the erosion can be eliminated by obliteration. The mitigation factor to be applied to the model is obtained by subtracting the sum of all mitigation measures to be applied from 1. The resulting mitigation factor (a value ranging from 1.0 to 0.2) is then applied to the basic road erosion rates to reduce the amount of soil loss expected to occur.

Basic road erosion rates are modified as needed to apply to other than the standard road. Road erosion rates are then multiplied by the geologic erosion factor, the mitigation factor and the area disturbed by the road to arrive at total on-site erosion due to roads. This calculation is applied to road segments within each land unit. The analysis is repeated for any time period of interest to planning using reduced basic road erosion rates as shown in Table 3 for subsequent years.

(2) Fire

Fire has been shown to increase sediment yield from a variety of landscapes (Tiedemann et al. 1979). The amount of increase is extremely variable and can be attributed to intensity of burn, slope gradient, and proximity to streams. Megahan and Molitor (1975) report that a very intense fire produced approximately 550 tons/square mile the first year after the burn . Megahan (personal communication) indicates that this increase should return to near natural levels after approximately four years. This information was used to derive basic erosion rates for fire (Table 3) using a logarithmic function to scale recovery rates to pre-fire conditions. The standard reference fire is assumed to have burned at very high intensity. Fires of less burn intensity do not destroy as much of the vegetation, litter, and humus that protect the soil surface from erosion. Therefore, the basic erosion rate from fire is modified by a fire intensity factor which decreases basic erosion rates.

Fire intensity classes of low, medium, and high are determined as described in the Burn-Area Emergency Rehabilitation Handbook (FSH 2509.13 - Chapter 20 - Section 23.31) and presented in Table 5.

The standard fire is one of high intensity and therefore is assigned a fire intensity factor of 1.0. Connaughton (1935) studied erosion relative to fire intensity as a percentage of study plots showing erosion after fire. Approximately half as many plots showed erosion under medium intensity fire compared to high intensity fire and low intensity fire caused erosion in 20 percent of the plots. Based on his findings, fire intensity factors of 0.5 on 0.2 are assigned to medium and low intensity fires, respectively, in Table 5. These factors are used to modify the basic fire erosion rates in Table 4 according to the intensity of burn. An average fire intensity factor is determined for each land unit by weighted averaging fire intensity factors according to the percent of the area burned in each fire intensity class.

Basic fire erosion rates and intensity factors refer to both wildfire and controlled burning. The variability in sediment production from both types of

fires is great and a function of factor previously mentioned. A conservative average value has been selected. It should be adjusted to local conditions depending on the level of planning involved. The introduction of probability of occurrence concepts may be appropriate when analyzing wildfires in a planning context.

Table 5 - Fire intensity classes and corresponding fire intensity factors

Fire Intensity Class	Description	Fire Intensity Factor
Low	Soil surface litter and humus have not been destroyed by fire. (a) Root crowns and surface roots will resprout. (b) Potential surface erosion has not changed as a result of fire.	0.2
Medium	On up to 40 percent of the area, the soil surface litter and humus have been destroyed by fire and the A horizon has had intensive heating. (a) Crusting of soil surface produces accelerated surface erosion. (b) Intensively burned areas may be water repellent. (c) Root crowns and surface roots of grasses in the intensively burned area are dead and will not resprout.	0.5
High	On 40 percent or more of the area, soil surface litter and humus have been completely destroyed by fire and the A horizon has had intensive heating. (a) Crusting of soil surface produces accelerated surface erosion. (b) Intensively burned areas may be water repellent. (c) Root crowns and surface roots of grasses in the intensively burned areas are dead and will not resprout.	1.0

Three possible combinations of logging plus fire can occur: (1) slash burning in conjunction with a logging operation; (2) wildfire on a previously logged area; and (3) wildfire followed by salvage logging. Additive models of fire and logging effects are suggested to estimate surface erosion on the areas affected.

Surface erosion in areas disturbed by fire (and logging) is also assumed to vary by topographical characteristics of landforms - primarily slope; that is, steeper slopes will increase erosion rates more than gentler slopes. It was assumed that this variability is generally in the range 0.5 to 2.0 of the basic erosion rates for slopes in the range of 10-75 percent. The relative value of this modifier is adapted from the slope factor relationship of the Universal Soil Loss Equation scaled from 0.5 to 2.0 using equation 1. This

means that when the land unit slope factor is applied to basic fire and logging erosion rates, activities on slopes of zero percent will have basic erosion rates reduced by one-half (a factor of 0.5), slopes of 45 percent are the base with a factor of 1.0, and slopes of 75 percent, with a factor of 2.0, will cause the basic erosion rate to double.

$$\text{Land unit slope factor} = \frac{((0.43 + 0.30s + 0.043s^2) \times 0.0374)}{6.613} + 0.50 \qquad (1)$$

where: s = average slope of land unit in percent.

The land unit slope factor is applied to the basic fire erosion rates as are the fire intensity and geologic erosion factor to modify the erosion rates to reflect site-specific conditions. The modified erosion rate is then multiplied by the area disturbed by fire to arrive at total on-site erosion due to fire. The calculation is applied to the fire for each land unit within which the fire occurred. The analysis is repeated for any number of years of interest to planning.

(3) Logging

Basic erosion rates for clearcut logging with tractor yarding over time are shown in Table 3. Again, a logarithmic recovery function is used but the literature does not supply the end points on the curve in a convenient form. Anderson (1975b) indicates a measured total increase in sediment of 2 to 3 times the amount of sediment previous to logging for a variety of logging systems in Oregon. Megahan and Kidd (1972) found an average increase of 60 percent in sediment yield for a six-year period following skyline logging in Idaho. Based on this data, the logarithmic distribution function used to distribute sediment over the assumed 6-year recovery period indicated that 2.5 times the sediment normally produced should appear the first year decreasing to 0 for any time longer than 6 years. Since the data was measured as instream sediment values, it must be transformed to on-site erosion using a delivery ratio. The calculation for the first year's erosion appears in equation 2.

$$\frac{((2.5 \times 75) - 75)}{0.33} = 341 \text{ T/mi}^2\text{/yr} \qquad (2)$$

Where: 2.5 is the factor of increased erosion over natural, 75 is the tons of sediment produced by natural erosion assuming a delivery ratio of 0.33 (Boyce, 1975) on watersheds averaging 1 square mile in size, and 0.33 is the factor of conversion from skyline to tractor logging (table 6). The value of 75 is subtracted to get rid of natural erosion since the two processes are considered independently (75 tons erosion on-site is equivalent to 25 tons of sediment delivered to streams if the delivery ratio is 0.33).

Megahan (1980) published a table portraying the percentage of land surface disturbed by a variety of logging systems and cutting prescriptions. This information is adapted to this model and appears in table 6.

Table 6 - Derived logging system erosion factors for various logging systems and cutting prescriptions (after Megahan, 1980).

Logging system [1]	Bare soil (%)	Logging system erosion factor
	Clearcut logging	
Tractor	21	1.00
Cable	13	.62
Skyline	7	.33
Aerial	4	.19
	Selection logging	
Tractor	15	.71
Cable	9	.43
Skyline	6	.29
Aerial	3	.14

[1] See Glossary (Appendix A) for definitions of logging systems.

Logging system erosion factors were calculated from the averages of similar logging systems and cutting prescriptions using the tractor clearcut as a base reference value. This adjustment assumes that erosion is proportional to the percent bare soil observed for various logging systems. The logging system factors are used to modify basic logging rates according to logging system used to harvest timber.

Basic logging erosion rates are modified using the logging system erosion factor, the geologic erosion factor, the land unit slope factor, and the area actually disturbed by logging to arrive at total on-site erosion due to logging. This calculation is applied to cutting units within each land unit. The analysis can be repeated for any time period needed for planning.

b. Slope Delivery

As each surface erosion source is estimated, the eroded material must be delivered downslope to the stream system. This process when applied to each management activity stratified by land units within the watershed system, provides a gross estimate of potential sediment derived from surface erosion available to the stream system. The fluvial delivery process is a function of many variables. Wischmeier and Smith (1978) and Boyce (1975) provide general discussions of the process. WRENSS provides a systematic technique for determining slope delivery efficiency in Chapter 4, Surface Erosion, on pages IV-54 to IV-57. The sediment delivery portion of Chapter 4 is attached as Appendix D. It involves calculating the relative area derived from a polygon as a function of eight land characteristics, and applying this area to a conversion curve to determine slope sediment delivery. A slope sediment delivery coefficient must be developed for each land unit (landtype) being considered.

It is recommended that an adapted form of the WRENSS sediment delivery technique be used. Some of the eight variables in WRENSS may not be

applicable or significant in certain circumstances. Consequently, Forests will have to adapt the techniques to local conditions and data availability. In most applications, users will want to eliminate some of the eight factors either because they are not relevant to their area or because data is not available.

The following steps outline the overall procedure for estimating sediment from surface erosion (see Figure 4):

Step 1 Determine activities to be carried out within the watershed of interest. Same as watershed used to calculate natural sediment yield.

Step 2 Assemble information for each type of activity by land units

Roads:
- (1) Basic erosion rate for time period (age) to be modeled.
- (2) Area disturbed by roads
- (3) Mitigation measures to be used

Fire:
- (1) Basic erosion rate for time period (age) to be modeled.
- (2) Area disturbed by fire
- (3) Average fire intensity class for area burned
- (4) Average land unit slope

Logging:
- (1) Basic erosion rate for time period (age) to be modeled.
- (2) Logging system utilized
- (3) Area disturbed by logging
- (4) Average land unit slope

Step 3 By land types within each activity multiply the basic erosion rates for that activity by the geologic erosion factor and the factors from Step 2 applicable to that activity.

Step 4 Multiply by the slope sediment delivery coefficient to obtain sediment delivered to stream.

Step 5 Sum the delivered sediment from all land units and repeat Steps 3 and 4 for each activity.

Step 6 Sum the sediment delivered from all activities and convert to tons/square mile/year to obtain a weighted average for the watershed.

Step 7 Route sediment to critical reach (procedure to be discussed in subsequent section).

Step 8 Repeat Steps 2 through 7 for additional years for which sediment yields are needed.

3. Sediment From Mass Erosion

Mass erosion processes are distinctly different from surface erosion processes. Even though they may respond to similar driving variables, the two

processes respond differently to those variables. For this reason, sediment resulting from management-induced mass erosion is considered as a separate component in this model. Estimation of mass erosion is the most difficult and least understood, and hardest to quantify of the various components of this model.

Sediment from management-induced mass erosion may in many cases be an insignificant component in the estimation of total sediment. In these cases, it might reasonably be ignored in planning. Even if the potential exists, management-induced mass erosion hazards can be handled in planning by providing management direction so that certain activities will not be allowed to take place on land units with high mass erosion hazards.

If sediment from mass erosion due to management is significant, some estimate of sediment quantities is necessary. Chapter 5 in WRENSS (Appendix C) prepared by D. Swanston and F. Swanson contains a state-of-the-art review of soil mass movement and provides a basis for evaluating soil mass movement. The chapter identifies the primary elements necessary to evaluate the processes, and presents a methodology for obtaining quantitative estimates of sediment yield using data which must be developed locally.

In summary, if sediment from management-induced mass erosion is potentially a significant element in the watershed-sediment system, it should be estimated and quantified. The procedural techniques used should be based on the WRENSS procedure and must be developed by individual Forests.

4. Sediment Routing

Sediment delivered to channels must be transported through the stream system to the critical reach. Some of the sediment will be temporarily stored in channels and the rest will be tranported downstream. Local scour will pick up additional sediment that may be deposited at some point farther downstream or transported out of the watershed. The complexity of hydraulic variables in sediment routing is immense. Eight variables are considered most important including: stream discharge, width, depth, gradient, velocity, roughness of bed and bank materials, concentration of sediment, and size of sediment debris. Close interdependence between many of the variables often precludes the establishment of one-value relationships. In general, there is considerable variation in the results obtained from sediment transport equations. In addition, organic debris in lower order channels further complicates the sediment transport process.

Several formulas have been developed which attempt to describe this process and predict sediment yield at some point downstream. Since physical stream characteristics vary greatly among streams and along a single stream channel, use of these predictive equations requires detailed analyses of scores of channel segments. Sediment would need to be routed through each of these segments to arrive at sediment delivery to the critical reach. This requires short-term increments of predicted sediment inputs and streamflow rate which is only a practical methodology for detailed studies. Sediment yield formulas, at best, can only be expected to provide an estimate for a specific set of conditions (ASCE, 1975; Shen, 1971). In most forested mountain

watersheds, the energy available for sediment transport exceeds sediment supplies invalidating the use of most sediment transport equations. The limitations associated with existing sediment yield formulas invalidates their effectiveness in routing sediment through channel streams for Forest planning. Therefore, a more generalized procedure is used.

A basic premise is that the sediment yield rate for a large watershed is less than the sum of the sediment yield rates computed from its subwatersheds. If this is not done, sediment yield rates would not decrease with increasing watershed area as numerous studies have indicated (Boyce, 1975). This reduction is accomplished through the application of a channel sediment routing coefficient. The sediment that is not delivered to the critical reach is accounted for as channel storage consisting of storage in tributary channels, alluvial fans, floodplains, and behind organic debris.

The procedure selected is a modification of an empirical relation derived by Roehl (1962) using data from several locations in the United States. Roehl's sediment delivery ratios were derived from comparisons of erosion from small field plots and sediment trapped in downstream reservoirs. All losses due to surface and channel storage are incorporated into this relation. The model developed here delivers sediment from slopes to active first order drainages. The quantities determined reflect losses from surface storage but not for channel storage in a stream system. In order to avoid double accounting of hill slope storage, Roehl's graph has been shifted so that the channel sediment routing coefficient (Roehl's sediment delivery ratio) for watersheds up to one square mile is equal to 1.0 (Figure 5). An upward shift of the curve is further justified on the grounds that forested watershed generally have steeper slopes than the average watersheds studied by Roehl and, therefore, should be expected to deliver greater amounts of sediment to the stream system.

To arrive at the amount of sediment delivered to the critical reach, the natural and management-induced sediment yields are modified by the appropriate channel sediment routing coefficient based on the area of the planning watershed.

The following steps outline the overall procedure for routing sediment to critical reaches (see Figures 2, 4, and 5).

Step 1 Obtain the drainage area of the watershed above the critical reach.

Step 2 Obtain the corresponding channel sediment routing coefficient for the drainage area using the graph in Figure 5.

Step 3 Multiply the sediment yields for natural sediment, sediment from surface erosion, and sediment from mass erosion by the channel sediment routing coefficient to arrive at the corresponding sediment yields at the critical reach for each type of sediment yield.

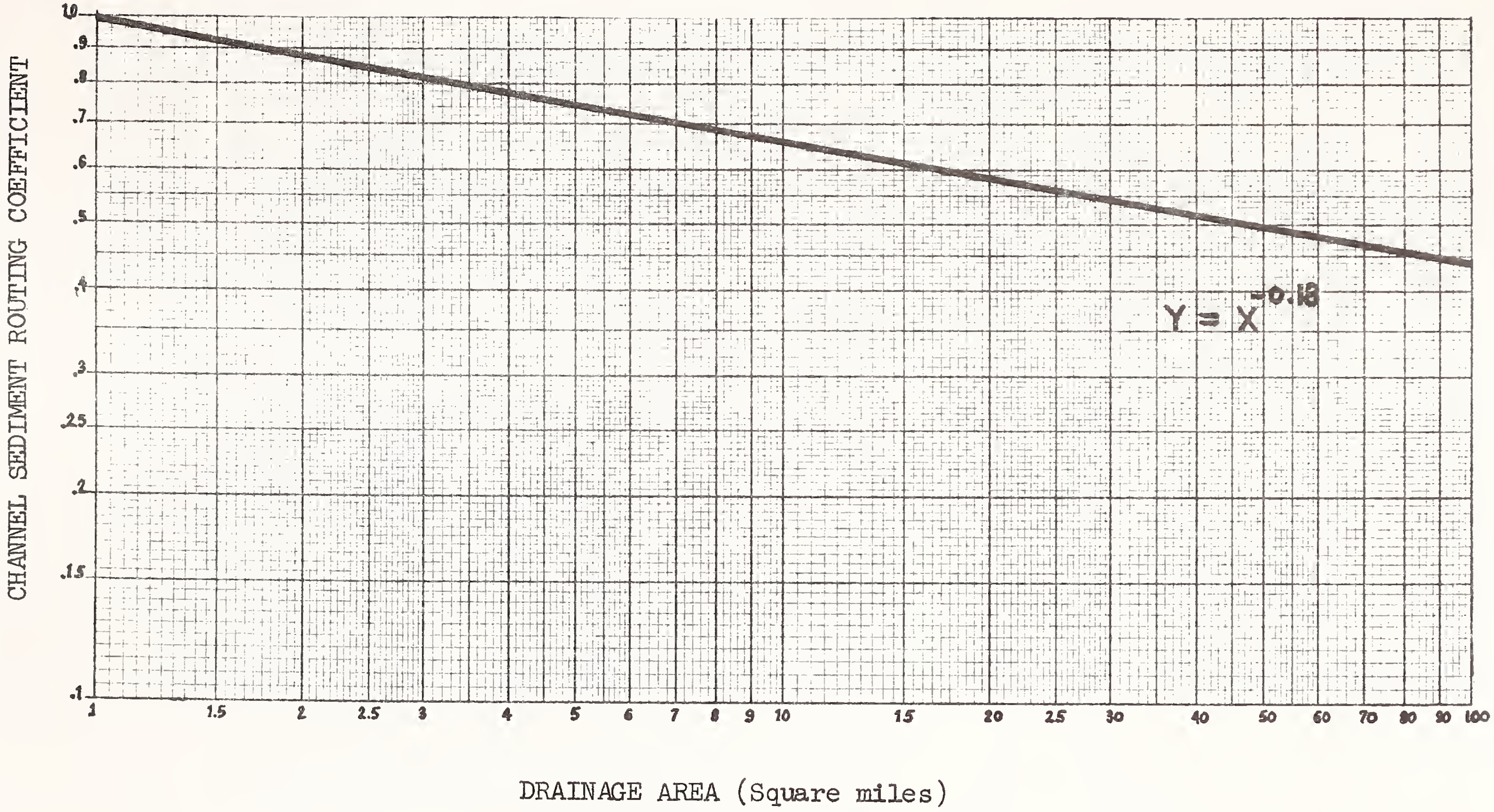


Figure 5: Channel sediment routing coefficient as it relates to drainage area in forested watersheds.

INTERPRETATIONS AND APPLICATION

The watershed-sediment phenomenon represents an extremely complex and highly variable system. Its basic elements: disturbance, erosion, slope hydrology, sediment transport, and sediment disposition (scour and deposition) are individually complex and are often poorly defined. The elements are interactive with each other. Any procedural technique or model, by necessity, must simplify and key on what are expected to be the primary and dominant controlling variables to produce a workable tool. The obvious dangers of this are oversimplification and nonrepresentation of the real-world system.

The conceptual model outlined in this guide is a very basic model. Individual processes are generally representative of observed responses in the Idaho Batholith. Features have been added to reflect the variability of these responses over the different land units that occur in the Idaho Batholith, and to extrapolate general responses to areas near the general boundaries of the Batholith.

A precise model is not intended. It is recommended that Forests follow the conceptual process, modifying specific values where local data or techniques are more applicable.

The value of the model's output is most valid when it is used to compare responses of different alternatives. Confidence is expected to decrease when absolute quantitative results are specifically used, and as the process is applied geographically further from the data source--the Idaho Batholith.

Two significant physical processes need more development. They are channel routing and sediment disposition. Channel routing to the critical reach is handled in the model by a general response curve based on data derived around the United States. For planning applications, this method is appropriate but should be localized and tested by research. The channel routing component of this model is definitely the weakest link in attempting to model the erosion and sediment transport process. Sediment routing was only included so that fisheries interpretations about the impact of sediment at critical reaches could be made. If these interpretations are not needed, users may wish to avoid attempting to route sediment through the watershed. No attempt is made to determine how sediment will be distributed within a critical reach, which includes deposition, scour, and sediment passing completely through the reach. Disposition of sediment in the critical reach should receive a high research priority as it has a profound effect on fisheries interpretations, channel condition, and water quality effects. At the present state of the art, the data needed for detailed sediment routing cannot be practically obtained in the realm of current National Forest System data acquisition efforts.

The conceptual model estimates quantitative average annual sediment yields at the critical reach derived from:

A. Natural sediment yield;

B. Sediment from management-induced surface erosion; and

C. Sediment from management-induced mass erosion.

These three sediment sources are summed to produce total sediment yield for the watershed under a given management scenario at a given time and then compared with natural sediment yields. Total sediment yield is calculated using equation 3.

$$\text{Total sediment yield} = A + B + C \tag{3}$$

where: A = natural sediment yield; B = sediment from management-induced surface erosion; and C = sediment from management-induced mass erosion. All values are in terms of tons/square mile/year.

Natural sediment yield is assumed to remain virtually unchanged over time on an average basis and, therefore, is the basis for comparison. Sediment due to management activities is the dynamic component in evaluating management effects. For planning purposes, interest will generally center around defining natural undisturbed sediment yield, the sediment yield under current management conditions, and the expected sediment yield for an array of proposed management strategies. In most instances, estimates of management-induced sediment yields will be desired for time periods ranging from 5 to 10 years into the future. The model developed here has the capability to provide these outputs.

Model outputs can be expressed as a definite quantity of sediment delivered to some point in a watershed, or as a relative index of sediment increase resulting from management activities at some point in a watershed. The type of output generated is a function of the purpose for which the sediment yield prediction is made. In general, greater reliability can be placed on relative evaluations of sediment yield increases than on absolute estimates of sediment quantity. All output values in the model are expressed as "average annual" quantities. These events are rarely observed in nature, but they are the most reliable events to statistically evaluate and verify. Average annual sediment yields should be thought of in the same context as the average annual erosion predictions derived using the Universal Soil Loss Equation. Predictions will differ considerably from actual sediment yield for any single year due to deviations in climatic conditions in any single year from the average. However, as a relative comparative tool, predicted yields still have value. Validation of predicted values must be based on the average of a number of years of data for a valid comparison.

It may be argued that extreme events (low frequency, high intensity) should be evaluated, since they are the most spectacular and do produce large quantities of sediment. However, a general technique is not available to do this with any reliability. On the other hand, average annual quantities and changes can be correlated to extreme events if such interpretations are required. It should be noted, that the extreme event argument is often countered by the notion that higher frequency events, that is, average flows, although less spectacular, are more responsive to management while rare events are not influenced significantly by management. This point of view argues that watersheds will react almost identically during low frequency, high intensity events regardless of the degree of management activities superimposed by man. That is to say, tremendous quantities of sediment will be mobilized during these events as part of the natural functioning of the watershed system.

Consequently, management effects are best observed and evaluated in relation to more common (average) flows. If this is true, then "average" event resolution is further supported.

When outputs are expressed as increases in sediment yield, the following standardized equations are recommended:

$$\begin{array}{l}\text{Sediment yield increase (\%)}\\ \text{(as a percent }\underline{\text{of natural}}\text{)}\end{array} = \frac{\text{Total sediment yield}}{\text{Natural sediment yield}} \times 100$$

$$= \frac{(A + B + C)}{A} \times 100 \tag{4}$$

$$\begin{array}{l}\text{Sediment yield increase (\%)}\\ \text{(as a percent }\underline{\text{over natural}}\text{)}\end{array} = \frac{\text{Sediment increase due to management}}{\text{Natural sediment yield}} \times 100$$

$$= \frac{(B + C)}{A} \times 100 \tag{5a}$$

$$= \left[\frac{(A + B + C)}{A} \times 100\right] - 100 \tag{5b}$$

Where: A, B, and C are as previously defined.

Using equation 4, a doubling of total sediment in the stream is expressed as an increase of 200 percent of natural, or is more commonly referred to as 2 times natural. Using equation 5, a doubling of sediment in the stream is expressed as a 100 percent increase over natural. User's are cautioned to be very careful in selecting terminology when referring to sediment yield increases because an increase of 200 percent of natural is not the same as an increase of 200 percent over natural. Fishery interpretations currently use equation 5b and it is recommended that this form be adopted for general use.

The major reason for calculating sediment yield increase according to equations 4 or 5b is that the quantity (A+B+C), that is, total sediment yield, is a measurable quantity for monitoring purposes. The quantity (B+C), on the other hand, in equation 5a, which is the quantity of sediment produced due to management alone, should not be used because this amount of sediment cannot be meaningfully separated from total sediment for monitoring purposes. Increasingly we are required to monitor how well our predictions conform to real-life situations. The National Forest Management Act specifically states that the Forest Service must be able to monitor the Forest Plan. The results of monitoring can only be used to evaluate the attainment of planning objectives when used in either equations 4 or 5b.

EXAMPLE

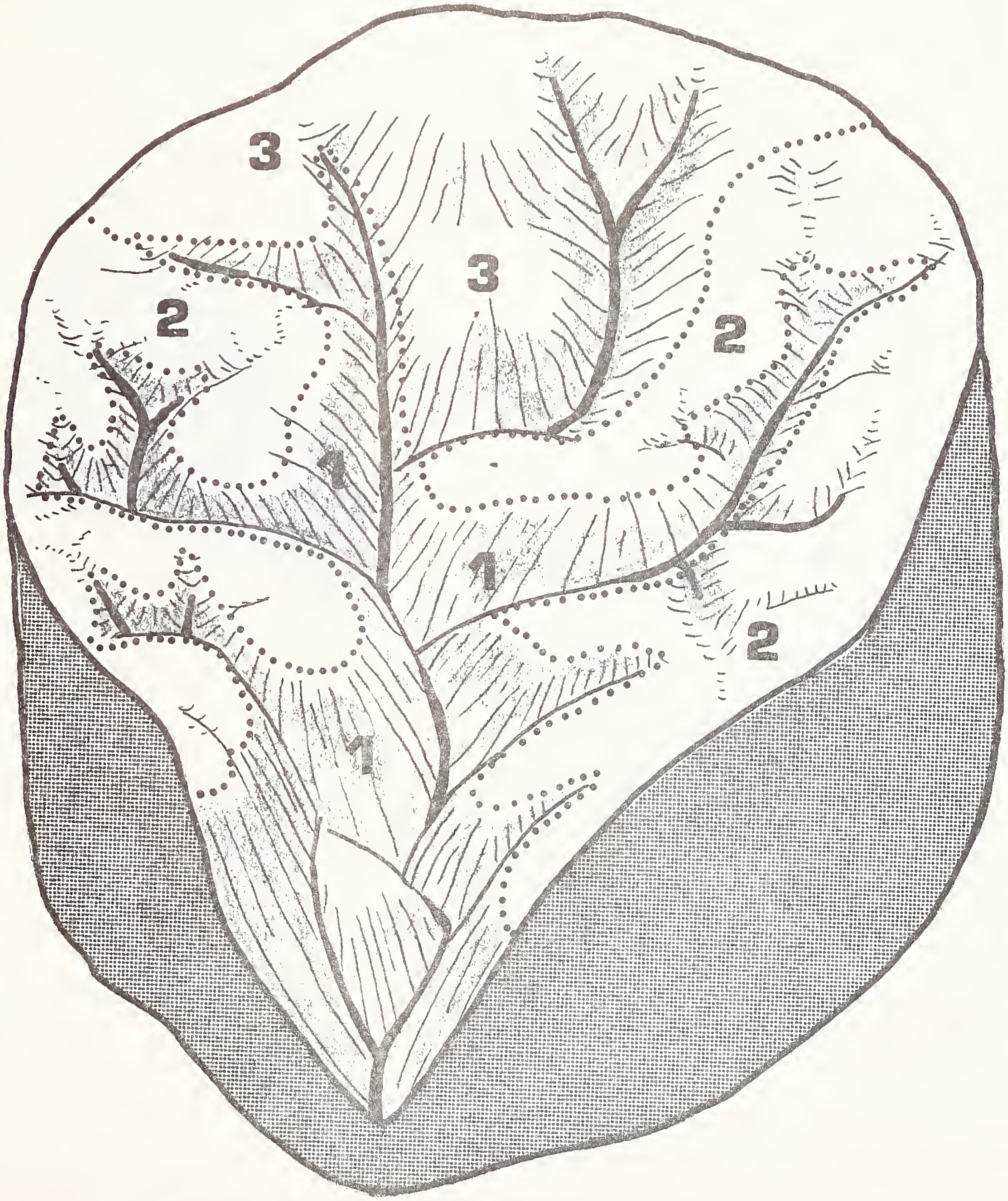
The following hypothetical example was selected to demonstrate the calculations necessary to properly apply the sediment yield model and to illustrate several possible uses of the model.

