KEYNOTE ADDRESS, THEME 4

Management of Steepland Erosion: An Overview

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ABSTRACT

Steepland erosion is a composite of surface, channel, and mass erosion. The relative importance of each process is determined by an interaction between climate, soil, geology, topography, and vegetation. A change in any of these components can increase or decrease the rate of erosion. The key to successful management of erosion is the ability to 1) identify potentially erodible sites, 2) correctly assess appropriate activities at those sites, and 3) have a political/regulatory system that allows for the exclusion of hazardous sites from land treatment. Steepland erosion is controlled most effectively — both in physical and economic terms — by preventative land-use practice rather than corrective action.

INTRODUCTION

Erosion is the detachment and transportation of material from a surface. It takes place whenever the eroding or driving forces exceed the resisting forces. To manage erosion, it is necessary to understand the forces that cause material to move and to resist movement. The most effective management is prevention because once human activities accelerate natural erosion, corrective action is not only expensive but seldom entirely successful.

Much of the concern about steepland erosion is generated, not so much over the loss of soil, as over the degradation of stream resources by eroded material. Consequently, erosion management is often deemed successful if eroded material does not enter a stream system. Furthermore, it is commonly assumed that ground disturbance and erosion are closely correlated and that soil detachment and movement increase the likelihood that sediment will be transported to and by a stream. These assumptions are usually weak links in understanding erosional processes and in successfully managing erosion.

Steepland erosion is the result of complicated interactions between climate, soil, geology, topography, and vegetation. A change in any of these components may result in an adjustment of the driving or resisting forces and lead to increased or decreased erosion. Because of these interactions, generalizations about the management of erosion are both difficult and risky to make. It is usually possible to find as many examples where a generality does not apply as where it does apply. Generalizations may lead managers to select one standardized "best" approach to evaluate erosion hazards and to thereby justify management prescription without adequate consideration of the processes involved — much less their interactions. The more "simple" the erosional process, the more likely that process will eventually be incorporated into a management guideline.

Management guidelines addressing complex erosional processes are scant. Consequently, most laws or management rules include specific required measures to reduce erosion generated by the simple, easily understood processes, and generally ignore the complex processes and their interactions which require detailed on-site study. The land manager is often forced by statute to modify practices to reduce one type of erosion, which may be only a minor and insignificant portion of the total erosion from the site, but not be required by law to modify practices affecting other, more complex and often more significant types of erosion.

An alternative to management by statute is management by professional judgment; for example, structural design by an engineer or architect. Prescriptive statutes are easier to enforce than is professional competence. In the example, enforcement is accomplished by holding the designer professionally and financially liable for error in judgment.

This paper describes how the interactions of climate, soil, geology, topography, and vegetation affect the management of steepland erosion. Three types of erosion are considered: surface, channel, and mass erosion. Each type can occur singly or in combination, and, in actuality, steepland erosion is a composite of the three.

SURFACE EROSION

In surface erosion, individual soil particles are removed by raindrops, thin film flow, and concentrated surface runoff in the form of sheet and rill erosion. Surface erosion is characterized by the lack of permanent channels. In undisturbed steepland forests, surface erosion is generally insignificant because infiltration rates usually exceed rainfall intensities. Logging, road construction, wildfires, or mass erosion, however, can expose mineral soil where the naturally high porosity of forest soils may be severely reduced by raindrop impact and compaction by heavy equipment. Fire can also produce water repellency in steepland soils. If the resultant flow of water over these bare areas is not controlled, surface erosion may progress from sheet to rill to gully erosion as channels are formed.

Perhaps the best known method for predicting surface erosion is the Universal Soil Loss Equation developed for agricultural lands by the Soil Conservation Service of the United States Department of Agriculture. Attempts to apply it to steepland forest areas generally have been unsuccessful — mainly because of the invalid basic assumption that most erosion from forest soils results from sheet overland flow.

Many erosion control techniques have been developed to manage surface erosion including contour terracing, grass seeding, and mulching. These methods are intended to reduce both raindrop impact and the energy of surface sheet wash and to create a root network to hold individual soil particles in place. More effort has been devoted to reducing surface erosion than to any other form because it is the most easily controlled. But surface erosion is the least important of the erosion types found in forested steeplands.

