TFW-SH10-91-002

PROPOSAL FOR RESEARCH IN GEOMORPHOLOGICAL WATERSHED ANALYSIS

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TIMBER FISH
& WILDLIFE

July 15, 1991

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July 15, 1991

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GEOMORPHOLOGICAL WATERSHED ANALYSIS

INTRODUCTION

A. Statement of the Problem and Purpose of the Project

Forested, mountainous landscapes have not been the subject of coordinated, quantitative geomorphological analysis similar, for example, to the work of Trimble (1974, 1977) and others in forested and cultivated landscapes of the Appalachians and Upper Midwest. This is due partly to: poor accessibility and geomorphic complexity of the mountain landscape; partly to the difficulty of observing episodic, violent processes; and partly to the fact that streams rarely achieve flow conditions that are theoretically tractable because their channels are subject to impedance by immobile rocks and large woody debris. In addition, episodic sediment influx and complex storage mechanisms promote rapid form adjustment in channels.

Nevertheless, pressures to utilize mountainous forested watersheds for timber production while maintaining robust populations of fish and wildlife require that new concepts and methods be developed for prediction of hillslope and stream-channel responses to meteorological events and to land management. These methods need to be flexible enough to be useful over the range of processes, landforms, types of timber management, and variety of fish habitats that occur at least within the Pacific Northwest.

We propose to continue a project, begun in January 1991 with funding from the SHAMW Committee (see the progress report in the appendix), that involves a coordinated set of geomorphological studies to address the quantitative relationships between channel morphology and watershed conditions of hydrology, sediment supply, and large channel obstructions in forested mountainous watersheds. Because sediment supply and channel obstructions (such as woody debris, coarse-sediment dams, and active deep-seated landslides) depend on hillslope processes, our coordinated research will be organized into a channel component and two hillslope components (see Figure 1).

The results of the research will include basic advances in the understanding of mountain watersheds and river channels, as well as methods, derived from these improvements, for assessing the effects of forest management on hillslopes and channels. The assessment methods will be usable by M.S.-level personnel trained in earth-science fields such as geomorphology, hydrology, or geotechnical engineering.

The studies have been designed after extensive consultation with the resource-management community in Washington and Oregon. We accomplished this consultation during the six-month start-up period during which we (1) held meetings with various members of the SHAMW and CMER Committees, (2) attended a CMER workshop, (3) organized a workshop in conjunction with the SHAMW Committee to obtain the views of resource professionals from various federal, state, and tribal agencies and industry, and (3) travelled to various field areas in both Eastern and Western Washington to discuss technical needs and field sites with timber managers and scientists. It is our hope that such consultation can be maintained throughout this project. We have also kept in touch with various members of the University of Washington who are designing studies under the CMER umbrella. These include T. W. Cundy and D. P. Lettenmaier, who are planning a study of the potential effects of vegetation removal on snowmelt floods; L. L. Conquest and R. J. Naiman, who are developing methods for the systematic characterization of fish habitat and channel morphology for the CMER Ambient Monitoring Committee, and P. Petersen, who is studying the processes by which sediment accumulates in salmon beds.

B. Goals and Objectives

The overall goal of the study is to provide the scientific basis and methods for predicting the response of hillslopes and stream channels in forested mountains to (1) long-term average conditions (such as climate, geology, topography, and forest type) and (2) to short-term episodic perturbations (such as fires, extreme weather conditions and particularly timber harvest).

We propose to make progress toward this goal by first dividing the entire complex, watershed problem into three related sub-problems: (1) the channel system; (2) hillslopes from which the sediment supply to channels is from shallow sources (such as surface wash from roads, debris avalanches, and debris flows); and (3) complex terrains that are unstable to great depth and supply sediment to streams by either catastrophic or chronic, slow landsliding, creep, or seepage erosion mechanisms. The main body of this proposal is organized into three sections which detail our various plans for each of these topics. However, as indicated in Figure 1, we view the three components as being intimately linked as parts of the watershed sediment budget. For example, the sediment released from shallow sources on hillslopes is transported along stream channels and valley floors where it alters the morphological and sedimentological characteristics of fish habitat. Stream channel morphology is also controlled in other basins by sediment supplied by deep-seated mass failures, which may in their turn be triggered or accelerated by lateral migration of the stream channel. Thus, throughout the study we will have a strong motivation to combine the three components of the drainage basin in a watershed-scale geomorphic analysis.

The proposed research will be conducted by a team of faculty members, graduate students, and post-doctoral research assistants from the Department of Geological Sciences, University of Washington, and the Department of Geology and Geophysics, University of California, Berkeley, (through a sub-contract with the University of Washington). The group will conduct field and theoretical studies oriented towards developing objective, physically based procedures for assessing and interpreting the current condition of channels and hillslopes, and for predicting their response to timber harvest and other perturbations.

We envision our results being used by specialists in applied geomorphology. Hence we are not trying to devise procedures that can be used blindly. It is a presumption that such specialists would have sufficient background in the earth sciences that the influence of such factors as bedrock type and structure, glaciation, and runoff generation mechanisms on erosion processes would be understood in such a way that our procedures would be put to valuable use. Nonetheless, one of the fundamental research questions in all three coupled proposals is how to generate a general quantitative approach, applicable to any landscape, to assess management effects on the hillslope-channel system.

SHALLOW SEDIMENT SOURCES IN WATERSHED ANALYSIS

Improved analysis and prediction of shallow sediment sources in watersheds requires two scientific advances:

1. Prediction of the location of sediment sources.
2. Prediction of the sediment influx to stream channels under natural and managed conditions.

1. Locations of sediment sources

Statement of the Problem

Shallow debris flows from in-unit failures and roads, and the influx of fine sediment to spawning gravels from road wash and debris-flow scars, are responsible for much of the habitat degradation in channels that results from forest practices. Hence a critical component of the proposed TFW watershed analysis plan should be the development of procedures that can identify potentially unstable lands and predict downstream influence of sediment loading on downstream reaches. It is clear from our conversation with forest managers that they want to be able to specify a particular proposed harvest unit in a watershed and ask what potential is there for landsliding due to forest practices. Fisheries biologists, on the other hand, want to know what will happen in a proposed harvest unit, but they are also concerned about all the other sediment sources that may affect the channel habitat. What is needed, therefore, is a procedure that can provide site-specific answers, but can do so in the context of the general sediment budget of the watershed.

Current practice regarding slope-stability prediction varies considerably between federal, state and private industry and geographically throughout the Northwest. Most commonly a decision is made regarding the stability of a proposed harvest unit with little or no ground inspection based on the experience of individuals from various regulatory agencies who generally have little or no formal training in slope stability. This problem is specifically recognized in the recent CMER (1991) report on cumulative effects. Several approaches have been taken to using empirical studies and theoretical analyses for predicting sites of instability as guides in decision making (see brief review in Reid, 1991). These approaches range from empirically-derived regional statistical relationships (e.g. Duncan et al., 1987; Rice and Lewis, 1989) to locally developed check lists (as used, for example, in the Siuslaw National Forest, F. Swanson, pers. comm.) and to detailed field investigation and theoretical stability analysis of individual sites (e.g. Burroughs et al., 1985). The latter approach, which is currently used in the Oregon Coast Range by the Bureau of Land Management (Barry Williams, pers.

comm.), results in designated "leave areas" when the analysis yields a high potential for instability.

None of these approaches links potential slope stability to potential downslope consequences. The statistical and check list approach have unknown regional application whereas the detailed site investigation requires considerable investment of personnel and time. It should also be pointed out that with the now common practice of limiting roads to ridge tops wherever possible, the problem of slope stability has come to focus more on in-unit failures where no road influence is apparent and on stability and rehabilitation of older road systems.

For the purposes of the proposed TFW watershed analysis what is needed is a process-based procedure that provides information about the entire watershed yet can be used to make local harvest-unit-scale decisions. Not only should sites of potential instability be identified, but the likely influence on downstream channels by individual debris flows should be estimated. The debris flow potential needs to be seen in the light of the potential impact on downstream resources. Ideally, on the watershed scale the problem of change in debris-flow frequency and rates of sediment input due to past and anticipated forest practices would also be estimated.

While an understanding of the process of road wash flux to drainage channels has emerged in recent years (see brief review in Reid, 1991), a watershed-scale procedure for evaluating the contribution of specific existing and planned roads is not generally used in forest practices planning. Although the runoff and erosion processes are reasonably well understood, the detailed ground information regarding road characteristics that generate the runoff make a process-based predictive model cumbersome for the purposes of watershed analysis of all the 200-plus watersheds to be included in the TFW process. Nonetheless, some process-based procedures are needed in order to identify the contribution of fines from roads to spawning gravels.

Goals and Objectives

The problem of location shallow sediment sources will be divided into three distinct goals:

(1) Prediction of locations prone to instability under natural and managed conditions.
(2) Prediction of runout distances and patterns of scour and deposition induced by debris flows.
(3) Prediction of the location and type of sediment source associated with roads.

Proposed Methods

With the advent of inexpensive, powerful computing in the past decade a new field is emerging of landscape analysis based on digital representation of topography and other spatial attributes. We propose to explore the utility of applying topographic analysis software to address the three goals outlined above. Federal, state, and private forest management groups are all now actively pursuing the use of geographical information software for a variety of applications. Hence digital data on such attributes as topography, vegetation, soils, geology, and harvest patterns are now being generated. In particular it is worth noting that the current program by the Department of Natural Resources to generate high-resolution digital elevation data. These data have just been or are currently being generated and represent an unprecedented opportunity to test the practical utility of computer-based predictions of landscape processes.

Such data inherently provide an opportunity to address both the local- and watershed-scale questions that lie at the heart of the watershed analysis problem. Consequently, we will also propose in the channel section of this document the use of topographic analysis software to predict channel properties.

Many digital elevation models (DEM) have been developed recently which could generate the numerical surface needed for computer-based watershed analysis. We will use the program TOPOG which has its origins in the work by O'Loughlin (1986). A brief review of the model and its potential applications can be found in Vertessy et al. (1990). The model consists of three integrated programs. One program generates a digital surface from a DEM. A second program discretizes the surface by an automated procedure by projecting flow lines across contour lines and thereby dividing hillslopes into discrete small catchments. A third program simulates steady-state runoff by shallow subsurface and saturation overland flow. Each of these programs has distinct advantages for our intended applications. The first program makes unusual effort to assure accurate portrayal of the topography and in particular avoids generating artificial holes and peaks in the topography. The second program provides a computational framework to perform morphologic and mass transport calculations of particular value to the proposed work. The third program provides a means to add for the first time a physics-based hydrologic component to prediction of landslide locations in a watershed.

Location of unstable slopes

Preliminary investigation of the use of TOPOG has yielded encouraging results. Figure 2 shows a topographic map modified from a US Geological Survey source on which the channel network and areas of thick colluvial accumulation were located in the field. Recent low-altitude aerial photographs of this area were digitized, generating over 15,000 data points for the western catchment shown in Figure 2. Figure 3 shows the discretized surface of this western catchment. Over 5000 elements (each element is defined on the sides by two adjacent flow lines and on the top and bottom by successive contours) were created for this 1.2 km^2 watershed. Note how the flow lines clearly define the divergent topography of the ridges and the convergent topography of the valleys.

The hydrologic model assumes that runoff occurs by shallow subsurface and saturation overland flow that follows the topographic contours (i.e. the elevation head dominates). For each element the model calculates the ratio of the steady-state subsurface flux to the discharge that would occur at saturation. This dimensionless ratio is W(x,y), the wetness index, and varies from 1.0 at saturation to 0 when dry:

$$W(x,y) = \frac{1}{b}\frac{\int q(x,y)\,da}{MT} \tag{1}$$

where b is the length of contour across which the upslope catchment area, a, drains, M is the surface slope, and T is the transmissivity of the soil. The lateral drainage flux, q, is

$$q(x,y) = R - E - D \tag{2}$$

in which R is the rainfall (this could be modified for snowmelt), E is the evaporation, and D is deep percolation. For the simplest case of spatially uniform drainage flux and transmissivity equation (1) can be simplified to

$$W = \frac{qa}{TMb}\,. \tag{3}$$

Hence wetness in this case can be viewed as the product of two ratios, q/T which characterizes the hydrologic control, and a/bM which characterizes the topographic control on wetness. Kirkby (1978) originally pointed out the importance of this topographic ratio in controlling the tendency towards saturation in hilly landscapes.

Figure 4 shows a plot of this topographic ratio for the site depicted in Figures 2 and 3. If, as a simple first approximation, it is assumed that the transmissivity is spatially uniform then, as shown in Figure 4, once this value is chosen and equation (3) is set equal to one, the magnitude of lateral flux required for saturation can be specified for each class of a/bM. Figure 4 can then be read to indicate how the saturated zones would be expected to expand up valleys and footslopes with increasing lateral flux and consequently smaller a/bM needed to cause saturation. (In this calculation the drainage caused by incised channels has not been considered.) For example, for a transmissivity of 34,560,000 mm^2/day, a/bM values of 100, 1000, and 10,000 m require 347, 34.7 and 3.5 mm/day, respectively of steady state lateral drainage flux to cause saturation. The transmissivity in this case was determined from a large data set on the spatial variation in saturated conductivity collected at a nearby site of intensive monitoring (Wilson and Dietrich, 1987; Wilson et al., 1989). At this site because of the large reduction in saturated conductivity with depth on both shallow ridge soils and thick unchanneled valley soils we found that a reasonable first approximation consistent with the simple hydrologic model described here is to assume transmissivity is spatially uniform. This is not, however, required by the model.

Because of the drought in this Californian example only limited data have been obtained on the spatial pattern of ground saturation in this catchment. After one storm of approximately 75 mm depth, we found excellent agreement between the upslope extent of lateral saturation in four of the tributaries in this catchment and the predicted location for a 30 mm/day lateral flux (equivalent to the a/bM class of 1000 to 2000 meters).

We have also applied TOPOG to our study site in the southern Oregon Coast Range, where in collaboration with and support from Weyerhaeuser Company we have been conducting experimental studies to understand controls on in-unit failures (Montgomery et al., 1990). Here we actually applied steady-state rain until steady-state runoff was obtained. The predicted pattern of wetness was quite similar to that observed.

In the simplest case of shallow slope instability (on a failure surface roughly parallel to the ground surface) due to partial or complete ground saturation, the calculated values of wetness can be used to predict sites of potential instability. Note that in the case of flow parallel to a shallow failure plane

$$q = K \sin\theta \; h \cos\theta$$

in which q is the local drainage flux per unit contour width, k is the saturated conductivity, h is the thickness of the saturated zone and θ is the local surface slope. At saturation for a total soil thickness, z.

$$MT = Kz\sin\theta\cos\theta$$

and consequently,

$$W = \frac{K \sin\theta h \cos\theta}{K \sin\theta z \cos\theta} = \frac{h}{z}. \quad (4)$$

With these approximations, wetness can be thought of as the proportion of the surface layer that is saturated.

