SUBSURFACE DRAINAGE ERODES FORESTED GRANITIC TERRANE

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Abstract: Solution and landsliding, the dominant erosion processes in undisturbed forested mountainous watersheds, are both influenced by subsurface drainage. Biological processes that generate organic acids accelerate loss of dissolved solids by promoting the dissolution of primary minerals in granitic rock. These organic acids can also disperse the secondary minerals, kaolinite and ferric hydroxide. This accelerates erosion by subsurface drainage through suffusion and piping, particularly in well-drained, gap-graded soils. Solution, suffusion, and piping on steep slopes can promote conditions suitable for debris avalanches by forming weak, permeable zones. Consequently, subsurface drainage shapes topography over time, from the slow continual dissolution of rock to rapid episodic mass failures. Trees reduce the ratio of physical to chemical erosion while timber harvesting increases it.

INTRODUCTION

Over the past 20 years, forest hydrologists have been disproving and rejecting the Hortonian ideas concerning how a forested hillslope drains. Instead of accepting the infiltration theory of surface runoff, they have favored subsurface drainage models such as the variable source area concept (Hewlett and Hibbert, 1967). More recently, a study of a forested watershed in New Zealand showed that subsurface flow through macropores and seepage zones was the predominant mechanism of draining stormflow to channels (Mosley, 1979).

Horton used his model to explain how overland flow can erode slopes and shape topography (Horton, 1945). More recent erosion models, such as the Universal Soil Loss Equation (Wischmeier and Smith, 1965), still focus on Hortonian concepts. However, the present acceptance of forest drainage through macropores should lead us to consider how subsurface drainage can influence erosion and topography.

Erosion by subsurface drainage includes chemical (solution), physicochemical (suffusion), and physical (piping and landsliding) processes. On undisturbed forested watersheds in mountainous areas, erosion occurs predominantly by landsliding and solution (Rice, Rothacher, and Megahan, 1972; Clayton, 1981). Overland flow is associated with surface erosion primarily in disturbed areas and is rare in undisturbed coarse-granitic soils. A hydrologic study of granitic terrane in southern California found that infiltration rates were high and overland flow was limited, even during flood runoff periods (Krammes, 1968). Swales are common in forested granitic watersheds with no indication of previous surface runoff. Can the questionable origin of such topographic features be explained by subsurface drainage?

This paper describes how subsurface drainage rather than surface runoff can dominate the erosion of mountainous granitic terrane. It also addresses the role of trees

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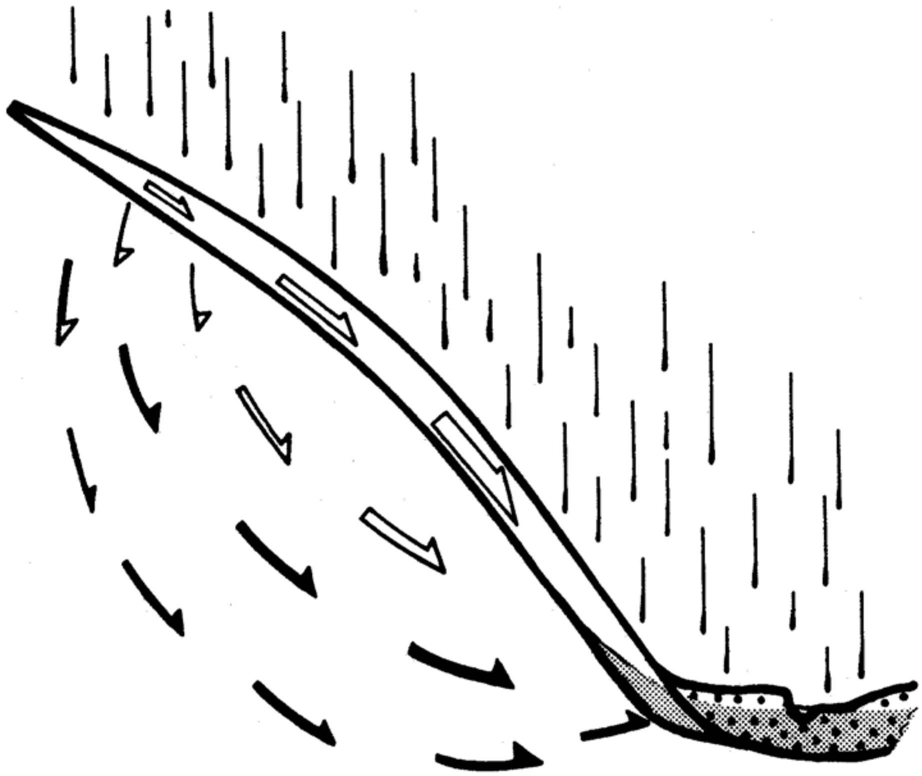