Statement of Sample Problem: The Forest soil and water specialists have been asked to predict sediment yields from a 15 square mile watershed. The mouth of the watershed has been identified as a critical reach by the Forest fishery biologist. Management would like to harvest timber in this previously undisturbed watershed. To complicate matters, a wildfire has just burned almost two square miles of the watershed. To simplify the analysis, it is assumed that logging and road construction are scheduled to begin the same season the fire took place. A management constraint on proposed activities has been previously identified which states that any sediment yield increase for this watershed must be held to less than 150 percent as measured at the critical reach. The Forest Supervisor has further stated that the timber from this area is vital to meeting Forest timber targets. Management wants an estimate of sediment yield from this watershed under natural conditions, under present conditions (with the wildfire), and for proposed conditions (fire plus road construction and logging) for each year of a 5-year planning period. Is the proposed management acceptable, given the above constraints? If not, what are some possible alternatives given that "don't cut the timber" is not an acceptable solution?

A relief sketch of the example watershed, including delineation of landtypes, is shown as Figure 6. Figure 7 shows a map of the same watershed with the proposed system roads, timber sale areas, and burned area. Additional basic information about these activities is also included.

In this example, sediment yield, due to mass erosion, is assumed insignificant and will not be considered. If mass erosion is important, the procedure in WRENSS should be followed and adapted to local conditions. This example will only concern itself with the calculation of natural sediment yield and sediment yield due to management-induced surface erosion. A further assumption will be made that, for the example, no local data is available and, consequently, all values used are as found in this guide. In most instances, Forests will have some data on hand and are encouraged to modify factors to local conditions.

This example consists of determining three kinds of sediment yields: (1) Natural sediment yield; (2) Sediment yield under present management; and (3) Sediment yield under proposed management. Interpretation of model outputs will be briefly discussed at the end of the example. Common data needs for the various portions of the model will be discussed first.



(Diagram adapted from Clearwater National Forest)

Figure 6: Relief sketch of example watershed showing landtypes.

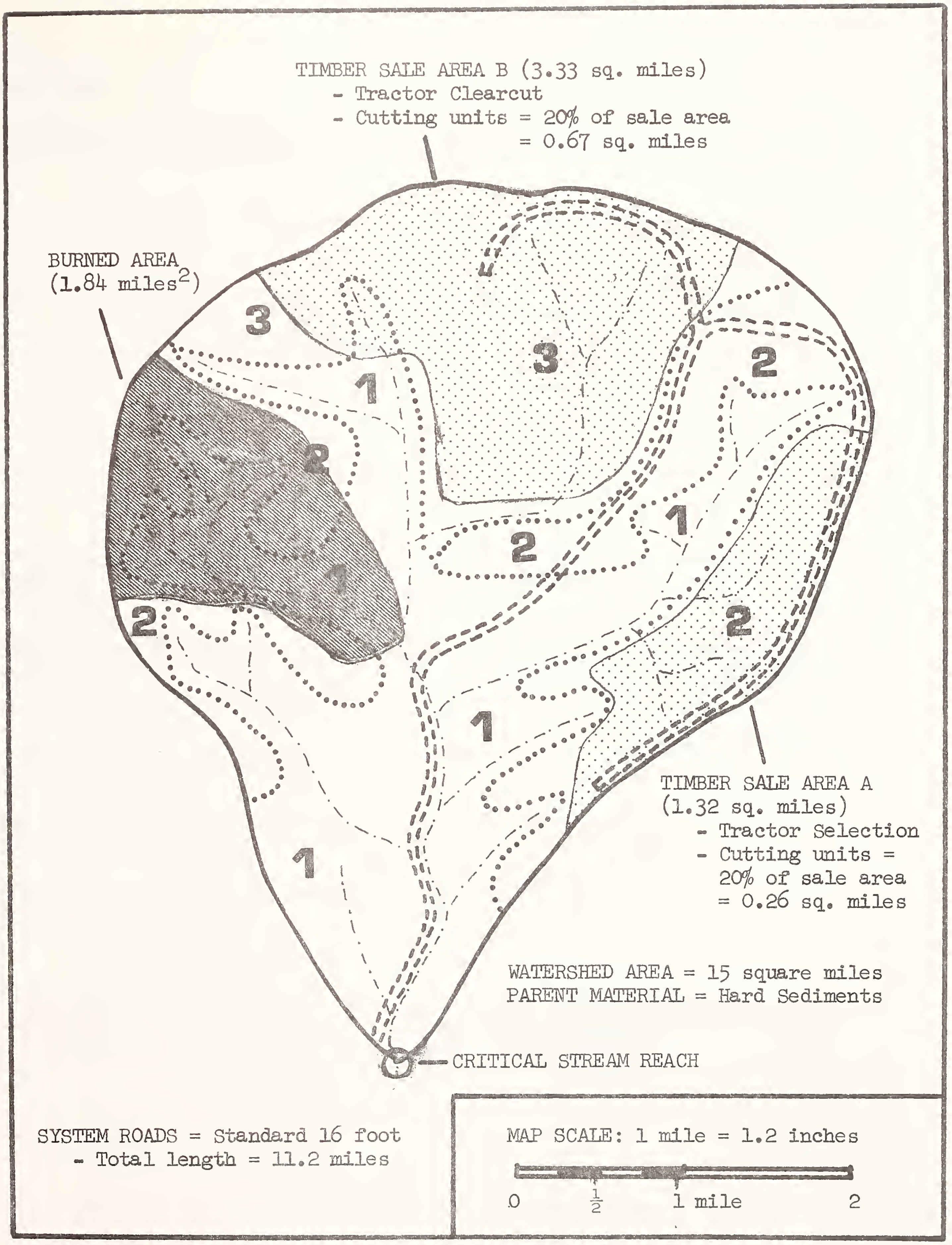


Figure 7. Map of example watershed.

Common Data Needs

The following data is needed for various portions of the model. This data is aggregated by land units (landtypes in our example) and presented in Table 7.

Table 7 - Common data needed for more than one part of the sediment model.

Land Unit (Landtype) (LT) Number	(1) Geologic Erosion Factor	(2) Mass Erosion Hazard Rating	(3) Average Slope (%)	(4) Land Unit Slope Factor	(5) Slope Sediment Delivery Ratio
1	0.52	40	70	1.81	0.60
2	0.52	18	25	0.70	0.15
3	0.52	25	40	0.96	0.20

Column

1 Geologic erosion factor. Parent material bedrock for the example watershed is assumed to be hard sediment. The geologic erosion factor from Table 2 for hard sediment is 0.52.

2 Mass erosion hazard ratings are determined according to procedures in WRENSS, Chapter 5 (Appendix C). Assumed mass erosion hazard ratings for the landtypes in the example are given in the table.

3 Average slope is the average slope of each landtype as determined from the land systems inventory.

4 The land unit slope factor is calculated using equation (1) in the text. The calculation for landtype (LT) 1 is as follows:

$$\text{Land Unit Slope Factor} = \frac{((0.43 + (0.30)(70) + (0.043)(70)(70) \times 0.0374)}{6.613} + 0.50$$

$$= 1.81 \quad \text{(70 in the above equation is the average slope)}$$

5 Slope sediment delivery ratios are determined using the procedure in WRENSS, Chapter 4 (Appendix D). Assumed slope sediment delivery ratios for the landtypes in this example are given in the table.

NATURAL SEDIMENT YIELD

The data that must be tabulated to calculate natural sediment yield is given in Table 8. Refer to Figure 2 for a flow chart of the procedure.

Table 8 - Data needed to calculate natural sediment yield.

Landtype Number	(1) Landtype Area (mi^2)	(2) Mass Erosion Hazard Rating	(3) Average Natural Sed. Rate ($T/mi^2/yr$)	(4) Land Unit Natural Sediment (T/yr)
1	6.51	40	41	266.9
2	4.62	18	12	55.4
3	3.87	25	15	58.0
Totals	15.00			380.3

Column

1 The area of each landtype is determined from the map (Figure 7).

2 Mass erosion hazard rating determined as explained under Table 7.

3 Average natural sediment rate can be determined in one of two ways:

Option 1: Develop estimate for each landtype on the Forest based on local data and local expertise or USLE. Document procedure used.

Option 2: Use relationship between mass erosion hazard rating and average natural sediment rate given in Figure 3. For LT#1, mass erosion hazard rating equals 40. Entering Figure 3, 40 on the x-axis results in a value of 41 on the y-axis as the average natural sediment rate.

4 Land unit natural sediment = (Avg. nat. sed. rate) (LT Area)

LT#1: $(41\ T/mi^2/yr)\ (6.51\ mi^2) = 266.9\ T/yr$
LT#2: $(12\ T/mi^2/yr)\ (4.62\ mi^2) = 54.4\ T/yr$
LT#3: $(15\ T/mi^2/yr)\ (3.87\ mi^2) = 58.0\ T/yr$
380.3 T/yr = total for all landtypes

Convert to unit area basis:

$$\frac{\text{(Total land unit nat. sediment)}}{\text{Total watershed area}} = \frac{380.3\ T/yr}{15\ mi^2} = 25.4\ T/mi^2/yr$$

Route sediment to critical reach:

Use Figure 5 to obtain the channel sediment routing coefficient. For a drainage area of 15 sq. miles, enter the x-axis at 15 and read y-axis as a channel sediment routing coefficient of 0.61.

Watershed Natural Sediment Yield = (total land unit natural sediment) times (channel sediment routing coefficient)

$$= (25.4\ T/mi^2/yr)(0.61) = 15.5\ T/mi^2/yr$$

The natural sediment yield for the 15 sq. mile example watershed is 15.5 $T/mi^2/yr$.

SEDIMENT YIELD UNDER PRESENT MANAGEMENT

The example watershed is assumed to have been undisturbed by man's activities until the occurrence of the fire. Present sediment yield, therefore, consists of natural sediment yield plus any sediment yield increase due to the wildfire.

The data that must be tabulated to calculate sediment yield for the present condition of the watershed is given in Table 9. Refer to Figure 2 for a flow chart of the procedures for fire.

Table 9 - Data needed to calculate sediment yield under present management.

Landtype Number	(1) Basic Fire Erosion Rate (T/mi^2/yr)	(2) Disturbed Area (mi^2)	(3) Fire Intensity Class % of total area			(4) Average Fire Intensity Factor	(5) Total Fire Erosion (T/yr)	(6) Delivered Sediment (T/yr)
			High	Med	Low			
1	550	0.94	20	80	-	0.60	292.0	175.2
2	550	0.90	10	50	40	0.43	77.5	11.6
3	550	None	-	-	-	-		
Totals		1.84						186.8

Column

1 Basic fire erosion rates are obtained from Table 3. Since this is the first year after the fire, the value 550 T/mi^2/yr is used.

2 The area disturbed by fire within each landtype is obtained from the map Figure 7).

3 Fire intensity class is expressed as a percent of the total disturbed area in each landtype that falls within each of the three fire intensity classes. Fire intensity classes are defined in Table 5. Values in Table 9 were assumed for this example.

4 The average fire intensity factor is calculated for each landtype by weighting according to the percent of area in each class. Fire intensity factors are found in Table 5.

Av. fire intensity factor = (High fire intensity factor)(% area burned)
+ (Med. fire intensity factor)(% area burned)
+ (Low fire intensity factor)(% area burned)

Avg. fire intensity (LT#1) = (1.0)(0.20) + (0.5)(0.80) + (0.2)(0) = 0.60
Avg. fire intensity (LT#2) = (1.0)(0.10) + (0.5)(0.50) + (0.2)(0.40) = 0.43

5 Total fire erosion = (basic fire erosion rate) times (geologic erosion factor) times (land unit slope factor) times (fire intensity factor) times (disturbed area)

Total fire erosion (LT#1) = (550)(0.52)(1.81)(0.60)(0.94) = 292.0 T/yr
Total fire erosion (LT#2) = (550)(0.52)(0.70)(0.43)(0.90) = 77.5 T/yr

6 Delivered sediment = (total fire erosion)(slope sediment delivery ratio)
Delivered sediment (LT#1) = (292.0 T/yr)(0.60) = 175.2 T/yr
Delivered sediment (LT#2) = (77.5 T/yr)(0.15) = 11.6 T/yr
186.8 = total delivered sediment

Convert to unit area basis: $\frac{\text{Total delivered sediment}}{\text{Total watershed area}} = \frac{186.8\ \text{T/yr}}{15\ \text{sq. mi.}}$

$= 12.5\ \text{T/mi}^2\text{/yr}$

Route sediment to critical reach:
Channel sediment routing coefficient for 15 sq. mile watershed = 0.61 as determined from Figure 5.

Sediment yield due to fire = (total delivered sediment) times (channel sediment routing coefficient)
$= (12.5\ \text{T/mi}^2\text{/yr})(0.61) = 7.6\ \text{T/mi}^2\text{/yr}$

Year 1 sediment yield due to fire = 7.6 $\text{T/mi}^2\text{/yr}$. Year 2 sediment yield due to fire is calculated by substituting the year 2 basic fire erosion rate into the equation used to calculate column 5. Since only one factor changes, total sediment yield for year 2 can be quickly calculated as a ratio of year 2 basic fire erosion rate to the base year 1 basic fire erosion rate. As an example, year 1 basic fire erosion rate = 550; year 2 basic fire erosion rate = 120. Year 2 divided by year 1 (120/550) shows year 2 to be 21.8 percent of the base year. Multiplying the year 1 sediment yield due to fire (7.6) by 21.8 percent results in the year 2 sediment yield due to fire ($7.6 \times 0.218 = 1.7\ \text{T/mi}^2\text{/yr}$). Total sediment yield due to fire for years 3,4, and 5 can be calculated in a similar manner assuming that only one factor in the equations changes.

Total sediment yield = (Natural sediment yield) + (Sediment yield due to fire) for each year in the planning cycle. The results of these calculations for all years are shown in Table 10.

Table 10 - Sediment yield under present management for a 5-year period.

Year	Natural Sediment Yield ($\text{T/mi}^2\text{/yr}$)	Sediment Yield Due to Fire ($\text{T/mi}^2\text{/yr}$)	Present Condition Total Sed. Yield ($\text{T/mi}^2\text{/yr}$)	Increase Over Natural (%)
1	15.5	7.6	23.1	49
2	15.5	1.7	17.2	11
3	15.5	0.3	15.8	2
4	15.5	0.1	15.6	1
5	15.5	0.0	15.5	0

Sediment yield increase over natural was calculated using equation 5b in the text.

SEDIMENT YIELD UNDER PROPOSED MANAGEMENT

Proposed management for the example watershed is to consist of two planned timber sales and the construction of one road. For the sake of simplicity to assist in explaining the calculation procedure, road construction and the two timber sales are assumed to take place in the same year. Similarly, sediment yield impacts due to fire are also assumed to occur during this year and must be added to sediment yield calculated for the proposed management since they occur simultaneously on the watershed.

Sediment yield will be calculated first for the roads and then for the logging. The data that must be tabulated to calculate sediment yield for proposed roading is given in Table 11. Refer to Figure 2 for a flow chart at the procedure.

Table 11 - Data needed to calculate sediment yield under proposed management - roads.

Landtype Number	(1) Basic Road Erosion Rate (T/mi^2/yr)	(2) Road Length (miles)	(3) Width of Disturbed Area (feet)	(4) Width of Disturbed Area (miles)	(5) Disturbed Area (mi^2)	(6) Mitigation Factor
1	67,500	3.4	50	0.00947	0.032	0.60
2	67,500	5.9	23	0.00436	0.026	0.58
3	67,500	1.9	27	0.00511	0.010	0.58

Landtype Number	(7) Total Road Erosion (T/yr)	(8) Delivered Sediment (T/yr)
1	673.9	404.3
2	529.3	79.4
3	203.6	40.7
Total		524.4

Column

1 Basic road erosion rates are obtained from Table 3.

2 Road length is obtained from the map (Figure 7).

3 Width of the disturbed area is the horizontal distance from the top of the cut slope to the bottom of the fill slope. Tables of geometry, such as provided by Megahan (1976), are useful for making this determination. A standard 16-foot road is assumed with balanced construction, fill slope gradient of 1.5:1 and cut slope gradient of 1:1. Using the average slope for the landtype, geometry tables can be entered

directly to obtain the disturbed width. This was done for landtypes 2 and 3. An alternate method is to use geometric relationships to calculate these values. For landtype 1 (average slope 70%), the standard road assumed above was not felt to be realistic due to long fill slopes. Consequently, full bench construction with end-haul of materials was assumed for roads on this landtype. Consequently, only the width disturbed by the road surface and the cut slope were used to calculate width.

4 The width of the disturbed area in feet is converted to width in miles for ease of subsequent calculations (feet divided by 5280 feet/mile).

5 Disturbed area = (road length)(width of disturbed area)
Disturbed area (LT#1) = (3.4 miles)(0.00947 miles) = 0.032 sq. miles
Disturbed area (LT#2) = (5.9 miles)(0.00436 miles) = 0.026 sq. miles
Disturbed area (LT#3) = (1.9 miles)(0.00511 miles) = 0.010 sq. miles

6 Assumed mitigation measures to be applied to all roads are seeding and fertilization of all cut and fill slopes and planning for adequate buffer strips. In addition, roads in landtypes 2 and 3 are assumed to have grades less than 5 percent on the average. Percent erosion reduction for these measures are obtained from Table 4.

Seed and fertilizer application	25% erosion reduction
Buffer strips	15% erosion reduction
Grades less than 5%	2% erosion reduction

The mitigation factor is the sum of the percent reduction in erosion for all mitigation measures applied subtracted from 1.0.
Mitigation factor (LT#1) = 1.0 - (0.25 + 0.15) = 1.0 - 0.40 = 0.60
Mitigation factor (LT#2) = 1.0 - (0.25 + 0.15 + 0.02) = 0.58
Mitigation factor (LT#3) = 1.0 - (0.25 + 0.15 + 0.02) = 0.58

7 Total road erosion = (basic road erosion rate) times (geologic erosion factor) times (disturbed area) times (mitigation factor)
Total road erosion (LT#1) = (67,500)(0.52)(0.032)(0.60) = 673.9 T/yr
Total road erosion (LT#2) = (67,500)(0.52)(0.026)(0.58) = 529.3 T/yr
Total road erosion (LT#3) = (67,500)(0.52)(0.010)(0.58) = 203.6 T/yr

8 Delivered sediment = (total road erosion)(slope sediment delivery ratio)
Delivered sediment (LT#1) = (673.9 T/yr)(0.60) = 404.3 T/yr
Delivered sediment (LT#2) = (529.3 T/yr)(0.15) = 79.4 T/yr
Delivered sediment (LT#3) = (203.6 T/yr)(0.20) = 40.7 T/yr
524.4 T/yr = total delivered sediment

Convert to unit area basis: $\frac{\text{Total delivered sediment}}{\text{Total watershed area}} = \frac{524.4 \text{ T/yr}}{15 \text{ sq. mi.}}$

= 35.0 T/mi^2/yr

Route to critical reach:
Channel sediment routing coefficient = 0.61 (see Figure 5)
Sediment yield due to roads = (total sediment delivered) times (channel sediment routing coefficient)
= (35.0 T/mi^2/yr)(0.61) = 21.4 T/mi^2/yr

Year 1 sediment yield due to roads = 21.4 T/mi^2/yr.
Year 2 sediment yield due to roads is calculated by substituting the year 2 basic road erosion rate into the equation used to calculate Column 7 and then performing the remaining calculations as demonstrated. An alternate quick method is to use the ratio procedure as described for fire in the previous section.
Year 2 sediment due to roads = 18,000/67,500 = 26.7 percent and 26.7 percent of 21.4 = 5.7 T/mi^2/yr.
Total sediment yield due to roads for years 3, 4, and 5 are calculated in a similar manner, assuming only the basic road erosion rate factor changes. If other factors, such as mitigation measures, also change, the long procedure should be used. Total sediment yield due to roads for subsequent years will be displayed after the discussion of logging.

The data that must be tabulated to calculate sediment yield due to proposed logging is given in Table 12.

Table 12 - Data needed to calculate sediment yield under proposed management - logging.

Landtype Number	(1) Timber Sale Area	(2) Logging System Erosion Factor	(3) Total Sale Area (mi^2)	(4) Disturbed Area (mi^2)	(5) Basic Logging Erosion Rate (T/mi^2/yr)	(6) Total Logging Erosion (T/yr)	(7) Delivered Sediment (T/yr)
1	B	1.00	0.13	0.03	340	9.6	5.8
2	A	0.71	1.32	0.26	340	22.8	3.4
3	B	1.00	3.20	0.64	340	108.6	21.7
Total							30.9

Column

1 Timber sale areas are defined in Figure 7.

2 Logging system erosion factors are obtained from Table 6. Sale area A is assumed clearcut tractor selection; sale area B is assumed clearcut tractor.

3 The total sale area in each landtype is obtained from the map (Figure 7).

4 The area actually disturbed by logging operations and temporary roads is the area within timber sale boundaries composed of cutting units and temporary roads. For this example, cutting units were assumed to be 20 percent of the total sale area.

5 Basic logging erosion rates are taken from year 1 of Table 3.

6 Total logging erosion = (basic logging erosion rate) times (geologic erosion factor) times (land unit slope factor) times (logging system factor) times (disturbed area)
Total logging erosion (LT#1) = (340)(0.52)(1.81)(1.00)(0.03) = 9.6 T/yr
Total logging erosion (LT#2) = (340)(0.52)(0.70)(0.71)(0.26) = 22.8 T/yr
Total logging erosion (LT#3) = (340)(0.52)(0.96)(1.00)(0.64) = 108.6 T/yr

7 Delivered sediment = (total logging erosion)(slope sediment delivery ratio)
Delivered sediment (LT#1) = (9.6 T/yr)(0.60) = 5.8 T/yr
Delivered sediment (LT#2) = (22.8 T/yr)(0.15) = 3.4 T/yr
Delivered sediment (LT#3) = (108.6 T/yr)(0.20) = 21.7 T/yr
30.9 T/yr = total delivered sediment

Convert to unit area basis:

$$\frac{\text{Total delivered sediment}}{\text{Total watershed area}} = \frac{30.9 \text{ T/yr}}{15 \text{ sq. mi.}}$$

$$= 2.1 \text{ T/mi}^2\text{/yr}$$

Route to critical reach:
Channel sediment routing coefficient = 0.61 (see Figure 5)
Sediment yield due to logging = (total sediment delivered) times (channel sediment routing coefficient)
= (2.1 T/mi^2/yr)(0.61) = 1.3 T/mi^2/yr

Year 1 sediment yield due to logging = 1.3 T/mi^2/yr.
Year 2 sediment yield due to logging is calculated by substituting the year 2 basic logging erosion rate into the equation used to calculate column 6 and then performing the remaining calculations as demonstrated.
An alternate quick method is to use the ratio procedure as described for fire in the sediment yield under the present management section.
Year 2 sediment due to logging = 180/340 = 52.9% and 52.9% of 1.3 = 0.7 T/mi^2/yr.
Total sediment yield due to logging for years 3, 4, and 5 are calculated in a similar manner assuming only the basic logging erosion rate factor changes.

Proposed Management:
Total sediment yield = (Natural sediment yield) + (Sediment due to management-induced surface erosion)
= Natural sediment yield) + (Sediment due to roads) + (Sediment due to logging) + (Sediment due to fire)
Total Sed. Yield (Year 1) = (15.5) + (21.4) + (1.3) + (7.6) = 45.8 T/mi^2/yr.

Percent increase in sediment yield over natural is calculated according to equation 5b in the text. For year 1:

$$\text{Percent increase over natural} = \left(\frac{(15.5) + (21.4) + (1.3) + (7.6)}{15.5} \times 100\right) - 100$$

$$= 195 \text{ percent}$$

The results of all these calculations for all 5 years are presented in Table 13.

Table 13 - Sediment yield under proposed management for a 5-year period.

Year	Natural Sed. Yield ($T/mi^2/yr$)	Management-Induced Sed. ($T/mi^2/yr$) Roads	Logging	Fire	Total Sediment Yield ($T/mi^2/yr$)	Increase Over Natural (Percent)
1	15.5	21.4	1.3	7.6	45.8	195
2	15.5	5.7	0.7	1.7	23.6	52
3	15.5	1.6	0.5	0.3	17.9	15
4	15.5	1.6	0.3	0.1	17.5	13
5	15.5	1.6	0.2	0.0	17.3	12

Interpretations: Year 1 total sediment yield is predicted to be greater than the 150 percent increase over natural which is considered the acceptable level of increase for the purposes of this example. Comparing sediment yield estimates in Table 13, it is readily apparent that roads contribute the greatest amount of sediment and that sediment yields decrease rapidly over time. Consequently, two approaches to reducing sediment yields are possible. One is to modify activities, especially during the first year, to reduce sediment yields; the other is to spread sediment yields over a longer time period.

One possible alternative is to increase mitigation measures on the road system until acceptable total sediment yield increases are achieved. By maximizing mitigation measures to 80 percent, percent increase over natural can be reduced to 104 percent. Using the other approach of spreading impacts over time, road construction could be staged over several years as could the logging. Numerous other alternatives can be developed and evaluated such as changing road design, investigating alternate road locations, using different harvesting systems, deferring entry until fire effects are reduced, or combinations of the above.

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APPENDIX A: GLOSSARY

Bedload - Material moving on or near the streambed by rolling, sliding, and, sometimes, making brief excursions into the flow a few diameters above the bed.

Critical stream reach - A reach of the stream that is selected because it is the point in the watershed where the importance of sediment yield will be interpreted.

Erosion - The wearing away of the land surface by detachment and movement of soil and rock fragments through the action of moving water and other geologic agents.

The following terms are used to describe different types of erosion:

> Accelerated erosion - Erosion, at a rate greater than normal, is usually associated with the activities of man which reduce plant cover and increase runoff. Accelerated erosion is discussed as management-induced surface erosion and management-induced mass erosion.
>
> Natural erosion - The erosion process, on a given land form, that is not associated with the activities of man. Natural erosion delivered downstream results in what is referred to as natural sediment yield.
>
> Mass erosion - Movement of large masses of earth materials in response to gravity, either slowly or quickly. This includeds, slumps - rotation of a soil block with small lateral displacement, debris avalanches - rapid, shallow movement of soil mantle and rock fragments, landslides - sudden downslope movement of earth and rock, and soil creep - slow, gradual, more or less continuous permanent deformation of soil under gravitational stress.
>
> Surface erosion - The wearing away of the land surface by running water or wind. This includes: sheet erosion, the removal of a surface soil by runoff water; rainsplash erosion, the spattering of small soil particles caused by the impact of raindrops on the soil surface; and rill and gully erosion.

Land unit - The basic area of land displaying relatively uniform characteristics and defined in a manner to provide necessary physical information needed to drive the model. Landtypes in the land systems inventory, generally, provide this kind of information.

Logging systems - The following definitions are used for these logging systems:

> Tractor refers to tractors working directly on-site.
>
> Cable refers to ground cable systems where logs are dragged without suspension, including jammer and high lead systems.
>
> Skyline refers to suspended cable systems that allow at least partial log suspension for all or part of the yarding distance.

Aerial refers to aerial systems (helicopter or balloon) that allow for essentially complete log suspension.

Routing - (1) The derivation of an outflow hydrograph of a stream from known values of upstream inflow. (2) Computing the flood at a downstream point from the flood inflow at an upstream point, and taking channel storage into account.

Sediment - Particles derived from rocks or biological materials that have been transported by a fluid.

Sediment delivery - Two types of sediment delivery are discussed. 1) slope sediment delivery is the material brought to the stream channel from surrounding hillslopes by surface and mass erosion, and 2) channel sediment delivery is the movement of sediment through the stream channel system in response to stream hydraulics.

Sediment delivery ratio - The volume of sediment material actually delivered to a point in a watershed divided by the total amount of material available for delivery. Two types of delivery ratios are discussed: (1) slope sediment delivery ratio, and (2) channel sediment routing coefficient as respectively discussed under sediment delivery above.

Sediment routing - (1) The process of determining progressively the timing and shape of a sediment wave at successive points along a river; (2) term used to discuss the movement of sediment within a stream channel system.

Sediment yield - The total sediment outflow from a drainage basin in a specified period of time. It includes bedload as well as suspended load, and is expressed in terms of mass, or volume per unit of time. The standard unit of expression for our purpose is tons/square mile/year.

Suspended sediment - Sediment that is carried in suspension by the turbulent components of the fluid or Brownian movement.

Total sediment load - All of the sediment in transport; that part moving as suspended load plus that part moving as bedload.

APPENDIX B: DESCRIPTION OF BOISE NATIONAL FOREST LANDTYPES (corresponds to 25 $T/mi^2/yr$ natural sediment yield)

Map Symbol 120c

STRONGLY DISSECTED MOUNTAIN SLOPE LANDS

Shallow and Moderately Deep Sandy and Sandy Skeletal Soils Over Soft Bedrock

Location: This unit is common along Lick Creek and around the Deadwood Reservoir.

Landtype Characteristic: These lands are steep southerly slopes that have been deeply incised by a stream cutting. Side slopes have numerous dendritic dissections 30 to over 50 feet deep and less than 500 feet apart. In areas where dissections are more widely spaced, entrenchment is deeper. Slope gradients range from 40 to 70 percent. Ridges are relatively sharp with little exposed bedrock. The slopes are moderately well timbered with forest crown densities ranging from 10 to 60 percent. The shallow and moderately deep sandy and sandy skeletal soils are underlain by moderately to well weathered granite that is extremely well fractured or masked.