For cohesionless material, the infinite slope analysis (e.g. Selby, 1982) gives

$$\rho_s \, z \tan\theta > (\rho_s \, z - \rho_w h) \tan\theta \quad (5)$$

at failure with ρ_s and ρ_w equal to the bulk densities of the soil and water, respectively and ϕ is the angle of internal friction. Equation (5) can be rearranged and combined with (4) to give at slope failure

$$W = \frac{h}{z} \geq \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\phi}\right) \quad (6)$$

Using the definition of W from equation (3), (6) can be rewritten as

$$\frac{a}{b} = \frac{\rho_s}{\rho_w} \left(1 - \frac{\tan\theta}{\tan\phi}\right) \frac{T}{q} M \tag{7}$$

Note that equation (6) is valid only up to values of h/z equal to 1.0 and

$$\tan\phi \geq \tan\theta > \left[1 - \frac{\rho_w}{\rho_s}\right] \tan\phi$$

In order to use equations 6 or 7, mechanical properties of the colluvium must be estimated and the hydrologic ratio, T/q, must be selected. We have shown (Dietrich et al., in prep.) that the hydrologic ratio can be estimated for an extreme event from approximate knowledge of what areas in a watershed are likely to saturate. Although the runoff model is steady state it can be used to mimic the wetness pattern of a rare hydrologic event capable of inducing landslides. In this particular case we have observed significant saturation overland flow in the hollows but not on the ridges or side slopes, hence a value of T/q was selected that reproduced that pattern. Equation (7) was used to calculate the location of unstable slopes for a large storm (T/q = 345.6 m) from predicted wetness values, an estimated angle of internal friction of 40 degrees, and a saturated ground to water density ratio of 2 (see Reneau et al., 1984 for data on these values).

Figure 5 shows the predicted sites of failure. Note that stability is evaluated at each individual element, representing areas often less than 20 m wide. Aerial photographs and field inspection were used to map shallow landslide scars in this area and a comparison between observed locations and the area of predicted instability is shown in Figure 6. All but 5 of the 39 landslide scars fall within the predicted zone of instability. This prediction uses a geomorphically constrained estimate of the hydrologic ratio (T/q) and measured colluvium physical properties, hence we feel this excellent agreement strongly supports this model.

There are many questions, nonetheless, that we will need to resolve in order to evaluate the usefulness of this model in watershed analysis. First, it is essential that high-resolution digital elevation data be used. We have already examined commercially available US Geological Survey data and found it to be inadequate (Bauer, in prep.). The data files generated by the Department of Natural Resources will be an important source and we have discussed with their personnel what areas they will be digitizing next that would be most useful for this project. Obvious problems of recognizing the details of topography under canopy cover in old-growth forest exist. We may be able to predict hollow density where they cannot be resolved on aerial photographs by some field mapping results that relate hollow density to hillslope gradient. On plantations, aerial photographs shortly after timber harvesting can be used.

Second, use of the steady-state hydrologic model needs to be evaluated. It is a premise that steady state estimates of relative saturated conditions on hillslopes can be used to mimic extreme hydrologic events that induce failures. The hydrologic ratio, T/q, is the only free parameter in this model but it can be highly constrained by knowledge of what part of the landscape is likely to saturate. We will be collaborating with the authors of TOPOG via Cathy Wilson, who did her Ph.D. at Berkeley and now works at CSIRO in Canberra. They are in the early phases of testing a non-steady state or dynamic version of the hydrologic model. This model may become available during the project. This would allow us to deal with the probabilistic aspects of slope instability and to examine the hydrologic effects of forest practices on slope stability. A simple approach to predicting slope failure in storms of realistic duration can be obtained from the analysis of topography already available from TOPOG if the source code (which is on file at both of our institutions) is altered slightly to convolve rainstorm intensity and duration with the drainage area-distance relationship above any point. This technique was demonstrated by Iida (1984) and applied to the stochastic prediction of landslides in a bedrock hollow of idealized geometry by Dunne (1991).

A third issue is the choice of slope stability model used to identify unstable portions of hillslopes. Equation 7 is based on the infinite slope model and ignores the contribution of cohesion either due to soil properties or as apparent cohesion due to root strength, which is known to be vital to the stability of forested hillslopes. Hence this equation may represent the minimum stability after loss of all root strength due to vegetation removal. If root strength contribution is added by assuming roots penetrate across the potential failure plane, then the depth of this plane must be known. If root strength is contributed primarily to the sides of a potential landslide mass (as Reneau and Dietrich, 1987, suggested) then the area and perimeter (that is the length and width) of the potential landslide mass must be estimated. In either case an additional scale is added to the analysis which is difficult to estimate without detailed field work. If a more complete analysis of the type proposed by Burroughs et al. (1985) is used still further detailed information is needed about ground conditions and material properties. Also a more realistic representation of the ground condition would include some indication of the probability of the colluvium as influenced by vegetation being in some state of strength (i.e. Lumb, 1970). As part of this project we will explore how more physically realistic models of slope stability can be used in the proposed DEM framework. This work will have the advantage over other probabilistic analyses that the topographic analysis will locate predicted landslide zones, rather than simply calibrating the average number in a watershed.

The fourth issue is the problem of how to interpret the pattern of predicted versus observed landslide locations. Can landuse decisions be based on element scale calculations (such as the pattern given in Figure 5) or should the uncertainty about physical properties require instead a delineation of unstable zones, as shown in Figure 6? When testing our procedure against field observations about landsliding, we must decide how to interpret prediction of site failure where no landslide scar is observable. The most cautious interpretation is that given the approximate nature of any available theory and geotechnical data set, as long as most of the observed failures occur in areas of predicted instability, then all areas predicted to fail should be treated as unstable zones. We note, however, that in the example shown in Figure 6, a portion of the predicted zone of instability is occupied by bedrock outcrop where the theory does not apply. Such effects can be looked for and included in the interpretation.

Analysis of slope-stability model

Given the relatively short period of this project and amount of field and laboratory work needed to generate data, we will attempt to use existing data from previous or ongoing projects to conduct tests of our model of debris-flow source prediction. Because of the active program in the Department of Natural Resources to generate digital elevation data and to address landslide concerns, close contact with personnel in this agency will be extremely valuable. Such contact has already been initiated. In addition, we are collaborating with Weyerhaeuser Company in southern coastal Oregon in a slope stability related project. Landslide mapping is completed and, as mentioned above, preliminary tests of the hydrologic component of TOPOG with detailed field observations are quite encouraging. Soil strength properties have already been analyzed by others (Burroughs, 1985, and references therein), and we are currently digitizing the Weyerhaeuser base maps. It is our goal to test this procedure in at least three watersheds.

Location of scour and deposition by debris flows

Another sediment source that can be located within watersheds is the channel erosion caused by debris flows. The work by Benda (1985) of our group has improved our ability to predict the location of this erosion as a function of initiation site and travel-path gradient. Such an analysis can be included in a DEM-based approach because the orientation of landslide sources relative to channels and the gradients of channels can be determined from the calculated numerical surfaces. Some field work needs to be done, however, to broaden the coverage of his empirical results into other lithological regions beyond the Oregon Coast Range. We will then be able to make predictions for a wider range of conditions and test them through field work. Ideally, this analysis can be conducted in the same watersheds as those used for testing predictions of debris-flow source locations.

Location of sediment sources associated with roads

A third sediment source which will be easy to locate is water erosion from road rights-of-way. However, recognition of mass-failure processes along roads (or proposed roads) will require techniques drawn from the components of this project dealing with shallow and deep-seated failures, as well as with other TFW-funded efforts to predict road failures.

2. Sediment influx to channels

This part of the study will not be funded by the present proposal. We will seek funds for it elsewhere. We include a brief description here so that it is clear how the various components of the project, related to channels and hillslopes, will be linked.

Statement of the Problem

The construction of sediment budgets provides a link in this coordinated project between the hillslope responses to natural and management-related processes and the responses of the channel system. A method is required for translating the predictions of the locations of sediment sources into predictions of the quantity and grain-size distribution of sediment delivered to channels. It is our conclusion from discussions with the SHAMW Committee that they would like to see a Geomorphological Watershed Analysis methodology based on this unifying sediment-budget framework. Members of our group (Dietrich and Dunne, 1978; Reid, 1981; Dietrich et al., 1982; Madej, 1982) have already developed methods for doing this, but the methods need further refinement. During the period of the proposed research we will continue our efforts in this direction so that every watershed sediment budget does not require many months of labor to produce an objective, defensible result.

Goals and Objectives

We see the status and needs for spatially distributed sediment budgets as follows:

Status

(i) The sediment budget clearly organizes knowledge about the sediment sources and transport system in a watershed;
(ii) It rapidly identifies qualitatively the most important sediment sources;
(iii) It relates sediment sources to their controlling factors in a quantitative manner, if sufficient time and labor are available.

Needs

(i) The requirements for intensive, skilled labor need to be reduced;
(ii) The complexity of the analysis needs to be reduced or made more transparent;
(iii) The amount of spatial information in the sediment budget needs to be increased (i.e. the sites of erosion need to be defined);
(iv) Current methods of prediction, which are usually empirically based transfers of measurements between watersheds or between time periods, need to be extended by introducing more physically based theoretical predictions.

Proposed Methods

Our specific plans for new developments to be tried during this research period are as follows:

(i) To base each sediment budget on a topographic analysis of the locations of various erosion processes, as described above;

(ii) To make mechanically based calculations of the frequency and magnitude of sediment influx to channels under "natural" conditions from this topographic analysis. For example, the background flux of sediment to channels and to debris-flow source areas in hollows occurs by creep and biogenic soil transport. This transport rate per unit width of hillside (q_s) appears to vary with slope (s) according to

$$q_s = Ks$$

where K is a diffusion constant related to soil, climate, and possibly other factors. Estimates of K for the coastal mountains of Oregon and Washington have been made by Dietrich et al. (in prep.). If the long-term average supply rate to a potential debris-avalanche source and the geometry of the site are known, theoretical slope-stability calculations allow us to predict the episodic nature of mass-failure inputs of sediment to the channel; i.e. we should be able to predict the general nature of the sediment supply and grain size entering channels.

(iii) To combine DEMs with information on vegetation changes, road networks, geology, rainfall, and other variables relevant to the acceleration of sediment loss from managed areas.

(iv) To combine information in the database with simple mechanically based models of landsliding, debris-flow scour, and road wash to calculate the frequency and magnitude of sediment influx to channels under managed conditions. Improved prediction of the sediment supply from in-unit failures and from roads using a DEM-based approach requires that the software be refined for finite-duration storm calculations and that we incorporate rainstorm size, root-strength and other geotechnical properties into a probabilistic analysis of failure (Dunne, 1991). In the meantime, we can continue to incorporate into the sediment-budget analysis both empirically based prediction methods, based on our own group's field work (Reid, 1990) and the field work and probabilistic analysis of other workers.

Procedures for estimating wash from roads now exist (e.g. Reid and Dunne, 1984), providing annual or storm totals of sediment supply to culverts. They can be combined with a GIS database containing topography, climate, and road distribution and use to predict sediment yield under different management scenarios. As with the case of the above-mentioned empirical studies of debris-flow scour, we need to extend our field studies of road wash. This will not be done in the context of this proposal, however. We will seek other funding for such a study.

One field area in which the various components of the shallow-sediment source part of the study could be tested is the Clearwater and Hoh River basins on the Olympic Peninsula, where work by Reid (1981), Cederholm et al. (1981), Reneau and Dietrich (1989), and Department of Natural Resources personnel can be up-dated and used. Other basins in Washington where sediment budgets have been constructed that might be useful are Big Beef Creek Basin (Madej, 1982) and Deer Creek Basin (Eide, 1989).

Deliverables

1) Development of an interactive team of faculty, students, public agency personnel and private company resource specialists concerned with shallow hillslope sediment problems.
2) A method for determining how well digital elevation data represent actual watershed topography to the degree necessary for locating sediment sources.
3) A test of the use of a steady state shallow subsurface runoff model to predict spatial distribution of ground saturation in steep, realistically complex terrain.
4) A method for predicting areas prone to shallow landsliding in a watershed through the use of topographic analysis software.
5) Development and test of DEM-based predictions of channels most likely affected by debris flows.

Schedule

1991
August-December: Begin employment of graduate students and assistants, contact Department of Natural Resources personnel (i.e. Jim Hurst) and other resource specialists to acquire digital elevation data, suggest places useful for digital elevation modelling, begin work on modelling debris flow path and sediment budget prediction.

1992
January-June: Complete digitization of topography of first site. Field inspection to evaluate accuracy of maps and digital elevation model. Test prediction of landslide location by comparison with landslide map. Coordinate with "channel response" group.
June-December: Complete digitization of topography of second site. Field inspection to evaluate accuracy of maps and digital elevation model. Test prediction of landslide location by comparison with landslide map. Coordinate with "channel response" group.
October: Briefing of SHAMW Committee on progress
December: Organization of a special session of the American Geophysical Union Meeting (San Francisco) on "Applications of digital terrain models to practical and theoretical problems in geomorphology."

1993
January-June: Digitize topography of third site. Field inspection to evaluate accuracy of maps and digital elevation model. Test prediction of landslide location by comparison with landslide map. Coordinate with "channel response" group.
June: Delivery of report to the SHAMW Committee.

DEEP-SEATED MASS FAILURE IN WATERSHED ANALYSIS

Statement of the Problem

Deep-seated mass failures play an important geomorphic role in certain lithological regions, especially in the presence of mechanically weak rocks or high hillslopes. The large volume of sediment mobilized by a single deep failure can dominate the sediment budget of a watershed (Reid et al., 1981; Eide, 1989) and cause expensive, unanticipated engineering problems. During our field trips in the first phase of the project we were shown many examples of such problems. Thus, the capacity to anticipate such failures and to predict the flux of sediment involved in them would prove useful both to the geomorphologist studying slope and drainage basin evolution and to the resource professional managing timber harvest and sediment control.

Technical understanding of deep-seated mass failures is usually based on the analysis of large failures immediately after their occurrence. This approach, which involves expensive geotechnical and hydrological exploration and is usually aimed at designing stabilization methods, is applicable to high-value lands in urban areas and along major transportation corridors, but is too expensive for basin-wide prediction in relatively low-level terrain or for theoretical geomorphology. These latter require **pre**-failure analysis over entire basins or regions, and the ability to predict how existing or potential mass failures will respond to changes in the basin. Such changes may include: variations in rainfall; alterations in ground-surface geometry by channel erosion or road construction; or the hydrologic effects of timber harvest.

Goals and Objectives

We intend to explore the feasibility of combining digital topographic data and geological information in a geographical information system with slope-stability and groundwater flow-field calculations to search systematically for all those sites in a watershed where one might expect a past, continuing, or future deep-seated mass failure. The theoretically based predictions will then be tested against field and air-photo surveys of such failures, and anomalies will receive special field investigation which should either indicate that a failure is imminent (on a geological time scale) or that the model needs to be extended. Through this hypothesis-testing approach we hope to provide a geotechnical investigation tool of successively greater power and geographical applicability.

Prediction at any level may seem an ambitious goal, given the great diversity of conditions and types of failures observed in the field. Deep-seated failures encompass a range of scales from single slumps to earth flows that move entire hillslides or hillslope complexes, and a variety of processes from slippage on bedrock joint surfaces to progressive erosion of granular sediments. We can, however, delineate those combinations of material properties, surface/subsurface geometry, and groundwater flow fields which produce stable hillslopes and those which do not. We can also predict the direction and approximately the rate of change if some change occurs in the controls of stability.