Fig. 1. Saturation extends upslope as water is added to soil. Heavy black lines delineate zones of differing permeability, solid arrows indicate saturated flow, and open arrows show unsaturated drainage.

in landscape evolution. Various granitic areas serve as examples; emphasis is on the granitic batholiths in the Klamath Mountains of northwestern California and southwestern Oregon in the United States, specifically the Little North Fork study area on the English Peak batholith.

KLAMATH MOUNTAINS

The topography of the Klamath Mountains is rugged with elevations greater than 2700 m. The annual precipitation ranges from 100 to 300 cm and falls predominantly from October through April. The seasonal precipitation can cause striking changes in runoff patterns. During summer many small tributaries dry up, and streams are limited to base flow produced by the groundwater system. At the other extreme, during winter stormflow periods the surface drainage system may extend upslope to ephemeral and intermittent channels.

According to the variable source area concept (Hewlett and Hibbert, 1967) and personal observations, the subsurface flow system also expands and contracts sea-

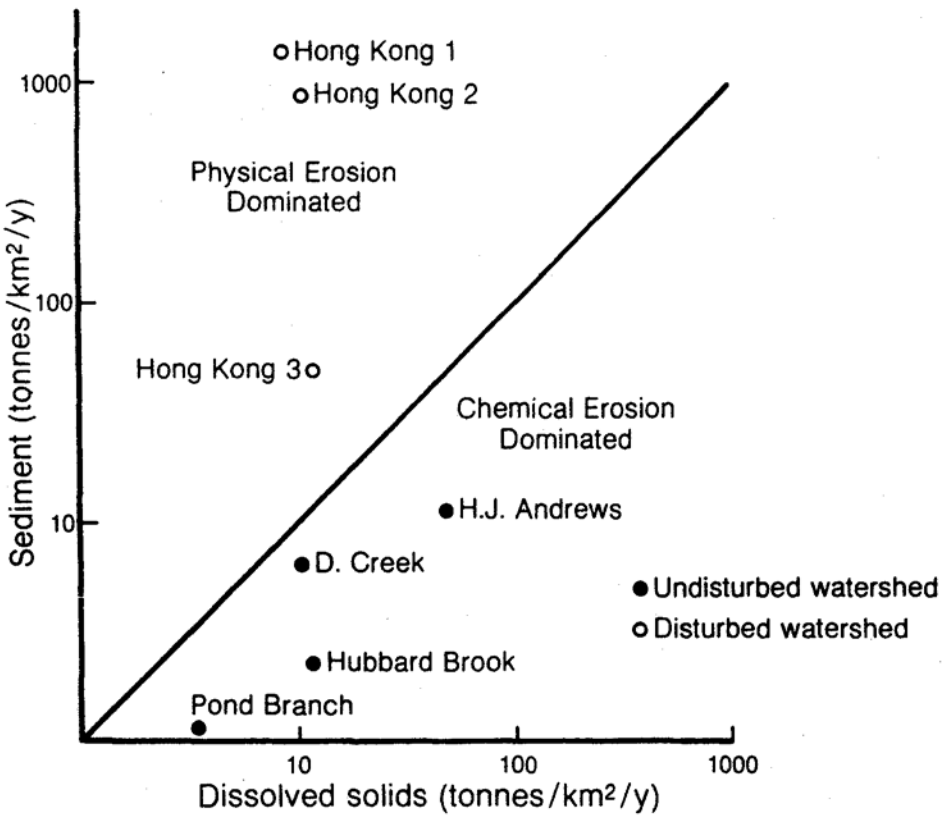

Fig. 2. Chemical erosion appears to be more important than physical erosion in undisturbed forested watersheds. Location of watersheds: Hong Kong 1, 2, 3, Hong Kong; H. J. Andrews, Oregon, United States; D Creek, Idaho Batholith, United States; Hubbard Brook, New Hampshire, United States; Pond Branch, Maryland, United States. (Source: Clayton, 1981; Lam, 1978).

sonally. During rainstorms soil moisture increases and provides water to interflow systems with saturated zones that thin upslope. These saturated areas are concentrated in swales that transport subsurface water to stream channels (Fig. 1). When storms pass, the saturated zones in the subsurface contract. The residence time for subsurface storm drainage is brief (Harr, 1977) compared with that for water that drains through the bedrock fractures and into the perennial groundwater system.

LOSS OF DISSOLVED SOLIDS-SOLUTION

Comparison of dissolved solids in seven small watersheds shows the relative importance of physical and chemical erosion (Fig. 2). For Hubbard Brook, in a small forested watershed on metamorphic and igneous bedrock, solution was the dominant erosion process. Loss of dissolved substances from undisturbed sites was about 5 times greater than losses of particulate matter (Likens, Bormann, Pierce, Eaton