Soils: The dominant soil (80%--JEFA-1), on most mid and lower slopes, has a 0 to 1-inch organic layer over a brown gravelly sand, 20 to 60 inches deep, with 20 percent fine gravels. A minor soil (20%--JEFA-2) is a shallow phase of the dominant soil and contains 40 percent coarse fragments dominated by fine gravels.

Vegetation: The slopes of this landtype are moderately timbered with the following habitat types represented: Douglas-fir/spirea, Douglas-fir/wheat grass, Douglas-fir/pinegrass, Douglas-fir/ninebark, and ponderosa pine/bitterbrush. Forest crown density is 10 to 60 percent and brush crown density is 40 to 70 percent.

Hydrology: Mean annual precipitation is 20 to 35 inches and mean water yield is 5 to 15 inches. Snowpacks are low to moderate and snowmelt can occur on and off in late winter on southerly aspects. Runoff is usually spread over a three to four-month period ending in mid to late May. Runoff from normal snowmelt conditions is shallow to moderately deep subsurface flow and deep percolation through the soft bedrock. These areas receive 8 to 15 inches of water input from heavy rainstorms and rain-on-snow events on an average of about once in ten years. Under these conditions, heavy runoff occurs in a few days dominantly as shallow subsurface flow which accumulates in concave incipient draws and moves down these draws until forced to the surface. These slopes release the water delivered to them at a moderate to rapid rate and dry rapidly after snowmelt. Water held in weathered bedrock provides much of the summer moisture for deep rooted vegetation.

Management Qualities: Construction hazards are rated dominantly high on this landtype. Interception of subsurface flow, spalling bedrock, and sedimentation are the most important considerations.

Roads. The characteristics of this landtype are generally poor for road location except on upper slopes and ridges. Poorly graded, incompetent,

spalling bedrock, combined with the probable interception of subsurface flow on lower slopes, will result in unstable cuts and fills. These factors will increase the probability that sediment will reach adjacent drainages. Accelerated surface erosion will be a major problem from disturbed soil surfaces and construction.

Wood, These units are some of the more productive on the District. The timber productivity rating is dominantly moderate with ponderosa pine; the most productive seral species of the Douglas-fir habitat types. Limitations to reforestation are severe and are related to water holding capacity and high evapotranspiration losses.

Water. Interception of subsurface flow is a moderate hazard in normal runoff years because runoff is spread over a number of months. However, during the abnormally heavy rains and rain-on-snow events, which can occur in fall, winter or spring, subsurface flow interception and concentration is a very serious hazard because of the large amount of runoff during a short period. The hazard for serious erosion and sedimentation from concentration of intercepted subsurface flow during these periods is very high. A combination of moderately deep cuts and disturbed soil near drainage channels will increase the hazard for serious sedimentation. Road crossings of the deeply entrenched second and third order streams have a high sedimentation hazard. The convex upper slopes are less hazardous due to the lack of deeply entrenched drainage channels and less accumulated subsurface runoff water.

Forage. The potential production for this landtype is 400 to 900 pounds per acre per year of usable dry forage. The lower yield is associated with the exposed upper ridge positions and the shallow, coarse-textured soils. On these areas, water holding capacity is low. The higher yields are related to the more moist micro-climate on protected lower slopes and drainages. The vegetation is dominated by browse species. Grasses and forbs are limited. Grazing, however, will greatly accelerate the erosional process by removing the protective vegetation and litter. Surface creep hazard will also be accentuated.

Recreation. The potential for recreation on these units are related to aesthetics and providing a "Forest Experience." The landtype provides a timbered scenic backdrop for vistas but is generally unstable for most recreational developments and roads. Big game hunting is a major fall activity on these units. Trails will be highly erosive but have fair to good trafficability.

Map Symbol 120c-11
STRONGLY DIESSECTED MOUNTAIN SLOPE LAND
Moderately Deep and Deep Fine Loamy and Loamy Skeletal Soil

Location: This landtype is common to those heavily timbered steep north slopes over most of the District. The north slopes above the Middle Fork of the Payette River are typical.

Landtype Characteristics: These fluvial lands are the steep north slopes that have been strongly (less than 500 feet apart) incised by stream cutting, intermittent concentrations of overland flow and the rapid concentration of shallow and moderately deep subsurface flow. Sideslopes are of moderate length and steep with numerous parallel dissections. Ridges are relatively sharp with little exposed bedrock. Slope gradients range from 50 to 70 percent. The moderately deep and deep coarse loamy and loamy skeletal soils have developed over masked or well fractured, moderately to well weathered granite bedrock.

Soils: The dominant soil (60%--IFBA-5) has a 0 to 4-inch organic layer over a dark brown to dark yellowish brown gravelly sandy loam 40 to 60 inches deep, with 25 percent fine gravel, and 20 to 30 percent rock. This soil is most common on mid and upper slopes. A less extensive soil (40%--IFBA-3) on more exposed upper east and west slopes and areas of highly weathered granite on north slopes, has a 0 to 3-inch organic layer over a very dark grayish brown to dark brown gravelly sandy loam to gravelly loamy coarse sand, 20 to 60 inches deep, with 10 to 20 percent fine gravels and less than 10 percent rock.

Vegetation: This landtype is one of the better timber producing units on the District with forest crown densities ranging from 30 to 80 percent. The dominant habitat types are ponderosa pine/wheatgrass, Douglas-fir/chokecherry, Douglas-fir/spiraea, and Douglas-fir/ninebark. Brush crown densities range from 30 to 80 percent.

Hydrology: Mean annual precipitation is 28 to 40 inches and mean water yield is 10 to 20 inches. Snowpack is moderate to heavy and persists into June on the highest areas and into May on the lower areas. Major runoff is in April and May when heavy discharge of subsurface flow occurs. Overland flow from summer storms is rare on undisturbed areas. Runoff is about evenly divided between moderately deep subsurface flow above bedrock and ground-water flow through the upper weathered and fractured portion of bedrock. The accumulation of this runoff increases going downslope and moving from convex to straight to concave shaped slopes. Greatest concentration of subsurface flow is in the incipient drainageways on the lower two-thirds of the slope. Ground-water is most concentrated and nearest the surface on deep soiled slopes and deposits adjacent to the more deeply entrenched streams. Debris-laden flash flows seldom occur in drainageways in this landtype. Outflow rate of water delivered to these slopes is slow to moderate.

Management Qualities: Most hazards for this landtype are rated moderate to very high. High surface erosion hazards and mass stability problems associated with interception of subsurface flow will be major limitations. Bedrock spalling will be common in most exposed road cuts. This landtype, however, is one of the most productive for commercial timber species.

Roads. The qualities of this landtype present many hazards to road construction. Very poorly graded,noncompetent, spalling bedrock combined with probable interception of subsurface flow will result in very unstable road cuts and fills. These problems combine with a high surface erosion hazard greatly increasing the probability that sediment will reach adjacent drainages. The least impact has been observed where roads have been restricted to the upper one-quarter of slopes althogh surface erosion and interception of subsurface water are still problems in selected areas.

Some areas of very well weathered granite bedrock, clay pockets, are of limited extent but very significant because of the problems they create in construction. These heavy textured soils are restricted to the more moist northerly aspects that are heavily vegetated. Where possible, these areas should be avoided.

Wood. This landtype is one of the better commercial timber producing units on the District. Timber productivity ratings range dominantly from moderate to very high for the major habitat types, Douglas-fir/spirea and Douglas-fir/ninebark. Reforestation site limitations are moderate to severe with high evapotranspiration losses on south slopes and vegetative competition on all slopes the major limiting factors.

Water. Hazard of intercepting large quantities of subsurface flow is hgih at concave swales and incipient draws. Hazard of ground-water interception is high adjacent to streams. Sedimentation hazard is high to very high for roads crossing the deeply entrenched streams on the lower one-half of these slopes and moderate to high on the upper one-half. The combination of hazards presents an overall hazard to hydrologic characteristics of high to very high on lower slopes and moderate to high on upper slopes.

Forage. Forage production potential on this landtype is rated low to high with the vegetation dominated by browse species. Grasses and forbs are limited, most common under the ponderosa pine habitat types on southerly ascpects. Grazing, however, will greatly accelerate the erosional processes by removing the protective vegetation and litter. Surface creep will also be accelerated increasing the frequency of debris slides.

APPENDIX C
WRENSS - Chapter 5
Soil Mass Movement

Chapter V

SOIL MASS MOVEMENT

this chapter was prepared by the following individuals:

Douglas Swanston
Frederick Swanson

with major contributions from:

David Rosgen

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INTRODUCTION

Accurate models and the data needed to predict soil mass movement hazard and magnitude of delivery to stream courses over broad areas are currently lacking. Existing techniques for site specific stability analyses (based on the Mohr-Coulomb Theory of Earth Failure) are quite accurate in assessing the strength-stress relationships in a small area. These techniques, however, require accurate measurement of the engineering properties of the soils involved and specific knowledge of the geology and ground water hydrology at the site. Such data are costly to obtain and vary greatly among sites, even under the same geologic and climatic settings, making this mechanistic approach impractical for broad area hazard assessment.

A more practical approach is to combine:

1. A subjective evaluation of the relative stability of an area using soils, geologic, topographic, climatic, and vegetative indicators obtained from aerial photos, maps, and field observations.
2. A limited strength-stress analysis of the unstable sites using available or easily generated field data.
3. Estimates of sediment delivery to streams based on failure type, distance from the stream channel, and certain site variables such as slope gradient and slope irregularity.

This information can be integrated to provide a measure of mass movement hazard and the level of sediment contributed to adjacent stream channels.

Such an approach is developed in this chapter to provide a uniform framework for slope stability assessment and estimation of sediment delivery to channels by soil mass movement. A flow chart of this procedure is presented in figure V.1.

The primary objectives of the procedure are to determine: (1) natural stability of the site, (2) the sensitivity of the site to natural and man-induced soil mass movement events (the hazard index of soil mass movement generation or acceleration), (3) the probable volume of material released by soil mass movement, and (4) the amount of soil mass movement material delivered to the nearest drainageway.

Several common site and climatic factors which vary greatly over a wide region are related to soil mass movements. To provide for continuity over multiple geographic areas, the major factors controlling slope stability are summarized here by dominant failure types and placed in a framework of hazard index analysis.

If the user does not have experience in delineating potential soil mass movement sites, additional assistance will be required from specialists in the allied fields of geology, geotechnical engineering, and soil science. Users are strongly advised to seek assistance from these specialists whenever possible.

This chapter examines two groups of erosion processes: (1) rapid, shallow soil mass movements, collectively termed "debris avalanches-debris flows", but including a broad range of processes such as debris slides and rapid mudflows (Varnes 1958); and (2) slow, deep-seated soil mass movements, termed "slumps" and "earthflows" or collectively "slump-earthflows." These mass movement processes are described further in the section, "Principals and Interpretations of Soil Mass Movement Processes."

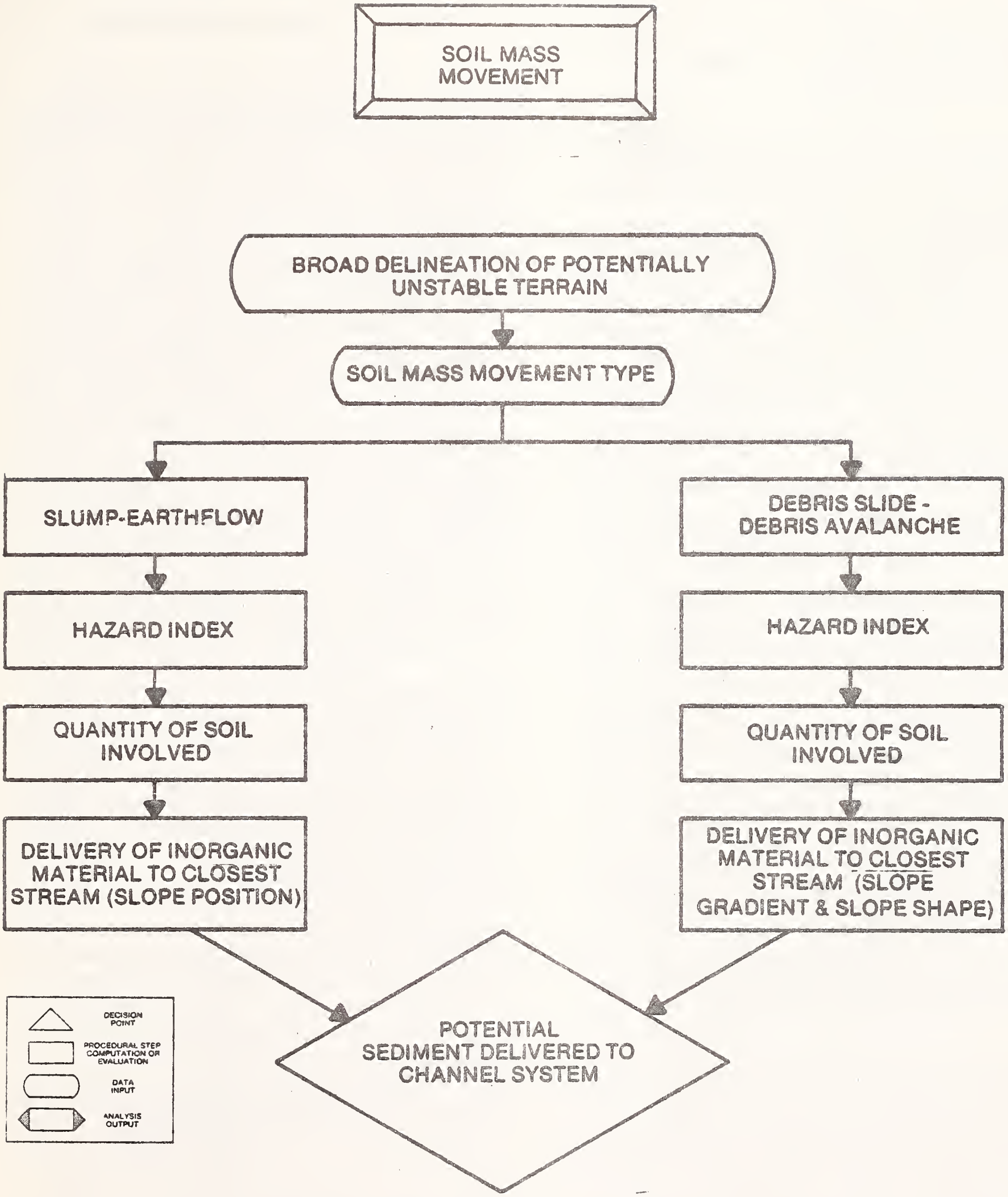

Figure V.1.—General flow chart of the soil mass movement procedure.

DISCUSSION

REVIEW OF RELEVANT WORK

Although quantitative assessment of all factors contributing to mass movement is complex and difficult, a consistent analysis of the major contributing factors can benefit the land manager, whose activities may affect slope stability. Burroughs and others (1976) discuss the effects of geology and structure in northern California and western Oregon on landslides generated by road construction; Swanston and Swanson (1976) describe the effects of geomorphology, climate, and forest management activities on debris avalanche and slump-earthflow activity in the western Cascades; Greswel, and others (in press) have assessed the effects of clearcut logging and road construction on accelerated debris avalanche activity during a single high intensity storm in the Oregon Coast Range; Burroughs and Thomas (1977) have analyzed the declining root strength in Douglas-fir, after felling, as a factor in slope stability; and Flaccus (1958), Hack and Goodlet (1969), and Williams and Guy (1973) discuss the effects of hurricane and cloudburst triggered soil mass movement in the eastern United States.

Some interesting and successful techniques also have been developed for predicting unstable ground and identifying controlling and contributing factors. Pillsbury (1976), for example, using a linear discriminant functions analysis, attributed 90.5 percent of the debris avalanches in clearcut areas of a northern California watershed to the factors of slope percent and percent cover by dominant and understory vegetation. Both of these factors were determined by photogrammetric techniques with no ground control. An additional 1.5 percent of debris avalanche occurrences was determined by adding in the site factors of soil weathering and percent quartz in bedrock. Using photogrammetric procedures, Kojan, Foggin, and Rice (1972) were able to predict 84.4 percent of the debris slides following major storms in the Santa-Ynez-San Rafael Mountains, California, based on past landslide activity.

The factor of safety is commonly used as a quantitative expression of the hazard index of a soil mass movement. In soil mechanics, it is customary to express the balance of forces acting on a simple slope as:

$$\text{Factor of safety (F)} = \frac{\text{Resistance of the soil to failure (shear strength)}}{\text{Forces promoting failure (shear stress)}}$$

A safety factor of one ($F=1$) would indicate imminent failure. For broad land use planning purposes, this technique is valid only for rapid, shallow soil mass movements, such as debris avalanches and debris flows. Quantitative models utilizing this approach have been outlined in Swanson and others (1973), Brown and Sheu (1975), Bell and Swanston (1972), and Simons and Ward (1976). The difficulty in determining some of the factors (such as tensile strength of roots, location of the failure surface, and water table position for various storm intensities) has until recently, restricted the use of such models to highly instrumented sites where expensive investigations were warranted. New data and techniques are being developed, however, which are making these models more practical as land management tools.

Swanston (1972, 1973) has employed a factor of safety technique using a simplified infinite slope model to predict slope stability hazard and stratify lands according to management impact in southeast Alaska. This technique uses slope gradient as a prime hazard index. Bell and Keener (1977) have developed a method of predicting stable cut-slope heights based on the factor of safety analysis of natural slopes. Burroughs and Thomas (1977) have analyzed the effects of soil shear strength, slope gradient, soil depth, ground water rise, and root strength on stability hazard in the central Coast Range of Oregon. Prellwitz (1977) has made substantial progress in utilization of the factor of safety approach without the need for expensive site investigation. The equations account for buoyant density, fluctuating water tables, and moisture density.

Soil mass movements can yield substantial sediment. Megahan (1972) and Megahan and Kidd (1972a, 1972b) evaluated the effects of logging and road construction on high erosion hazard land in the Idaho Batholith. They report sediment yields 1.6 times greater from jammer logged sites than from undisturbed areas (they did not differentiate between surface erosion and soil mass movement). Soil mass movements from logging roads in the same area average 550 times greater than control

areas. Swanston and Swanson (1976) report debris avalanche erosion rates 2 to 4 times greater from clearcuts and 25 to 344 times greater from roads than from undisturbed sites in selected areas of the Coast Range and Cascade Mountains of Oregon, Washington, and British Columbia.

Prediction of sediment yield from individual soil mass movement processes is not well documented. Individual failure release volumes are available for a few areas, but there is little information on how much of the total volume initially reaches the stream versus how much remains on the slope for slow release over time. A summary of average debris avalanche volume from six studies in the Pacific Northwest reveals a broad range in average volumes from area to area (Swanson and others 1977). For example, in the Mapleton Ranger District of the Oregon Coast Range, an area of steep, intricately dissected terrain with very shallow soil, average debris avalanche volume is less than 100 yd^3(76 m^3), whereas steep areas of lower drainage density and deeper soils have had debris avalanches averaging more than 1,000 yd^3(765 m^3). In the Mapleton area, Swanson and others (1977) estimated that 65 percent of the material moved by debris avalanches in forests entered streams.

Since sediment yield values for individual soil mass movements are very limited, a series of conceptual delivery curves were developed for this handbook to approximate the sediment transport potential of dominant soil mass movement processes. These curves are presented as first approximations only, and it may be necessary to develop specific delivery curves to more accurately represent local conditions. Delivery relations are needed to estimate sediment supply to streams where it will be routed through the channel network. The delivery curves in the analysis section were developed from studies of recent failures in the western Cascades and Coast Range of Oregon, and were based on estimates of the percent of material released during the initial failure that actually entered a stream. The site variables which appeared particularly sensitive to the amount of soil delivered to a drainageway were: slope gradient and slope irregularity for debris avalanche-debris flows, and slope position with respect to the closest drainageway for slump-earthflows.[1] Slump-earthflow failures not adjacent to streams, are not considered principal contributors to channel loading in this analysis since their potential impact on short-term sediment loading is negligible because of their low delivery efficiencies. Most of the sediment from mid- and upper-slope failures of this type remain on the slope following initial failure and is delivered to the channel over extended periods, mainly by surface erosion and creep.

ASSUMPTIONS

The procedures in this chapter are presented as a guide for assessing the stability of natural slopes, the potential impacts of silvicultural activities on slope stability, and predicting sediment contributions to drainageways from soil mass movements. In the absence of proven local techniques, these procedures will provide the best available estimates of soil mass movement. The procedures are not rigid. They are a frame of reference within which local data and variables may be applied to provide better estimates of relative soil stability and contributions by soil mass movement to nonpoint source pollution.

Because of the complex nature of processes and variables and the need to present the procedures in a format usable on an inter-regional basis, the following simplifying assumptions are necessary:

1. The determination of hazard index will be based on the assumption of a maximum 10-year return period, 24-hour rainfall (precipitation intensity/duration) as a potential storm event triggering mass movement. If slides in a particular region occur frequently, with storms less than a 10-year return period, the hazard evaluation should reflect this (i.e., a 10-year event is not necessary for a high hazard index).
2. A three-part hazard index will be used. The numerical ratings are subjective and depend on what is considered to be acceptable for a particular land management activity. For purposes of this analysis:
    a. "High hazard" means a greater than 66 percent chance for a soil mass movement within the area evaluated for a 10-year return period storm event.
    b. "Medium hazard" means a greater than 33 and less than 66 percent chance for a soil mass movement within the area evaluated for a 10-year return period storm event.

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[1] *Swanston and Swanson, unpublished data.*

c. "Low hazard" means a less than 33 percent chance for a soil mass movement within the area evaluated for a 10-year return period storm event.

3. Large organic debris contributions to drainageways, resulting from soil mass movement are not considered in estimates of sediment delivery. Although large quantities of organic debris are incorporated in the total volume of material released to the channel by soil mass movement, much of it remains in the channel near the point of entry.
4. Sediment delivery to the stream can be estimated from relationships between failure type and slope gradient, slope position (point of origin of failure), and morphology of the surface.
5. Volume of sediment delivered to the channel per unit area is a more realistic measure of soil mass movement impact than is number of events.
6. The instructions provided for quantifying volumes can be readily applied by field scientists.
7. Processes of soil mass movement described at this broad planning level can be readily identified and characterized regardless of geographic location.
8. Only slump-earthflows and debris avalanches-debris flows will be used to evaluate direct, short-term contributions of sediment to streams.

   Each of these two categories have been identified and described on the basis of material characteristics, failure geometry, and mechanism of movement. These categories are most affected by silvicultural activities and have the greatest potential for short-term water quality degradation.
9. Surface erosion of landslide material remaining on the slope will be determined in another section which deals with surface erosion delivery to stream channels.
10. Debris torrents will not be evaluated directly. It is assumed that when the hazard is high for debris avalanches-debris flows, it will also be high for debris torrents.
11. Sediment delivered to streams from erosion caused by creep will not be directly evaluated because of the close interrelationships of the variables involved in both creep and slump-earthflow processes. Sediment contributions from creep will be indirectly assessed using the channel erosion processes evaluated in "Chapter VI: Total Potential Sediment".

PRINCIPLES AND INTERPRETATIONS OF SOIL MASS MOVEMENT PROCESSES

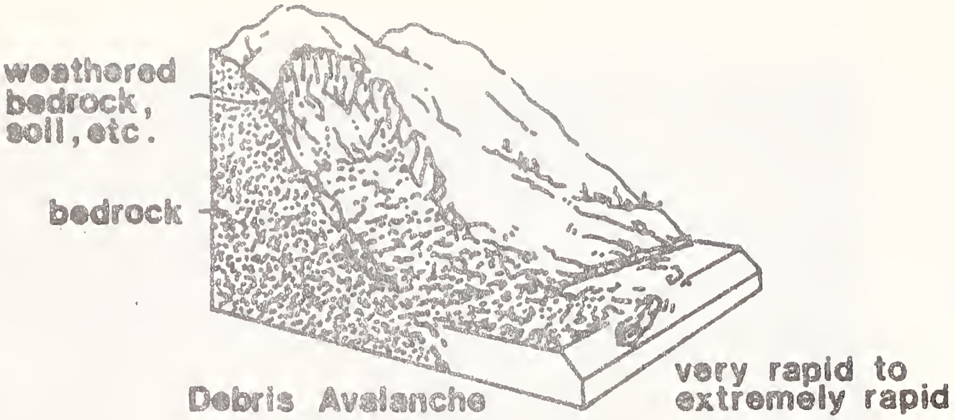
Silvicultural activities in mountainous regions, particularly forest harvest and road construction, can have a major impact on site erosion and can accelerate transport of soil materials downslope by soil mass movement. The resultant downstream damage from aggradation and degradation of the channel may cause bank erosion, disrupt aquatic habitat, and produce undesirable changes in estuarine configuration and habitat by siltation and channel alterations. This is particularly true for areas with steep slopes subject to high intensity rain and/or rapid snowmelt.

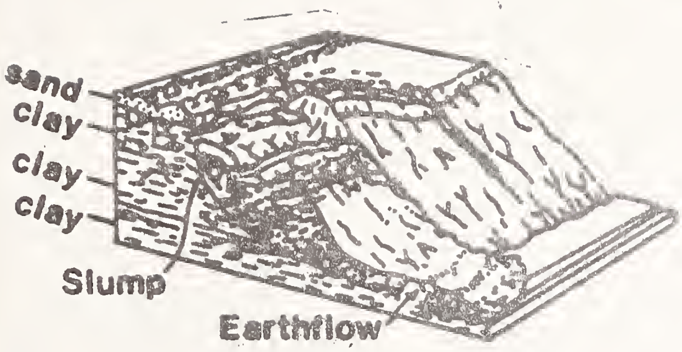
Where heavy forest vegetation covers the slope, the high infiltration capacity of the forest soils and covering organic materials generally protect the slopes from surface erosion. Under these conditions, soil mass movement processes are generally the dominant natural mechanisms of soil transport from mountain slopes to stream channels. Only where bare mineral soil is exposed by disturbance of the vegetative and organic litter cover, either by natural processes or silvicultural activities, does surface erosion significantly contribute to this slope transport process.

Principal Soil Mass Movement Processes

Downslope soil mass movements result primarily from gravitational stress. It may take the form of: (1) failure, both along planar and concave surfaces, of finite masses of soil and forest debris which move rapidly (debris avalanches-debris flows) or slowly (slump-earthflows) (fig. V.2); (2) pure rheological flow with minor mechanical shifting of mantle materials (creep); and (3) rapid movement of water-charged organic and inorganic matter down stream channels (debris torrents).

Slope gradient, soil depth, soil water content, and physical soil properties, such as cohesion and coefficient of friction, control the mechanics and rates of soil mass movement. Geological.





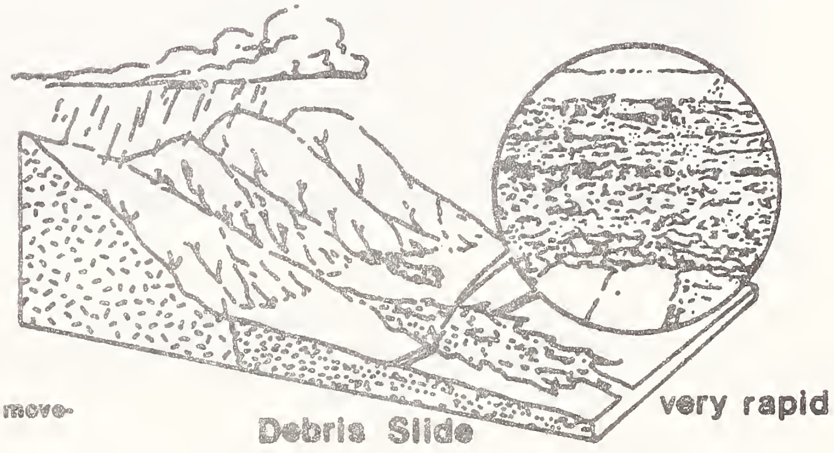


Figure V.2.—Illustration of various types of soil mass movement processes.

hydrological, and vegetative factors determine occurrence and relative importance of such processes in a particular area.

Slump-Earthflows

Where creep displacement has exceeded the shear strength of soil, discrete failure occurs and slump-earthflow features are formed (Varnes 1958). Simple slumping takes place as a rotational movement of a block of earth over a broadly concave slip surface and involves little breakup of the moving material. Where the moving material slips downslope and is broken up and transported either by a flowage mechanism or by gliding displacement of a series of blocks, the movement is termed slow earthflow (Varnes 1958) (fig. V.3). Geologic, vegetative, and hydrologic factors have primary control over slump-earthflow occurrence. Deep, cohesive soils and clay-rich bedrock are especially prone to slump-earthflow failure, particularly where these materials are overlain by hard, competent rock (Wilson 1970, Swanson and James 1975). Earthflow movement also appears to be sensitive to long-term fluctuations in soil water content (Wilson 1970, Swanston 1976).