Proposed methods

Modern computers provide the potential for rapidly making regional assessments of deep-seated mass wasting. Such assessments require methods of effectively combining available information, such as the regional mapping mentioned above, into a readily evaluated format. We will explore means of coupling Geographical Information System (GIS) type databases and digital elevation models (DEM) to numerical models of ground water flow and slope stability. This directly ties a description of the basin to the stability analysis so that all factors (at least all factors we can pull out of the information available on the basin) influencing the slope are included.

We have a variety of numerical methods to experiment with. Techniques for evaluating slope stability vary from simple two dimensional limit-equilibrium concepts to detailed three dimensional finite-element analysis, and we have used examples of each. The type of model used is dictated, in part, by the kind of information we have about the slope: the less information we have, the simpler the model must be. A regional analysis, which must work with general information at relatively low resolution, requires a simple analysis. We seek the simplest model which adequately describes the mass wasting processes we observe.

The model must be able to deal with a very wide range of possible field conditions. The observations on which these models are based, however, are limited by the field sites which have been examined. Detailed physical models play a role here, for they can be used to extend the range of conditions by which simple models are evaluated and improved. We can model a wide range of hypothetical field conditions on the computer very rapidly and compare the predictions of the simple (low information) techniques we are developing to the results obtained from detailed (high information) models.

The automation of data storage and analysis opens to us a range of possibilities. One goal, given a set of existing or potential conditions for a particular basin, is to predict the location and type of (deep seated) mass wasting occurrences. This is a regional analysis. The procedure envisioned above also allows us to zero in on a single failure. Having coupled a database describing the basin with a numerical model describing the failure (or a potential failure), we can evaluate the consequences changes in the basin will have for a particular site.

The ability to make predictions provides a test of our methods and ideas. In gathering information and assembling predictive models, we will produce a picture of how deep seated mass wasting works in a particular area. This is a picture we can compare to reality. We will hypothesize a method of prediction, a hypothesis which can be rigorously tested and improved. This is an integral aspect of the proposed research. It is particularly important for developing methods feasible for use at the scale of a basin: we need to know just what (and how little) information about the basin is needed to get useful results. Failure of the hypothesis is the means of determining that.

Field areas for which a variety of regional mapping is available (e.g. topography, geology, etc., preferably at a fine scale) and with a documented history of (deep seated) landsliding is required both to assemble and test hypotheses for predicting landslide location. The field visits we made in June and discussions with state and industry representatives indicate that several potential field sites with various levels of mapping and documentation are available to us (e.g. Weyerhaeuser sites in the Skookumchuck drainage near Vail, Washington and Washington State DNR land in the Siuxon basin). Likewise, to test and improve our ability to predict landslide behavior requires sites of active, or potentially active, deep seated mass wasting which can be observed as changes occur within the basin. Again, we know of several potential sites and will look for more. To develop a widely applicable model, we need a wide range of field conditions.

Deliverables

1. A method for systematic prediction of potential sites of deep-seated mass failures in a watershed.
2. A method for predicting the alteration of stability as a result of changes in hydrology due to natural weather fluctuations or to management.
3. Guidelines for field studies to refine predictions in areas that have been flagged as potentially unstable.

Schedule

1. August 1, 1992: Have combined topographic and geologic data in a GIS with a two-dimensional limit-equilibrium model of slope stability, including ground water conditions.
2. October, 1992: Briefing for the SHAMW Committee on progress.
3. December, 1992: Organization of a special session at the American Geophysical Union Meeting (San Francisco) on "Applications of digital terrain models to practical and theoretical problems in geomorphology."
4. June 30, 1993: Report on the testing of this model against field mapping, and on refinements of it that prove to be necessary.
5. Summer, 1993: Writing of scientific papers.

ASSESSMENT OF CHANNEL CONDITION AND RESPONSE

Statement of the Problem

The primary concern in the proposed watershed analysis program is the protection and enhancement of stream fisheries. Because of the clear importance of specific habitat attributes in channels and the sensitivity of these attributes to altered sediment yield and runoff, many fisheries biologists have focused in recent years on documenting channel characteristics under varying natural and disturbed conditions. To structure this work toward a common method for watershed analysis the CMER Committee (CMER, 1991) has made specific recommendations for stream classification and field work has been initiated to test and refine this classification approach.

There are four related questions about channels and land disturbance that need to be addressed. First, we want to know what "state" the channel is in now. This is largely the intent of stream classification work in which "state" would be interpreted to mean availability of some assemblage of habitat. But "state" should also mean relative geomorphic stability or activity. Is the channel aggrading or degrading? Is the channel receiving high or low sediment supply? Classification to be useful should reveal something about stream behavior as well as appearance, and to be useful in a predictive watershed analysis context it should have some theoretical footing.

Second, most larger watersheds have already been disturbed, with often the riparian zone most severely altered. In order to interpret channel conditions we need to estimate what the natural channel would have been like and try to separate natural disturbances such as floods and debris flows from direct management-related riparian changes such as organic debris removal and from changes due to altered sediment load and runoff due to hillslope disturbances. What are channels being managed for, their approximate natural state or some optimum habitat characteristics?

The third question is about the future condition of the channel under proposed forest practices. Is the channel vulnerable to destructive debris flow scour and sediment burial? Will increased sediment load destabilize the channel or reduce habitat quality? In the case of regulated flows is there a discharge regime needed to transmit the sediment load and generate essential habitat? This question is strongly tied to the fourth: what is the potential for a particular channel which has experienced significant habitat loss or degradation to "recover?" Can intervention of some kind hasten the recovery? This fourth question is also strongly linked to the first two.

For all four questions a mixture of theoretical and empirical approaches is needed. Theoretical studies must provide mechanistic foundation for empirical analysis. Such studies are essential to investigate how sediment routing and consequent channel response occurs in a watershed context. Empirical analysis, on the other hand, should provide observations that can be used to address the four questions described above.

Current understanding of fluvial systems, particularly of mountain watersheds, is not sufficiently advanced that we simply need only apply available knowledge to solve the practical watershed analysis problems. This is particularly true with regard to the interaction of wood loading and stream dynamics. Nonetheless, recent advances in fluvial geomorphology provide a variety of approaches which may prove effective in this area.

Goals and Objectives

We propose to form a team of faculty, post-graduate and graduate students to perform both field surveys and theoretical investigations to develop tools for diagnosing channels for watershed analysis. Although we will strive for general approaches, these tools will be intended for people with advanced training in fluvial geomorphology who can make decisions about application on individual watersheds. This is in keeping with the CMER (1991) recommendation that watershed analysis be done by specialists.

We see two primary problems: (1) the use of channel characteristics to predict sensitivity of channels to altered land use, and (2) the routing of sediment through channel networks to predict disturbance magnitude and recovery rate. To address the first problem we have as a methodological goal the development of a mechanics-based prediction of channel properties based on local and watershed attributes which would allow rapid mapping of channel types (i.e. classification). To address the second question we will investigate various quantitative procedures to route sediment through channel reaches and networks. This second question can be broken down into two parts: (i) the routing of sediment through a roughly fixed channel morphology, and (ii) the morphological and sedimentological consequences of sediment migration in fish habitat. Whereas the first goal is based on simple theory and is likely to produce useful procedures, the second goal is at the forefront of fluvial geomorphology and may not yield something of practical utility within the two-year study. Nonetheless, the theoretical work is essential to obtaining a general understanding and supporting empirical studies. It is a crucial part of establishing a "science-based" methodology.

Proposed Methods

Background for empirical investigation

As a theoretical reference point for analyzing channel disturbance we propose to use the concept of a threshold channel. A gravel bedded river with low gravel supply will tend to have a bed surface that only becomes mobile at approximately bankfull stage. Hence, the bankfull discharge should apply a boundary shear stress approximately equal to the critical boundary shear stress of the bed. Empirical and theoretical studies show that the critical boundary shear stress (τ_c) on a bed of heterogeneous size sediment is roughly scaled by the median grain size (D_{50}) and that the dimensionless critical boundary shear stress is about 0.047 (e.g. Kirchner et al., 1990). Thus,

$$\frac{\tau_c}{(\rho_s - \rho_w) g D_{50}} = 0.047 \quad (1)$$

$$\tau_c = \rho_w g h_{bf} s \quad (2)$$

and by substitution

$$D_{50} = 12.89\, h_{bf} s \quad (3)$$

where ρ_s, ρ_w are the sediment and water density of 2.65 and 1.0 gm/cm^3 respectively, and g is gravitational acceleration, s is water surface slope (usually assumed equal to local channel slope), and h_{bf} is the bankfull mean flow depth. Equation (3) does not apply to fine gravel and sand bedded channels where much of the boundary shear stress results from large form drag over bars and smaller scale bedforms rather than grain resistance. On slopes steeper than about 0.02 the equation may not apply due to the presence of large grains that protrude through the flow and to the development of supercritical flow areas. Such steep channels typically have what Grant et al. (1990) call stepped-bed morphology. Apparently this morphology is associated with relatively low sediment supply; at high sediment supply the channel will braid. Such morphology may be found on slopes up to 0.1, but at slopes in the range 0.05-0.10 the influence of debris flows on channel form and behavior becomes significant. Figure 7 summarizes the various slope-dependent conditions of the channel.

Most stream classification models recognize the dominant role played by channel slope (i.e. Rosgen, 1985; Beechie and Sibley, 1990). In the Rosgen method, primary stream type is defined by channel gradient, with secondary type defined almost entirely by bed sediment size. All of Rosgen's alluvial stream types can be plotted without significant overlap on Figure 7. The advantage of Figure 7 is that it is based on simple mechanics and dominance of process, hence it should have more predictive utility in a watershed analysis context. The TFW procedure investigated by Beechie and Sibley (1990) includes adjacent valley slope conditions, but not surface grain size. Valley conditions either in steepness of slope or width of valley floor affect bank properties, sediment supply, flow depth at extreme discharge events, and wood recruitment to the stream. We will evaluate correlation of channel properties with valley conditions.

Field, laboratory and theoretical analyses (Dietrich et al., 1989; Kinerson, 1990) indicate that for a given flow depth and slope, the greater the sediment supply the finer the bed surface (as shown by the arrow in Figure 7). Figure 8 illustrates surface texture changes in a laboratory flume study in which the sediment supply was progressively decreased as the water discharge was held constant (the imposed changes were of opposite sign to that suggested in Figure 7). In response to diminished supply, zones of less active coarser bed developed and the spatially averaged median grain size of the bed increased. Even in the low sediment supply case, however, parts of the bed where most of the sediment transport occurred remained similar in size to that of the high supply case. It is important to point out that the initial high supply case had a bed surface whose median size was the same as the load, hence with decreasing supply the surface became progressively coarser than the load or the subsurface material.

The experimental results illustrated in Figure 8 are expected because bedload transport rate increases rapidly with small increases in the difference between boundary shear stress and the critical boundary shear stress. If the critical shear stress of the bed is scaled by the median grain size of the bed, as shown in equation (1), then relatively small changes in surface coarseness can cause large differences in transport rate. Hence, if the sediment supply were to increase on a threshold channel (as described above) then fining of the surface will increase the difference between the boundary shear stress and the critical value and the channel may transmit the additional load without significant aggradation.

Dietrich et al. (1989) proposed the dimensionless ratio, q_*, to describe what state the channel is in relative to an imposed sediment supply. This ratio is the transport rate of the surface normalized by the transport rate for a surface as fine as the sub-surface or load. If

$$q_b = k(\tau_b - \tau_c)^n$$

where q_b is the bedload transport rate and k and n are empirically determined (n is usually close to 1.5) and equation (1) is used, then

$$q_* = \left(\frac{\tau_b - \tau_{cs}}{\tau_b - \tau_{cl}}\right)^{1.5} = \left(\frac{\frac{\tau_b}{\tau_{cl}} - \alpha\frac{D_{50_s}}{D_{50_l}}}{\frac{\tau_b}{\tau_{cl}} - 1}\right)^{1.5} \qquad (4)$$

where τ_{cs} and τ_{cl} are the critical boundary shear stresses of the surface and the sub-surface or load, respectively, the parameter α for gravel with uniform specific gravity is unity, and D_{50_s}, and D_{50_l} are the median grain size of the surface and load, respectively. Figure 9 shows a comparison between equation (4) and experimental results which strongly supports this model.

The expectation, then, is that in natural or disturbed channels the greater the sediment supply to a channel the weaker the development of the coarse surface layer. Channels near a threshold condition defined in Figure 7 would have a well-developed armor layer, although patches of finer, less- or un-armored channel would be present. An increase of sediment supply will cause the finer patches to expand and the average grain size of the bed to decline, causing the sediment transport rate to increase and q_* to increase.

Some field date now exist to support the use of q_* as a tool to understand bed texture and sediment supply. Figure 10 shows a comparison of q_* calculated from equation (4) and measured surface and subsurface median grain sizes for 6 channels in California. Lagunitas Creek was sampled just downstream of a dam and, in this case of no sediment supply has a well developed coarse surface layer. Sagehen Creek lies in an alpine meadow and receives relatively little sediment, it too has a coarse surface layer and a low q_*. Note, however, that two sample points lack a coarse surface layer. These samples were in a short unarmored reach in an otherwise well-armored channel. The high q_* values for Wildcat and Prairie Creek appear consistent with high sediment influx from earthflows and bank erosion, respectively. The high q_* values of Caspar Creek are also consistent with the disturbance due to poor forest practices used in logging the basin about 90 years ago.

The study by Lisle and Madej (in press) present armoring and flow data that confirm a high q_* in the sediment rich Redwood Creek; however, they also emphasize the role of low and moderate flows in reworking the surface. They also find that the coarser the bed surface the stronger the armoring and that most of the low and moderate flow sediment transport occurs in the finer unarmored bed surface.

Empirical investigation: morphological relations

We plan to investigate the usefulness of the threshold channel and sediment supply concepts represented in Figures 7-10 through literature review, and through predicted and measured channel characteristics using a digital elevation model. We will review previous field studies where grain size and slope were carefully measured in order to begin an evaluation of Figure 7. Simultaneously, we will investigate the use of computer models of topographic analysis as a tool to predict channel characteristics. Here we will use the same DEM and data source as that proposed in the shallow sediment sources part of the project. Other sites may also be investigated. To use equation (7) we must estimate local channel slope from the DEM and bankfull depth from regional hydraulic geometry relationships that relate bankfull depth to drainage area. Field work will be needed to construct the hydraulic geometry relationships, although some field studies already completed can provide some of the information needed.

At the sites where we measure hydraulic geometry and bed-material grain size we will also measure other morphological features of the channel. We have not yet tested which of these features we can measure efficiently, although some of them have already been measured routinely by us and others. The features which we will consider initially are:

1. Bar characteristics—area, shape and number of: (i) free alternate bars; (ii) bars forced by channel bends; (iii) bars forced by obstructions
2. Coarse-particle accumulations: channel units of Grant et al. (1990)
3. Pools: areas, depths, flow velocities
4. Gravel accumulations that block surface low flow
5. Scour-fill depths: inter-storm; seasonal
6. Distribution of intrusion by fines
7. Channel margin complexity
8. Side-channel characteristics

Other scientists have already used some of these features to develop channel classification schemes. We intend to consolidate our own and others' morphological work into a mechanically based calssification scheme that can be interpreted in the light of basin morphology (drainage area, slope, valley characteristics), hydrology (magnitudes of flows in the natural and managed states), sediment supply (defined for managed and natural states in the sediment budget), and the supply of large organic debris. For example, one might expect some characteristic such as pool depth or bar area, or width/depth ratio to vary systematically with an index that combines the predicted sediment yield with a measure of annual sediment transport capacity. The latter measure might be originally based on a detailed computation of bed-material discharge, but later might be condensed to a drainage area-slope measure that could be obtained from a DEM. The DEM-based hydrological modelling planned by Drs. Lettenmaier and Cundy will be compatible with providing such a measure of long-term sediment transport capacity for managed and natural conditions. Such a research opportunity provides yet another linkage between these TFW-funded projects.