and Johnson, 1977). The Hong Kong watersheds, adjacent to each other on granitic terrane, have undergone extensive disturbance (Lam, 1978). They are similar except that watershed 3 was covered by a dense regrowth of pine and the other two had severe surface erosion with some badlands. The reforested watershed had less suspended sediment and a higher dissolved load than the deforested watersheds. These data suggest that physical erosion is less important than chemical erosion in undisturbed forested watersheds and that disturbance shifts the relationship toward more physical erosion.

The amount of total dissolved solids is misleading for estimating rates of chemical denudation because much dissolved material is from the atmosphere or from atmosphere-biosphere interactions (Janda, 1971). This criticism also applies to comparisons between chemical and physical erosion, although the discrepancy may be somewhat offset by the substantial amounts of organic matter (e.g., 40% in streams of the Oregon Coast Range (Beschta, O'Leary, Edwards and Knoop, 1981) computed as sediment in forested watersheds. Clayton (1981) took these factors into account when he calculated the actual denudation for the four watersheds dominated by chemical erosion (Fig. 2), but their classification remained the same.

Chemical Erosion Process

Chemical erosion depends on a number of variables that include: (1) climate-increased precipitation promotes a greater loss of dissolved solids; (2) relief-as relief increases more fresh rock is exposed to chemical weathering; (3) tune-longer contact times promote higher concentrations of dissolved solids; and (4) vegetation-trees increase chemical erosion (Drever, 1982). The role of vegetation will be stressed because man has the greatest influence on that variable.

Water draining through granitic soil and rock causes chemical weathering and removes dissolved ions. By hydrolysis, the dominant weathering process, hydrogen is added to feldspar or other granitic minerals, weakening the crystal and putting bases and silica (H_4SiO_4) into the soil solution. The elements are then leached through the soil by acids of mobile anions. Cations such as Na^+ and K^+, released by weathering, exchange with H^+ of the acids and are bound by mobile organic anions (Gamble, 1973) or join with inorganic anions such as HCO_3^-. Together, they can be leached through the soil. The limiting factor in this process is mobile anion availability (Johnson and Cole, 1980).