CHANNEL EROSION

Channel erosion is the detachment and movement of material from a gully or stream channel. The material may be individual particles derived from the channel skin, *per se;* or it may be sediment eroded by surface or mass erosion that was deposited in the channel, for example, when an undercut stream bank collapses into the channel. The amount of channel erosion may be directly related to the amount and size of material being transported within the channel. This condition is evident particularly in channels where energy available to transport material and the supply of that material are at an equilibrium. If the supply to a stream is increased, the transport capability may be exceeded, and net channel bed erosion ceases while the channel aggrades. If the supply is decreased below the transport capability, the channel bed tends to erode. As channel beds aggrade, bank erosion may be accelerated if the stream is directed against vulnerable banks by the aggraded bed. In steep-gradient mountainous channels, however, there is generally an energy excess and a supply deficiency — at least for the smaller grain-sizes. Channel erosion there is related more to the physical characteristics of the bed material and the resistance of the geologic parent material to erosion, than to the availability of energy to transport that material.

Other steepland channels have developed an erosion resistant bed which becomes unstable only when an energy threshold is exceeded. Such erosion resistance may be provided by a bed composed of relatively large particles, commonly called an armour layer, and by the incorporation of large organic debris into the channel. Organic debris reduces the local channel gradient and creates a stepped channel where energy is spent as turbulence when water cascades over successive logs into pools. Upstream of these logs is a flat reach containing readily transportable material. If the large particles or logs are moved, by high discharge or by decay of the organic debris, erosion can proceed rapidly until new bed resistance is encountered. Finally, some steepland channels may be rapidly eroding at a rate dependent upon the energy supply. An example of such channels are newly-forming and transient gullies in mass erosion terrain.

Land management activities influence channel erosion principally by placing readily erodible material in existing channels; by introducing large organic debris into small perennial channels; by increasing surface runoff from bare and compacted soils; by modifying the surface microdrainage network by roads, tractor trails, and ditches; and by converting subsurface drainage to surface runoff (i.e., by intersecting subsurface flow with road cuts). When the existing drainage network is modified, some channels may receive less water while others receive more. Erosion would be expected to be reduced in the channel with reduced flow and increased in the channel receiving the additional water. If water is routed from an actively eroding channel to a resistant one, however, net channel erosion could be reduced.

MASS EROSION

Mass erosion is the downslope movement, *en masse*, of soil or rock in response to gravitational stress. In steeplands, mass erosion includes a large variety of processes that range from slow and subtle deformation of the soil mantle to rapid, discrete failure of hillsides and stream channels. In undisturbed forested steeplands, mass erosion is the dominant mechanism by which soil materials are transported from hillslopes to stream channels. Land management activities can dramatically increase the probability of certain types of mass erosion, but exercise little influence on other types.

Creep is the slow downslope movement of the soil mantle where the long-term gravitational shear stress is large enough to produce permanent deformation, but too small to cause discrete failure. Creep is the most common and widespread mass erosion process in steeplands, but is the least understood and documented. It occurs at varying rates and depths in all sloping cohesive soils. Changes in the rate of creep of a given slope seems to be correlated with changes in the piezometric level in the slope. Measurements of borehole deformation in a variety of geologic materials in forested areas of the Pacific Rim in the United States suggest annual creep rates of less than 10 mm/yr in areas not associated with earthflows. These rates vary widely within the same geologic material and with climatic stress. Consequently, the effect of land management on creep rates is poorly documented.

Although direct measurement of management-induced changes in creep rate may be nearly impossible, the quantity of material delivered to the numerous stream channels in the area can be large. For example, if timber cutting increased the average creep rate in a catchment from 3 to 10 mm/yr, the change would probably not be noticed even by detailed hillslope observation. But the quantity of soil added to stream channels would be trebled, and the change in sediment transport may be easily detected. In ephemeral streams, the delivery of material to channels may be continuous throughout the year, but transported from the channels only during large storms; thereby sediment is yielded as episodic pulses.