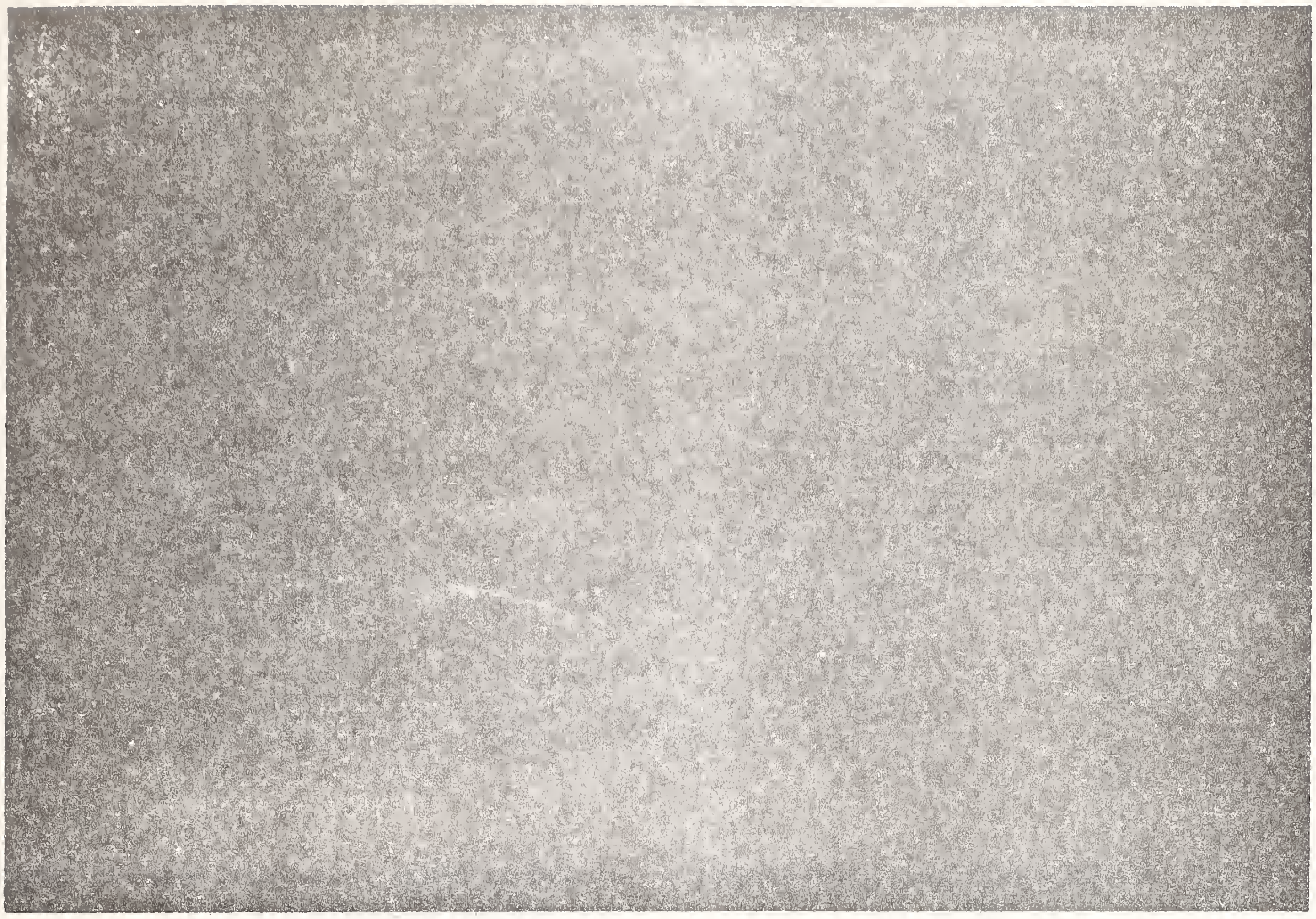


Figure V.3.—Slump and earthflow in deeply weathered sandstones and siltstones in the Oregon Coast Ranges. The slump occurred almost instantaneously. The resulting earthflow, over a period of several hours, dammed a perennial stream and produced the lake in the lower foreground.

Because earthflows are slowly moving, deep-seated, poorly drained features, individual storms probably have much less influence on their movement than on the likelihood of occurrence of debris avalanches-debris flows. Where planes of slump-earthflow are more than several meters deep, weight of vegetation and vertical root anchoring effects are insignificant.

Earthflows can move imperceptibly slowly to more than 1 m/day in extreme cases. In parts of northwest North America, many slump-earthflow areas appear to be inactive (Colman 1973, Swanson and James 1975). Where slump-earthflows are active, rates of movements have been monitored directly by repeated surveying of marked points and inclinometers and by measuring deflection of roadways and other inadvertent reference systems. These methods have been used to estimate the rates of earthflow movement shown in table V.1 (Swanston and Swanson 1976, Kelsey 1977).

The area of occurrence of slump-earthflows is mainly determined by bedrock geology. For example, in the Redwood Creek basin, northern California, Colman (1973) observed that of the 27.4 percent of the drainage which is in slumps, earthflows, and older or questionable soil mass movements, a very high percentage of the unstable areas are located in clay-rich and pervasively sheared sedimentary rocks. Areas underlain by schists and other more highly metamorphosed rock are much less prone to deep-seated soil mass movement. The area of occurrence of slump-earthflows in volcanic

Table V.1.—Observations of movement rates of active earthflows in the western Cascade Range, Oregon (Swanston and Swanson 1976) and Van Duzen River Basin, northern California (Kelsey 1977)

Location	Period of record	Movement rate	Method of observation
	years	cm/yr	
Landes Creek[1] (Sec.21 T.22S, R.4E.)	15	12	Deflection of road
Boone Creek[1] (Sec.17 T.17S, R.5E.)	2	25	Deflection of road
Cougar Reservoir[1] (Sec.29 T.17S, R.5E.)	2	2.5	Deflection of road
Lookout Creek[1] (Sec.30 T.15S, R.6E.)	1	7	Strain rhombus Measurements across active ground breaks
Donaker Earthflow[2] (Sec.10 T.1N, R.3E.)	1	60	Resurvey of stake line
Chimney Rock Earthflow[2] (Sec.30 T.2N, R.4E.)	1	530	Resurvey of stake line
Halloween Earthflow[2] (Sec.6 T.1N, R.5E.)	3	2,720	Resurvey of stake line

[1] Swanston and Swanson 1976.
[2] Kelsey 1977.

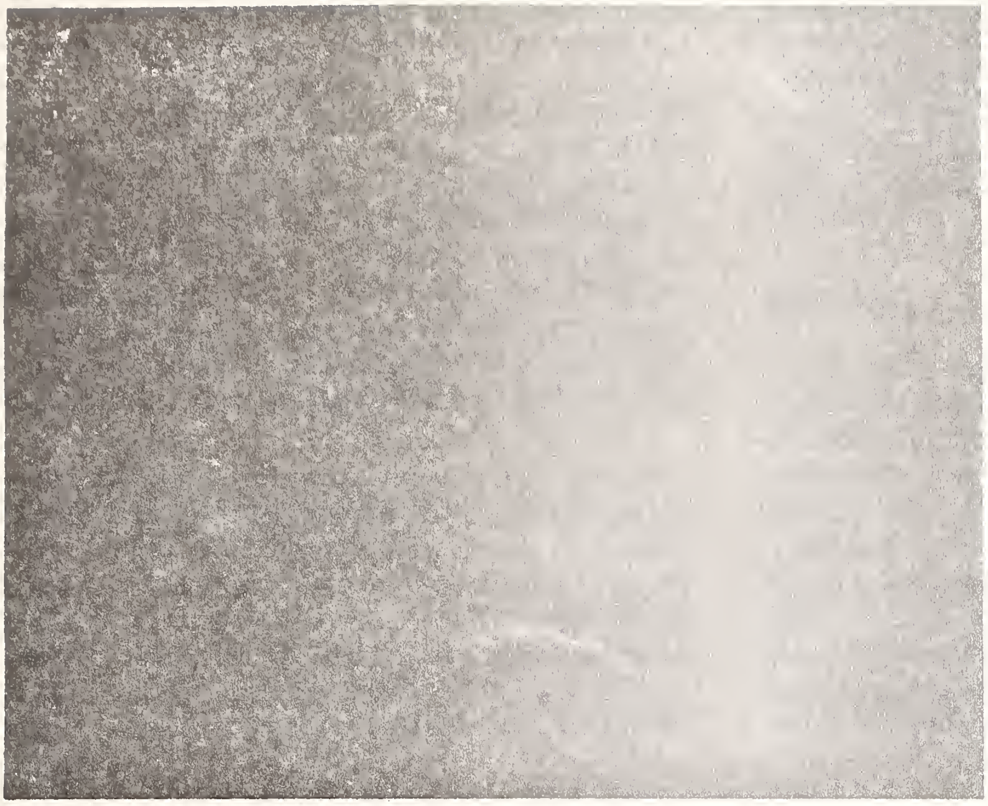
terrains has also been closely linked to bedrock (Swanston and Swanson 1976). There are numerous examples of accelerated or reactivated slump-earthflow movement after forest road construction in the western United States (Wilson 1970). Undercutting the toes of earthflows and piling rock and soil debris on slump blocks are common practices which influence slump-earthflow movement. Stability of such areas is also affected by modification of drainage systems, particularly where road drainage systems route additional water into the slump-earthflow areas. These disturbances may increase movement rates from a few millimeters per year to many centimeters. Once such areas have been destabilized, they may continue to move at accelerated rates for several years.

Although the impact of deforestation alone on slump-earthflow movement has not been demonstrated quantitatively, evidence suggests that it may be significant. In massive, deep-seated failures, lateral and vertical anchoring by tree root systems is negligible. Hydrologic impacts of deforestation, however, appear to be important. Reduced evapotranspiration will increase soil moisture availability. This water is, therefore, free to pass through the rooting zone to deeper levels of the earthflow.

Debris Avalanches-Debris Flows

Debris avalanches-debris flows are rapid, shallow soil mass movements from hillslope areas. Here the term "debris avalanche-debris flow" is used in a general sense encompassing debris slides, avalanches, and flows which have been distinguished by Varnes (1958) (fig. V. 4) and others on the basis of increasing water content and type of included material. From a land management standpoint, there is little purpose to differentiating among the types of shallow hillslope failures, since the mechanics and the controlling and contributing factors are the same. Areas prone to debris avalanches-debris flows are typified by shallow, noncohesive soils on steep slopes where subsurface water may be concentrated by subtle topography on bedrock or glacial till surfaces. Because debris avalanches-debris flows are shallow failures, factors such as root strength, anchoring effects, and the transfer of wind stress to the soil mantle are potentially important influence. Factors which influence antecedent soil moisture conditions and the rate of water supply to the soil during snowmelt and rainfall also have significant control over the time and place of debris avalanches-debris flows.

The rate of occurrence of debris avalanches-debris flows is controlled by the stability of the



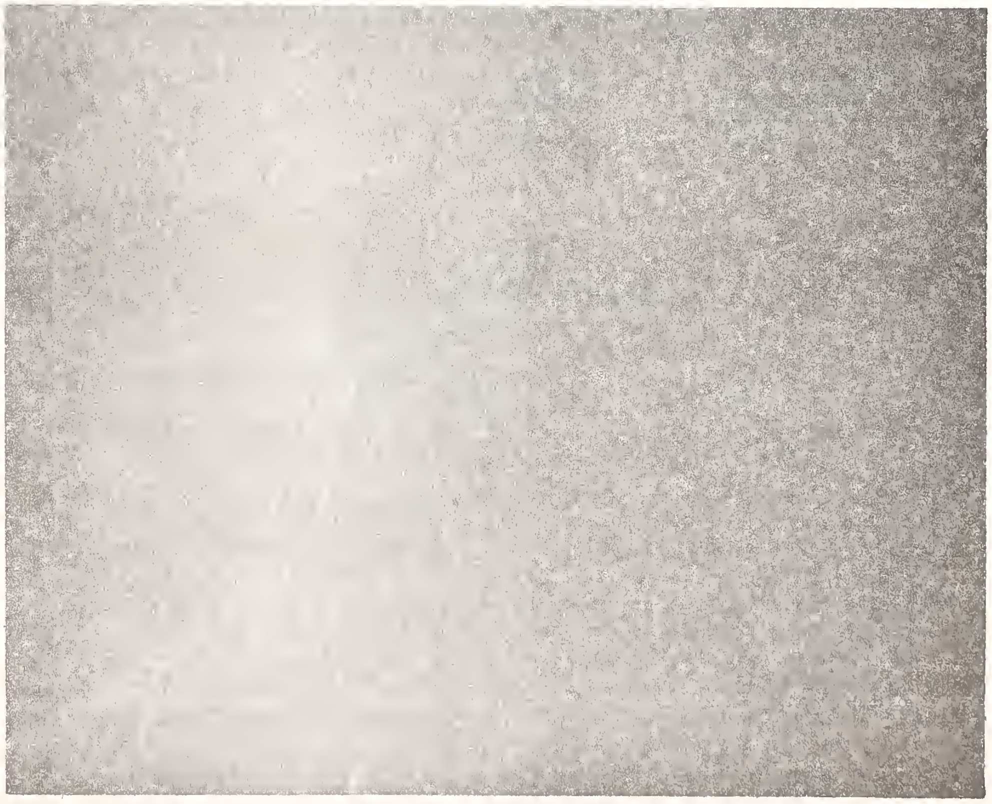


Figure V.4.—Debris avalanche and debris torrent development on steep forested watersheds in northwestern North America. (a.) Debris avalanche developed in shallow cohesionless soils on a steep, forested slope in coastal Alaska. (b.) Debris torrent developed in a steep gully, probably caused by failure of a natural debris dam above trees in foreground.

landscape and the frequency of storm events severe enough to trigger them. Therefore, the rates of erosion by debris avalanches-debris flows will vary from one geomorphic-climatic setting to another. Table V.2 (Swanston and Swanson 1976) shows that annual rates of debris avalanche erosion from forested study sites in Oregon and Washington in the United States, and British Columbia in Canada, range from 11 to 72 m³/km²/yr. These estimates are based on surveys and measurements of debris avalanche erosion during a particular time period (15 to over 32 years) over a large area (12 km² or larger).

An analysis of harvesting impacts in the western United States (Swanston and Swanson 1976) (table V.2) reveals that timber harvesting commonly results in an acceleration of soil mass movement activity by a factor of 2 to 4 times relative to forested areas. In the four study areas listed in table V.2, road-related debris avalanche erosion was increased by factors ranging from 25 to 340 times the rate of debris avalanche erosion in forested areas. The great variability in the impact of roads reflects not only differences in the natural stability of the landscape, but also, and more importantly from an engineering standpoint, differences in site location, design, and construction of roads.

Soil Creep

Soil creep is defined as the slow, downslope movement of soil mantle materials as the result of long-term application of gravitational stress. The mechanics of soil creep have been investigated experimentally and theoretically (Terzaghi 1953, Goldstein and Ter-Stepanian 1957, Saito and Uezawa 1961, Culling 1963, Haefeli 1965, Bjerrum 1967, Carson and Kirkby 1972). Movement is quasi-viscous; it occurs under shear stresses sufficient to produce permanent deformation, but too small to result in discrete failure. Mobilization of

Table V.2.—Debris avalanche erosion in forest, clearcut, and roaded areas (Swanston and Swanson 1976)

Site	Period of record	Area		Number of slides	Debris avalanche erosion	Rate of debris avalanche erosion relative to forested areas
	years	percent	km²		m³/km²/yr	
Stequaleho Creek, Olympic Peninsula, Washington, U.S.A. (Fiksdal 1974):						
Forest	84	79.0	9.3	25	71.8	1.0
Clearcut	6	18.0	4.4	0	0.0	0.0
Road	6	3.0	0.7	83	11,825.0	165.0
			24.4	108		
Alder Creek, Western Cascade Range, Oregon, U.S.A. (Morrison 1975):						
Forest	25	70.5	12.3	7	45.3	1.0
Clearcut	15	26.0	4.5	18	117.1	2.6
Road	15	3.5	0.6	75	15,565.0	344.0
			17.4	100		
Selected drainages, Coast Mountains, S.W. British Columbia, Canada:[1]						
Forest	32	83.9	246.1	29	11.2	1.0
Clearcut	32	9.5	26.4	18	24.5	2.2
Road	32	1.5	4.2	11	[1]282.5	25.2
			276.7	58		
H. J. Andrews Experimental Forest, western Cascade Range, Oregon, U.S.A. (Swanson and Dyrness 1975):						
Forest	25	77.5	49.8	31	35.9	1.0
Clearcut	25	19.3	12.4	30	132.2	3.7
Road	25	3.2	2.0	69	1,772.0	49.0
			64.2	130		

[1] Calculated from O'Loughlin (1972, and personal communication), assuming that area involving road construction in and outside clearcuts is 16 percent of area clearcut. Colin L. O'Loughlin, is now at Forest Research Institute, New Zealand Forest Service, Rangiora, New Zealand.

the soil mass is primarily by deformation at grain boundaries and within clay mineral structures. Both interstitial and absorbed water appear to contribute to creep movement by opening the structure within and between mineral grains, thereby reducing friction within the soil mass. Creeping terrain can be recognized by characteristic rolling, hummocky topography with frequent sag ponds, springs, and occasional benching due to local rotational slumping. Local discrete failures, such as debris avalanches and slump-earthflows, may be present within the creeping mass (fig. V.5).

Natural creep rates monitored in different geological materials in the western Cascade and Coast Ranges of Oregon and northern California indicate rates of movement between 7.1 and 15.2 mm/yr, with the average about 10 mm/yr (Swanston and Swanson 1976) (table V.3). The most rapid movement usually occurs at or near the surface, although the significant displacement may extend to variable depths associated with incipient failure planes or zones of ground water movement. Active creep depth varies greatly and largely depends on parent material origin, degree and depth of weathering, subsurface structure, and soil water content. Most movement appears to take place during rainy season maximum soil water levels (fig. V.6 a), although creep may remain constant throughout the year in areas where the water table does not undergo significant seasonal fluctuation (fig. V.6 b). This is consistent with Ter-Stepanian's (1963) theoretical analysis which shows that the downslope creep rate of an inclined soil layer is exponentially related to piezometric level in the slope.

There have been no direct measurements of the impact of deforestation on creep rates in the forest environment, mainly because of the long periods of records needed both before and after a disturbance. There are, however, a number of indications that creep rates are accelerated by harvesting and road construction.

In the United States, Wilson (1970) and others have used inclinometers to monitor accelerated creep following modification of slope angle, compaction of fill materials, and distribution of soil mass at construction sites. The common occurrence of shallow soil mass movements in these disturbed areas and open tension cracks in fills along roadways suggests that similar features along forest roads indicate significantly accelerated creep movement.

On open slopes where deforestation is the principal influence, impact on creep rates may be more subtle, involving modifications of hydrology and root strength. Where creep is a shallow phenomenon (less than several meters), the loss of

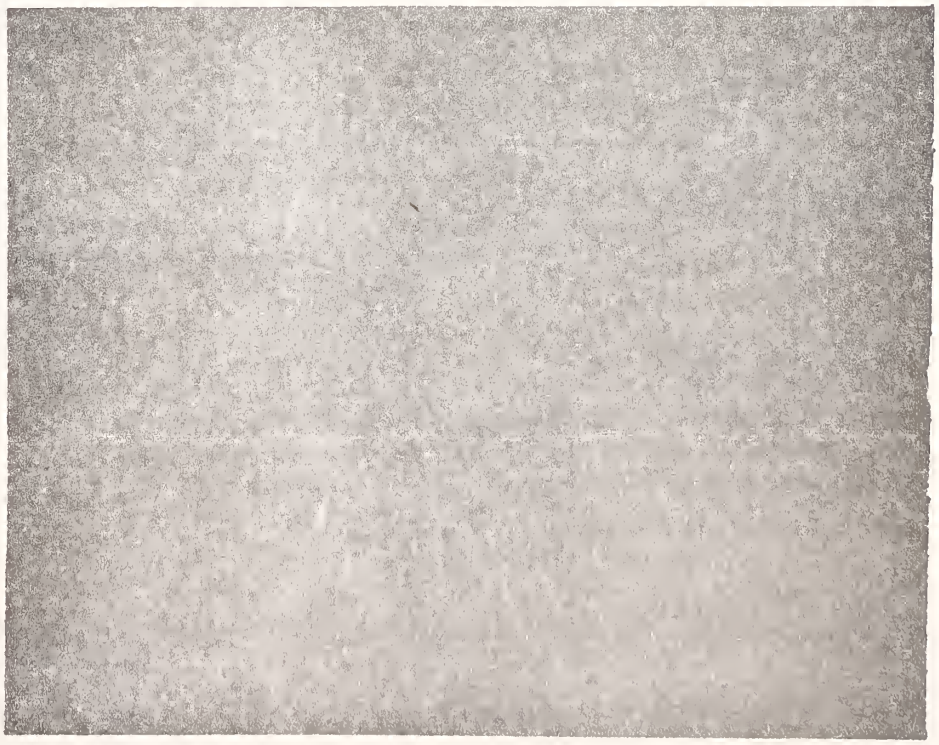
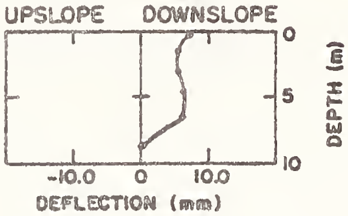
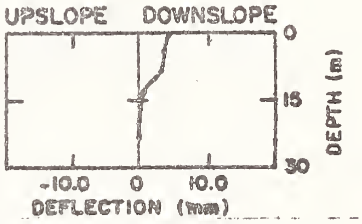
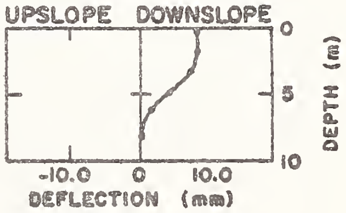
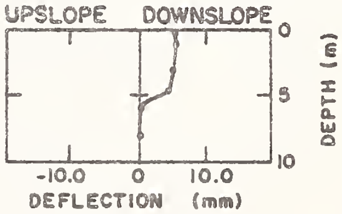


Figure V.5.—An example of soil creep and slump-earthflow processes on forest lands in northern California. The entire slope is undergoing creep deformation, but note the discrete failure (slump-earthflow) marked by the steep headwall scarp at top center and the many small slumps and debris avalanches triggered by surface springs and road construction.

Table V.3—Examples of measured rates of natural creep on forested slopes in the Pacific Northwest (Swanston and Swanson 1976)

Location	Data source	Parent material	Depth of significant movement	Maximum downslope Creep rate: Surface	Maximum downslope Creep rate: Zone of accelerated movement	Representative creep profile
			m	mm/yr	mm/yr	
Coyote Creek, South Umpqua River drainage, Cascade Range of Oregon, Site C-1	Swanston[1]	Little Butte volcanic series; deeply weathered, clay-rich, andesitic dacitic, volcaniclastic rocks	7.3	13.97	10.9	
Blue River drainage - Lookout Creek, H. J. Andrews Exp, Forest, Central Cascades of Oregon, Site A-1	Swanston[1]	Little Butte volcanic series Same as above	5.6	7.9	7.1	
Blue River drainage, IBP Experimental Watershed 10, Site No. 4	McCorison[2] and Glenn	Little Butte volcanic series	0.5	9.0	---	
Baker Creek Coquille River Coast Range, Oregon Site B-3	Swanston[1]	Otter Point formation highly sheared and altered clay-rich argillite and mudstone	7.3	10.4	10.7	
Bear Creek Nestucca River Coast Range, Oregon Site N-1	Swanston[1]	Nestucca formation deeply weathered pyroclastic rocks and interbedded, shaley siltstones and claystones	15.2	14.9	11.7	

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[1] Douglas N. Swanston, unpublished data on file at Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oreg.

[2] F. Michael McCorison and L. F. Glenn, data on file at Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oreg.

Table V.3—Examples of measured rates of natural creep on forested slopes in the Pacific Northwest (continued)

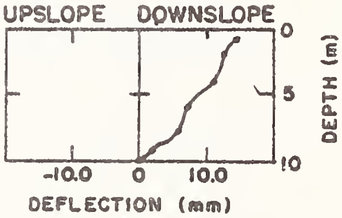
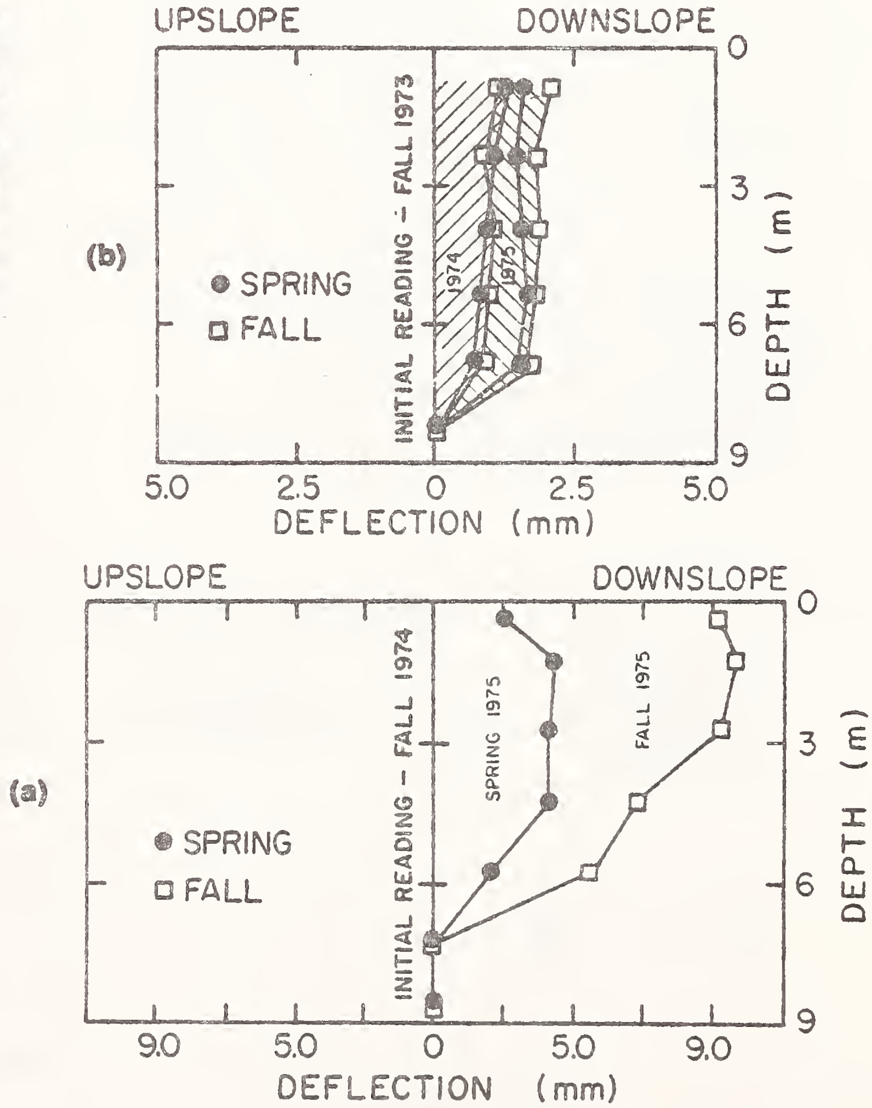
Redwood Creek Coast Range Northern California	Swanston[1]	Kerr Ranch schist sheared, deeply weathered clayey schist	2.6	15.2	10.4	
Site 3-B						

Figure V.6.—Deformation of inclinometer tubes at two sites in the southern Cascade and Coast Ranges of Oregon (Swanston and Swanson 1976). (a) Coyote Creek in the southern Cascade Range showing seasonal variation in movement rate as the result of changing soil water levels. Note that the difference in readings between spring and fall of each year (dry months) is very small. (b) Baker Creek, Coquille River, Oregon Coast Ranges, showing constant rate of creep as a result of continual high water levels.



root strength caused by deforestation is likely to be significant. Reduced evapotranspiration after clearcutting (Gray 1970, Rothacher 1971) may result in longer duration of the annual period of creep activity and, thereby, increase the annual creep rate.

Debris Torrents

Debris torrents involve the rapid movement of water-charged soil, rock, and organic material down steep stream channels. They typically occur in steep, intermittent, and first- and second-order channels. They are triggered during extreme discharge by debris avalanches from adjacent hillslopes which enter a channel and move directly downstream or by the breakup and mobilization of debris accumulations in the channel (fig. V.4b). The initial slurry of water and associated debris commonly entrains large quantities of additional inorganic and organic material from the streambed and banks. Some torrents are triggered by debris avalanches of less than 100 yd^3 (76 m^3), but ultimately involve 1,000 yd^3 (760 m^3) of debris entrained along the track of the torrent. As the torrent moves downstream, hundreds of meters of channel may be scoured to bedrock. When a torrent loses momentum, there is deposition of a tangled mass of large organic debris in a matrix of sediment and fine organic material covering areas of up to several hectares.