Trees and other vegetation accelerate chemical erosion by increasing both the ionization of elements and the availability of mobile anions. The controlling factor is the production of organic acids that act as chelating agents. This erosional process has been referred to as "cheluviation" (Swindale and Jackson, 1956). Although it is generally associated with movement of metals to the B horizon, it can also refer to their removal from the soil profile and eventual introduction to a stream channel. Organic acids, together with bicarbonate ions released from roots (Nye, 1981), provide the great majority of mobile anions in a forested ecosystem (Cronan, Reiners, Reynolds and Lang, 1978). Bicarbonate plays the major role in tropical forests with organic acids dominating northern forest soils (Johnson, Cole, Gessel, Singer, and Minden, 1977).

Water-soluble organic acids are particularly common in the fulvic acid fraction of organic matter. The dissolved organic matter found in streams and in soil solutions has been referred to as "yellow organic acids" or "mobile fulvic acid" and consists of complex aromatic hydroxycarboxylic acids (Dawson, Hrutfiord, Zasoski and Ugolini,1981).

The mobile fulvic acid is derived from a variety of sources. Studies have shown that as raindrops fall through a forest canopy they pick up organic acids (Hoffman, Lindberg, and Turner, 1980; Malcolm and McCracken, 1968). Rainwater then drains through the decomposing litter where fungi produce organic acids, particularly oxalic acid. The oxalic acid may be decomposed by soil organisms, held in the litter as calcium oxalate, or leached down into the soil together with other dissolved organic matter (Graustein, Cromack, and Sollins, 1977).

As water infiltrates the soil, it drains rapidly through the channels of roots, both live and dead (Aubertin, 1971). Water flowing along the root-soil interface encounters numerous root tips. The tips are active respiration sites, taking up nutrients, water, and oxygen while giving off CO_2, HCO_3^-, and organic substances. Root tips have a high H^+ concentration and a strong ability to exchange their hydrogens for other cations (Williams and Coleman, 1950).

The root tip is surrounded by a layer of mucigel and usually does not come into direct contact with the mineral grains. The mucigel is composed of sugar acids that act as intermediaries between the root and mineral and function in the exchange of nutrients. Clays can perform the same function as acids because they also provide exchange sites between the root and mineral (Keller and Frederickson, 1952).

Trees exude organic acids from the root tip, apparently to a greater degree with hardwoods than with conifers (Ketchie and Lopushinsky, 1981; Smith, 1976). Studies have shown that these organic acids, particularly oxalic acid, accelerate the breakdown of mica and feldspar (Boyle and Voigt, 1973; Boyle, Voigt, and Sawhney, 1974). Fungi, bacteria, and lichens also produce mineral-weathering organic acids (Duff, Webly, and Scott, 1963; Henderson and Duff, 1963; Schatz, 1963; Weed, Davey, and Cook, 1969).

Primary Minerals

The dominant plutonic rock in the Klamath Mountains is quartz diorite and the major plutonic minerals are plagioclase feldspar (52%), mafic minerals (26%) that include hornblende and biotite, quartz (16%), and potassium feldspar (5%) (Hotz, 1971). Feldspars tend to weather into kaolinite in the humid temperature climate of the Klamath Mountains.

The most easily weathered feldspar is calcium-rich anorthite (Graham, 1950), followed by the more sodic feldspar, and then potash feldspar. Hydrolysis of the sodium-rich feldspar, albite, has been described by Frederickson (1951). The hydrogen ion enters the albite and substitutes for the sodium ion. This leads to the eventual collapse of the feldspar crystal lattice and the formation of colloids or very small fragments of the silicate frameworks. The end products include kaolinite, H_4SiO_4(aq) and SiO_2(s), Na^+(aq) and Al_2O_3(s).