Earthflow can be considered accelerated creep where shear stress exceeds the strength of the soil mantle and results in discrete failures. These failures may range from less than a hectare in area and a metre in depth to several square kilometres in area and tens of metres in depth. The rate of movement of earthflows, as with creep, may be imperceptibly slow, but can exceed a metre per day. Movement may be continuous, seasonal, or episodic. Like creep, deep-seated earthflows may be affected little by timber cutting or road building unless the distribution of mass or the water relationships within the slide changes substantially. The distribution of mass can be changed by excavations which undercut the toe of the earthflow, removing downslope support. Road fill can add mass to the head of an earthflow, adding to the gravitational forces contributing to slope failure. Roads can also modify the water relations within the earthflow. Road cuts can intercept subsurface flow. If this water or surface road drainage is diverted away from the earthflow, the slide below the road may become more stable. If water is diverted onto the slide, dormant earthflows may be reactivated. Timber cutting can also modify the internal water relations of the earthflow.

Evapotranspiration by forests may deplete 50 to 75 cm of soil moisture per year. In a Mediterranean-type climate having warm, dry summers, a substantial soil moisture deficit develops which can reduce both piezometric head and the slide mass. The more active earthflows are often moving too rapidly for trees or other deep-rooted perennial vegetation to become established. Dormant landslides may be reactivated, however, if existing forests are removed. This step effectively adds water normally removed from the slope by evaporation. The potential effect of management on earthflows is correlated with both the scale of the earthflow feature and of the management activity. A small tractor trail crossing a massive earthflow would have less effect than a large road undercutting a small, shallow potential failure surface.

There are interactions and feedback mechanisms between erosion types. In some cases, channel incision undercuts the toes of earthflows, upsetting the balance of forces on the hillslope. In other cases, aggradation with accompanied increases in bank erosion undercut the toes of earthflows. In small steep streams, incision is more common than aggradation, while in large low-gradient streams the reverse is true. Accelerated earthflow erosion, in turn, can modify other types of erosion.

Debris avalanches are rapid, shallow hillslope failures generally found in shallow noncohesive soils on steep slopes where subsurface water becomes concentrated. Plant roots can reduce the frequency of these shallow failures. Roots can anchor through the soil mass into fractures in bedrock. They can also develop lateral support by crossing zones of weakness to more stable soil as well as providing long fibrous binders within a weak soil mass. In deeper soils, anchoring to bedrock becomes negligible, but the lateral support by roots remains. In marginally stable areas, debris avalanche frequency may increase after trees are cut and their root systems progressively decay. The influence of evapotranspiration in depleting soil water is important principally in that additional rainfall is required to bring the slope to saturation. Debris avalanches occur primarily during periods of rapid snow melt or high rainfall when piezometric levels are high. Once soil moisture deficits are satisfied and the soil is saturated, the influence of winter evapotranspiration on soil water content becomes negligible. The movement of subsurface water in unaltered forest soils is often rapid — taking place through interconnected root channels and other macropores. When forest soils are disturbed, these subsurface conduits can collapse or become plugged, delaying drainage, increasing piezometric levels, and resulting in slope failure.

Although many studies have documented debris avalanche erosion following logging, roads appear to increase the frequency of debris avalanche much more than does timber cutting. In addition to profoundly affecting the soil water regime, road cuts can intersect and undercut the shallow failure surface, and road fills can add a substantial mass surcharge to the slope. These effects become relatively less important as the depth to the failure surface increases.

Debris torrents are the failure and rapid movement of water-saturated soil, rock, and organic debris in small, steep stream channels. Debris torrents might be considered a transitional link between debris avalanche mass erosion and channel erosion. They typically occur during periods of high precipitation and streamflow. They may be started by a debris avalanche which enters the channel or they may result from an initial failure of accumulatd debris within the channel. Typically, as debris from the initial failure moves downslope, it entrains large quantities of additional material obtained from the channel banks and bed. The resulting channel may be scoured to bedrock for a great distance until the channel gradient lessens and deposition occurs.

Debris torrents may start in channel reaches where fluvial channel erosion is typically small. In these reaches, water may flow through the interstices of accumulated organic material and coarse non-cohesive rock and soil. As the volume of subsurface flow increases, the piezometric level within the accumulated debris rises, ultimately leading to failure at some critical piezometric head. Debris torrents appear to be episodic. They recur whenever there is enough noncohesive debris accumulated in the steep channel and water to mobilize that debris.