This DEM-based procedure may allow us to quickly identify those portions of the channel network in a watershed that due to the imposed slope and contributing drainage area tend to support spawning gravels and complex habitats. Field investigations to test the DEM predictions should then allow us to recognize the effects of sediment supply, large woody debris or other things that cause the channel to deviate from the threshold state. Hence, this combination of prediction and field study should help us identify the relative importance of various agents on channel properties. We anticipate that some of the channel unit types that have been identified by fisheries biologists will be correlated with channel properties predicted by the DEM approach.

Field study to support the DEM analysis and some of the theoretical work described below will entail the making of quantitative planform maps that also depict the spatial distribution of bed surface texture, morphological features listed above, and the location of large woody debris. Surveys of channel cross-sections and longitudinal profiles are essential. Bankfull discharge will not be easily identified in all cases and in some reaches (particularly the steeper channels) may not be a useful concept. We will investigate techniques that might provide a method for rapid quantification of the channel state, as the more detailed work needed to test models requires about one day per 100 m. We hope to coordinate with the other TFW efforts, particularly the channel mapping program and the habitat classification project directed by Drs. Naiman and Conquest at the University of Washington. The methodologies used by fisheries biologists (particularly regarding slope and grain size measurements) appear to be too inaccurate for our purposes, but we feel that without a significant increase in effort more useful data can be collected.

Theoretical analysis: sediment routing

We will examine three different approaches to modelling the routing of sediment through the fluvial system. Each of these approaches is intended to gain insight about rates and processes of sediment transit as a function of position in the watershed and relative degree of sediment supply disturbance. Such modelling would not necessarily be part of a watershed analysis methodology, but instead as mentioned above, the scientific backup to more empirical approaches.

First, the routing method based on reservoir theory originally proposed by Dietrich and Dunne (1978) and developed more formally by Dietrich et al. (1982) will be used to examine residence times and transit times of sediment through the channel network. Application of this theory by Kelsey et al. (1987) and Nakamura (1986) in disturbed environments shows that this approach can be used with fruitful results. This was accomplished despite the required assumption of steady-state storage reservoirs. We will need to do field work to get data on sediment storage; we will collect such data in the same channels subject to the empirical analysis.

The second theoretical investigation will be to route sediment using very simple transport theories through idealized representations of the channel network. The approach would be similar to that used to route stream discharge such as described by Surkan (1969) and which later led to the geomorphological instantaneous unit hydrograph (see papers and references in Gupta et al. (1986). Crucial elements of this model we will need to explore include estimation of the travel time of sediment as a function of stream order or magnitude (perhaps obtained from the reservoir theory above), the effects of particle-size reduction during storage and transport, and examining the effects of spatial distribution of sediment input. This problem is made considerably more difficult than the hydrologic one because the appropriate transport laws over the time-scale (years) of importance are not known, the transport process tends to change downstream, and input functions are spatially highly variable.

It will be necessary to incorporate into sediment routing a theory of the fate of large organic debris. We intend to examine large organic debris in the same generalized framework that we use for other sediment of low mobility. We would identify sources, sizes, supply rates, storage, decomposition, and transport by water and by debris flow. During storage we would examine the amount and form of blockage of finer sediment, thus providing an explanatory link between the sediment routing and morphological components of channel assessment.

The third modelling approach will be to perform illustrative analysis of selected reaches using computer models for three-dimensional flow and sediment transport. Here we anticipate using recently developed numerical models such as by G. Parker or J. Nelson and J. Dungan Smith (see, for example, articles in Ikeda and Parker, 1989). These models have generally not been applied to rivers with the complex topography found in wood influenced rivers of forested watersheds. None of these models have dealt with varying sediment supply and quantitative theories for grain sorting mechanics are only now emerging. We anticipate conducting this detailed investigation on only a few reaches for the purpose of explaining relationships between the expressions of river behavior that we have chosen to work with on the basin scale (e.g. sediment supply from the sediment budget approach outlined elsewhere in this proposal, streamflow predictions of the type provided by regional flood-frequency relationships and the Lettenmaier/Cundy TFW hydrology project, and regional channel geometry relations described above) and the reach-scale morphological features that we will study in the empirical phase of the project and that are of interest for fish habitat.

Deliverables

1) Formation of an interactive team of faculty, post-docs, graduate students and technical support staff involved in analyzing and explaining channel routing and response.

2) Test of the ability of digital elevation data to resolve local channel slope with sufficient accuracy to be useful for geomorphic modelling and habitat classification.
3) Summary of existing data on channel properties from forested mountainous watersheds that can be used to test our threshold and transport controlled characterization of channels.
4) A method for prediction of channel attributes from a DEM and field observations that test the predictions.
5) Methods for predicting sediment flux through a channel netowrk.

Schedule

1991
August-December: Collect data from previous studies to examine threshold channel hypothesis, begin work on generating regional hydraulic geometry relationships to test this hypothesis, work with shallow sediment sources team on acquiring and using digital elevation data.

1992
January-June: Application of DEM-based approach to first field site, compare field and model channel slopes, map channels for bed surface texture and morphology.
June-December: Analysis of second study site in conjunction with shallow sources team, do requisite field studies, make field measurements useful for sediment routing models.
October: Briefing of the SHAMW Committee on progress.
December: Organization of a special session of the American Geophysical Union Meeting (San Francisco) on "Applications of digital terrain models to practical and theoretical problems in geomorphology."

1993
January-April: Analysis of third site and coordination with shallow sediment sources team. Explore three modelling approaches to sediment routing.
April-June: Manuscript preparation.

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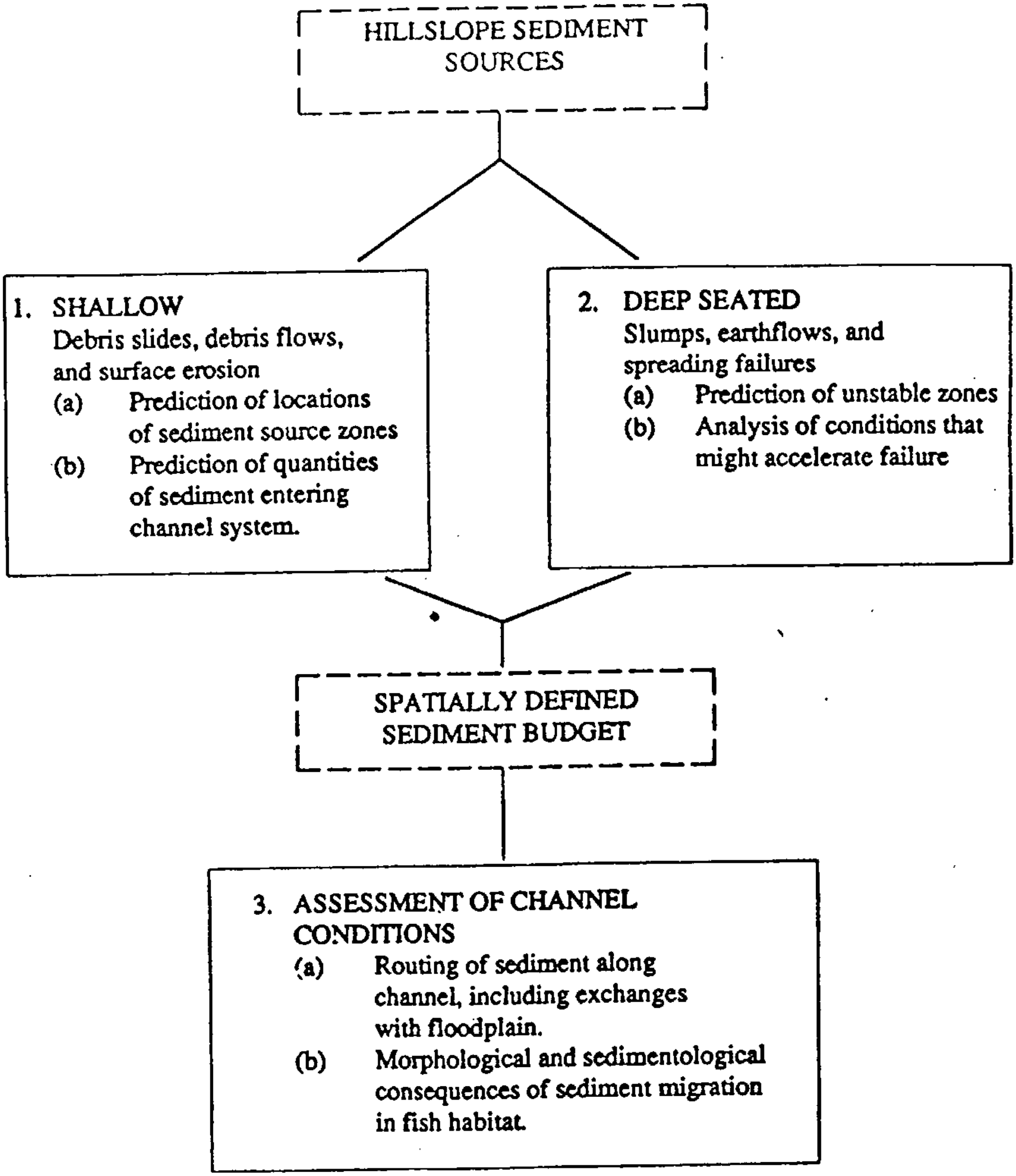


Figure 1: Flow chart of the interrelationships among the components of the project.

Figure 2: Channels and colluvial deposits in the Tennessee Valley of Marin County, California. Both continuous and discontinuous channels are indicated by heavy black lines and the approximate extent of colluvial deposits are indicated by the stippled areas. Small triangle in middle left of the figure represents a channel head associated with a road drainage culvert. The black pattern in the area near center of figure denotes a man-made pond (from Montgomery and Dietrich, 1989).

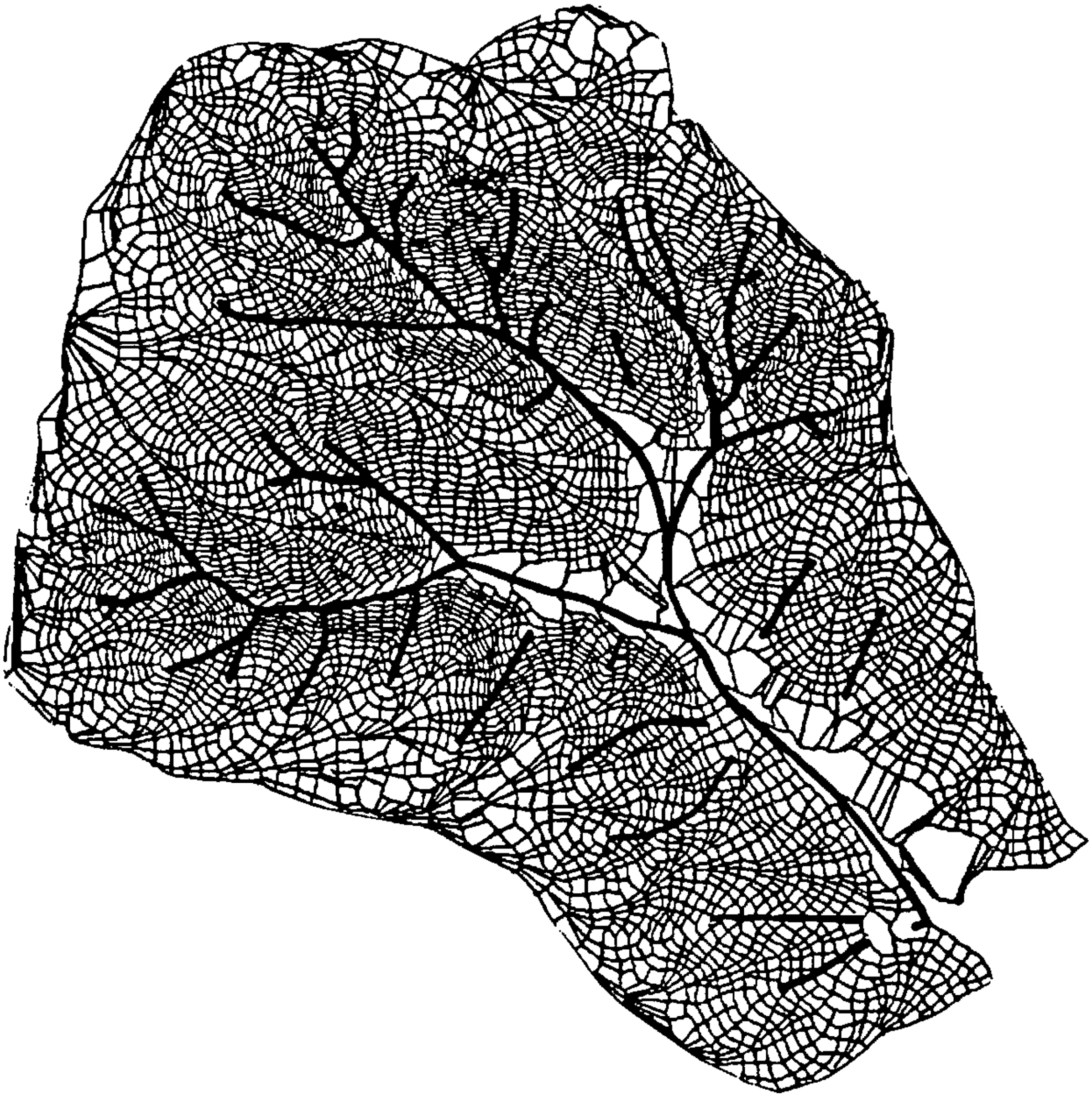
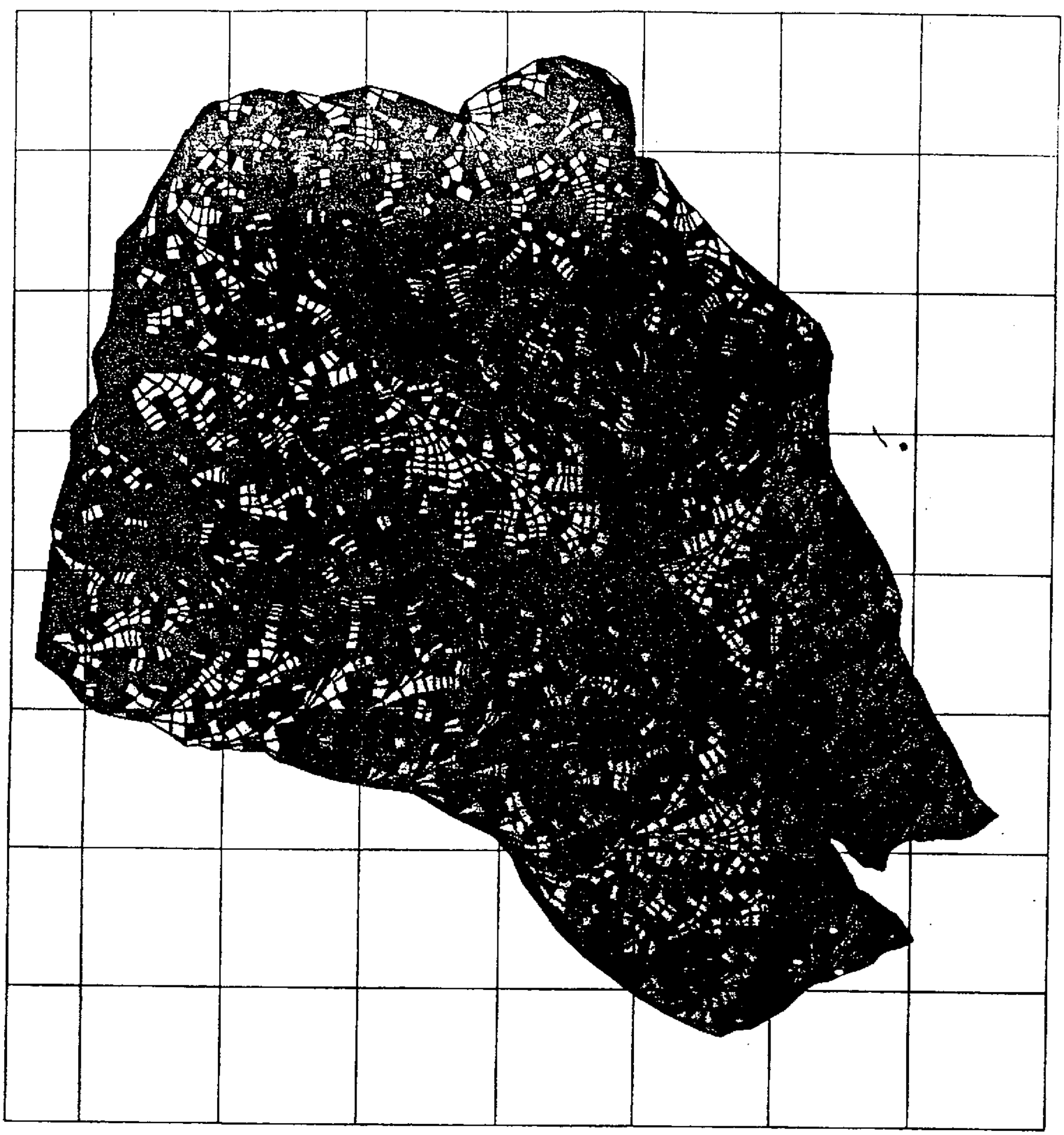