Feldspar weathering is similar if organic acids are involved (Graham, 1941). Hydro gen ions substitute for metal ions in the crystal and organic anions associate with the metals, thereby putting them into solution. The organic acids with the strongest complexing capacities are the most effective at dissolving feldspar (Huang and Kiang, 1972).

Hornblende is an easily weathered mineral in granite. It can weather to a chlorite with vermiculitic secondary products (Stephen, 1952). Chlorite can in turn be decomposed further by fulvic acid and its constituents put into solution (Kodama and Schnitzer, 1973).

Weathering research has focused on biotite because it is a source of potassium for plants. Strong organic acids, notably oxalic acid and fulvic acid, can chelate metals in the biotite, resulting in an amorphous weathered edge that is subject to rapid dissolution (Boyle, Voigt and Sawhney, 1974; Schnitzer and Kodama, 1976). Weaker organic acids, such as galacturonic acid of root mucigel, convert biotite to vermiculite which then weathers to kaolinite (Angeles, Hernandez, and Robert, 1975). A study on the influence of tree seedlings growing on biotite found that some biotite was converted to kaolinite in only one year (Spyridakis, Chesters, and Wilde, 1967).

Quartz is classed as a primary or secondary mineral and is most resistant to weathering of the common granitic minerals (Goldich, 1938). The most stable form of quartz is silica, and it has the lowest solubility. In contrast, amorphous silica, resulting from weathering of other minerals, is the least stable form with the greatest solubility (Krauskopf, 1956). A study of chemical weathering by forest vegetation found no signs of quartz dissolution (Graustein, 1981).

A consequence of chemical weathering and erosion is the breakdown of primary minerals into secondary minerals. The dominant constituents of the average granitic rock in the Klamath Mountains are silica (61%) and alumina (16%) (Hotz, 1971). The monovalent and divalent bases are easier to extract with organic acids than are higher valency cations such as silicon, aluminum, and ferric iron. Higher valency cations become proportionately more abundant in the weathering residuum that forms secondary minerals including quartz (SiO_2), gibbsite ($Al(OH)_3$), kaolinite ($Al_2(SiO_2O_5)(OH_4)$), and goethite ($FeO(OH)$) (Chesworth, 1973).

The impact of timber harvesting on leaching of dissolved solids is generally small or negligible (McColl, 1978; Sopper, 1975). However, clear-cutting can reduce the export of dissolved organic carbon from a forest (Meyer and Tate, 1983).

Accleration of the breakdown of granitic rock from primary to secondary minerals by organic acids together with a forest's resistance to surface erosion helps explain why chemical erosion by subsurface drainage can dominate undisturbed forested watersheds.

LOSS OF COLLOIDS-SUFFUSION

Colloids and collidal clays are commonly measured as dissolved solids when monitoring water quality of streams. On one hand, erosion of colloids may be considered physical erosion because insoluble particles are being moved; however, the particles are so small that their surface charges influence their movement. Erosion of colloids is referred to here as physicochemical erosion.

Water can flow through soil, detach colloids, and carry them along by suffusion, the movement of colloids through soil pores (Kezdi, 1979). Colloids may be moved a short distance through soil, down into bedrock fractures, or completely out of the system and into a stream. Suffusion is difficult to verify, but Pilgrim, Huff, and Steele (1978) presented a strong case for it in a sandstone soil and Ugolini, Dawson, and Zachara (1977) provided evidence of its occurrence in a volcanic soil. Suffusion has been reported specifically for granitic rocks in Hong Kong (Ruxton and Berry, 1957) and the Sudan (Ruxton, 1958). Suffusion can lead to soil piping as drainage routes form and progressively larger material is eroded until a pipe forms.

Favorable Conditions

Conditions suited to suffusion include: (1) well-drained soil, because much of the movement depends on the quantity and rate of leaching water (Kovenya, Mel'nikova, and Frid, 1972); (2) appropriate geometric conditions with a gap-graded soil (bimodal size distribution) which is more conducive to fine material moving through macropores; and (3) dispersed particles, which are more easily detached and transported in suspension (Curry, Barker, and Strach, 1965). All three conditions are commonly met in granitic soils.