The main factors controlling the occurrence of debris torrents are the quantity and stability of debris in channels, steepness of channel, stability of adjacent hillslopes, and peak discharge characteristics of the channel. The concentration and stability of debris in channels reflect the history of stream flushing and the health and stage of development of the surrounding timber stand (Froehlich 1973). The stability of adjacent slopes depends on factors described in previous sections. The history of storm flows has a controlling influence over the stability of both soils on hillslopes and debris in stream channels.

Although debris torrents pose significant environmental hazards in mountainous areas of northwestern North America, they have received little study (Fredriksen 1963, 1965; Morrison 1975; Swanson and others 1976). Velocities of debris torrents, estimated to be up to several tens of meters/second, are known only from a few verbal and written accounts. Torrents have been systematically documented in only two small areas of the Pacific Northwest, both in the western Cascade Range of Oregon (Morrison 1975, Swanston and Swanson 1976). In these studies, rates of debris torrent occurrence were observed to be 0.005 and 0.008 events/km^2/yr for forested areas (table V.4). Torrent tracks initiated in forest areas ranged in length from 328 to 7,480 ft (100 to 2,280 m) and averaged 2,000 ft (610 m) of channel length. Debris avalanches have played a dominant role in triggering 83 percent of inventoried torrents

Table V.4—Characteristics of debris torrents with respect to debris avalanches[1] and land use status of initiation in the H. J. Andrews Experimental Forest[1] and Alder Creek Drainage (Morrison 1975)

Site	Area of watershed	Period of record	Debris torrents triggered by debris avalanches	Debris torrents with no associated debris avalanche	Total		Rate of debris torrent occurrence relative to forested areas
	km^2	yr	number	number	number	km^2/yr	
H. J. Andrews Experimental Forest, western Cascades, Oregon							
Forest	49.8	25	9	1	10	0.008	1.0
Clearcut	12.4	25	5	6	11	0.036	4.5
Road	2.0	25	17	-	17	0.340	42.0
	64.2		31	7	38		
Alder Creek drainage, western Cascade Range, Oregon							
Forest	12.3	90	5	1	6	0.005	1.0
Clearcut	4.5	15	2	1	3	0.044	8.8
Road	0.6	15	6	-	6	0.667	133.4
	17.4		13	2	15		

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[1] Frederick J. Swanson, unpublished data, on file at Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oreg.

(Swanston and Swanson 1976). Mobilization of stream debris not immediately related to debris avalanches has been a minor factor in initiating debris torrents in headwater streams.

Deforestation appears to dramatically accelerate the occurrence of debris torrents by increasing the frequency of debris avalanches. Although it has not been demonstrated, it is also possible that increased concentrations of unstable debris in channels during forest harvesting (Rothacher 1959, Froehlich 1973, Swanson and others 1976) and possible increased peak discharges (Rothacher 1973, Harr and others 1975) may accelerate the frequency of debris torrents.

The impact of clearcutting and road construction on frequency of debris torrents (events/km^2/yr) may be compared to debris torrent occurrence under natural conditions. In the H. J. Andrews Experimental Forest and the Alder Creek study sites in Oregon, timber harvesting appeared to increase occurrence of debris torrents by 4.5 and 8.8 times; and roads were responsible for increases of 42.5 and 133 times relative to forested areas.

Although the quantitative reliability of these estimates of harvesting impacts is limited by the small number of events analyzed, there is clear evidence of marked acceleration in the frequency of debris avalanches-debris flows as a result of forest harvesting and road building. The histories of debris avalanches-debris flows in the two study areas clearly indicate that increased debris torrent occurrence is primarily a result of two conditions: debris avalanches trigger most debris torrents (table V.4) and the occurrence of debris avalanches-debris flows is temporarily accelerated by deforestation and road construction (table V.2).

Mechanics of Movement

Direct application of soil mechanics theory to analysis of soil mass movement processes is difficult because of the heterogeneous nature of soil materials, the extreme variability of soil water conditions, and the related variations in stress-strain relationships with time. However, the theory provides a convenient framework for discussing the general mechanism and the complex interrelationships of the various factors active in development of soil mass movements on mountain slopes.

In terms of factor of safety analysis, the stability of soils on a slope can be expressed as a ratio between shear strength, or resistance of the soil to sliding, and the downslope pull of gravity or gravitational stress. As long as shear strength exceeds the pull of gravity, the soil will remain in a stable state (Terzaghi 1950, Zaruba and Mencl 1969).

It is important to remember that soil mass movements result from changes in the soil shear strength-gravitational stress relationship in the vicinity of failure. This may involve a mechanical readjustment among individual particles or a more complex interaction between both internal and external factors acting on the slope.

Figure V.7 shows the geometrical relationship of factors acting on a small portion of the soil mass. Any increases in gravitational stress will increase the tendency for the soil to move downslope. Increases in gravitational stress result from increasing inclination of the sliding surface or increasing unit weight of the soil mass. Stress can also be augmented by: (1) the presence of zones of weaknesses in the soil or underlying bedrock produced by bedding planes and fractures, (2) application of wind stresses transferred to the soil through the stems and root systems of trees, (3) strain or deformation in the soil produced by progressive creep, (4) frictional "drag" produced by seepage pressure, (5) horizontal accelerations due to earthquakes and blasting, and (6) removal of downslope support by undercutting.

Shear strength is governed by a more complex interrelationship between the soil and slope characteristics. Two principal forces are active in resisting downslope movement. These are: (1) cohesion or the capacity of the soil particles to adhere together, a soil property produced by cementation, capillary tension, or weak electrical bonding of organic colloids and clay particles; and (2) the frictional resistance between individual particles and between the soil mass and the sliding surface. Frictional resistance is controlled by the angle of internal friction of the soil — the degree of interlocking of individual grains — and the effective weight of the soil which includes both the weight of the soil mass and any surface loading plus the effect of slope gradient and excess soil water.

Pore water pressure — pressure produced by the head of water in saturated soil and transferred to the base of the soil through the pore water — acts to reduce the frictional resistance of the soil by reducing its effective weight. In effect, its action causes the soil to "float" above the sliding surface.

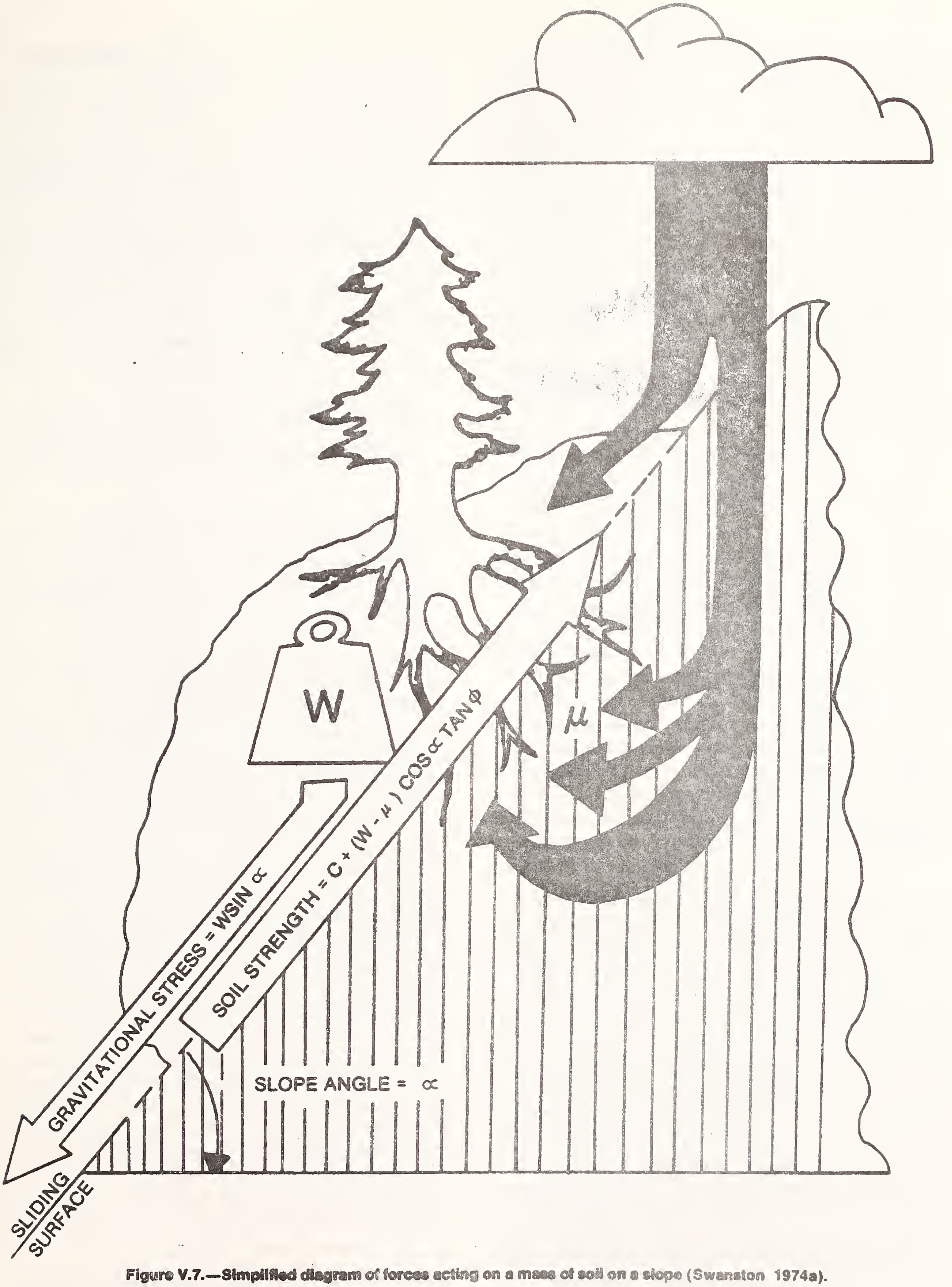


Figure V.7.—Simplified diagram of forces acting on a mass of soil on a slope (Swanston 1974a).

Controlling And Contributing Factors

Particle size distribution or "texture" (which governs cohesion), angle of internal friction, soil moisture content, and angle of sliding surface are the controlling factors in determining stability of a steepland soil. For example, shallow coarse-grained soils low in clay-size particles have little or no cohesion, and frictional resistance determines the strength of the soil mass. Frictional resistance is, in turn, strongly dependent on the angle of internal friction of the soil and pore water pressure. A low angle of internal friction relative to slope angle or high pore water pressure can reduce soil shear strength to negligible values.

Slope angle is a major indicator of the stability of low cohesion soils. Slopes at or above the angle of internal friction of the soil indicate a highly unstable natural state.

Soils of moderate to high clay content exhibit more complex behavior because resistance to sliding is determined by both cohesion and frictional resistance. These factors are controlled to a large extent by clay mineralogy and soil moisture. In a dry state, clayey soils have a high shear strength with the internal angle of friction quite high (>30°). Increasing water content mobilizes the clay through absorption of water onto the clay structure. The angle of internal friction is reduced by the addition of water to the clay lattices (in effect reducing "intragranular" friction) and may approach zero in saturated conditions. In addition, water between grains — interstitial water — may open the structure of the soil mass. This permits a "remolding" of the clay fraction, transforming it into a slurry, which then lubricates the remaining soil mass. Some clays are more susceptible to deformation than others, making clay mineralogy an important consideration in areas characterized by quasi-viscous flow deformation of "creep." Swelling clays of the smectite group (montmorillenite) are particularly unstable because of their tendency to absorb large quantities of water and to experience alternate expansion and contraction during periods of wetting and drying which may result in progressive failure of a slope. Thus, clay-rich soils have a high potential for failure given excess soil moisture content. Under these conditions, failures are not directly dependent on sliding surface gradient as in cohesionless soils, but may develop on slopes with gradients as low as 2° or 3°.

Parent material type has a major effect on the particle size distribution, depth of weathering, and relative cohesiveness of a steepland soil. It frequently can be used as an indicator of relative stability or potential stability problems. In humid regions where chemical weathering predominates, transformation of easily weathered primary minerals to clays and clay-size particles may be extensive. Siltstones, clay stones, shales, nonsiliceous sandstones, pyroclastics, and serpentine-rich rocks are the most easily altered and are prime candidates for soil mass movement of the creep and slump-earthflow types. Conversely, in arid or semiarid regions, slopes underlain by these rocks may remain stable for many years due to slow chemical weathering processes and lack of enough soil moisture to mobilize existing clay minerals. On steep lands underlain by resistant rocks, especially where mechanical weathering prevails, soils are usually coarse and low in clay-size particles. Such areas are more likely to develop soil mass movements of the debris avalanche-debris flow type.

Parent material structure is a critical factor in stability of many shallow soils. Highly jointed bedrock slopes with principal joint planes parallel to the slope provide little mechanical support to the slope and create avenues for concentrated subsurface flow and active pore water pressure development, as well as ready-made zones of weakness and potential failure surfaces for the overlying material. Sedimentary rocks with bedding planes parallel to the slope, function in essentially the same way, with the uppermost bedding plane forming an impermeable boundary to subsurface water movement, a layer restricting the penetration and development of tree roots, and a potential failure surface.

Vegetation cover generally helps control the amount of water reaching the soil and the amount held as stored water against gravity, largely through a combination of interception and evapotranspiration. The direct effect of interception on the soil water budget is probably not large, especially in areas of high total rainfall or during large storms, when most soil mass movements occur. Small storms, where interception is effective, probably have little influence on total soil water available for activating mass movements.

In areas of low rainfall, the effect of evapotranspiration is much more pronounced, but it is particularly dependent on region and rainfall. In areas characterized by warm, dry summers, evapotranspiration significantly reduces the degree of saturation resulting from the first storms of the fall recharge period. This effect diminishes as soil

water deficit is satisfied. Once the soil is recharged, the effects of previous evapotranspirational losses become negligible. Conversely, in areas of continuous high rainfall or those with an arid or semiarid climate, evapotranspirational effects are probably negligible. Depth of evapotranspirational withdrawals is important also. Deep withdrawals may require substantial recharge to satisfy the soil water deficit, delaying or reducing the possibility of saturated soil conditions necessary for major slide-producing events. Shallow soils, however, recharge rapidly, possibly becoming saturated and most unstable during the first major storm.

Root systems of trees and other vegetation may increase shear strength in unstable soils by anchoring through the soil mass into fractures in bedrock, providing continuous long fiberous binders within the soil mass, and tying the slope together across zones of weakness or instability.

In shallow soils, all three effects may be important. In deep soils, the anchoring effect of roots becomes negligible, but the other parameters will remain important. In some extremely steep areas in western North America, root anchoring may be the dominant factor in maintaining slope equilibrium of an otherwise unstable area (Swanston and Swanson 1976).

Snow cover increases soil unit weight by surface loading and affects delivery of water to the soil by retaining rainfall and delaying release of much water. Delayed release of melt water, coupled with unusually heavy storms during a midwinter or early spring warming trend, has been identified as the principal initiating factor in recent major landslide activity on forest lands in central Washington (Klock and Helvey 1976).

CHARACTERIZING UNSTABLE SLOPES IN FORESTED WATERSHEDS

The following guidelines are designed to help delineate the hazards of unstable slopes on forested lands.

There are six environmental qualities that should be carefully considered when judging stability of natural slopes in terms of surface erosion and soil mass movement. They are:

A. landform features
B. soil characteristics
C. bedrock lithology and structure
D. vegetative cover
E. hydrologic characteristics of site
F. climate

Each of these qualities encompasses a group of factors which control stability conditions on the slope and determine or identify the type of processes and movements which are most likely to occur.

Key factors identifying potentially unstable slopes on any mountainous terrain include slope gradient (a landform quality) and concentration of precipitation (both intensity and duration). Soil properties, including soil depth and such diagnostic characteristics as texture, permeability, angle of internal friction, and cohesion determine the types of processes that will dominate and, to some degree, determine the stable slope gradient within a particular soil type. Bedrock structure, especially attitude of beds and degree of fracturing or jointing, are important contributing factors controlling local stability conditions. Many of these factors are identifiable on the ground or in readily available support documentation (climatological records, etc.).

The following outline discusses the six environmental qualities important for judging stability of natural slopes and the key factors associated with each.

A. Landform features

1. **Landforms on which subject area occurs.** — A qualitative indicator of potentially unstable landform types. Obtainable from air photos and topographic maps. For example, alpine glaciated terrain characteristically exhibits U-shaped valleys with extensive areas of very steep slope. Fracturing parallel to the slope is common, and soils, either of colluvial or glacial origin, are usually shallow and cohesionless. The underlying impermeable surface may be either bedrock or compact glacial till. Such terrain is frequently subject to debris avalanche-debris flow processes.

   Areas formed by continental glaciation commonly exhibit rolling terrain consisting of low hills and ridges composed of bedrock, glacial till, and stratified drift separated by areas of ground moraine and glacial outwash. Glaciolacustrine deposits may be present locally, consisting of thick deposits of silt and clay which may be particularly subject to slump-earthflow processes if disturbed.

Fluvially formed landscapes underlain by bedded sedimentary and meta-sedimentary rocks may have slope steepness controlled by jointing, fracturing, and faulting; by orientation of bedding; and by differential resistance of alternating rock layers. Debris avalanche-debris flow failures frequently occur in shallow colluvial soils along these structurally controlled surfaces. Slump-earthflow failures may occur in clay-rich or deeply weathered units, in deeply weathered soils and colluvial debris on the lower slopes, and in valley fills adjacent to active stream channels.

Volcanic terrain consisting of units of easily weathered volcaniclastic rocks and hard, resistant flow rock commonly exhibit slump-earthflow failures in deeply weathered volcaniclastic materials. Such failures usually occur just below a capping flow or just above an underlying flow due to concentration of ground water. Debris avalanche-debris flow failures are common in shallow residual or colluvial soils developed on the resistant flow rock units.

Because of the large variability in landform processes and the modifying influence of climatic conditions on weathering rates and products, geologists with some knowledge of the area should be consulted.

2. **Slope configuration.** — Shape of the slope in the area of consideration. A qualitative indicator of location and extent of most highly unstable areas on a slope. Obtainable from air photos and topographic maps. On both concave and convex slopes, usually the steepest portions have the greatest stability hazard. Convex slopes may have oversteep gradients in lower portions of the slope. Concave slopes have oversteep gradients in their upper elevations.

3. **Slope gradient.** — A key factor controlling soil stability in steep mountain watersheds. Slope gradient may be quantified on the ground or from topographic maps. It determines effectiveness of gravity acting to move a soil mass downslope. For debris avalanche-debris flow failures, this is a major indicator of the natural soil mass movement hazard. For slump-earthflow failures, this is not as important since, given the right conditions of soil moisture content, soil texture, and clay mineral content, failures can occur on slope gradients as low as 2° or 3°. Slope gradient also has a major effect on subsurface water flow in terms of drainage rate and subsequent susceptibility to temporary water table buildup during high intensity storms.

B. Soil Characteristics

1. **Present soil mass movement type and rate.** — Obtainable from air photos and field checks. This is a qualitative indicator of size and location of potential stability problems, type of recent landsliding, and kinds of soil mass movement processes operative on the slope. These, in turn, suggest probable soil depth and certain dominant soil characteristics. For example, debris avalanches-debris flows most frequently develop in shallow, coarse-grained soils which have a low clay content and low internal cohesion. Soil creep, massive slumping, and large-scale earthflows usually develop in deep, cohesive soils high in clay content or in deeply weathered pelitic sediments, serpentinite, and volcanic ash and breccia.

2. **Parent material.** — A qualitative indicator of probable shape of soil particles, bulk density (or weight), degree of cohesion or clay mineral content, soil depth, permeability, and presence or absence of impermeable layers in the soil. These, in turn, suggest types of soil mass movement processes operative within an area. This information is obtainable from existing geologic and soil survey maps, by air photo interpretation, and by field check.

   Soils developed from colluvial or residual materials and some tills and pumice soils commonly possess little or no cohesion. Failures in such soils are usually of the debris avalanche-debris flow type.

   Soils developed from weathered fine grained sedimentary rocks (mudstones, claystones, nonsiliceous sandstones, shales), volcaniclastics, and glacio-lacustrine clays and silts possess a high degree of cohesion and characteristically develop failures of the slump-earthflow type.

   The mica content also has a major influence on soil strength. Ten to twenty percent mica will produce results similar to high clay content.

3. **Occurrence of compacted, cemented, or impermeable layer.** — A qualitative indicator of the depth of potentially unstable soil and probable principal planes of failure

on the slope. This information is obtainable from borings, soil pits, and inspection of slope failure scars in the field.

4. **Evidence of concentrated subsurface drainage (including evidence of seasonal saturation).** — A qualitative indicator of local zones of periodic high soil moisture content including saturation and potentially active pore water pressures during high rainfall periods. These identify potential areas of slope failure. This information is obtainable by air photo interpretation and ground observation. Diagnostic features include broad linear depressions perpendicular to slope contour, representing old landslide sites and areas of concentrated subsurface drainage, and damp areas on the slope, representing springs and areas of concentrated ground water movement.

5. **Diagnostic soil characteristics.** — Key factors in determining dominant types of soil mass movement process mechanics of motion and probable maximum and minimum stable slope gradients for a particular soil. This is identifiable through field testing, sampling, and laboratory analysis. Data on benchmark soils also may be obtained from soil surveys and engineering analyses for road construction in or adjacent to the proposed silvicultural activity.
   a. **Soil depth.** — Principal component of the weight of the soil mass and an important factor in determining soil strength and gravitational stress acting on an unstable soil.
   b. **Texture.** — (Particle size distribution) the relative proportions of sand (2.0 - 0.5 mm), silt (.05 - .002 mm), and clay (<.002 mm) in a soil. Texture, along with clay mineral content, are important factors in controlling cohesion, angle of internal friction, and hydraulic conductivity of an unstable soil.
   c. **Clay mineralogy.** — An indicator of sensitivity to deformation. Some clays are more susceptible to deformation than others, making clay mineralogy an important consideration in areas where creep occurs. "Swelling" clays of the smectite group (montmorillonite) are particularly unstable.
   d. **Angle of internal friction.** — An indicator of the internal frictional resistance of a soil caused by intergranular friction and interlocking of individual grains, an important factor in determining soil shear strength or resistance to gravitational stress. The tangent of the angle of internal friction times the weight of the soil constitute a mathematical expression of frictional resistance. For shallow, cohesionless soils, a slope gradient at or above the angle of internal friction is a good indicator of a highly unstable site.
   e. **Cohesion.** — The capacity of soil particles to stick or adhere together. This is a distinct soil property produced by cementation, capillary tension, and weak electrical bonding of organic colloids and clay particles. Cohesion is usually the direct result of high (20 percent or greater) clay particle content and is an important contributor to shear strength of a fine grained soil.

C. Bedrock Lithology and Structure

1. **Rock type.** — A qualitative indicator of overlying soil texture, clay mineral content, and relative cohesiveness. It provides a regional guide to probable areas of soil mass movement problems and dominant processes. For example, in the Cascades and Coast Range of Oregon and Washington, areas underlain by volcanic ash and breccias and silty sandstone are particularly susceptible to slump-earthflows. Where hard, resistant volcanic flow rock is present, shallow planar failures dominate. Slopes underlain by granites and diorites are also more susceptible to shallow planar failures, although where extensive chemical weathering has occurred, such rocks may exhibit slump-earthflow features. The slope stability characteristics of a particular rock type or formation largely depend on mineralogy, climate, and degree of weathering, and must be determined for each particular area.
2. **Degree of weathering.** — A qualitative indicator of soil depth and type of soil mass movement activities. In some rock types, it is also an indicator of degree of clay mineral formation.
3. **Attitude of beds.** — Quantifiable on the ground, from geologic maps, and occasionally

from air photos. This is an important contributing factor to unstable slopes, especially where attitude of bedding parallels or dips in the same direction as the slope. Under these conditions, the bedding planes form zones of weakness along which slope failures can occur due to high pore water pressures and decreases in frictional resistance. Conversely, bedding planes dipping into the slope frequently produce natural buttresses and increase slope stability. Care must be taken in assessing the stabilizing influence of horizontal or in-dipping bedding planes particularly where well-developed jointing is present (see no. 4).

4. **Degree of jointing and fracturing.** — Quantifiable on the ground and occasionally from geologic maps as dip and strike of faults, fractures, and joint systems. Joints in particular are important contributing factors to slope instability, especially on slopes underlain by igneous materials. Joints parallel to or dipping in the same direction as the slope, create local zones of weakness along which failures occur. Jointing also provides avenues for deep penetration of groundwater with subsequent active pore water pressure development along downslope dipping joint planes.

   Valleys developed along high angle faults in mountainous terrain may have exceptionally steep slopes. Deep penetration of ground water into uneroded fault and shear zones can result in extensive weathering and alteration of zone materials, resulting in generation of slump-earthflow failures. Such zones can also form barriers to ground water movement causing redirection and concentration of water into adjacent potentially unstable sites.

D. Vegetative Characteristics

1. **Root distribution and degree of root anchoring in the subsoil.** — An indicator of effectiveness of tree roots as a stabilizing factor in shallow steep slope soils. Quantifiable on the ground by observing the degree of penetration of roots through the soil and into a more resistant substratum and by measuring the biomass of the roots contained in a potentially unstable soil. High biomass of contained roots is an expression of the binding capacity or "reinforcing" effect of roots to the soil mass.
2. **Vegetation type and distribution.** — Cover density, vegetation type, and stand age are qualitative indicators of the history of soil mass movement on a site and soil and ground water conditions. This information is obtainable by air photo interpretation and ground checking.

E. Hydrologic Characteristics

1. **Hydraulic conductivity.** — A measure of water movement in and through soil material. This is quantifiable in the field and in the laboratory using pumping tests and permeameters. Low hydraulic conductivities mean rapid storm generated saturation and a high probability of active pore water pressure, which produces highly unstable conditions in steep slope soils.
2. **Pore water pressure.** — A measure of the pressure produced by the head of water in a saturated soil and transferred to the base of the soil through the pore water. This is quantifiable in the field through measurement of free water surface level in the soil. Pore water pressure is a key factor in failure of a steep slope soil, and operates primarily by reducing the weight component of soil shear strength.

F. Climate

1. **Precipitation occurrence and distribution.** — A key factor in predicting regional soil mass movement occurrences. Most soil mass movements are triggered by soil saturation and active pore water pressures produced by rainfall of high intensity and long duration. Isohyetal maps of rainfall occurrences and distribution, constructed from data obtainable from local monitoring stations or from the Weather Bureau, can be used to pinpoint local areas of high rainfall concentration. It is advisable to develop a simple relationship between rainfall intensity and pore water pressure development for a particular soil type or area of interest so that magnitude and return period of damaging storms can be identified. This can be done simply by locating a rain gage at the site or using nearby rainfall data and correlating this with piezometric data obtained from open-ended tubes installed to the probable depths of failure at the site. Each storm should be monitored.

ESTIMATING SOIL MASS MOVEMENT HAZARD AND SEDIMENT DELIVERED TO CHANNELS

This section delineates a procedure to be used on potentially unstable areas to analyze the hazard of soil mass movement associated with silvicultural activities and to determine the potential volume and delivery of inorganic material to the closest drainageway. This is a broad level analysis designed to determine where specific controls or management treatment variations are required because of possible water quality changes resulting from soil mass movement. This procedure will not substitute for site specific analysis of road design, maintenance, and rehabilitation as may be required under current management procedures.

To assess soil mass movement hazards that might deliver inorganic material to a stream course, a basic qualitative evaluation is undertaken based on the following information:

1. A delineation of hazard areas and dominant soil mass movement types using aerial photo and topographic map interpretation with minimum ground reconnaissance.
2. An estimate of the likelihood of failure or "sensitivity" of an area caused by both natural and man-induced events, using subjective analysis of controlling and contributing factors within defined hazard areas.
3. An estimate of the volume of material released by soil mass movements during storm events with a 10-year return interval or less.
4. An estimate of the volume of sediment released by soil mass movements which actually reach a water course based on slope position, gradient, and shape and type of movement.

Although soil mass movements are too infrequent for effective direct annual evaluation, delivery volumes can be expressed on an average annual basis for purposes of comparison between pre- and post-silvicultural activity conditions.

A broad delineation of potentially unstable terrain by slope characteristics and soil mass movement types is an essential part of the hazard analysis. A detailed flow chart (fig. V.8) shows the sequence of analysis once the delineation of unstable terrain is accomplished.

The limits placed on variable ranges for high, medium and low hazard indices are approximations based on the collective experience of practicing professionals. The weighted values for hazard indices are guides only, and they were determined from consultation with practicing professionals as well as a limited analysis of several unstable areas in Colorado and western Oregon. However, they do reflect the relative importance of the individual factors and their effects on likelihood of failure by the major soil mass movement types. These weightings and the ranges of hazard index should be adjusted to reflect the conditions prevalent within a given area.

PROCEDURAL DESCRIPTION

The following information describes each step of the procedural flow chart, fig V.8. Data from the Horse Creek example are used to illustrate the following procedure. This complete example is presented in "Chapter VIII: Procedural Example."