Land management activities may increase the frequency of debris torrents by increasing the quantity of water delivered to a channel or by increasing the quantity of debris in a channel. Channel flow can be dramatically changed by roads intercepting subsurface flow, rerouting of microdrainage networks, and the concentrating of surface runoff from compacted road or tractor trails. Material from accelerated hillslope erosion can increase the amount of debris accumulated in channels. Road fills at stream crossings place a large mass of rock and soil in channels. It is common for road culverts in small steep stream channels to plug with soil and organic debris, resulting in saturation and failure of the road fill. Failure of road crossings is a principal cause of accelerated channel erosion and debris torrents in many forested steepland areas.

DISCUSSION

Where and how land management is conducted are the two primary considerations in efforts to reduce steepland erosion. The "how" consideration is often thought to be completed with planning. Although good planning is a major and necessary step in minimizing erosion, the carrying out of the plan is all too often underplayed. The on-the-ground operator is the key to success or failure of a plan. Commonly, little effort is expended to include operators in the planning process. In general, their skills have been developed through personal experience of what seems to work. Unfortunately, what works best for dragging a log or constructing a stream crossing may not be best for managing erosion. An important part in managing steepland erosion is successful interactions between planners and operators. Success is often based as much on personalities as on technical abilities.

Many management rules approach prevention as though there was an equal probability of erosion occurring at any given location. It is becoming increasingly clear that most steepland erosion occurs in a limited number of areas and that most of the area produces only a small amount of erosion.

The cumulative impact of management activities on erosion is a matter of concern. Some persons maintain that if a small proportion of the area is logged, the rest will buffer the effect of the logging on downstream values. The proportion of catchment that can be logged without undue degradation of the stream resource is, however, a matter of conjecture. This sort of assessment is appealing in its simplicity, but assumes erosion sources are uniformly distributed. To effectively manage erosion in steeplands, it is more important to specify *where* land is to be treated than to be concerned with *how much* land is to be treated. A very small amount of activity conducted in the wrong place can result in a great deal more erosion than a large amount of activity conducted in locations which are erosion resistant.

The key to successful management of erosion is the ability to 1) identify potentially erodible sites, 2) correctly assess appropriate activities on those sites, and 3) have a political/regulatory system that allows for the exclusion of hazardous sites from land treatment. In some cases, the most appropriate activity on a site may be no activity. The cost required to correct management-induced erosion is often far beyond the benefits obtained from the land management activity or the costs required to follow a more sensitive alternative plan.

Also, the time frame in which costs are related to benefits must be lengthened. In general, the period of concern of land management-related erosion is short — several years at the most. This is perhaps acceptable for surface erosion, but channel erosion and mass erosion may follow land treatment by many years or even decades. Since channel erosion and mass erosion are usually associated with rare meteorological events, the causal relationship to land management is less demonstrable than that of prompt surface erosion.

Guidelines tend to address control of erosion on the basis of the "typical" event. It is, however, normally the "unusual" event which produces the erosional characteristics that are generally considered to be "unacceptable". Efforts to control erosion from the typical runoff event could lead to more erosion during the large storm. For example, small log check dams may effectively trap sediment and curtail erosion during average-size storms, but may provide a large source of material if these small dams fail during a major event. Such an erosion control effort may not reduce the amount of material transported during the long term, but simply change the time-related distribution of sediment yield. In some cases, the transport of a large quantity of material within a short time period may be more destructive than the same quantity being transported over a long period. Large sediment pulses may produce pronounced deposition downstream. Channel aggradation may then lead to secondary erosion from deflected flow, which undercuts and over-steepens stream banks. Accumulation of material behind small check dams in a steep channel may also predispose the channel to mass failure as a debris torrent which may be many times more destructive to downstream values than would continued transport of eroded materials.