Well-drained soils: Water drains rapidly through macropores formed by mineral weathering in conjunction with root and other biological activity in granitic material of forest soils. For example, the weathering of albite or orthoclase feldspar to kaolinite decreases the volume of solids by about 50% (Grant, 1963). The new porosity allows weathering biotite flakes to expand, promoting grus formation (Isherwood and Street, 1976). Water can then drain along the planes of mineral contact and through microfractures while progressively weathering the rock as more surface area becomes subject to chemical attack. The resulting intergranular voids can provide channels for colloid movement.

To be effective in draining a slope, macropores must be highly interconnected. Microscopic examination of granitic materials has shown that with advanced weathering, fissures (porous weathered zones that channel drainage water) develop from microfissures and voids (Meunier and Velde, 1979). In addition, tree roots or animal burrows produce drainage channels by connecting pores and fissures in weathered granite. A study of drainage through forest soils showed that water can drain rapidly through root channels even though the surrounding soil is unsaturated (Aubertin, 1971).

Gap-graded soils: Granitic soils tend to consist of abundant sand with small amounts of clay. Also suffusion promotes high sand fractions because fine-grained material is washed out. Such coarse-grained materials promote the continual removal of clays as they become available.

Dispersed particles: Colloids transported from soils include both organic and inorganic materials and their movements through the soil are comparable. Organic matter, such as forest litter, breaks down to form hydrophobic humic acids and hydrophilic fulvic acids. Organic colloids formed from fulvic acids are anionic, dispersed, and can move through the soil system. However, organic colloids do not necessarily act independently from inorganic colloids; they may combine and move together through the soil (Durgin and Chaney, in press).

In granitic soils the major secondary materials are kaolinite, silica, and ferric hydroxide (Chesworth, 1973). Kaolinite forms by a combination of aluminum and monomeric silica (Si(OH)4) with fulvic acid promoting its crystallization (Linares and Huertas, 1971). Fulvic acids can attach to the edge of the kaolinite particle by ligand exchange and produce a negatively-charged edge (Durgin and Chaney, in press). As a result, the kaolinite will be dispersed and more easily mobilized by suffusion (Hunter and Alexander, 1963).

Organic acids can also disperse ferric hydroxide (Shanmuganathan and Oades, 1983). Trivalent carboxylic acids and polycarboxylic acids are specifically adsorbed to the ferric ion and make the surface more negative, thereby promoting dispersion.

Dispersion of kaolinite and ferric hydroxide allows Al, Si, and Fe to be more easily carried out of the soil system by suffusion. Clues to the movement of these materials are clay skins found on peds. A micromorphological study found that kaolinite and iron oxide were transported into fissures as well as forming in fissures (Meunier and Velde, 1979). Grant (1963) found less kaolinite in weathered granite rocks than he calculated theoretically. The reasons may be that aluminum and silica were lost by solution or that kaolinite was removed by drainage water.

Timber Harvesting

The influence of clearcutting on the resisting forces of colloids to erosion is not clear. However, changes in the driving forces have been studied. Investigation of disturbance of a forest floor showed that water drained through the soil matrix instead of root channels (de Vries and Chow, 1978). The result would be a slower drainage rate, and water moving through the soil matrix might develop new drainage paths, thereby enhancing suffusion.

LOSS OF SOIL

The loss of dissolved solids and colloids promotes granular disintegration of rock and formation of soil. Soil may be lost physically in association with subsurface drainage as particles in piping, or en masse in landsliding. Organic acids lose their importance, and water's physical characteristics-its potential and kinetic energy-become critical factors.

Surface erosion means a loss of soil and also classifies as physical erosion. However, subsurface drainage can even influence surface erosion through exfiltration (Tanaka, 1982).