**BROAD DELINEATION OF
POTENTIALLY UNSTABLE AREAS**

Guidelines have been presented that provide a qualitative characterization of unstable or potentially unstable slopes on forested lands. Using these guidelines, evaluate the area of the proposed silvicultural activity to ascertain the stability of the site.

**IDENTIFY AND MAP AREAS BY
SOIL MASS MOVEMENT TYPE**

If the area is generally unstable or potentially unstable, delineate the hazard areas and dominant soil mass movement types (debris avalanches-debris flows and slump-earthflows) using aerial photos and topographic map interpretation. Potentially unstable areas are those that may become unstable due to the proposed silvicultural activity. Unstable areas are those that have or presently are undergoing a soil mass movement.

CHARACTERIZE SOIL MASS MOVEMENT TYPE

Soil mass movements have been classified into two major types: debris avalanches-debris flows and slump-earthflows. Several site parameters and management activities can be used to evaluate the possibility of soil mass movement. Although both movement types have similar factors that can be used to evaluate the hazard of a failure, the relative importance of these factors may be different between the two movement types. In addition, each kind of soil mass movement has some site or management activity parameters that are specific for that movement. Therefore, to evaluate the hazard of a soil mass movement, each type must be evaluated separately using the factors that have been found to be significant in characterizing that particular kind of failure.

DEBRIS AVALANCHE-DEBRIS FLOW

Areas prone to debris avalanches-debris flows are typified by shallow, noncohesive soils on steep slopes where subsurface water may be concentrated by subtle topography on bedrock or glacial till surfaces.

NATURAL HAZARD SITE CHARACTERISTICS

For debris avalanches-debris flows, the following site characteristics have been found to be critical in evaluating the potential hazard of a natural soil mass movement: slope gradient, soil depth, subsurface drainage characteristics, soil texture, bedding structure and orientation, surface slope configuration, and precipitation input. This information can be obtained from geologic and soils maps, pertinent literature, field knowledge of local experts, etc. The relative importance of each site characteristic is indicated in table V.5 and worksheet V.1 by the weighting value assigned.

MANAGEMENT INDUCED HAZARD CHARACTERISTICS

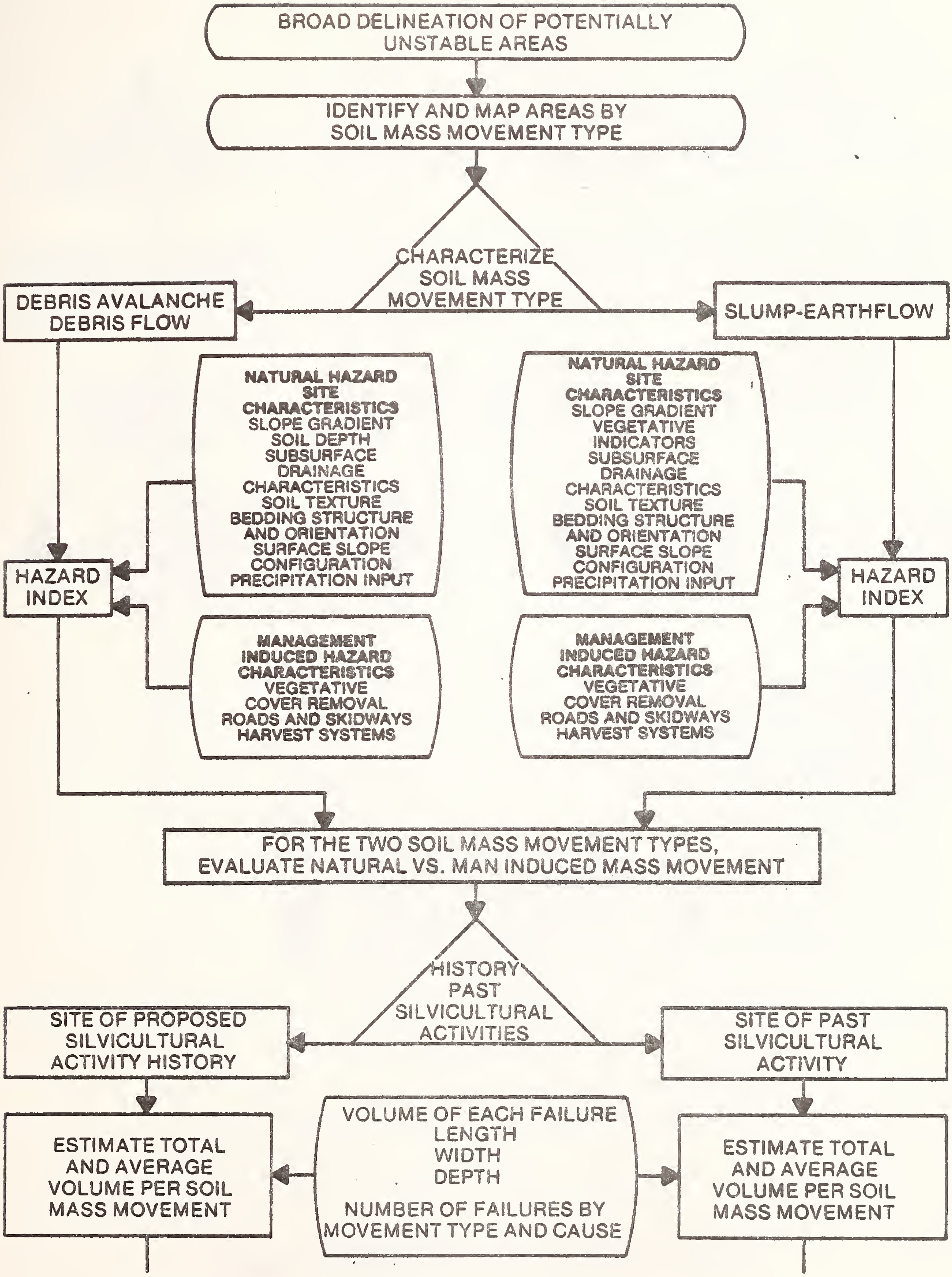
For debris avalanches-debris flows, the following management activities have been found to be critical in evaluating the potential hazard for initiation or acceleration of a soil mass movement: vegetative cover removal, roads and skidways, and harvest systems. This information can be obtained from past records of silvicultural activities or from proposed silvicultural activity plans. The relative importance of each management activity is indicated in table V.6 and worksheet V.2 by the weighting value assigned.

HAZARD INDEX

The hazard index analysis procedure places weighted values on the factors affecting different types of soil mass movement. A three-part hazard index is used: high, medium, and low. The numerical ratings are subjective and depend on what is considered acceptable for a particular silvicultural activity. Assumptions 1 and 2 in the procedure detail and define a high, medium, and low hazard.

The natural hazard index for debris avalanches-debris flows is determined by summing the weighted values from worksheet V.1 and comparing this value to the ranges of values for high, medium, and low hazard indices. For example, if the sum of the weighted values for the natural hazard index (worksheet V.1) was 31, the hazard index would be medium. The value 31 falls within the range of values (21-44) for the medium hazard.

The relative hazard for debris avalanches-debris flows caused by silvicultural activities is determined by summing the weighted values from worksheet V.2. The overall hazard index caused by natural plus existing or proposed silvicultural activities is determined by adding the total weighted value for the natural hazard. This overall weighted value is compared with the range of values given for a high, medium, or low hazard index. For example, if the silvicultural activities resulted in a total weighted value of 31, the overall weighted value of both the natural (31) plus the silvicultural activity (31) would be equal to 62 and the overall hazard index would be high.


BROAD DELINEATION OF POTENTIALLY UNSTABLE AREAS
IDENTIFY AND MAP AREAS BY SOIL MASS MOVEMENT TYPE
CHARACTERIZE SOIL MASS MOVEMENT TYPE
DEBRIS AVALANCHE DEBRIS FLOW
SLUMP-EARTHFLOW
NATURAL HAZARD SITE CHARACTERISTICS
SLOPE GRADIENT
SOIL DEPTH
SUBSURFACE DRAINAGE CHARACTERISTICS
SOIL TEXTURE
BEDDING STRUCTURE AND ORIENTATION
SURFACE SLOPE CONFIGURATION
PRECIPITATION INPUT
NATURAL HAZARD SITE CHARACTERISTICS
SLOPE GRADIENT
VEGETATIVE INDICATORS
SUBSURFACE DRAINAGE CHARACTERISTICS
SOIL TEXTURE
BEDDING STRUCTURE AND ORIENTATION
SURFACE SLOPE CONFIGURATION
PRECIPITATION INPUT
HAZARD INDEX
HAZARD INDEX
MANAGEMENT INDUCED HAZARD CHARACTERISTICS
VEGETATIVE COVER REMOVAL
ROADS AND SKIDWAYS
HARVEST SYSTEMS
MANAGEMENT INDUCED HAZARD CHARACTERISTICS
VEGETATIVE COVER REMOVAL
ROADS AND SKIDWAYS
HARVEST SYSTEMS
FOR THE TWO SOIL MASS MOVEMENT TYPES, EVALUATE NATURAL VS. MAN INDUCED MASS MOVEMENT
HISTORY PAST SILVICULTURAL ACTIVITIES
SITE OF PROPOSED SILVICULTURAL ACTIVITY HISTORY
SITE OF PAST SILVICULTURAL ACTIVITY
ESTIMATE TOTAL AND AVERAGE VOLUME PER SOIL MASS MOVEMENT
VOLUME OF EACH FAILURE
LENGTH
WIDTH
DEPTH
NUMBER OF FAILURES BY MOVEMENT TYPE AND CAUSE
ESTIMATE TOTAL AND AVERAGE VOLUME PER SOIL MASS MOVEMENT

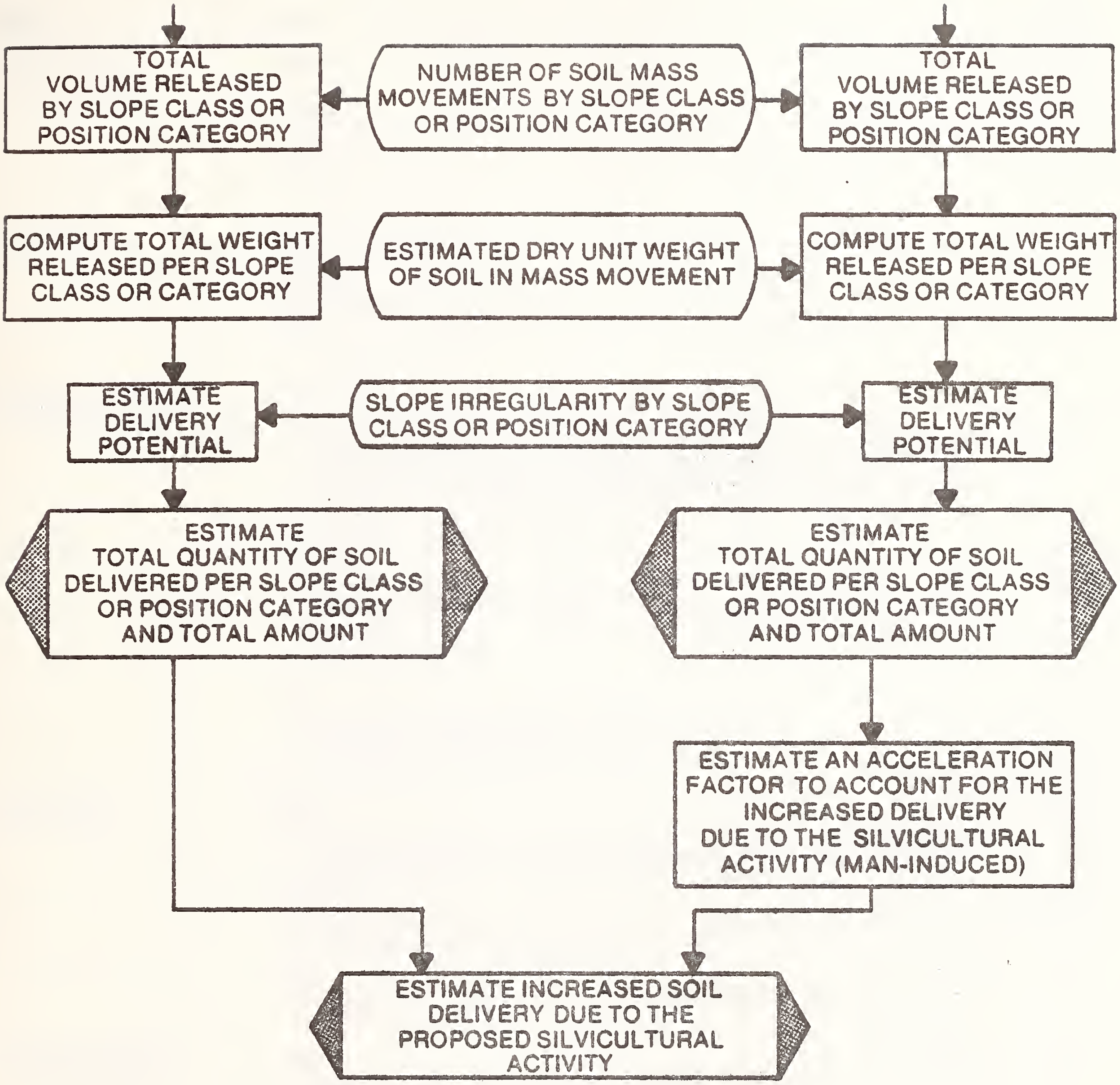


Figure V.8.—Detailed flow chart of the soil mass movement procedure.

Table V.5.—Weighting factors for determination of natural hazard of debris avalanche-debris flow failures

Factor	Hazard index and range	Weight
Slope gradient	High >34°	30
	Medium 29° -34°	15
	Low <29°	5
Soil depth	High Shallow soils, <5 ft	3
	Medium Moderately deep soils, 5-10 ft	2
	Low Deep soils, >10 ft	1
Subsurface drainage characteristics	High High density, closely spaced incipient drainage depressions Presence of bedrock or impervious material at shallow depth which restricts vertical water movement and concentrates subsurface flow Presence of permeable low density zones above the restricting layer indicative of saturated flow parallel to the slope Evidence of springs on the slope	3
	Medium Presence of incipient drainage depressions, but widely spaced Presence of impervious material at shallow depths, but no low density zones present Springs are absent	2
	Low Incipient drainage depressions rare to absent No shallow restricting layers present No indications of near-surface flow	1
Soil texture	High Unconsolidated, non-cohesive soils and colluvial debris including sands and gravels, rock fragments, weathered granites, pumice and noncompacted glacial tills with low silt content (<10%) and no clay	3
	Medium Unconsolidated, non-cohesive soils and colluvial debris with moderate silt content (10-20%) and minor clay (<10%)	2
	Low Fine grained, cohesive soils with greater than 20% clay sized particles or mica	0
Bedding structure and orientation	High Extensive jointing and fracturing parallel to the slope Bedding planes parallel to the slope Faulting or shearing parallel to the slope (the stability influence of bedding planes horizontal or dipping into the slope is offset by extensive parallel jointing and fracturing)	3
	Medium Bedding planes are horizontal or dipping into the slope with minor jointing at angles less than the natural slope gradient Minor surface fracturing — no faulting or shearing evident	2
	Low Bedding planes are horizontal or dipping into the slope Jointing and fracturing is minor — no faulting or shearing evident	1

Table V.5.—Weighting factors for determination of natural hazard of debris avalanche-debris flow failures — continued

Factor	Hazard index and range	Weight
Surface slope configuration	**High** Smooth, continuous slopes unbroken by benches or rock outcrops Intermittent steep channels occur frequently with lateral spacing of 500 ft (152 m) or less Perennial channels frequently deeply incised with steep walls of rock or colluvial debris Numerous breaks in canopy due to blow-downs — frequent linear or tear-drop shaped even-age stands beginning at small scarps or spoon-shaped depressions indicative of old debris avalanche-debris flow activity	3
	Medium Smooth, continuous slopes broken by occasional benches and rock outcrops Intermittent, steep gradient channels occur less frequently with a lateral spacing of 500-800 ft (152-244 m) Infrequent evidence of blow-down or past landslide activity	2
	Low Slope broken by rock benches and outcrops intermittent, steep gradient channels spaced 900 ft (275 m) or more apart	1
Precipitation input	**High** Area characterized by rainfall greater than 80 in/yr (203 cm/yr) distributed throughout the year or greater than 40 in/yr (102 cm/yr) distributed over a clearly definable rainy season Locale is subjected to frequent high intensity storms capable of generating saturated soil conditions on the slope leading to active pore-water pressure development and high stream flow — area has a high potential for mid-winter or early spring rainfall-on-snowpack events Storm intensities may exceed 6 in/24 hr at 10 yr recurrence intervals or less	12
	Medium Area characterized by moderate rainfall of 20 to 40 in/yr (51 to 102 cm/yr) Storms of moderate intensity and duration are common High intensity storms are infrequent, but do occasionally occur Moderate snowpack, but rain-on-snow events very rare Storm intensities may exceed 6 in/24 hr (15 cm/24 hr) at recurrence intervals greater than 10 yrs.	5
	Low Rainfall in area is low (less than 20 in/yr) Storms infrequent and of low intensity Stored water content in snowpack, when present, is low and only rarely subject to rapid melting	3

WORKSHEET V.1

Debris avalanche-debris flow natural factor evaluation form

Index	Slope gradient	Soil depth	Subsurface drainage characteristics	Soil texture	Bedding structure and orientation	Slope configuration	Precipi-tation input
High	30	3	[✓ 3]	3	3	3	12
Medium	[✓ 15]	[✓ 2]	2	[✓ 2]	[✓ 2]	[✓ 2]	[✓ 5]
Low	5	1	1	0	1	1	3

Factor summation table

Gross hazard index	Factor range	Natural
High	Greater than 44	31
Medium	21 - 44	
Low	Less than 21	

Table V.6.—Weighting factors for determination of management-induced hazard of debris avalanche-debris flow failures

Factor	Hazard index and range	Weight
Vegetation cover removal	High Total removal of cover — large clearcuts with openings continuous downslope — such removal is sufficient to increase soil moisture levels and reduce strength Broadcast burning of slash	8
	Medium Cover partially removed with slope sections >34° left undisturbed — clearcuts in small patches or strips less than 20 ac (8 ha) and discontinuous on slopes	5
	Low Cover density altered through partial cutting — no clearcutting — no broadcast burning of sites with >34° slope	2
Roads and skidways	High High density (>15% of area in roads) on potentially unstable slopes (>28°) — cut and fill construction Roads and skidways located on steep, unstable portions of the slope (>34°) Uncontrolled fills with poor compaction produced by side-casting over organic debris Inadequate cross drainage (poor location; improper spacing and maintenance, size too small for 10 yr storm flow) Lack of fill slope protection of drainage outlets Concentrations of drainage water directed into identifiable unstable areas	20
	Medium Mixed road types, both fully benched and cut-and-fill (balanced) — moderate road density (8-15% of area) Areas with slopes >34° or with identifiable landslide activity have been avoided or fully benched On potentially unstable slopes >29° skidways and cut-and-fill type construction are limited Ridgetop roads have large fills in saddles Fills, where present, are constructed by sidecasting over organic debris with little controlled compaction Roads generally have adequate cross drains for normal runoff conditions (number and location) but are undersized for the 10 yr storm flow Fill slopes below culvert outfalls protected by rip-rap dissipation structures at potentially unstable sites Major concentrations of water into identifiable unstable areas avoided	8
	Low Very few roads on slopes above 28° — low road density (less than 8% of area) with roads on potentially unstable terrain (slopes between 29° and 34°) predominantly of full bench type — most road locations or construction limited to ridgetops with minimum fills in saddles and lower slopes — adequate cross drains with major water courses bridged and culverts designed for 10 yr storm flow or larger	2
Harvest systems	High Operation of tractor yarding, jammer yarding and other ground lead systems on slopes >29° (53%)	3
	Medium No tractor logging — high lead with partial suspension on slopes >29° (53%)	2
	Low Helicopter and balloon yarding — full suspension of logs by any method — yarding by any method on slopes <29° (53%)	0

WORKSHEET V.2

Debris avalanche-debris flow management related factor evaluation form

Index	Vegetation cover removal	Roads and skidways	Harvest methods
High	[✓ 8]	[✓ 20]	[✓ 3]
Medium	5	8	2
Low	2	2	0

Factor summation table

Gross hazard index	Range	Natural + management
High	Greater than 44	31+31 = 62
Medium	21 - 44	
Low	Less than 21	

SLUMP-EARTHFLOW

Slump-earthflow prone areas are typified by deep, cohesive soils and clay-rich bedrock overlying hard, competent rock. Slump-earthflow soil mass movement also appears to be sensitive to long-term fluctuations.

NATURAL HAZARD SITE CHARACTERISTICS

For slump-earthflows, the following site characteristics have been found to be critical in evaluating the potential hazard of a natural soil mass movement: slope gradient, sub-surface drainage characteristics, soil texture, surface slope configuration, vegetative indicators, bedding structure and orientation, and precipitation input. This information can be obtained from soils maps, vegetative cover maps, pertinent literature, field knowledge of local experts, etc. The relative importance of each site characteristic is indicated in table V.7 and worksheet V.3 by the weighting value assigned.

MANAGEMENT INDUCED HAZARD CHARACTERISTICS

For slump-earthflows, the following management activities have been found to be critical in evaluating the potential hazard for initiation or acceleration of a soil mass movement: vegetative cover removal, roads and skidways, and harvest systems. This information can be obtained from past records of silvicultural activities or from proposed silvicultural activity plans. The relative importance of each management activity is indicated in table V.8 and worksheet V.4 by the weighting value assigned.

HAZARD INDEX

The hazard index analysis procedure places weighted values on the factors affecting different types of soil mass movement. A three-part hazard index is used: high, medium, and low. The numerical ratings are subjective and depend on what is considered acceptable for a particular silvicultural activity. Assumptions 1 and 2 in the procedure detail and define a high, medium, and low hazard.

The natural hazard index for slump-earthflows is determined by summing the weighted values from worksheet V.3 and comparing this value to the ranges of values for high, medium, and low hazard index. For example, if the sum of the weighted values for the natural hazard index (wksht. V.3) was 38, the hazard index would be medium. The value 38 falls within the range of values (22-44) for the medium hazard.

The relative hazard for slump-earthflows caused by silvicultural activities is determined by summing the weighted values from worksheet V.4. The overall hazard index resulting from natural plus existing or proposed silvicultural activities is determined by adding the total weighted value from silvicultural activities to the total weighted value for the natural hazard. This overall weighted value is compared with the range of values given for a high, medium, or low hazard index. For example, if the silvicultural activities resulted in a total weighted value of 8, the overall weighted value of both the natural (38) plus the silvicultural activity (8) would be equal to 46, and the overall hazard index would be high.

FOR THE TWO TYPES OF SOIL MASS MOVEMENTS, EVALUATE NATURAL VS. MAN-INDUCED MASS MOVEMENT

Determine the quantity of material delivered to a stream channel for each soil mass movement type and evaluate any man-induced increase in mass movement over that naturally occurring.

Table V.7.—Weighting factors for determination of natural hazard of slump-earthflow failures

Factor	Hazard index and range	Weight
Slope gradient	High greater than 30° (58%)	6
	Medium 15 - 30° (27%-58%)	4
	Low under 15° (27%)	2
Subsurface drainage characteristics	High Area exhibits abundant evidence of impaired groundwater movement resulting in local zones of saturation within the soil mass — short, irregular surface drainages which begin and end on the slope Impaired drainage, indicated at the surface by numerous sag ponds with standing water, springs and patches of wet ground Impaired drainage involves more than 20% of the area	6
	Medium Some indications of impaired drainage, but generally involving less than 10% of the area Active springs are uncommon, infrequent, or contain no standing water	4
	Low No evidence of impaired drainage	2
Soil texture	High Predominantly fine grained cohesive soils derived from weathered sedimentary rocks, volcanics, aeolian and alluvial silts and glaciolacustrine silts and clays Clay sized particle content generally greater than 20% Clay minerals predominantly of the smectite group (montmorillonite), exhibiting swelling characteristics upon wetting	15
	Medium Soils of variable texture including both fine and coarse grained components in layers and lenses The fine grained, cohesive component may contain a clay sized particle content greater than 20%, but clay minerals are predominantly of the illite and kaolinite groups, exhibiting lower sensitivity to changes in stress	10
	Low Soils of variable texture Some clayey soils present but widely dispersed in small layers or lenses	5
Slope configuration	High 40% or more of the area is characterized by hummocky topography consisting of rolling, bumpy ground, frequent benches and depressions locally enclosing sag ponds Tension cracks and headwall scarps indicating slumping are unvegetated and clearly visible Slopes are irregular and may be slightly concave in the upper 1/2 and convex in the lower 1/2 as a result of the downslope redistribution of soil materials Zones of active movement are abundant	5
	Medium 5% to 40% of the area is characterized by hummocky topography Occasional sag ponds occur, but slump depressions are generally dry Headwall scarps are revegetated and no open tension cracks are visible Active slump-earthflow features are absent	2

Table V.7.—Weighting factors for determination of natrual hazard of slump-earthflow — continued

Factor	Hazard index and range	Weight
	Low Less than 5% of the area is characterized by hummocky topography Old slump-earthflow features are absent or subdued by weathering and erosion No active slump earthflow features present, slopes are generally smooth and continuous from ridge to valley floor	1
Vegetative indicators	High Phreatophytic (wet site) vegetation widespread Tipped (jackstrawed) and split trees are common Pistol-butted trees occur in areas of obvious hummocky topography (note: pistol-butted trees should be used as indicators of active slump-earthflow activity only in the presence of other indicators — pistol-butting can also occur in areas of high snowfall and is often the result of snow creep and glide)	5
	Medium Phreatophytic vegetation limited to occasional moist areas on the open slope and within sag ponds Tipped trees absent	3
	Low Phreatophytic vegetation absent	0
Precipitation input	High Area characterized by high rainfall of greater than 80 in/yr (203 cm/yr) distributed throughout the year or greater than 40 in/yr (102 cm/yr) distributed over a clearly definable rainy season Locale is subjected to frequent high intensity, long duration storms capable of generating continuing saturated conditions within the soil mass leading to active pore water pressure development and mobilization of the clay fraction Area has a high potential for rain-on-snow events	18
	Medium Area characterized by moderate rainfall of 20 to 40 in/yr (51 cm/yr to 102 cm/yr) Storms of moderate intensity and duration are common Snowpack is moderate, but rain-on-snow events are rare	10
	Low Rainfall in the area is low (less than 20 in/yr) storms are infrequent and of low intensity and duration Stored water content in the snowpack, when present, is low throughout the winter with no mid-winter or early spring releases due to climatological events	2

WORKSHEET V.3

Slump-earthflow natural factor evaluation form

Index	Slope gradient	Subsurface drainage characteristics	Soil texture	Slope configuration	Vegetative indicators	Precipitation input
High	[✓ 6]	6	15	[✓ 5]	5	18
Medium	4	[✓ 4]	[✓ 10]	2	[✓ 3]	[✓ 10]
Low	2	2	5	1	0	2

Factor summation table

Gross hazard index	Range	Natural
High	Greater than 44	38
Medium	21 - 44	
Low	Less than 21	

Table V.8.—Weighting factors for determination of management induced hazard of slump-earthflow failures

Factor	Hazard index and range	Weight
Vegetation cover removal	High Total removal of cover or large clearcuts with openings continuous downslope — such removal would be sufficient to increase soil moisture levels and reduce root strength	3
	Medium Cover partially removed — clearcuts in small patches or strips less than 20 acres (8 ha) is size and discontinuous downslope	2
	Low Cover density altered through partial cutting, no clearcutting evident	1
Roads and skidways	High High density (>15% of area in roads) cut-and-fill type (balanced) construction Roads and skidways located or planned across identifiable unstable ground Roads crossing active or dormant slump-earthflow features Massive fills or spoil piles on slump benches Inadequate drainage creating concentrations of water at the surface with diversion of surface drainage into unstable areas	7
	Medium Mixed road types, both fully benched and cut-and-fill (balanced) — moderate road density (8-15% of area in roads), unstable areas features avoided Roads generally have adequate cross drains for normal runoff conditions but are undersized for 10 yr storm flows Diversions of concentrations of water into unstable sites avoided	4
	Low No roads present — if present, predominantly fully benched Road density less than 8% Most road location and construction on ridgetops or in alluvial valley floors Adequate cross drainage with dispersal rather than heavily concentrated surface flow	2
Harvest systems	High Operation of tractor yarding, jammer yarding or other ground lead systems causing excessive ground disturbance	3
	Medium High lead yarding with partial suspension and skyline with partial suspension No tractor yarding	2
	Low Helicopter and balloon yarding Full suspension of logs by any method	1

WORKSHEET V.4

Slump-earthflow management related factor evaluation form

Index	Vegetation cover removal	Roads and skidways	Harvest methods
High	[✓ 3]	7	[✓ 3]
Medium	2	4	2
Low	1	[✓ 2]	1

Factor summation table

Gross hazard index	Range	Natural + management
High	Greater than 44	38+8=46
Medium	21 - 44	
Low	Less than 21	

HISTORY OF PAST SILVICULTURAL ACTIVITIES

To estimate the man-induced increase in the amount of soil delivered to a stream channel caused by silvicultural activities, it is necessary to compare soil mass movement in an area that has not been subjected to silvicultural activities with soil mass movement in an area that has been subjected to silvicultural activities. It is essential that the area selected for its previous silvicultural activities be identical or very similar to the undisturbed area, not only in physical site conditions, but also in proposed silvicultural activities. The proposed site of the silvicultural activity may or may not have existing soil mass movement which could be measured and quantified. The other area should have a history, if possible, of soil mass movements from both natural and man-induced causes.