Figure 3: Topographic map and flow lines showing how TOPOG discretizes the digital surface. The intersection of a two flow lines and two contours forms the boundary of an individual element.



■	ABOVE	10000
■	5000 –	10000
■	2000 –	5000
■	1000 –	2000
■	500 –	1000
■	200 –	500
▒	100 –	200
■	50 –	100
■	BELOW	50

Figure 4: A plot of contributing area per unit contour length divided by local slope. Dimensions of the color scale for the elements is meters. Grid lines are 200 m apa

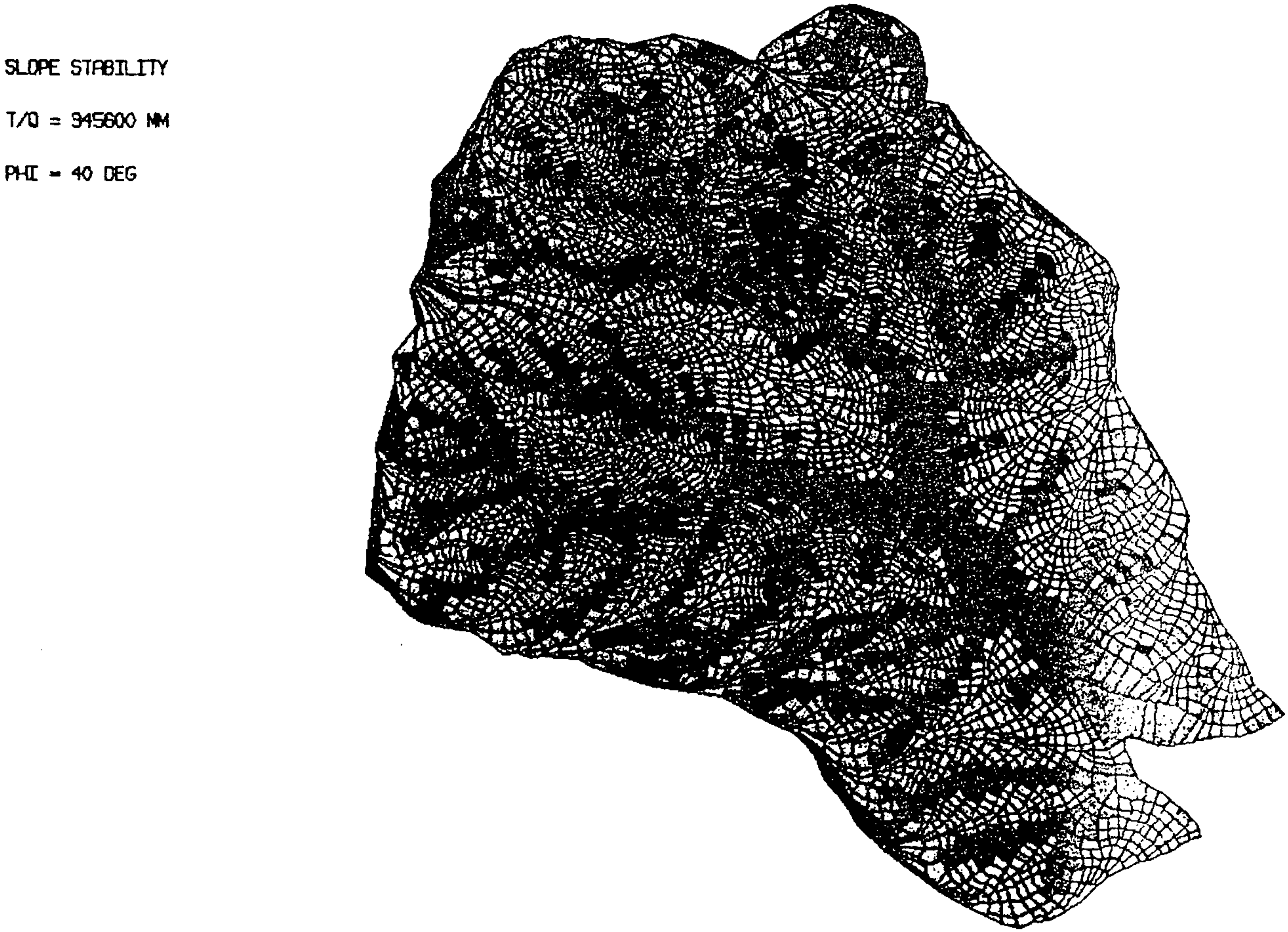


Figure 5: The predicted pattern of slope instability for a T/q of 345.6 m/day (approximately 100 mm/day runoff) and an internal angle of friction of 40 degrees. This value of T/q produces realistic distribution of ground saturation.

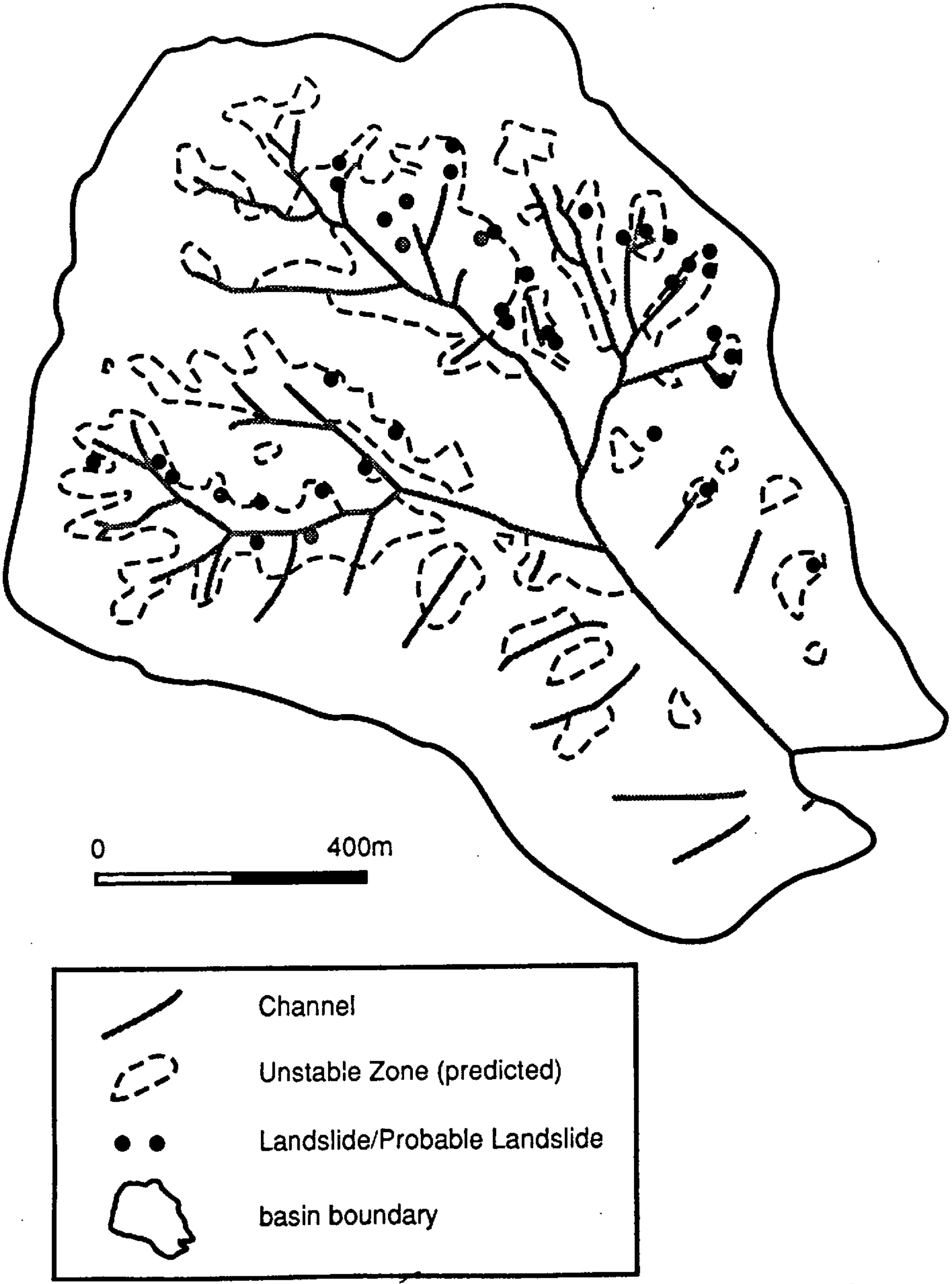


Figure 6: Comparison of the observed shallow landslide scars and the predicted zone of instability. Boundary lines of unstable zones either close on themselves or terminate on channels.

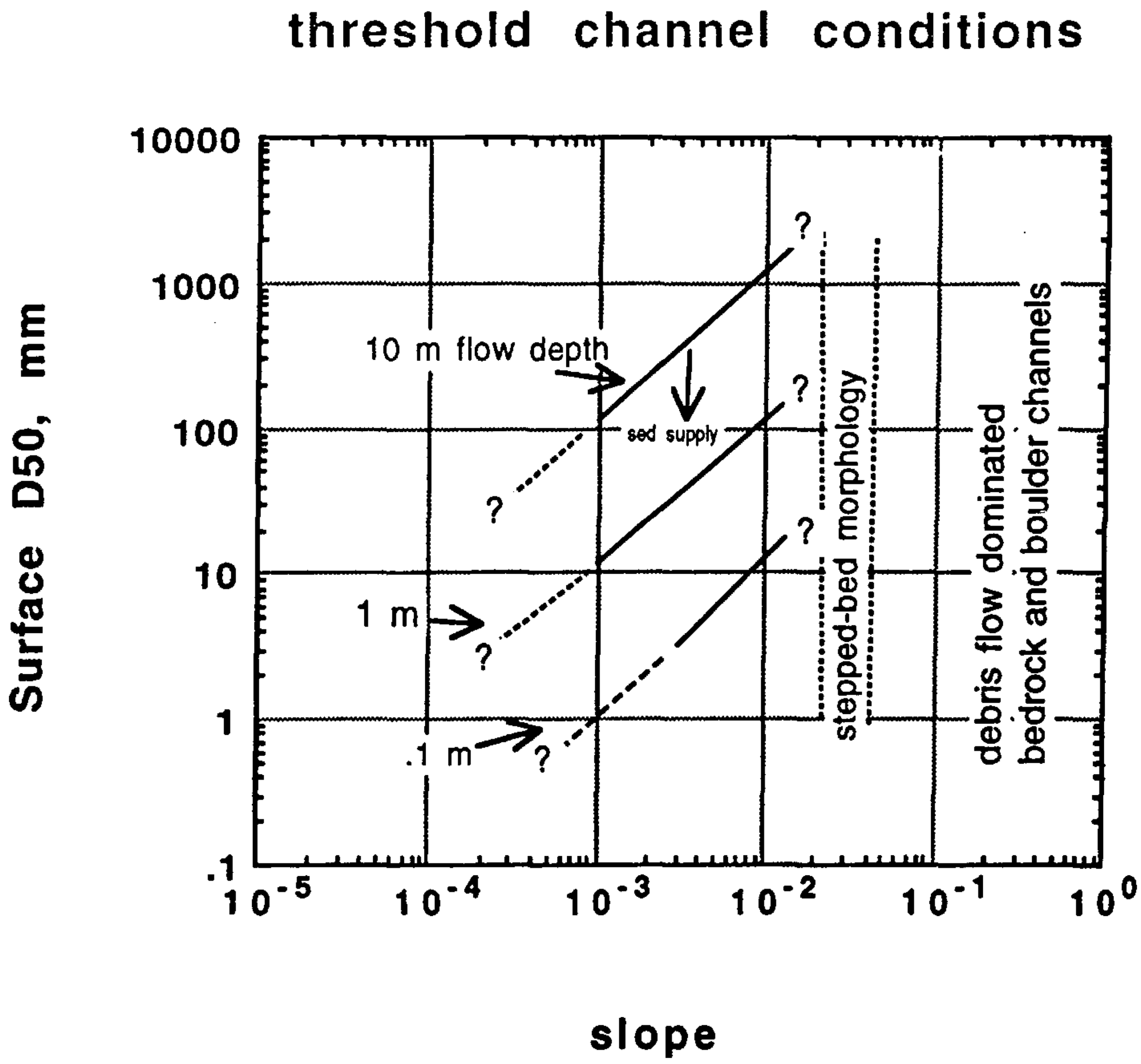


Figure 7: A plot of the threshold channel condition (equation 3) for various flow depths and slopes as indicated. The upper range of the application of equation 3 may be slope of about .02. Above that slope influences of boulders may form a framework which is resistant to movement except during rare flow events (Grant, et al., 1990). Steeper slopes tend to be dominated by debris flows. The lower range of the application of equation 3 depends on when well developed bars and dunes form. Note the hypothesized effect of increased sediment supply in mobilizing the bed.