Piping

As water drains through soil, it either moves into the underlying weathered bedrock to become deep seepage or remains as throughflow and converges in swales. At a granitic site in the Idaho batholith 35% of drainage was throughflow while 65% was deep seepage (Megahan, 1972).

The soil in swales commonly forms a wedge that thins upslope (Dietrich and Dunne, 1978; Lehre, 1981). A soil wedge has high transmissivity that allows rapid subsurface drainage during storms. The greatest stormflow is expected at the base of the wedge where soil particles are most likely to move. This promotes a form of piping, but the soil is not cohesive enough to form large pipe channels. Soil pipes, formed by roots or animals, are common in these swales and have been associated with slide scars (Tsukamoto, Ohta, and Noguchi, 1982).

Classic piping phenomena in areas of low local relief and even pseudokarst topography have been reported on a batholith in Colombia (Feininger, 1969). Steeper areas experienced creep or landsliding that obscured surface evidence of piping.

Landsliding

Failure process: Slope failures are related to subsurface stormflow in granitic terrane. The requirement for a debris avalanche is a steep slope that allows soil to move more easily and promotes higher hydraulic heads during subsurface stormflow. Debris avalanches tend to occur in swales and most commonly in the decomposed granitoid weathering stage (Durgin, 1977). Sassa, Takei, and Kobashi (1981) have divided the debris avalanche process into three stages: (1) formation of a loose soil zone resulting from concentration of subsurface flow; (2) saturation of the loose soil causing subsidence; and (3) liquefaction of the loose zone and flowage of the mass.

The loose soil zone forms in swales where subsurface drainage concentrates and is generally composed of cohesionless grus. Cheluviation, suffusion, and piping leave only a loose soil framework with low shear strength because the strength of sandy material is directly related to its relative density (Wu, 1957). High intensity storms or rapid snowmelt may cuase subsurface flow to saturate the loose soil zone and produce subsidence. Granitic soils confined to well-drained slopes have been found to collapse due to a leaching out of dissolved and colloidal materials (Brink and Kantey, 1961). A collapsing soil is below its critical void ratio. If subjected to strain, such a soil can develop high pore water pressures, lose its shear strength by liquefaction, and fail as a flow slide (Castro, 1969). This leaves a slide scar or swale that can undergo the failure process again after receiving colluvium (Dietrich and Dunne, 1978).

Slope angle: Slope is the main control of driving forces in debris avalanches. High slope angles facilitate soil movement and promote higher seepage forces. The other controlling variables-soil depth, shear strength, and water content-can easily be evaluated if the following simplifying assumptions are made: Granitic soil is cohesionless and has a 37° angle of internal friction (Lumb, 1962); unit weights of soil are 1920 kg/m^3 (dry), 2210 kg/^{3} (total wet), and 1200 kg/m^3 (buoyant); and soil is 1.2 m thick. The variables can be evaluated with a slope stability equation (Taylor, 1948) and combined into a graph (Fig. 3). Failed slopes averaged 32° in the Little North Fork study area, while those that did not fail averaged 22°. The failed slopes needed greater cohesion such as from roots as the level of subsurface flow rose in the soil.

Throughflow commonly becomes surface runoff at the headwaters of streams. Swales where throughflows converge have been termed zero-order basins and identified as sites of debris avalanches (Tsukamoto, Ohta,T. and Noguchi, H.1982). Data were collected on stream gradients in three Klamath Mountain batholiths to determine average hydraulic gradients from the major rivers up to the headwaters of first-order streams. Random locations of streams on the Wooley Creek, English Peak, and Ashland batholiths were selected and their gradients determined. The streams have adjusted so that their headwaters are commonly at an unstable 32° slope, suggesting that the zero-order basins are similar or steeper (Fig. 4). Subsurface stormflow can destabilize such slopes and promote landsliding as a major form of headward erosion in this terrane. Spring sapping is a related, slower process that promotes headward erosion by subsurface drainage and is also accelerated by high relief (Dunne, 1980).