SITE OF PROPOSED SILVICULTURAL ACTIVITY

If the proposed silvicultural activity is to be conducted in a previously undisturbed area, the inherent natural instability of the site can be estimated based upon existing failures or upon failures occurring on a similarly undisturbed site.

SITE OF PAST SILVICULTURAL ACTIVITY

Select an area adjacent to the proposed site of the silvicultural activity, with similar site characteristics and a history of similar silvicultural activities. The inherent natural instability of the area can be estimated based upon existing failures. Failures caused or accelerated by the silvicultural activity can also be measured.

VOLUME OF EACH FAILURE AND NUMBER OF FAILURES BY MOVEMENT TYPE & CAUSE

The site is inventoried using aerial photos and possibly a limited field reconnaissance and a record is made of each soil mass movement (the length, width, and depth), (figs. V.9 and V.10). The cause of each mass movement, either natural or in the case of areas that have been subjected to past silvicultural activity, man-induced, and the type of mass movement are noted. The number of soil mass movements by cause (natural vs. man-induced) and type is computed.

ESTIMATE TOTAL & AVERAGE VOLUME PER SOIL MASS MOVEMENT

The volume of individual soil mass movements (V) is computed on worksheet V.5 by multiplying the length (L), width (W), and depth (D) to obtain cubic feet of soil moved. The total soil mass movement by type (debris avalanche-debris flow and slump-earthflow) is computed by summing the volumes of the individual failures (wksht. V.5). These values are summed and recorded on worksheet V.6, step 1. The total number (N) of failures by soil mass movement type is recorded on worksheet V.6, step 2. The average volume per soil mass movement (V_A) by movement type is computed by dividing the total volume (V_t) by the number of failures (N) or $V_A = V_t/N$ and is recorded on worksheet V.6, step 3. For example, if the total volume (V_t) for debris avalanches-debris flows was 17,205 ft^3 (487 m^3) and the number of debris avalanche-debris flow (N) was 5, the average volume per debris avalanche-debris flow (V_A) would equal 3,441 ft^3 (162 m^3) or $V_A = 17{,}205\ ft^3/5 = 3{,}441\ ft^3$.

Figure V.9.—Dimensions of debris avalanche-debris flow failures for determining potential volumes. W = width; L = length; D = depth.

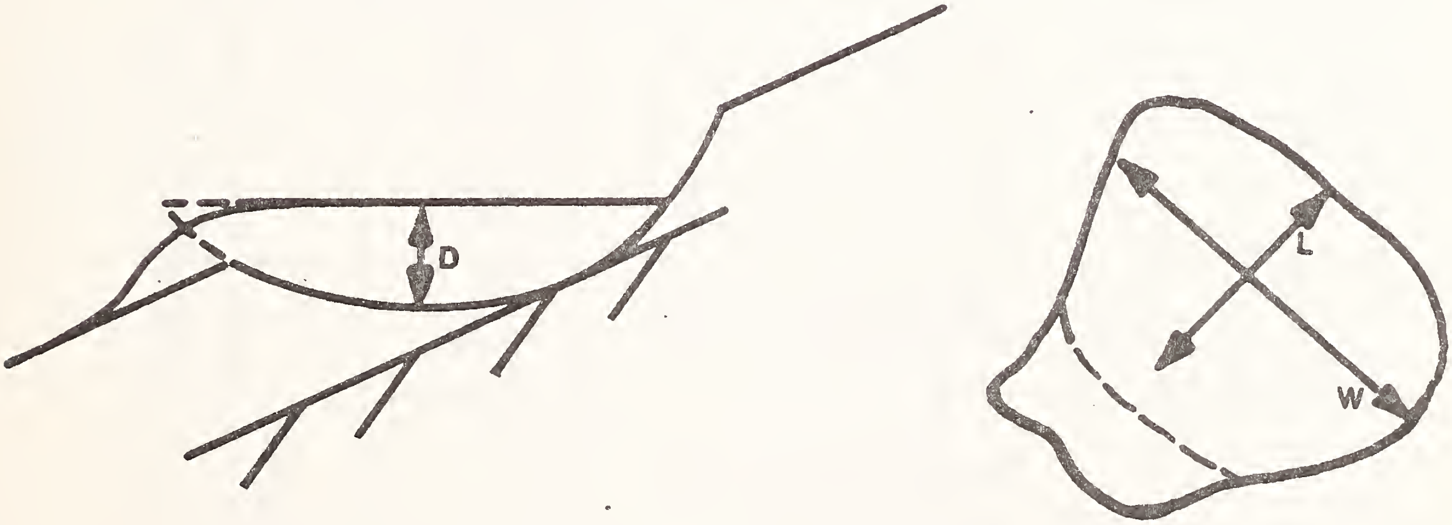


Figure V.10—Dimensions of slump-earthflow failures for determining potential volumes. W = width; L = length; D = depth.

WORKSHEET V.5

Estimation of volume per failure

	Debris avalanche-debris flow						Slump earthflow					
Slide Number	Natural	Man-induced	Length (ft)	Width (ft)	Depth (ft)	Volume (ft^3)	Natural	Man-induced	Length (ft)	Width (ft)	Depth (ft)	Volume (ft^3)
Horse	Creek											
1	X		84	28	1.5	3,528						
Mule	Creek											
1		X	80	24	1.5	3,880						
2		X	129	26	1.5	5,031						
3		X	121	17	1.5	3,086						
4		X	113	18	1.5	3,041						
5		X	95	23	1.5	3,278						
1	X		115	19	1.5	3,280						

WORKSHEET V.6

Estimation of soil mass movement delivered to the stream channel

(1) Watershed name Mule Creek

Factor (2)		Soil mass movement type			
		Debris avalanche-Debris flow		Slump flow	
		Natural (3)	Man-induced (4)	Natural (5)	Man-induced (6)
1 Total volume (V_t) in ft^3		3280	17205	—	—
2 Total number of failures (N)		1	5	—	—
3 Average volume per failure (VA)(ft^3)		3280	3441		
4 Number of failures per slope class	a	1	2		
	b	—	2		
	c	—	1		
5 Number of failures per slope position category	a'			—	—
	b'			—	—
	c'			—	—
	d'			—	—
6 Total volume per slope class or position category (V) in ft^3	V_a $V_{a'}$	3280	6882	—	—
$V = V_A \times N$	V_b $V_{b'}$	—	6882	—	—
	V_c $V_{c'}$	—	3441	—	—
	$V_{d'}$			—	—
7 Unit weight of dry soil material (γ_d) (lb/ft^3)		99	99	—	—

8 Total weight per slope class or position category (W) in tons $W = \frac{V \times \gamma_d}{2,000}$	W_a W_a'	163	341	—	—
	W_b W_b'	—	341	—	—
	W_c W_c'	—	171	—	—
	W_d'			—	—
9 Slope irregularity--smooth or irregular		smooth	smooth	—	—
10 Delivery potential (D) as a decimal percent for slope class or position category	D_a D_a'	0.62	0.50	—	—
	D_b D_b'	—	0.30	—	—
	D_c D_c'	—	0.15	—	—
	D_d'			—	—
11 Total weight of soil delivered per slope class or position category (S) in tons $S = W \times D$	S_a S_a'	101	171	—	—
	S_b S_b'	—	102	—	—
	S_c S_c'	—	26	—	—
	S_d'			—	—
12 Total quantity of sediment delivered to the stream channel in tons		101 (400)	299	—	—
13 Acceleration factor (f) $f = TS_{\text{silvicultural activity}}/TS_{\text{natural}}$		3		—	
14 Estimated increase in soil delivered to the stream channel due to the proposed silvicultural activity (TS) in tons $TS_{\text{silvicultural activity}} = TS_{\text{natural}} \times f$		—		—	

NUMBER OF SOIL MASS MOVEMENTS BY SLOPE CLASS OR POSITION CATEGORY

The soil mass movement recorded previously by type and cause must be differentiated by slope class or category. Debris avalanches-debris flows are differentiated by slope class which is based upon slope steepness. There are three classes: *a* is greater than 35° (70%), *b* is less than 35° (70%), and greater than 28° (53%), and *c* is less than 28° (53%). Slump-earthflows are differentiated by position on the slope. There are four position categories: *a'* is adjacent to the stream, *b'* is the lower 1/3 of the slope, *c'* is the middle 1/3 of the slope, and *d'* is the upper 1/3 of the slope. This information is recorded on worksheet V.6, step 4 for slope classes and step 5 for slope position categories.

TOTAL VOLUME RELEASED BY SLOPE CLASS OR POSITION CATEGORY

For both the proposed silvicultural activity area and the area previously subjected to a silvicultural activity, the total volume of soil mass movement (V_t) by type and slope class *(a,b,c)* or position category *(a',b',c',d')* is computed. The average volume per failure (V_A) is multiplied by the number of failures in each slope class *(a,b,c)* or position category *(a',b',c',d')* and recorded on worksheet V.6, step 6. For example, if the average volume per failure (V_A) was equal to 3,441 ft^3 (162 m^3) and there were two debris avalanches-debris flows in the 28° to 35° slope class *(b)*, the total volume for that soil mass movement type and slope class *(b)* would equal 6,882 ft^3 (324 m^3) or 3,441 ft^3 × 2 = 6,882 ft^3.

ESTIMATED DRY UNIT WEIGHT OF SOIL MASS MOVEMENT

Estimate the dry unit weight (γ_d) of the soil materials included in the failures (V), expressed in pounds/cubic foot. Use soil samples from the assessed area for this determination if possible. Otherwise, use the values for typical soils provided in table V.9. For example, the soil was measured, the dry unit weight was 99 lb/ft^3 (1.57 g/cm^3). The dry unit weight of soil material is recorded on worksheet V.6, step 7.

Table V.9—Unit weight of typical soils in the natural state (Terzaghi 1953)

Description	Unit weight γ_d[1]	γ_d
	lb/ft^3	g/cm^3
Uniform sand, loose	90	1.43
Uniform sand, dense	109	1.75
Mixed-grained sand, loose	99	1.59
Mixed-grained sand, dense	116	1.86
Glacial till	132	2.12

[1] γ_d = unit weight in dry state.

COMPUTE TOTAL WEIGHT RELEASED PER SLOPE CLASS OR CATEGORY

Estimate the total weight of material (W) released per slope class *(a,b,c)* or category *(a',b',c',d')*. For the previously disturbed site (that area subjected to a past silvicultural activity), differentiate between natural and man-induced failures. For example, if the dry unit weight was 99 lb/ft^3 and the total volume released by debris avalanche-debris flow with a slope class of 28° to 35° was 6,882 ft^3, the total weight released for this slope class would be 681,318 lb or 6,882 ft^3 × 99 lb/ft^3 = 681,318 lb. This is converted to tons by dividing by 2,000 lb/ton or 681,318 lb divided by 2,000 lb/ton = 341 tons (309 metric tons). These values are recorded on worksheet V.6, step 8, by slope class *(a,b,c)* or position category *(a',b',c',d')*, type of mass movement, and for the previously disturbed site, natural vs. man-induced failures.

SLOPE IRREGULARITY BY SLOPE CLASS OR POSITION CATEGORY

Estimate, by slope class *(a,b,c)* or position category *(a',b',c',d')*, the gross irregularity of the slope within the area of the proposed silvicultural

activity and the area of the past silvicultural activity. Two general classifications are used: smooth and irregular. Smooth slopes generally have a uniform profile with a few major breaks or benches which may serve to trap and collect soil mass movement material. Incipient drainage depressions and intermittent drainages have a constant grade and lead directly to main drainage channels. Irregular slopes generally have an uneven profile with frequent benching or breaks, which tend to trap and collect soil mass movement material. Incipient drainage depressions and intermittent drainageways have an uneven grade with frequent grade flattening and changes in direction. The classification is recorded on worksheet V.6, step 9.

ESTIMATE DELIVERY POTENTIAL

Determine the percentage of soil mass movement material delivered (D) to the stream channel. An estimated delivery relationship is presented in figure V.11, for debris avalanches-debris flows, and is based upon the slope class *(a,b,c)* and irregularity. An estimated delivery relationship is presented in figure V.12 for slump-earthflows and is based upon the slope position category *(a′,b′,c′,d′)*. Delivery in percent, is recorded on worksheet V.6, step 10. For example, the delivery potential of a debris avalanche-debris flow on a smooth 29° (55%) slope is 30%.

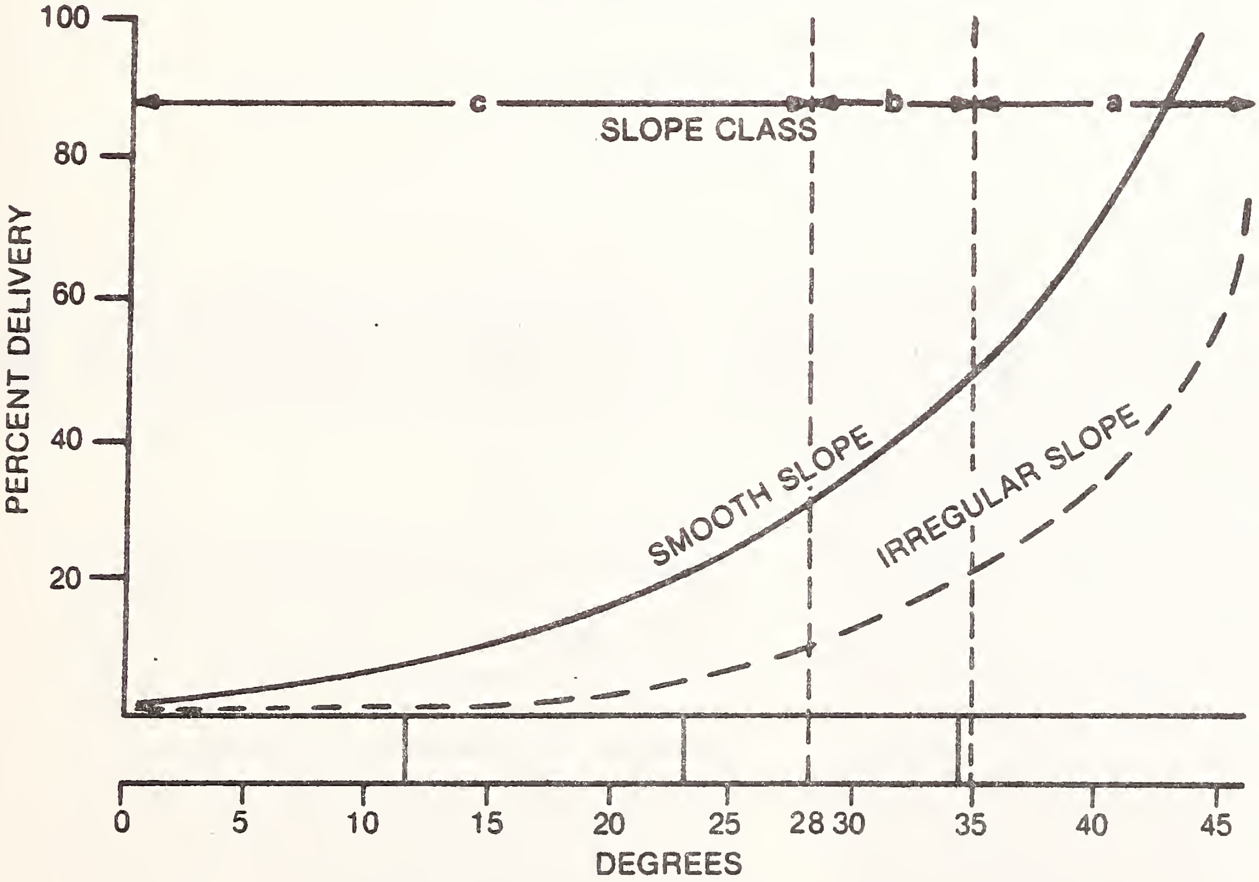


Figure V.11—Delivery potential of debris avalanche-debris flow material to closest stream.

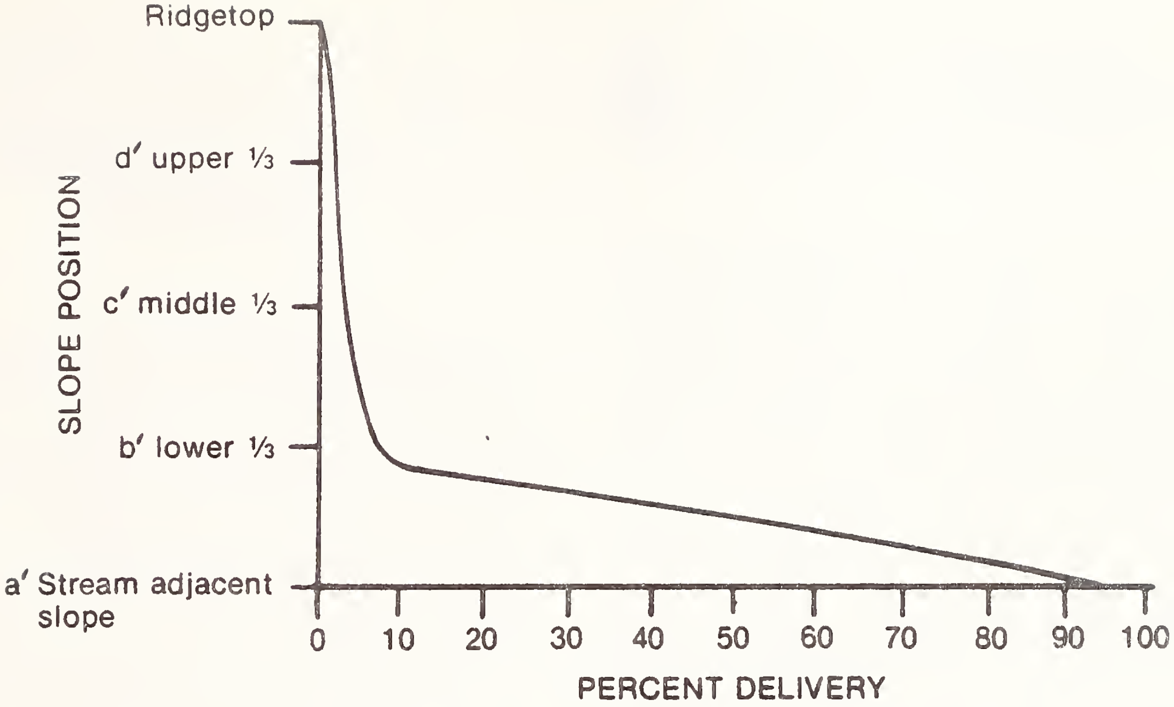


Figure V.12—Delivery potential of slump-earthflow material to closest stream.

ESTIMATE TOTAL QUANTITY OF SOIL DELIVERED PER SLOPE CLASS OR POSITION CATEGORY AND TOTAL AMOUNT

Determine the estimated quantity of soil mass movement material delivered to the stream channel (S) for each slope class *(a,b,c)* or position category *(a′,b′,c′,d′)*. For the area subjected to the past silvicultural activity, separate by natural vs. man-induced. The quantity of soil mass movement material delivered to a stream (S) is computed by multiplying the estimated total weight of released soil material (W) by the delivery potential (D) expressed as a decimal percent. This should be done for each slope class or position category. For example, if the total weight of a released debris avalanche-debris flow with a slope class of 28° to 35° class(*b*) was 341 tons, and the delivery potential was 30 percent, the amount of material delivered to a stream channel would be 102 tons or 341 tons × 0.3 decimal percent. These values are recorded in worksheet V.6, step 11. The total quantity of soil mass movement material (TS) delivered to the stream channel is computed by summing the material delivered by each slope class *(a,b,c)* or position category *(a′,b′,c′,d′)*. The total quantity delivered is recorded on worksheet V.6, step 12. For example, if the slope classes *(a,b,c)* for debris avalanche-debris flow had the following values: S_a = 171 tons, S_b = 102 tons, and S_c = 26 tons, the total quantity of material delivered to the stream channel by debris avalanche-debris flows would be equal to 299 tons. If slump-earthflows were present or possible, these values *(a′,b′,c′,d′)* would also be summed and added to the debris avalanche-debris flow value to get the quantity of total sediment delivered to the stream (TS).

The computation provides an estimate of the average total volume of material delivered to the stream channel (TS) in the area of proposed silvicultural activities under natural conditions and can be used directly in "Chapter VI: Total Potential Sediment."

ESTIMATE AN ACCELERATION FACTOR TO ACCOUNT FOR THE INCREASED DELIVERY DUE TO THE SILVICULTURAL ACTIVITY (MAN-INDUCED)

Estimate the change in sediment delivery to the stream channel on the previously disturbed area as a result of all silvicultural activities by comparing quantities and delivery rates for both natural and man-induced failures. The acceleration factor (f) is estimated by dividing the total quantity of soil delivered to the stream channel due to silvicultural activities (man-induced) (TS silvicultural activity) by that due to natural causes (TS natural), record on worksheet V.6, step 13. For example, if the quantity of soil delivered due to silvicultural activities was 299 tons and that delivered due to natural cause was 101 tons, the acceleration factor (f) would be 3.0. The acceleration factor is recorded on worksheet V.6, step 13. Note total from both natural and man-induced failures would be equal to 299 tons (silvicultural activity) plus 101 tons (natural) or 400 tons.

ESTIMATE INCREASED SOIL DELIVERY DUE TO THE PROPOSED SILVICULTURAL ACTIVITY

Estimate the increase in amount of soil mass movement material that would be delivered from the area being considered for the proposed silvicultural activity. The total quantity of soil mass movement material (TS) delivered to the stream channel (natural conditions) is multiplied by the acceleration factor (f) estimated from a site previously subjected to similar silvicultural activity, record on worksheet V.6, step 14. For example, if the existing natural condition delivered a total quantity of soil mass movement material to the stream channel of 64 tons and the acceleration factor estimated from a similar site subjected to a similar silvicultural activity was 3.0, the estimated potential soil mass movement material delivered to the stream channel would be equal to 192 tons. This completes the procedure for determining increased soil delivery.

APPLICATIONS, LIMITATIONS, AND PRECAUTIONS

Relating magnitude of management impact to hazard index ranking has the shortcoming that once a site is ranked as high hazard, alternate management practices do not change the estimate of management impact. Where data permit, quantification of hazard index should be set up so that management-caused changes in hazard index are directly proportional to degree of accelerated erosion. Such a system would permit realistic assessment of various management alternatives on the mass erosion rate. However, additional studies are needed to quantify the impact of numerous silvicultural activities.

CONCLUSIONS

This procedure is designed to quantify the potential volume of soil mass movement material that is delivered to the closest drainageway as a result of a proposed silvicultural activity. The analysis is conducted on areas that have previously been delineated as unstable. It should be reemphasized that if the user does not have experience in delineating unstable or potentially unstable areas, additional assistance from qualified specialists should be obtained.

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APPENDIX D
WRENSS - Chapter 4
Surface Erosion

Prepared by Gordon Warrington
Major Contributions by:
Kerry Knapp
Glen Klock
George Foster
Scott Beasley

Appendix D contains only the
"Sediment Delivery" Section of
Chapter 4

The term "sediment delivery index" used in WRENSS is equivalent to the term "slope sediment delivery ratio" used in this guide

DISCUSSION: SEDIMENT DELIVERY

GENERAL CONCEPTS OF SEDIMENT DELIVERY

To evaluate the effects of surface erosion on water quality, it is necessary to estimate the amount of eroded material that might be moved from the eroding site into a receiving stream channel system. Unfortunately, the processes which describe the delivery of eroded materials are less well understood than those for erosion, and data for sediment delivery are scarce.

Historically, the determination of the amount of sediment that reached a stream channel revolved around the concept of delivery ratios (Gottschalk and Brune 1950, Maner 1958, Maner and Barnes 1953, Roehl 1962, Williams and Berndt 1972). A delivery ratio is the volume of material delivered to a point in the watershed, divided by the gross erosion estimated for the slopes in the watershed above that point. Values range from zero to one.

Apparently, a characteristic relationship of sediment yield to erosion does not exist. Many factors influence a sediment delivery ratio; if these factors are not uniform from one watershed to another, the relationship between sediment yield and erosion shows considerable variation (Renfro 1975).

Factors Influencing Sediment Delivery

Sediment delivery from a disturbed site to a stream channel is influenced to varying degrees by the following factors (Foster and Meyer 1977, Megahan 1974, Renfro 1975). (There may be other factors, not listed here, that are also important in given situations.)

Sediment Sources

In terms of effects upon a sediment delivery index, there are at least three ways to describe sediment sources:

1. Type of disturbance — Materials originating from logging areas, skid trails, landings, and roads seem to have a range of delivery ratios that are characteristic of each disturbance type.
2. Type of erosion — Sheet, rill, gully, and soil mass movement have one or more sediment delivery parameters that are unique to that particular form of erosion.
3. Mineralogy of the source area — Delivery ratios are influenced by various physical characteristics of sediment materials. Size, shape, and density of individual particles and their tendency to form stable aggregates are usually reflected by their mineralogy. Wettability of particles may be a function of mineralogy or of unique biological systems both of which influence the efficiency of sediment delivery.

Amount Of Sediment

When the amount of potential sediment exceeds the runoff delivery capability, deposition occurs and the amount of sediment delivered to a stream channel is closely controlled by the amount of runoff energy. If the amount of sediment is less than the runoff delivery capability, then no deposition will occur between the disturbed area and a stream channel.

Proximity Of Sediment Source

The distance that sediment must move and the shape and surface area of the transport path all affect the amount of material that may be lost from the transport system.

Transport Agents

Surface runoff from rainfall and snowmelt is the main agent for transporting eroded material. Sediment transport is dependent on the volume and velocity of water as well as the character and amount of material to be transported.

Texture Of Eroded Material

Individual particles of fine-textured material can be moved easier than particles of coarse-textured material because the finer the particle, the less transport energy required. If a watershed is dominated by fine-textured material, it is likely to have more material delivered to a stream channel by surface runoff than an equivalent situation with

coarse-textured material — assuming that soil aggregates are not involved.

Deposition Areas

Microrelief that results in surface depressions or other irregularities will deliver less sediment than a smooth, flat surface. Decreases in slope gradient also promote deposition of large size fractions of transported material.

Watershed Topography

Size of the drainage area, overall shape of the land surface, (concave to convex), slope gradient, slope length, and stream channel density all affect the sediment delivery ratio by varying amounts.

Sediment Delivery Model

From the previous discussion concerning factors that influence sediment delivery over an area of land, it can be seen that the amount of eroded material deposited between a disturbed site and a drainage channel is due to a variety of interacting factors. To aid understanding overland sediment transport, the process can be divided conceptually into two parts.

The first requirement is a transporting agent with sufficient energy to move the sediment. In this case, surface runoff is the transporting agent. Its energy is a function of the amount and velocity of waterflow passing over a given area in a given time period.

The second part deals with factors which tend to stop or slow the movement of sediment and waterflow over a slope. Microrelief, slope gradient, slope length, slope shape, vegetation, and surface residues all play a part in reducing the amount of sediment that will actually reach a delivery point (Neibling and Foster 1977, Zingg 1940).

The shape of the area over which sediment is transported (fig. IV.21) also influences the amount actually delivered to a drainage channel. In one case, sediment entering delivery area A is funneled so that a given amount passes over progressively less surface during transit. This reduces the opportunities for deposition and also increases the energy of the transporting agent, thus resulting in increased sediment delivery efficiency. At the other extreme, delivery area C spreads material and water over progressively more area thus reducing the transporting energy and increasing opportunities for in-transit deposition. Delivery area B represents an intermediate situation between A and C. A relative comparison of the three areas would have A delivering more sediment than B, which delivers more than C.