A potentially useful system for managing erosion would be an Erosion Danger Rating — conceptually similar to the Fire Danger Rating used for forest fire planning. The Erosion Danger Rating would encompass a number of variables which predict the probability of erosion. Requirements for personnel and equipment would be based on predicted erosion damage. For example, if a large storm is forecast, certain measures might be taken to reduce road-related erosion — vulnerable culverts could be inspected and cleared in advance of the storm, critical road-side drainage ditches could be cleaned, road berms could be repaired. During the storm, additional workers could be hired to patrol roads to prevent minor problems from developing into major failures. This sort of approach has been used on several National Forests in the United States. The frequency of road-related erosion has been dramatically reduced.

One common method to minimize road-related debris torrents is to install "oversize" culverts or to bridge the water-course. This method is often discounted because of its high initial expense. Construction costs are frequently viewed in the short term and fail to include subsequent costs of maintenance and replacement. If the accounting system included the total costs required during the design life of the project, many current construction practices would probably be changed.

Innovative techniques have been successful in reducing the failure rate of downstream crossings. By identifying channels which have a high debris torrent potential, road crossings have been designed so that water and debris will easily pass over the road and down a resistant concrete/rock-faced fill. Another effective technique to reduce road failures has been to colour-code road posts at culverts to indicate the potential of plugging; for example, red for high, yellow for moderate, and green for low potential. Employees are instructed that whenever they cross a red culvert during the rainy season, they must stop and assure that it is free of debris. Yellow culverts are to be routinely checked after storms. Green culverts are only checked on a normal maintenance schedule.

Management activities can modify the stability of debris within the channel. The local gradient of a steepland channel, as well as its stability, is often controlled by bedrock. However, large woody debris, a natural component of forested steepland channels, can also control channel gradient. The residence time of large decay-resistant logs, such as redwood, in a channel may approach a geologic time scale — up to 1500 years. Large logs of Douglas-fir may remain in a channel for several hundred years. When this organic debris decays, accumulated material is subject to channel erosion and, further, is available for rapid mobilization into a debris torrent.

Management activities can influence both short- and long-term stability of debris deposits within channels. Mechanical removal of naturally accumulated large organic debris can release stored sediment within a short time, whereas, decay allows intermittent releases over a longer time while new deposits simultaneously form behind recently fallen trees. Logging residue can greatly add to the organic loading of a channel, thus providing additional opportunities for debris deposits. These additional deposits can increase the risk of debris torrents in steep channels or predispose channels to increased erosion years after logging as organic components eventually decay and release accumulated deposits. If channel stability is controlled by the long-term supply of large organic debris, and large trees adjacent to channels are eliminated by continued forest management, active channel erosion may follow the decay of existing logs because new larger logs are no longer available for replacement. In intermittent channels, live roots from surrounding trees provide substantial strength and reinforcement to the channel bed. If these trees are cut, the strength of the debris composing the bed will progressively weaken as the roots decay. This condition may result in accelerated channel erosion or increased risk of a debris torrent.

To manage steepland erosion successfully, it is important to define the erosional concern. If the principal concern is the loss of soil productivity, then on-site erosion control is perhaps appropriate. If the concern is reservoir aggradation, perhaps on-site soil loss is not important so long as eroded soil is deposited on the slope or in a stream before entering the reservoir.

Rational land management should evaluate the social costs and benefits of proposed management activities. Cost/benefit analyses of land management have generally been limited to traditional economic factors of short-term monetary outlay and income. The costs of erosion often enter the analysis only when road maintenance or other direct costs are affected. Indirect costs such as loss of fish habitat, soil productivity, and long-term slope instability are difficult to quantify, either physically or economically. Nonetheless, indirect costs must be assessed.

Considering these ambiguities, prudent management should identify the values at risk and direct erosion control activities toward processes most likely to affect those values. Steepland erosion is controlled most effectively — both in physical and economic terms — by preventive land-use practices rather than corrective action. Management of steepland erosion is merely the appropriate application of varying levels of care and caution when dealing with terrain of varying erosional sensitivity.

There is a great tendency to fix past mistakes. The public often demands that we attend to actively eroding sites — whether management induced or natural. However, unless more effort is devoted to looking forward toward prevention rather than backward toward correction, we will continually be trying to catch up. The successful management of erosion is as much a philosophical and political problem as a technical one.