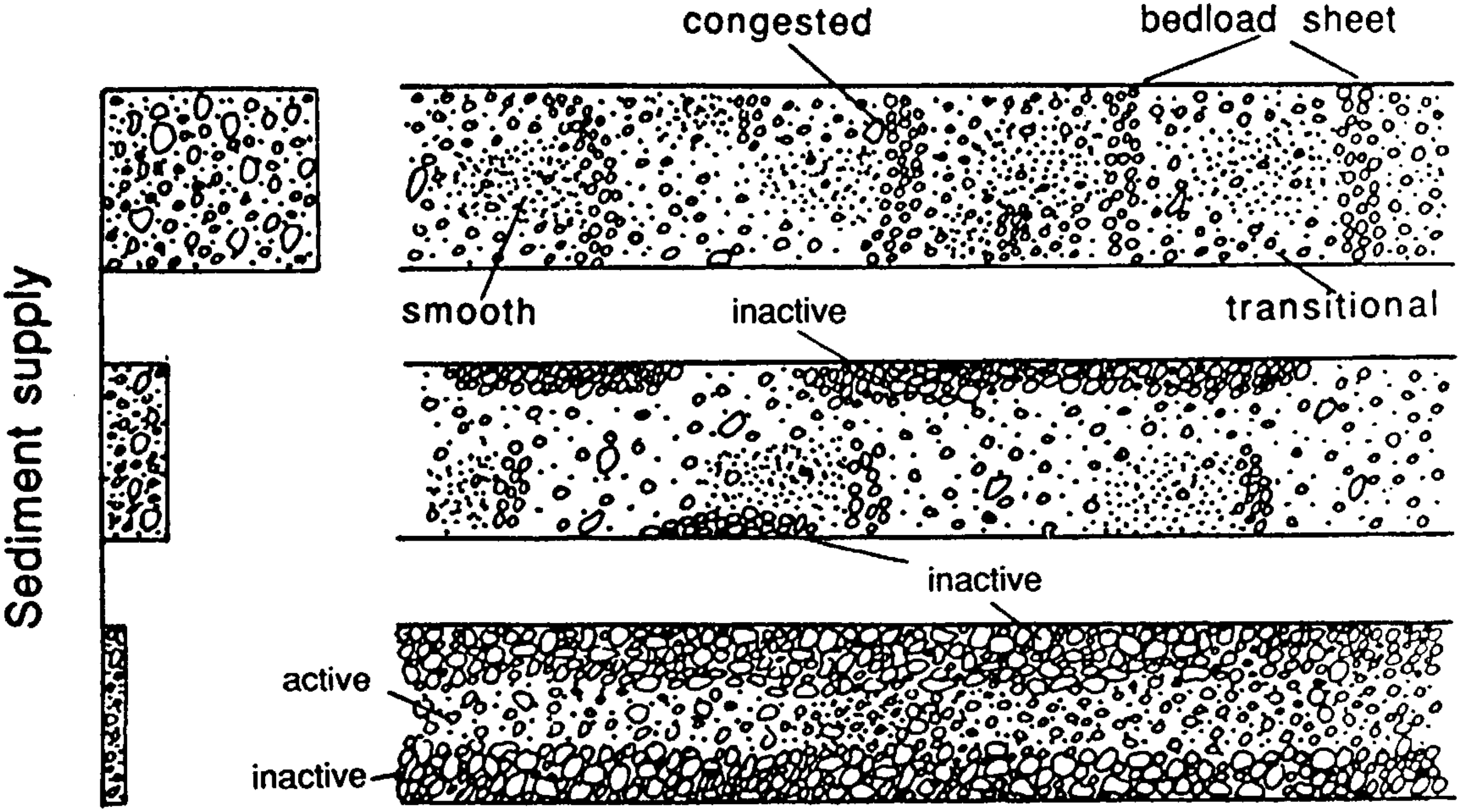


Figure 8: A plan view of a flume bed showing effect of sediment loading rate (indicated by 'supply' box) on lateral and longitudinal grain size segregation of bed surface. In this particular case at the highest supply rate the bedload travelled as thin rapidly migrating bedload sheets with relatively well sorted coarse 'congested' leading edges, followed by poorly sorted 'smooth' and 'transitional' zones. Reductions in sediment supply resulted in expansion of the coarse 'inactive' zones, in which little or no transport took place. (from Dietrich et al., 1989.

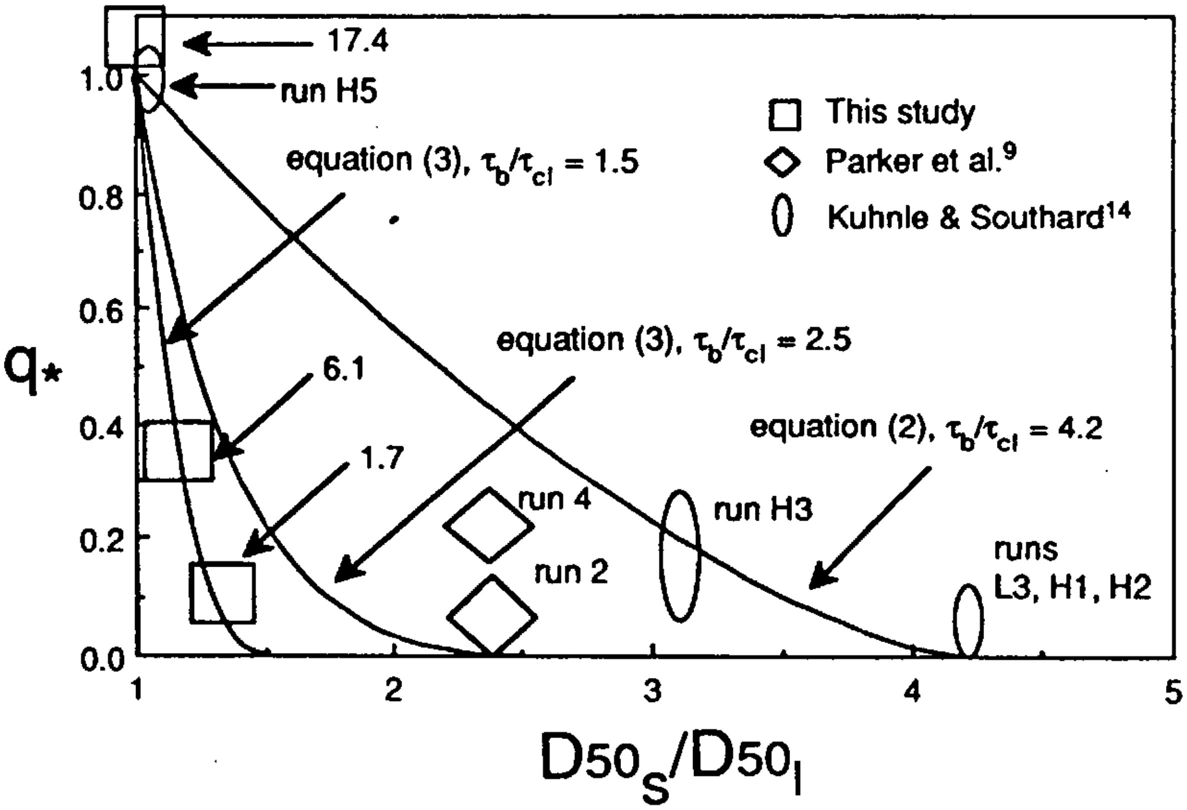


Figure 9: Comparison of the predicted transport ratio q* as a function of median grain diameter ratio, with the observed transport ratio and grain ratio for experiments by Dietrich et al. (1989), labelled 'this run', and two other experiments (see Dietrich et al. for references. (from Dietrich et al., 1989)

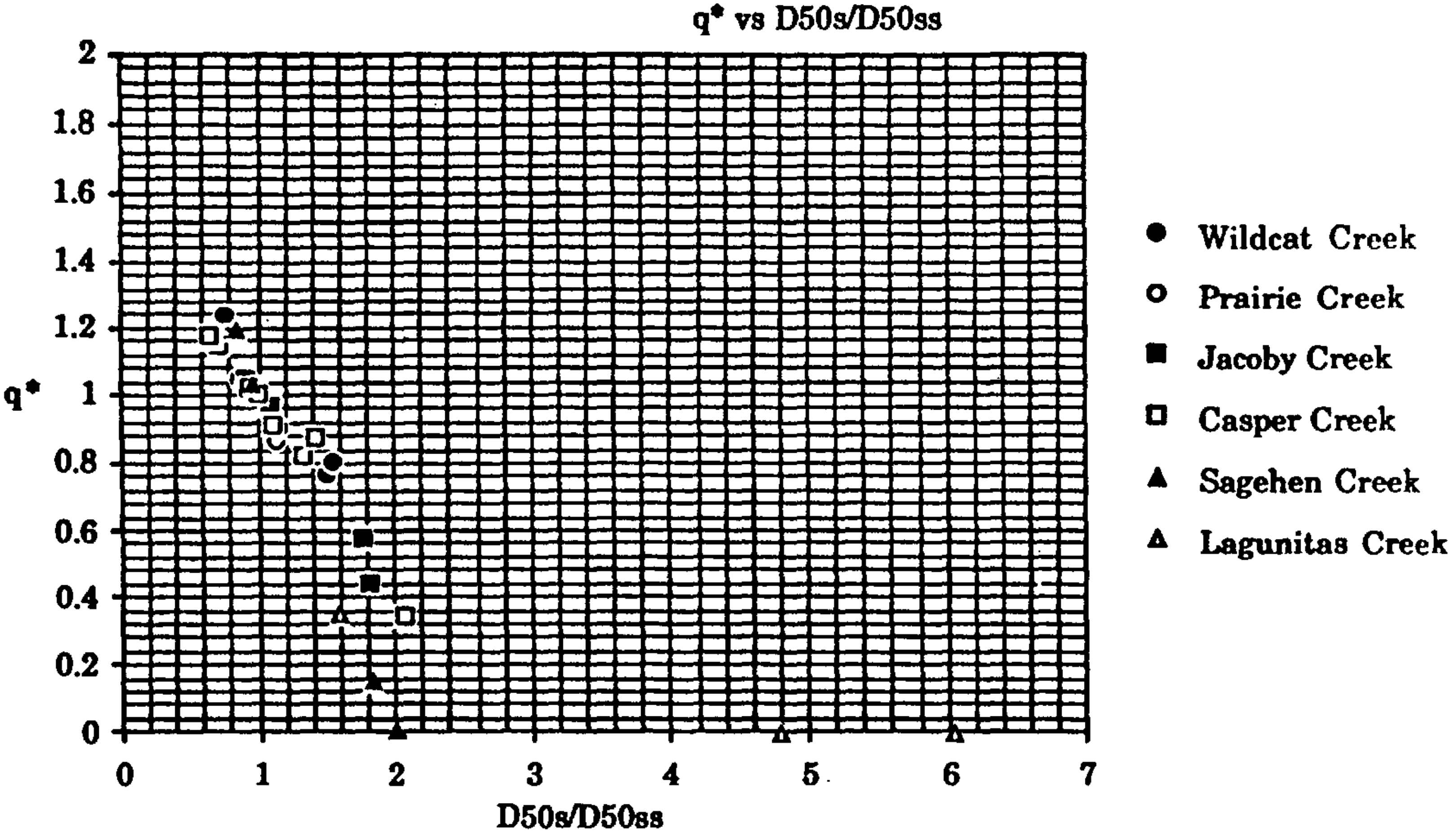


Figure 10: Calculated transport ratio q_* from equation 4 and observed grain ratio for six rivers in California. Channels are listed in order of sediment supply to the channel from the highest at Wildcat Creek to the lowest at Lagunitas. Sample points were selected to represent the range of bed surface textures observed, hence a representative q_* would not be the average position of the plotted points.

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CURRENT POSITION

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RESIDENCE

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DATE OF BIRTH

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CITIZENSHIP

United Kingdom and United States

LANGUAGES

English:	native tongue
French:	writes and speaks fairly well
Kiswahili:	can speak slowly

EDUCATION

B.A. 1964 Cambridge University, England (Geography). First-class honours, College Exhibition, and College Scholarship.

Ph.D. 1969 The Johns Hopkins University, Baltimore, Maryland (Geography)
Dissertation title: Runoff production in a humid area

HONORS

Fullbright Scholar, 1964
Robert E. Horton Award, American Geophysical Union, 1987.
Elected to National Academy of Sciences, 1988.
Fellow, American Geophysical Union, 1989.

CURRENT RESEARCH INTERESTS

Field and theoretical studies of drainage basin and hillslope evolution, incorporating the relations between climate, vegetation, hydrology, sediment transport, and soil properties. (Current activity involves mathematical modeling of hillslope evolution by rainsplash, sheetwash, rilling and gullying on the basis of field experiments conducted in Kenya).

Hydrology, sediment transport, and floodplain sedimentation in the Amazon River (Current activity involves computation based on first three years of data collection, and supervision of a continuing field study).

Debris flows, debris torrents, and sediment budgets of drainage basins.

EMPLOYMENT

1965-1968	Research Associate, Departments of Civil Engineering, University of Idaho and University of Vermont, and Agricultural Research Service, USDA, Danville, Vermont
1968-1971 (WAE)	Research Hydrologist, US Geological Survey, Washington, D.C.
1969-1973	Assistant Professor, Department of Geography, McGill University, Montréal. (1969-1971: at the University of Nairobi, Kenya).
1973-present	Assistant, Associate, and Professor, Department of Geological Sciences, University of Washington. (Chair 1984-1989).

PROFESSIONAL ORGANIZATIONS

American Geophysical Union
Geological Society of America
American Association for the Advancement of Science
Sigma Xi
British Geomorphological Research Group
Japanese Geomorphological Union

FIELD RESEARCH EXPERIENCE

1964 - 1966	Assistant on studies of: sediment transport and sorting in Maryland streams; geomorphological consequences of uplift during the 1964 Alaskan earthquake; and hillslope morphometry and sediment sources in Idaho. Sponsored by research advisor.
1966 - 1968	Hillslope runoff processes during rainfall and snowmelt in Vermont. Sponsored by U.S. Department of Agriculture.
1969 - 1971	Hydrology, sediment transport and chemistry of streams in Kenya. Sponsored by Rockefeller Foundation.