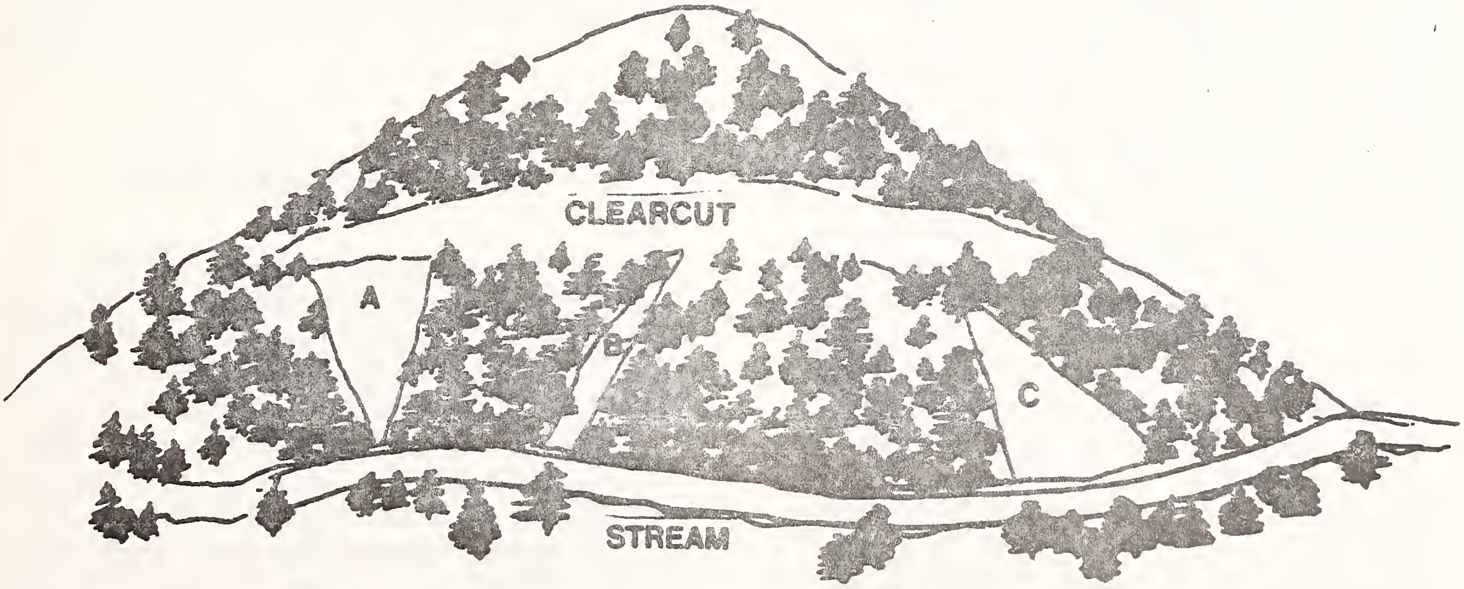

Figure IV.21.—Potential sediment transport paths (A,B, and C) for different parts of a slope.

Any working sediment delivery model must have clearly defined factors which represent the amount of surface runoff available for transporting sediment, the length of the transport path, the gradient of the path, the shape and changes in surface area of the path, a measure of surface microrelief, and a measure of ground cover. All of these factors should have measurable parameters and be combined together with the proper coefficients. To date, there is no accurate way to estimate the amount of surface runoff that might be available for sediment delivery in the forest environment, the actual shape and location of sediment delivery paths, degree of surface roughness, or characteristics of slope shape. An understanding of how to combine these factors or what coefficients to use is not known for most situations.

PROCEDURAL CONCEPTS: ESTIMATING SEDIMENT DELIVERY

This section discusses the concepts necessary for estimating sediment delivery and for evaluating the individual parameters involved. It is organized according to a conceptual perception of sediment delivery and corresponds with the flow chart of figure IV.1. An outline of the overall procedure for estimating sediment delivery to a stream from surface erosion sources is presented in "The Procedure" section of this chapter. A detailed example for using the procedure is provided in "Chapter VIII: Procedural Examples." All concepts discussed here are necessary for using the overall procedure.

The Sediment Delivery Index

An index approach is recommended to help bridge the gap between the need to estimate how much sediment reaches a stream channel and the lack of a working sediment delivery model to provide such estimates. This approach provides a relative evaluation of seven generally accepted environmental factors and one site specific factor that are considered important in the sediment delivery process. These eight factors are not necessarily the only ones that may be needed in all situations. This indexing procedure has not been validated by research. Therefore, the computed quantities may be different from measured quantities of sediment delivered to a stream channel. Use of the index is only an aid in evaluating the relative effects of different management practices on sediment delivery from a given forest area.

Evaluation Factors

For this discussion, each of the following eight factors is considered as though it acts independently of any other factor. In reality, these factors interact with each other in complex ways.

1. **Transport agent (e.g., water availability).** — Surface runoff from rainfall and snowmelt is an important factor in the movement of eroded material. It is estimated that overland flow rates from sheet and rill erosion rarely exceed 1 cfs on agricultural land and generally are less than 0.1 cfs on forest lands in the United States.
2. **Texture of eroded material.** — Assuming that aggregates do not form, individual particles of fine-textured soil material require less energy for delivery than particles of coarse-textured material. Sediment delivery efficiencies are higher on an area dominated by fine-textured material than on an area dominated by coarse-textured materials if the other factors influencing sediment delivery are equal.
3. **Ground cover.** — Ground cover (forest floor litter, vegetation, and rocks) creates a tortuous pathway for eroded particles to travel which allows time for the eroded material to settle from surface runoff water (Tollner and others 1976). Protective ground cover may also prevent raindrop impact energy from creating increased flow turbulance which would increase the carrying capacity of the runoff flow.
4. **Slope shape.** — Concave slopes between the source area and the stream channel promote deposition of the larger size fraction of the transported material (Neibling and Foster 1977). Convex slopes create more favorable conditions for increasing the material carrying capacity of the transporting agent. Slope shape is a difficult factor to quantify, but it seems to play an important role in sediment delivery.
5. **Slope gradient.** — Slope gradient, along with the volume of water available for sediment delivery, provides the necessary energy to deliver the eroded material. The efficiency of

the sediment delivery process increases with increasing slope gradient.

6. **Delivery distance.** — Increasing the distance from a sediment source to a stream channel or diversion ditch increases the effect that other factors have on the amount of sediment actually delivered. On the other hand, if a sediment source is very close to a stream channel, the other factors affecting sediment delivery have proportionally less opportunity to reduce the amount of sediment delivered.
7. **Surface roughness.** — Roughness of the soil surface affects sediment delivery similarly to that of ground cover. Rougher surfaces create more tortuous pathways for eroded particles to pass over and more surface area for water infiltration than smooth surfaces for a given area (Meeuwig 1970).
8. **Site specific factors.** — In many parts of the United States, unique forest environments and/or soil factors influence the sediment delivery efficiency. For example, soil nonwettability (DeBano and Rice 1975), mineralogy such as the Idaho batholith described by Megahan (1974), biological activity, or fire can change the sediment delivery efficiency of some forest lands. Within forested areas of the southeast United States, microrelief adjacent to stream channels may cause concentrated water flows, thus having a large effect on sediment delivery efficiency. Some soils have a greater tendency than others to form stable aggregates, hence reducing the sediment delivery efficiency.

Determining The Sediment Delivery Index

The stiff diagram shown in figure IV.22 uses vectors to display the magnitude and scale of each major factor identified as influencing sediment delivery. The area of the polygon created by connecting the observed, anticipated, or measured value for each factor is determined and related to the total possible area (the polygon formed by connecting the outer limits of each vector) of the graph. The percentage of area inside the polygon is coupled to the delivery index through the use of skewed probit transformations (Bliss 1935). Small polygonal areas surrounding the midpoint indicate a low probability of efficient sediment delivery, or, in other words, a very low sediment delivery index. Sediment delivery indexes will be low in most forest ecosystems managed by the best forest practices. Polygons approaching the outer limits of the stiff diagram indicate a high probability of efficient sediment delivery. The fraction of the total stiff diagram area formed by a given polygon is adjusted using figure IV.23, to give the sediment delivery index.

The scale and magnitude of the vectors in figure IV.22 have been defined as follows:

1. The magnitude of the transport agent is determined by the equation:

$$F = CRL \qquad \text{(IV.12)}$$

where:

F = water availability,

$C = 2.31 \times 10^{-5} \frac{\text{ft}^2\ \text{hr}}{\text{in sec}}$ (a conversion constant)

R = maximum anticipated precipitation and/or snowmelt rate minus infiltration in units of in/hr from local records, and

L = slope length in feet of the sediment source area (perpendicular to contours).

Values of F for given values of R and L are in table IV.8.

The maximum scale value in figure IV.22 is 0.1 cfs. If the flow is calculated to exceed 0.1 cfs, use the scale factor of 0.1 for water availability. This model assumes that the precipitation input exceeds the site infiltration capacity causing overland flow conditions at the lower boundary of the eroded material source area. If no water is available then the sediment delivery index is zero (0.0).

2. Texture of eroded material is expressed as percent of eroded material that is finer than 0.05 mm (silt size). A particle diameter less than 0.05 mm was shown to be highly transportable for sediment movement (Neibling and Foster 1977). A scale factor of zero indicates that the eroded material contains no material less than 0.05 mm diameter, and a factor of 100 percent indicates that all of the eroded material is 0.05 mm or less in diameter.
3. Ground cover that is in actual contact with the soil surface, is expressed in percent cover between 0 (bare soil surface) and 100 (mineral soil surface completely covered). This factor is scaled based on unpublished data by Dissmeyer[2] which relates relative ground cover

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[2] Personal communication of unpublished material from G. Dissmeyer, USDA Forest Service, State and Private Forestry, Atlanta, Ga.

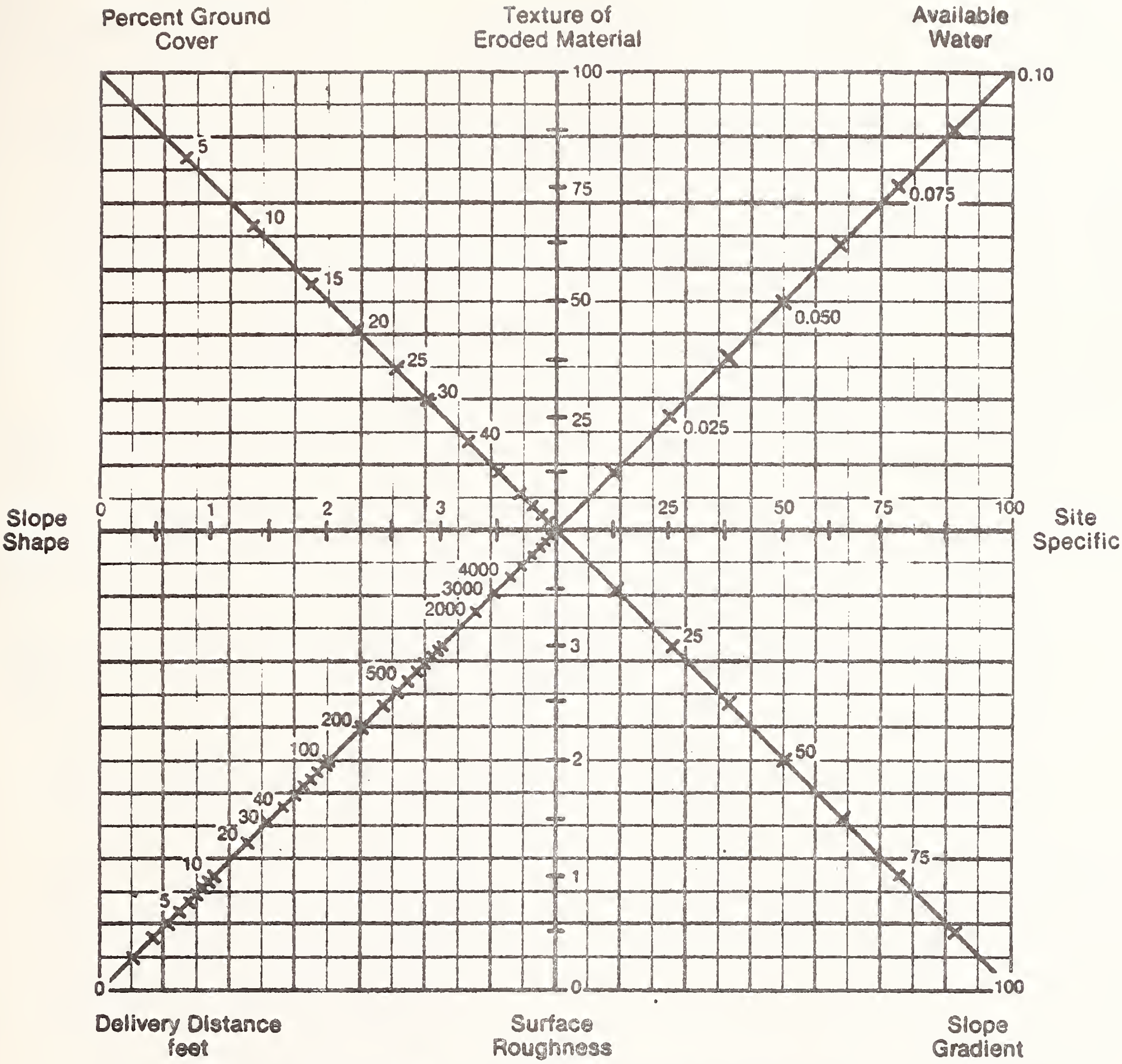

Figure IV.22—Stiff diagram for estimating sediment delivery.

density influence to overland water flow.

4. Slope shape is scaled in magnitude between 0 and 4, with 4 being a slope that is convex from the boundary of the source area to the stream channel. A scale factor of 0 describes a slope concave from the boundary of the source area to the stream channel, while a factor of 2 shows that one-half of the slope is concave and the other half is convex or that the entire slope is uniformly straight. A factor of 3 indicates that a larger percentage of the slope is convex in shape.
5. The slope gradient is the vertical elevation difference between the lower boundary of the source area and the stream channel divided by the horizontal distance and expressed as a percent between 0 and 100.
6. The distance factor is the $\log_{10}$ of the distance in feet from the boundary of the source area to a stream channel or ditch. Distances greater than 10,000 feet (3,050 m) are considered infinite. The distance vector is marked using a $\log_{10}$ scale so that distances are entered directly onto the vector in figure IV.22.

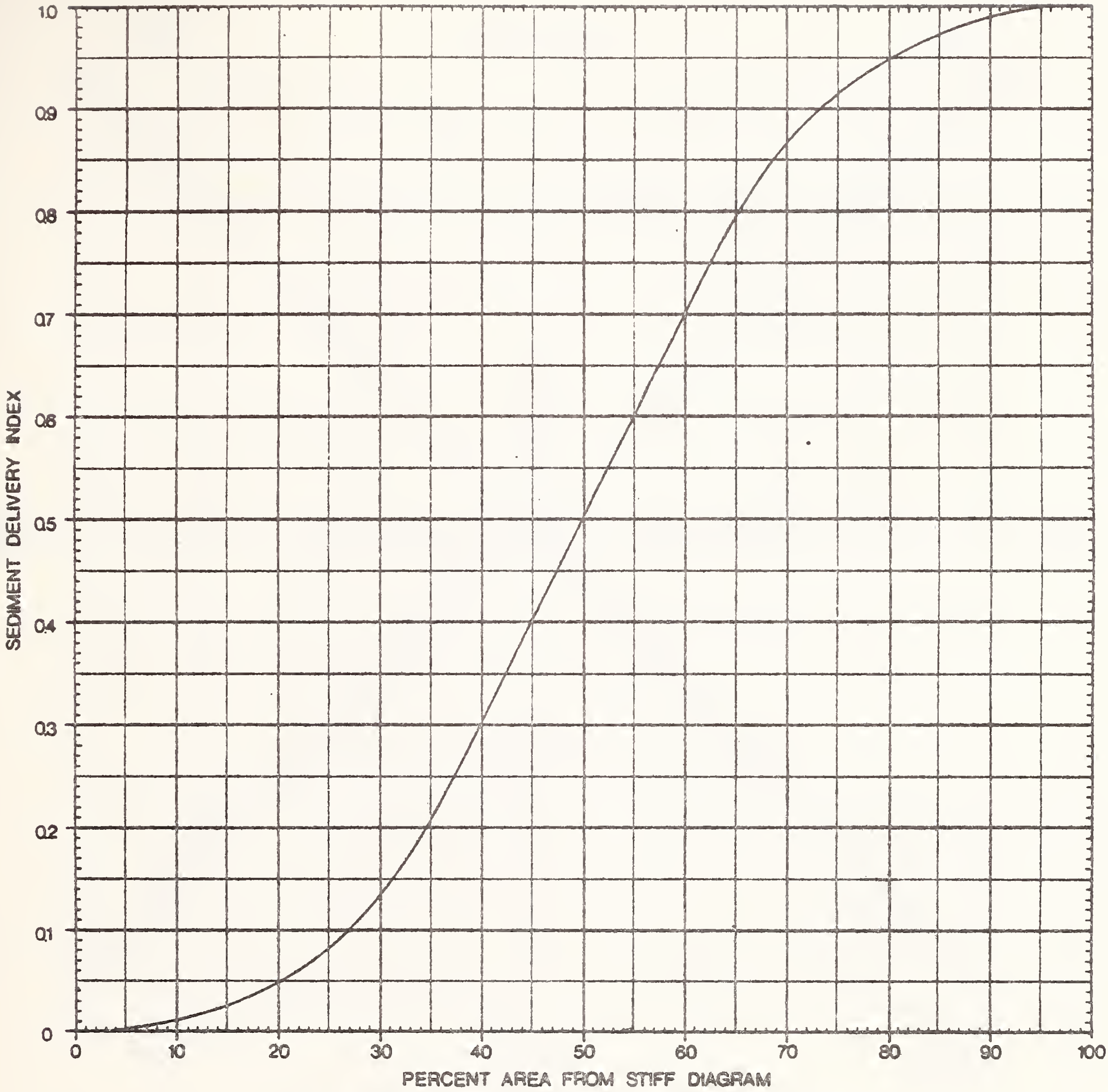

Figure IV.23.—Relationship between polygon area on stiff diagram and sediment delivery index.

7. The roughness factor is scaled in magnitude between 0 and 4 with 0 being an extremely smooth forest floor surface condition and 4 being a very rough surface. This is a subjective evaluation of soil surface conditions.

8. The site specific factor influencing delivery ratios is scaled between 0 and 100 and must be assigned its effective magnitude by a user familiar with the unique condition of the site.

Appropriate factor values are plotted on each vector of the graphic sediment delivery model (fig. IV.24). Lines are drawn to connect all plotted points to form an enclosed, irregular polygon. If a site specific factor is not used, draw a line directly between plotted points on the slope gradient and available water vectors. Determine the area inside the polygon by: measuring with a planimeter, estimating with a dot grid, or calculating and summing the areas of the individual triangles. Determine the percent of the total graph area that is

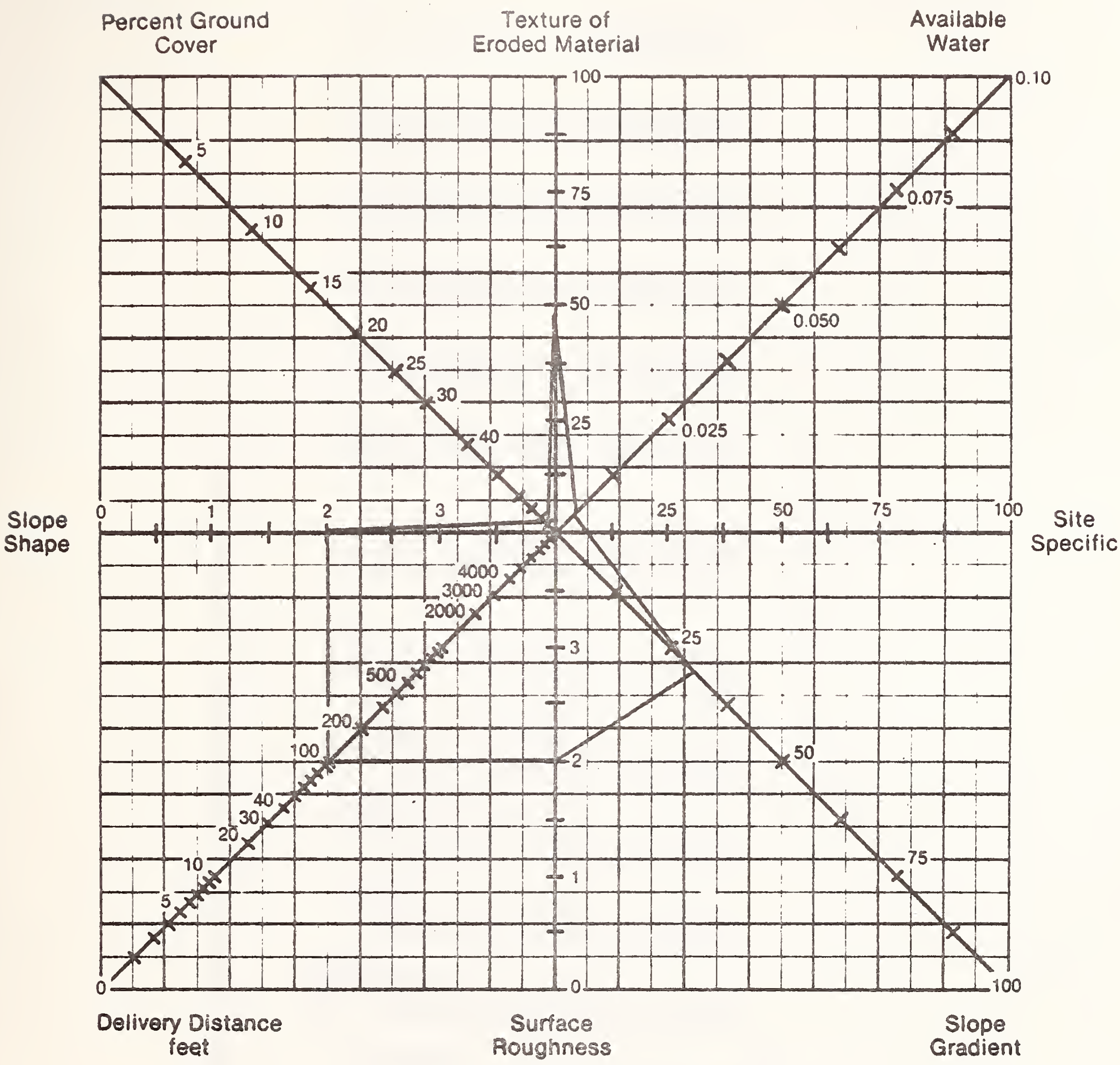

Figure IV.24.—Example of graphic sediment delivery model for road R3.1.

within the polygon. Using the S-shaped probit curve in figure IV.23, determine the sediment delivery index by using the percent area of the polygon from figure IV.24.

Table IV.8.—Water availability values for given source area slope length (ft) and runoff (in/hr)[1]

Surface slope length	Runoff															
	.025	.05	0.75	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75	3.0	3.25	3.5	3.75	4.0
10	.00006	.00012	.00017	.00023	.00029	.00035	.00040	.00046	.00052	.00058	.00064	.00069	.00075	.00081	.00087	.00092
20	.00012	.00023	.00035	.00046	.00058	.00069	.00081	.00092	.0010	.0012	.0013	.0014	.0015	.0016	.0017	.0018
30	.00017	.00035	.00052	.00069	.00087	.0010	.0012	.0014	.0016	.0017	.0019	.0021	.0023	.0024	.0026	.0028
40	.00023	.00046	.00069	.00092	.0012	.0014	.0016	.0018	.0021	.0023	.0025	.0028	.0030	.0032	.0035	.0037
50	.00029	.00058	.00087	.0012	.0014	.0017	.0020	.0023	.0026	.0029	.0032	.0035	.0038	.0040	.0043	.0046
75	.00043	.00087	.0013	.0017	.0022	.0026	.0030	.0035	.0039	.0043	.0048	.0052	.0056	.0061	.0065	.0069
100	.00058	.0012	.0017	.0023	.0029	.0035	.0040	.0046	.0052	.0058	.0064	.0069	.0075	.0081	.0087	.0092
150	.00087	.0017	.0026	.0035	.0043	.0052	.0061	.0069	.0078	.0087	.0095	.010	.011	.012	.013	.014
200	.0012	.0023	.0035	.0046	.0058	.0069	.0081	.0092	.010	.012	.013	.014	.015	.016	.017	.018
250	.0014	.0029	.0043	.0058	.0072	.0087	.010	.012	.013	.014	.016	.017	.019	.020	.022	.023
300	.0017	.0035	.0052	.0069	.0087	.010	.012	.014	.016	.017	.019	.021	.023	.024	.026	.028
350	.0020	.0040	.0061	.0081	.010	.012	.014	.016	.018	.020	.022	.024	.026	.028	.030	.032
400	.0023	.0046	.0069	.0092	.012	.014	.016	.018	.021	.023	.025	.028	.030	.032	.035	.037
450	.0026	.0052	.0078	.010	.013	.016	.018	.021	.023	.026	.029	.031	.034	.036	.039	.042
500	.0029	.0058	.0087	.012	.014	.017	.020	.023	.026	.029	.032	.035	.038	.040	.043	.046
1000	.0058	.012	.017	.023	.029	.035	.040	.046	.052	.058	.064	.069	.075	.081	.087	.092

[1]The table values were obtained by the formula:

$$F = \left(2.31 \times 10^{-5}\ \frac{\text{ft}^2\,\text{hr}}{\text{in sec}}\right)\left(\text{Runoff in/hr}\right)(\text{slope length ft.})$$

Estimating Sediment Delivery By Activity

Each land-disturbing activity should have an estimate of soil loss for the location where it occurs and a delivery index based on site characteristics. An estimate of the amount of sediment which might reach a stream channel can be obtained by multiplying the surface soil loss (tons/year) by the sediment delivery index for each erosion response unit.

All of the procedures used to arrive at an estimate of surface soil loss and sediment delivered to a stream channel only provide a way to evaluate alternative management practices. Only on-the-ground monitoring can verify if the objectives have been met by the management strategy.

CONSIDERATIONS FOR REDUCING SEDIMENT DELIVERY

Theoretically it is possible to reduce sediment delivered to a stream channel by making appropriate changes in any of the index factors. In actual practice, some factors are easier to change than others. The following tabulation describes the basic concepts underlying each factor and the changes brought about by controls for sediment delivery. This conceptual presentation is to aid understanding of controls and determining which control practice to use. Details of specific control practices may be found in "Chapter II: Control Opportunities."

Sediment delivery factors	Preventive	Mitigative
Water availability	Control over the rainfall rate is not likely to occur because it is a function of overall weather patterns.	
	Use management practices that maintain high infiltration rates. Avoid such things as soil compaction which changes soil structure and permeability. Control of soil moisture content by high consumptive use promotes infiltration.	Increase infiltration rates by breaking surface crusts, and incorporating organic matter or other soil amendments to improve aggregation of soil particles. Promote vegetative growth for high consumptive water use and desirable soil structure development.
	Where snowmelt is influential, use management practices which will not create significant increases in the amount of solar energy reaching the snow pack.	Reduce snowmelt runoff rates by increasing the interception of solar energy above the snow surface.
Texture of eroded material	Soil texture is controlled by soil-forming factors that are generally related to mineralogy and weathering.	
	Maintain natural, stable soil aggregates which will act as a coarse-textured material in response to sediment delivery forces.	Use soil amendments which promote floculation and development of aggregates.

Sediment delivery factors	Preventive	Mitigative
Ground cover	Control and design forest management activities to minimize forest floor disturbance.	Add mulch, establish vegetation, distribute residues, or use other practices to create long tortuous pathways for water flow and sediment delivery.
Slope shape	Control location and design of various types of construction and other activities that would create adverse slope shapes.	Design concave slope segments for sediment delivery control on construction sites or with other activities.
Slope gradient	Control location and design of various types of construction activities to minimize the creation of steep slopes.	Reduce slope gradients created by construction and other activities wherever possible.
Delivery distance	Locate activities well away from stream channels to maintain long delivery paths.	Relocate activity sites to increase overall delivery distance to a stream channel.
Surface roughness	Design activities to maintain natural surface roughness. Avoid creating channels that shortcut natural tortuous pathways.	Create ridges and depressions on the surface to trap sediment and increase water infiltration.
Site specific factors	This will depend upon the characteristics of the chosen site factor.	

APPLICATIONS, LIMITATIONS AND PRECAUTIONS: SEDIMENT DELIVERY

Very few attempts have been made to verify the reliability of sediment delivery models due to the difficulty of obtaining sufficient data for testing. The following limitations attributed to this model are not based on actual data but are deduced as being important. Future research may add to or change ideas about these limitations.

1. Only sheet flow surface runoff is addressed with the sediment delivery index. If channeled flow develops, other approaches must be used to describe sediment delivery.
2. The choice of factors used to describe sediment delivery is thought to apply in all cases; however, these may vary with future research.
3. The scaling of each factor on the stiff diagram is based on the best available information; however, new research information will probably show a need for some changes.
4. Many factors work together in various ways to influence sediment delivery. These interactions have not been studied extensively and may not be expressed correctly by the model.
5. The model assumes that the only water used to move the sediment is generated on the sediment delivery path. It does not consider the potential for additional water from other sources on the slope. Solution of this problem depends on the development of a satisfactory water routing model.
6. Individual sediment delivery routes have various shapes and overall surface areas which are not accounted for by the model.
7. Infiltration rates may be different on disturbed areas than in sediment filter strips. Only the infiltration rate for the disturbed site is used.
8. Antecedent soil moisture conditions are not incorporated into the model. If sediment delivery is most likely to occur during certain time periods with particular soil moisture characteristics, then some adjustments could be made in the infiltration rate.