1969 - 1971 (WAE)	Hillslope morphometry and erosion in the Western United States. Sponsored by U.S. Geological Survey.
1971 - 1973	Snowmelt runoff processes on the tundra and in the boreal forest of the Labrador sub-arctic. Sponsored by Canadian National Research Council and Environment Canada.
1973 - 1979	Hillslope erosion in Kenya. Sponsored by Rockefeller Foundation, United Nations Food and Agriculture Organization, and Government of Kenya.
1977 - 1981	River mechanics, Wyoming. Sponsored by NSF (Engineering).
1977 - present	Mass-wasting and the sediment budgets of drainage basins in the Oregon Coast Range, Olympic Mountains, and Cascade Mountains. Sponsored by Washington Department of Natural Resources, U.S. Forest Service, and NSF (Engineering).
1980 - 1985	Field and laboratory studies of mudflow mechanics and erosion processes associated with the eruption of Mt. St. Helens. Sponsored by Washington Department of Fisheries, Office of Water Resource Technology, U.S. Forest Service, U.S. Geological Survey, and Federal Emergency Management Agency.
1980 - present	Field experiments on the mechanics of erosion by rainsplash, sheetwash, and rillwash in Kenya. Sponsored by the National Science Foundation (Earth Sciences and Engineering).
1982 - present	Hydrology, sediment transport, sedimentary petrology and channel-floodplain sedimentation along the Amazon River, Brazil. Sponsored by NSF (Ecosystems), U.S. Geological Survey, NASA/JPL, NASA/EOS.
1987 - present	Debris-flow fans, Owens Valley, CA. Sponsored by NSF (Geosciences).
1991 - present	Role of topographically and tectonically induced stresses on valley evolution in rock masses. Sponsored by Battele Memorial Institute.

PUBLICATIONS

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C. G. Higgins,..., T. Dunne, and ten others!, Landform development: Chap. 42 in Hydrogeology, The Geology of North America, v. 0-2, Geological Society of America, Boulder, CO, 383-400, 1988.

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T. Dunne, Hydrology, mechanics, and geomorphic implications of erosion by subsurface flow; In Groundwater Geomorphology (Eds. C. G. Higgins and D. R. Coates) Geological Society of America Special Paper 252, 1-40, 1990.

T. Dunne, Stochastic aspects of the relations between climate, hydrology and landforms; Trans. Japanese Geomorphological Union, 12, 1-24, 1991.

W. E. Dietrich and T. Dunne, The channel head; In Channel Networks: A Geomorphological Perspective (Eds. K. J. Beven and M. J. Kirkby), (accepted for publication).

T. Dunne, W. Zhang, and B. F. Aubry, Effects of rainfall intensity, vegetation, and microtopography on infiltration and runoff; submitted to Water Resour. Res.

✓ T. Dunne, L. A. K. Mertes, J. E. Richey and R. H. Meade, Sediment transport and sedimentation along the Amazon River valley; soon to be submitted to Geol. Soc. Amer. Bull.

EDITED PUBLICATIONS

O. Slaymaker, A. Rapp, and T. Dunne (eds.), Field Instrumentation and Geomorphological Problems, Zeits. für Geomorphologie, Supplement Band 29, 1978.

O. Slaymaker, T. Dunne, and A. Rapp (eds.), Hillslope Experiments, Zeits. für Geomorphologie, Supplement Band 35, 1980.

S. Okuda, O. Slaymaker, and T. Dunne (eds.), Proceedings of the Third Meeting of the IGU Commission on Field Experiments in Geomorphology, Japanese Geomorphological Union, Kyoto, 1981.

F. J. Swanson, R. J. Janda, T. Dunne, and D. W. Swanston (eds.), Sediment Budgets and Sediment Routing in Forested Drainage Basins, U.S. Forest Service General Technical Report PNW-141, Pacific NW Forest and Range Expt. Sta., 1982.

REPORTS TO GOVERNMENTAL AND OTHER AGENCIES

Ecological survey of the middle and lower Nzoia River in Western Kenya, UNESCO Field Science Office for Africa, Nairobi, 139 pp., 1971 (with H. Walter, J. O. Kokwara, and T. Petr).

Kenya's national report to the United Nations on the human environment, Report to the U.N. Conference on the Human Environment, Stockholm, Government Printer, Nairobi, 102 pp., 1972 (with other members of the Study Committee on Environmental Aspects of a National Materials Policy).

Methodology for assessing soil degradation, Report of the FAO/UNEP Expert Consultation on World Soil Degradation, Food and Agriculture Organization of the United Nations, Rome, 1978 (with other members of the committee).

Flood and sedimentation hazards in the Toutle and Cowlitz River system as a result of the Mt. St. Helens eruptions, 1980, Report to the Federal Emergency Management Agency, Jan. 1981 (with L. B. Leopold).

Proceedings of the Workshop on Management of Renewable Resources: Problems, Strategies, and Policies, Katmandu, Nepal, U.S. National Research Council, 1981 (with other participants of the working group).

Effect of woodfuel harvest on soil erosion in Kenya, Report to Beijer Institute (Sweden) and Kenya Ministry of Energy, Nairobi, 1981 (with K. B. Aubry and E. K. Wahome).

An ordinal-scale classification of water-erosion intensity, Kenya Rangeland Ecological Monitoring Unit, Nairobi, 1981 (with E. K. Wahome and K. B. Aubry).

Resources and World Development: Energy and Minerals, Water and Land. Dahlem Konferenzen (eds. D. J. McLaren and B. J. Skinner), John Wiley & Sons (with other participants of the Dahlem Konferenzen, 1987).

OTHER PROFESSIONAL ACTIVITIES

NRC Committees	- Environmental Aspects of National Materials Policy, 1972-73 - International Environmental Programs, 1979-82 - Working Group on Management of Renewable Natural Resources in Nepal, Kathmandu, 1981 - U. S. Army Basic Research, 1983-88 - U. S. Geological Survey Water Resources Research, 1987-89 - Opportunities in the Hydrological Sciences, 1987-89
United Nations	- UNESCO Research team on Nzoia R., Kenya, 1970-71 - FAO Consultant on Soil Erosion and Desertification in Kajiado District, Kenya, 1976 - FAO Committee on Soil Erosion and Soil Conservation in Developing Countries, Rome, 1976 - FAO/UNEP Committee on a Methodology for Assessing World Soil Degradation, Rome, 1978
Other Committees	- Kenya National Committee on the Human Environment, Nairobi, 1970-71 - State of Washington, Governor's Commission on the Snohomish R. Basin, 1975 - International Geographical Union Commission on Field Experiments in Geomorphology, 1976-84 (Secretary, 1980-84) - Geological Society of America, Committee on the Penrose Medal, 1988-1990.
Editorial Boards	- Quaternary Research, 1982- - Catena, 1986-

OVERSEAS ASSIGNMENTS AND FIELD VISITS

Kenya:	Studies of river hydrology, sediment transport, and water chemistry, hillslope erosion, and effects of land use on erosion and sedimentation, 1969-present.
Tanzania:	Teaching field course on erosion and soil conservation, 1981.
France:	Visits to hydrological field experiments, 1978.
Poland:	Visits to geomorphological field sites, Tatra and Sudeten Mts., 1979.
Australia:	Visit to hydrological and geomorphological studies near Canberra and Blue Mountains, 1979.
New Zealand:	Visits to forest hydrology catchment experiments, South Island, and landslide areas, North and South Islands, 1979 and 1980.
Israel	Visits to hydrologic catchment experiments and to other field studies of tectonism and geomorphology and alluvial-fan deposition throughout the country, 1987.
Jordan:	Seminar on Environmental Monitoring for the Arab World, UNEP and Arab Development Institute, Amman, 1980.
Japan:	Visits to sites of field experiments in erosion control and geomorphology, Japanese Geomorphological Union, 1980. Visits to active volcanoes on Kyushu, Honshu, and Hokkaido, Japanese Society of Erosion-control Engineers, 1983, and Japanese Geomorphological Union, 1989.
India:	Workshop and field trip on Alternative Methods of Flood Control, New Delhi, 1981.
Nepal:	NRC Study team on Management of Renewable Natural Resources, Kathmandu, 1981.
Romania:	Visits to hydrological experiments and landslide investigations, Carpathian Mts., 1983.
Brazil:	Sampling cruise along entire Brazilian Amazon, 19481. Lecturing and advising on field research into forest hydrology and gully erosion, Rio de Janeiro, 1984. Field work on hydrology and erosion in forested and deforested areas of the Central Amazon basin, 1991.

Spain: Visits to hydrological experiments, Pyrenees Mts., Catalonia, Murcia and Granada, 1986.

China: Field excursion to study gullying and seismically generated landslides, Loess Plateau, 1989.

Italy:: Field excursion to Calabria to examine mass wasting induced by rapid uplift of the Appenine Mountains, 1990.

William Eric Dietrich — Vita

Personal:

Born October 29, 1950 in San Francisco, California

Education:

B.A., Occidental College, 1972
M.S., University of Washington, 1975
Ph.D., University of Washington, 1982

Present Position:

Professor, University of California, Berkeley, Department of Geology and Geophysics

Experience:

Summer intern, Water Resources Technical Division, Washington, State Department of Ecology, 1974
Research Assistant, University of Washington, 1978-1981
Assistant Professor, University of California, Berkeley, 1981-1986
Associate Professor, University of California, Berkeley, 1986- 1990
Occasional consultant on hydrology, fluvial and hillslope geomorphology

Honors:

Presidential Young Investigator, 1985-1990
Gordon Warwick Award, British Geomorphological Research Group, 1986

Academic Responsibilities:

Graduate Advisor, 1982-1985; 1990-
Undergraduate Advisor, 1986-1988; 1989-1990
Member of Group in Soil Science, 1983-
Affiliated Faculty of Energy and Resources Group, 1989-

Professional Societies:

American Geophysical Union
British Geomorphological Research Group
Japanese Geomorphological Union
Geological Society of America
American Geomorphological Field Group

Professional Responsibilities:

Member, American Geophysical Union Hydrology Section Unsaturated Zone Committee, 1984- and Erosion and Sedimentation Committee, 1984-

Chairman, Erosion and Sedimentation Committee of the American Geophysical Union Hydrology Section, 1988-1990

Member, Editorial Board, *Geology,* 1986-1988; 1990-

Member, National Science Foundation sponsored Japan-U.S. Cooperative Science Program on Mechanics of River Meanders, 1985-1987

Member, the Commission on Measurement, Theory and Application in Geomorphology, International Geographical Union, 1984-1988

Member, the Erosion Studies Scientific Advisory Committee of the California Department of Forestry and Fire Protection, 1986-

Member, Editorial Board, *Catena*, 1986-

William E. Dietrich — Publications

Papers

1. Dietrich, W.E., 1975, Surface water resources of San Juan County, *in*, Geology and Water Resources of the San Juans, R.H. Russel (ed.), Water Supply Bulletin No. 46, Washington Department of Ecology, p. 59-125.

2. Dietrich, W.E. and T. Dunne, 1978, Sediment budget for a small catchment in mountainous terrain: Zeit. für Geomorph., Suppl. Bd. 29, p. 191-206.

3. Dunne, T., W.E. Dietrich and M. Brunengo, 1978, Recent and past erosion rates in semi-arid Kenya: Zeit. für Geomorph., Suppl. Bd. 29, p. 130-140.

4. Dunne, T., W.E. Dietrich and M. Brunengo, 1979, Rapid evaluation of soil erosion and soil lifespan in the grazing lands of Kenya: Proc. Internatl. Assoc. Hydrol. Sci., Canberra Symposium on the Hydrology of Areas of Low Precipitation, p. 421-428.

5. Dietrich, W.E., J.D. Smith and T. Dunne, 1979, Flow and sediment transport in a sand bedded meander: Jour. of Geol., v. 87, p. 305-315.

6. Dunne, T., W.E. Dietrich and M. Brunengo, 1980, Simple, portable equipment for erosion experiments under artificial rainfall: Jour. Agric. Engineer. Res., v. 25, p. 1-8.

7. Dunne, T. and W.E. Dietrich, 1980, Experimental study of Horton overland flow on tropical hillslopes: I. Soil condition, infiltration and frequency of runoff: Zeit. für Geomorph., Suppl. Bd. 35, p. 40-59.

8. Dunne, T. and W.E. Dietrich, 1980, Experimental study of Horton overland flow on tropical hillslopes: II. Hydraulic characteristics and hillslope hydrographs: Zeit. für Geomorph., Suppl. Bd. 35, p. 60-80.

9. Dunne, T., W.E. Dietrich, N. Humphrey and D. Tubbs, 1981, Geologic and geomorphic aspects of gravel supply in western Washington, *in*, Proc. on Salmon-spawning Gravels, J.J. Cassidy (ed.), Wash. State Water Res. Center, Report No. 39, p. 75-100.

10. Dietrich, W.E., T. Dunne, N.F. Humphrey and L.M. Reid, 1982, Construction of sediment budgets for drainage basins: *in* Sediment Budgets and Routing in Forested Drainage Basins, F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanston (eds.), U.S.D.A. Forest Service General Technical Report PNW-141, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, p. 5-23.

11. Dunne, T. and W.E. Dietrich, 1982, Sediment sources in tropical catchments: Proc. Soil Erosion and Conservation in the Tropics, Amer. Soc. of Agronomy Symp., Colorado State University, August 1979, Spec. Publ., no. 43, p. 41-55.

12. Dietrich, W.E., 1982, Settling velocity of natural particles: Water Resources Research, v. 18, no. 6, p. 1615-1626.

13. Dietrich, W.E., 1982, Mechanics of a river meander: *in*, Field Trip Guidebook 1982 Conference of the American Geomorphological Field Group, Pinedale, Wyoming, L.B. Leopold (ed.), p. 18-29.

14. Dietrich, W.E., D. Windsor and T. Dunne, 1982, Geology, climate, and hydrology of Barro Colorado Island: *in*, Seasonal Rhythms and the Ecology of a Tropical Forest: Seasonal Rhythms and Long-term Changes, E.G. Leigh, Jr., A.S. Rand and D.M. Windsor (eds.), Smithsonian Institution Press, Washington, D.C., p. 21-46.

15. Dietrich, W.E. and J.D. Smith, 1983, Influence of the point bar on flow through curved channels, Water Resources Research v. 19, no. 5, p. 1173-1192.

16. Dietrich, W.E. and R. Dorn, 1984, Significance of thick deposits of colluvium on hillslopes: a case study involving the use of pollen analysis in the coastal mountains of Northern California, Jour. Geol., v. 92, p. 147-158.

17. Dietrich, W.E. and J.D. Smith, 1984, Processes controlling the equilibrium bed morphology in river meanders, in: Rivers '83: Proceedings of a Specialty Conference on River Meandering, October, 1983; Am. Soc. Civ. Engineers, p. 759-769.

18. Dietrich, W.E., J.D. Smith, and T. Dunne, 1984, Boundary shear stress, sediment transport and bed morphology in a sand-bedded river meander during high and low flow, in: Rivers '83: Proceedings of a Specialty Conference on River Meandering, October, 1983; Am. Soc. Civ. Engineers, p. 632-639.

19. Dietrich, W.E. and J.D. Smith, 1984, Bedload transport in a river meander, Water Resources Research, v. 20, p. 1355-1380.

20. Reneau, S.L., W.E. Dietrich, C.J. Wilson, and J.D. Rogers, 1984, Colluvial deposits and associated landslides in the northern S.F. Bay Area, California, USA, Proceedings IV International Symposium on Landslides, Toronto, 1984, pp. 425-430.

21. Dietrich, W.E. and J. Gallinatti, 1991, Fluvial geomorphology, in: Field Experiments and Measurement Programs in Geomorphology, O. Slaymaker (ed.), A.A. Balkema, Rotterdam, p.169-229.

22. Dietrich, W.E., C.J. Wilson and S.L. Reneau, 1986, Hollows, colluvium and landslides in soil-mantled landscapes, in: Hillslope Processes, Sixteenth Annual Geomorphology Symposium, A. Abrahams (ed.), Allen and Unwin, Ltd., p. 361-388.

23. Higgins, C.G., D.R. Coates, V.R. Baker, W.E. Dietrich, T. Dunne, E.A. Keller, R.M. Norris, G.G. Parker Sr., M. Pavich, T.L. Péwé, J.M. Robb, J.D.Rogers, and C.E. Sloan, 1988, Landform development, Chapter 42 in The Geology of North America, v. O-2, Hydrogeology, Geological Society of America, p. 383-400.

24. Reneau, S.L., W.E. Dietrich, R.I. Dorn, C.R. Berger, and M. Rubin, 1986, Geomorphic and paleoclimatic implications of latest Pleistocene radiocarbon dates from colluvium-mantled hollows, California, Geology, v. 14, p. 655-658.

25. Reneau, S.L. and W.E. Dietrich, 1987, The importance of hollows in debris flow studies, in: Debris Flows/Avalanches: Process, Recognition and Mitigation, Reviews in Engineering Geology, Volume VII, J.E. Costa and G.F. Wiezcorek (eds.), Geological Society of America, p. 165-180.

26. Brimhall, G.H. and W.E. Dietrich, 1987, Constitutive mass balance relations between chemical composition, volume, density, porosity, and strain in metasomatic hydrochemical systems: Results on weathering and pedogenesis, Geochimica et Cosmochima Acta, v. 51, no. 3, p. 567-587.

27. Dietrich, W.E., 1987, Mechanics of flow and sediment transport in river bends, in: River Channels: Environment and Process, K.S. Richards (ed.), Institute of British Geographers Special Publication No. 18, Basil Blackwell, Inc., p. 179-227.

28. Reneau, S.L. and W.E. Dietrich, 1987, Size and location of colluvial landslides in a steep forested landscape, Proc. Int. Symp. on Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987, Corvallis, Ore., Int. Assoc. Hydrological Sciences Bull., Pub. no. 165, p. 39-48.

29. Wilson, C.J. and W.E. Dietrich, 1987, The contribution of bedrock groundwater flow to storm runoff and high pore pressure development in hollows, Proc. Int. Symp. on Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987, Corvallis, Ore., Int. Assoc. Hydrological Sciences Bull., Pub. no. 165, p. 49-59.

30. Dietrich, W.E., S.L. Reneau and C.J. Wilson, 1987, Overview: "Zero-order basins" and problems of drainage density, sediment transport and hillslope morphology, Proc. Int. Symp. on Erosion and Sedimentation in the Pacific Rim, 3-7 August 1987, Corvallis, Ore., Int. Assoc. Hydrological Sciences Bull., Pub. no. 165, p. 27-37.

31. Whiting, P.J., W.E. Dietrich, L.B. Leopold, T.G. Drake, and R.L. Shreve, 1988, Bedload sheets in heterogeneous sediment, Geology, v. 16, p. 105-108.

32. Drake, T.G., R.L. Shreve, W.E. Dietrich, P.J. Whiting, and L.B. Leopold, 1988, Bedload transport of fine gravel observed by motion-picture photography, Journal of Fluid Mechanics, v. 192, p. 193-217.

33. Brimhall, G.H, C.J. Lewis, J.J. Ague W.E. Dietrich, J. Hampel, T. Teague, and P. Rix, 1988, Metal enrichment in bauxite by deposition of chemically-mature eolian dust, Nature, v. 333, p. 819-824.

34. Reneau, S.L., W.E. Dietrich, M. Rubin, D.J. Donahue, and J.T. Jull, 1989, Analysis of hillslope erosion rates using dated colluvial deposits, Journal of Geology, v. 97, p. 45-63.

35. Dietrich, W.E. and P.J. Whiting, 1989, Boundary shear stress and sediment transport in river meanders of sand and gravel, in S. Ikeda and G. Parker (Eds.), River Meandering, American Geophysical Union Water Resources Monograph 12, p. 1-50.

36. Montgomery, D.R., and W.E. Dietrich, Where do channels begin?, 1988, Nature, v. 336, p. 232-234.

37. Montgomery, D., and W.E. Dietrich, 1989, Channel initiation, drainage density and slope, Water Resources Research, v. 25, no. 8, p. 1907-1918.

38. Dietrich, W.E., J.W. Kirchner, H. Ikeda, and F. Iseya, 1989, Sediment supply and the development of the coarse surface layer in gravel-bedded rivers, Nature, v. 340, no. 6230, p. 215-217.

39. Wilson, C.J., Dietrich, W.E and T.N. Narasimhan,1989, Predicting high pore pressures and saturation overland flow in unchannelled hillslope valleys, Hydrology and Water Resources Symposium, Institution of Engineering Australia, p.392-396.

40. Reneau, S.L. and W.E. Dietrich, 1990, Depositional history of hollows on steep hillslopes, coastal Oregon and Washington, National Geographic Research, v. 6, no. 2, p. 220-230.

41. Kirchner, J., W.E. Dietrich, F. Iseya,, and H. Ikeda, 1990, The variability of critical boundary shear stress, friction angle, and grain protrusion in water-worked sediments, Sedimentology, v. 37, p. 647-672.

42. Reneau, S.L., W.E. Dietrich, D.J. Donahue, and A.J.T. Jull, 1990, Late Quaternary history of colluvial deposition and erosion in hollows, Central California Coast Ranges, Geological Society of America Bulletin, v. 102, no. 7, p. 969-982.

43. Dietrich, W.E., 1989, Slope morphology and erosion processes, in C. Wahrhaftig and D. Sloan (Eds.), Geology of San Francisco and Vicinity, Field Trip Guidebook T105, American Geophysical Union, p. 38-40.

44. Wilson, C. J., S. L. Reneau, and W. E. Dietrich, 1989, Hydrologic and erosional processes in hollows, Lone Tree Creek, Marin County, California, in W. M. Brown, III, (ed.), Landslides in Central California, Field Trip Guidebook T381, American Geophysical Union, p. 75-90.

45. Dietrich, W. E., and T. Dunne, in press, The channel head, in M. J. Kirkby and K. Beven (Eds.), Channel Network Functions, J. Wiley and Sons .

46. Whiting, P. J., and W. E. Dietrich,1991 Convective accelerations and boundary shear stress over a channel bar, Water Resources. Research,v. 27, no.5, p.783-796.

47. Whiting, P. J., and W. E. Dietrich, 1990, Boundary shear stress and roughness over mobile alluvial beds, Am. Soc. Civ. Eng., J. Hydraul. Eng., V.116 (12), p.1495-1511.

48. Reneau, S.L. and W.E. Dietrich, in press, Erosion rates in the southern Oregon Coast Range: evidence for an equilibrium between hillslope erosion and sediment yield., Earth Surface Processes and Landforms.

49. Buffington, J.L., W.E. Dietrich and J. Kirchner, in press, Friction angle measurements on a naturally formed gravel streambed: implications for critical boundary shear stress, Water Resources Research.

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Monaghan, M.C., J. McKean, W.E. Dietrich and J. Klein, ^{10}Be Chronometry of bedrock-to-soil conversion rates, submitted to Earth Planet. Sci. Lett.

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Danti,K. J.,G.H. Brimhall,and W.E Dietrich, Gold enrichment by regolith reduction and supergene oxidation of the Ok Tedi porphyry copper deposit, Papua New Guinea: transport rates and mineral transformation pathways, submitted to Economic Geology

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Dietrich, W.E., J.D. Smith and T. Dunne, 1981, Boundary shear stress, sediment transport, and the movement of sediment across the channel in meandering rivers, Abstracts to Proceedings of the Second International Conference on Fluvial Sediments: "Modern and Ancient fluvial systems," University of Keele, p. 30.

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Dietrich, W.E. and J.D. Smith, 1982, Flow through a river meander, EOS Trans., Amer. Geophys. Union, v. 63, no. 45, p. 937.

Dietrich, W.E., 1983, Slope and mass-wasting geomorphology, Invited Speaker, NAGT Symposium: Recent advances in geomorphology/implications for instructions, Geol. Soc. Amer. Abst., v. 15, no. 6, p. 558.

Dietrich, W.E., 1983, Runoff and erosion in a forested catchment, Barro Colorado Island, Panama, EOS Trans., Amer. Geophys. Union, v. 64, no. 45, p. 700.

Dietrich, W.E., S. Reneau, and C. Wilson, 1984, Importance of colluvium-filled bedrock hollows to debris flow studies, Invited Speaker: Symposium on debris flows/avalanches, Geol. Soc. Amer. Ann. Meetings, Reno, Nevada, Vol. 16, no. 6, p. 488.

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Dietrich, W.E., S.L. Reneau and C.J. Wilson, 1985, The geomorphology of "zero order basins," Invited Speaker: Symposium on Hydrology and Erosion Processes of Zero Order Basins, EOS Trans., Amer. Geophys. Union, v. 66, no. 46, p. 898.

Wilson, C.J. and W.E. Dietrich, 1985, Lag in the saturated zone and pore pressure development after peak run-off in hollows, EOS Trans., Amer. Geophys. Union, v. 66, no. 46, p. 898.

Reneau, S.L. and W.E. Dietrich, 1985, Landslide recurrence intervals in colluvium-mantled hollows, Marin County, California, EOS Trans., Amer. Geophys. Union, v. 66, no. 46, p. 900.

Whiting, P.J. and W.E. Dietrich, 1985, The role of bedload sheets in the transport of heterogeneous sediment, EOS Trans., Amer. Geophys. Union, v. 66, no. 46, p. 910.

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Whiting, P.J., W.E. Dietrich, L.B. Leopold, and L. Collins, 1985, The variability of sediment transport in a fine-gravel stream: Publication of the Third International Fluvial Sedimentology Conference, Ft. Collins, CO, August 7-9, 1985, p. 38.

Dietrich, W.E., S. Raugust and P. Whiting, 1985, Local boundary shear stress and bedload transport in rivers, Abstracts of First International Conference on Geomorphology, Manchester, UK, September 1985, p. 140.

Wilson, C.J. and Dietrich, W.E., 1986, The contribution of shallow groundwater flow in bedrock to storm runoff and high pore pressure development in hollows, EOS Trans. Amer. Geophys. Union, v. 67, no. 44, p. 957.

Reneau, S.L., W.E. Dietrich, M. Rubin, D.J. Donahue, and A.J.T. Jull, 1987, Erosion and climatic change in the Holocene: Evidence from colluvial deposits on the Olympic Peninsula, Washington, Geol. Soc. Am., Abst., v. 107, no. 7, p. 816.

Wilson, C., W.E. Dietrich, J. McKean, M. Alavi, and T.N. Narasimhan, 1987, Predicting pore pressure and runoff response in small basins with analytic models, Geol. Soc. Am., Abst., v. 107, no. 7, p. 892.

Whiting, P.J. and W.E. Dietrich, 1987, Grainsize variation in stratigraphy resulting from migration of sorted bed features, Geol. Soc. Am., Abst., v. 107, no. 7, p. 889.

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S.P. Anderson , D.R. Montgomery, Torres, R., W.E. Dietrich, and K. Loague, 1990, Hydrologic experiments in a steep unchanneled valley: (3) runoff chemistry dynamics, EOS v.71,No. 43, p. 1342.

BUDGET FOR CHANNEL ASSESSMENT COMPONENT

	Year 1	Year 2	Total
SALARIES			
David Montgomery (Research Asst. Prof., 21.5 mo)	31483	42154	73637
Post-doctoral Res. Asst. (7 mo)		23198	23198
Graduate Res.Assts.(2 for 21.5 mo)	17860	23914	41774
Hourly field assistants ($8/hr)	4000	5000	9000
Computer system manager (25% time)	6250	7950	14200
BENEFITS			
Res. Asst. Prof.	6611	8852	15463
Post-doc Res. Asst.		4872	4872
Graduate Res. Assts.	179	239	418
Hourly	450	540	990
Computer syst. mgr.	1812	2306	4118
EQUIPMENT			
Macintosh computer and software for graphics	6000		6000
Miscellaneous field equipment	3000	3000	6000
FIELD EXPENSES			
Travel and per diem	7500	7500	15000
MISCELLANEOUS			
Copying, telephone, supplies	2000	2000	4000
Graduate Operating Fee	6078	7718	13796
TOTAL DIRECT COSTS	93223	139243	232466
INDIRECT COSTS (29% of direct costs)	24425	39510	63935
TOTAL	117648	178753	296401

BUDGET FOR CHANNEL ASSESSMENT COMPONENT

	Total
B. DIRECT LABOR	187670
C. OVERHEAD (29%) AND ADMINISTRATIVE EXPENSES	81731
F. FACILITIES AND SPECIAL EQUIPMENT	12000
G. TRAVEL EXPENSES (local)	15000
TOTAL	296401

BUDGET FOR DEEP-SEATED MASS FAILURE COMPONENT

	Year 1	Year 2	Total
SALARIES			
Post-doctoral Res. Asst. (11mo)		36454	36454
Graduate Res. Asst. (22 mo.)	9400	11957	21357
BENEFITS			
Post-doctoral Res. Asst.		7655	7655
Graduate Res. Asst.	94	120	214
EQUIPMENT			
PC X-terminal (for use with SUN workstation)	4000		4000
Miscellaneous field equipment	1000	1000	2000
FIELD EXPENSES	2000	2620	4620
MISCELLANEOUS			
Telephone and copying	1000	1000	2000
Graduate Operating Fee	3039	3859	6898
TOTAL DIRECT COSTS	20533	64665	85198
INDIRECT COSTS (29% OF DIRECT COSTS)	4505	18463	22968
TOTAL	25038	83128	108166

BUDGET FOR DEEP-SEATED MASS FAILURE COMPONENT

B. DIRECT LABOR (including benefits)	65680
C. OVERHEAD (29%) AND ADMINISTRATIVE EXPENSES	31866
F. FACILITIES AND SPECIAL EQUIPMENT	6000
G. TRAVEL (local)	4620
TOTAL	108166

BUDGET FOR SHALLOW SEDIMENT SOURCE COMPONENT (to be subcontracted to the University of California, Berkeley)

SALARIES			
Visiting Scientist, C.J. Wilson (7.5% time, 144 hours/year)	2366	2479	4845
Graduate Res. Asst.	9818	14197	24015
Computer Syst. Mgr.(25%;12.5% time)	6000	3000	9000
Hourly assistant (to develop DEM data bases)	1000	1000	2000
BENEFITS			
Visiting Scientist	710	743	1453
Graduate Res. Asst.	394	418	812
Computer Syst. Mgr. (25% time)	1740	870	2610
Hourly assistant	90	90	180
MISCELLANEOUS			
Local travel and field expenses	3550	3198	6748
Air photos, maps, supplies	2000	2000	4000
Telephone, mail, etc.	614	119	733
Graduate Operating Fee	2718	2886	5604
TOTAL DIRECT COSTS	31000	31000	62000
INDIRECT COSTS (29% of direct costs)	8990	8990	17980
TOTAL	39990	39990	79980

BUDGET FOR SHALLOW SEDIMENT SOURCE COMPONENT

B. DIRECT LABOR	44340
C. OVERHEAD (29%) AND ADMINISTRATIVE EXPENSES	25640
D. DIRECT MATERIALS	4000
G. TRAVEL	6000
TOTAL	79980