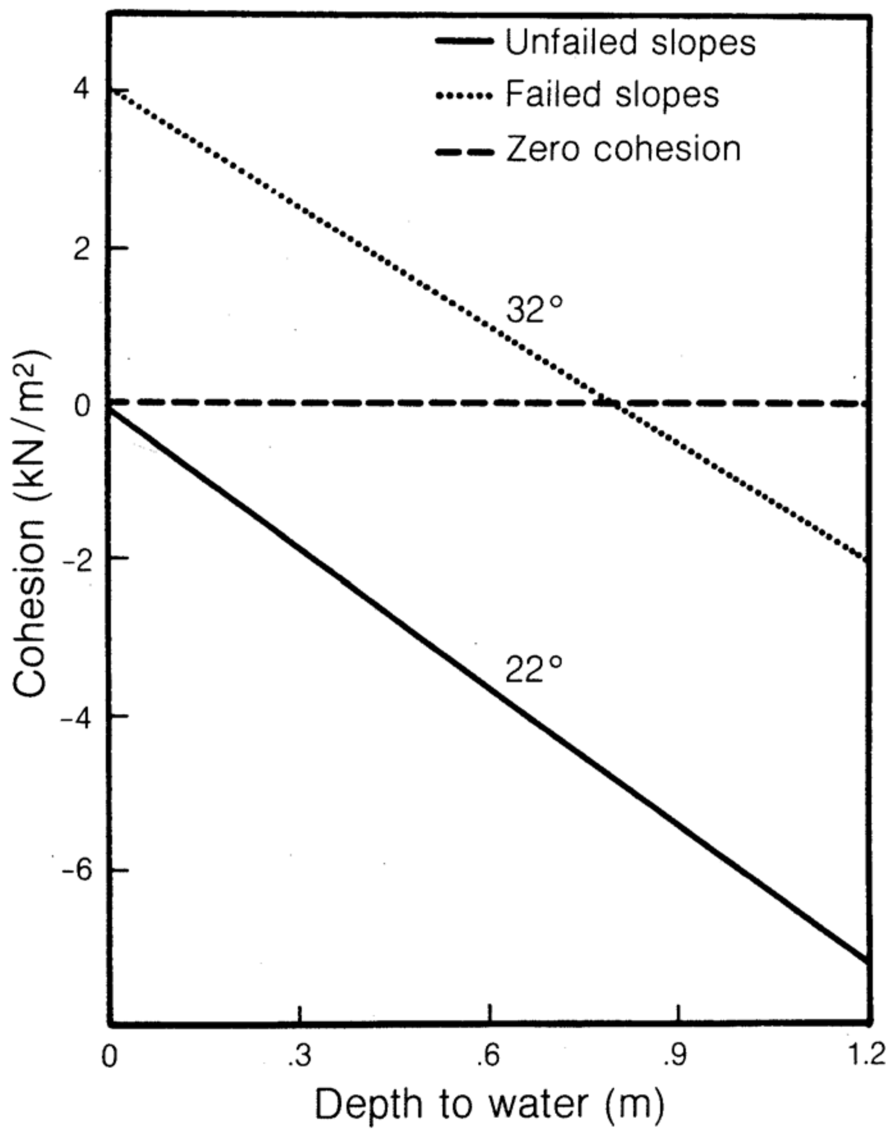

Fig. 3. The relationship of piezometric level and cohesion for two slope angles at safety factor of 1.0.

Timber Harvesting

Trees accelerate the weathering of granitic rocks, which brings a slope to its critical threshold for failure (F.S. = 1); however, trees also provide forces to counteract slope failure. Tree roots provide shear strength and have been shown to buttress soil and hold sand and gravel at 41˚, although the angle of repose was 33˚ (Rahn, 1969). Roots also channel water helping slopes drain and rapidly reducing the weight

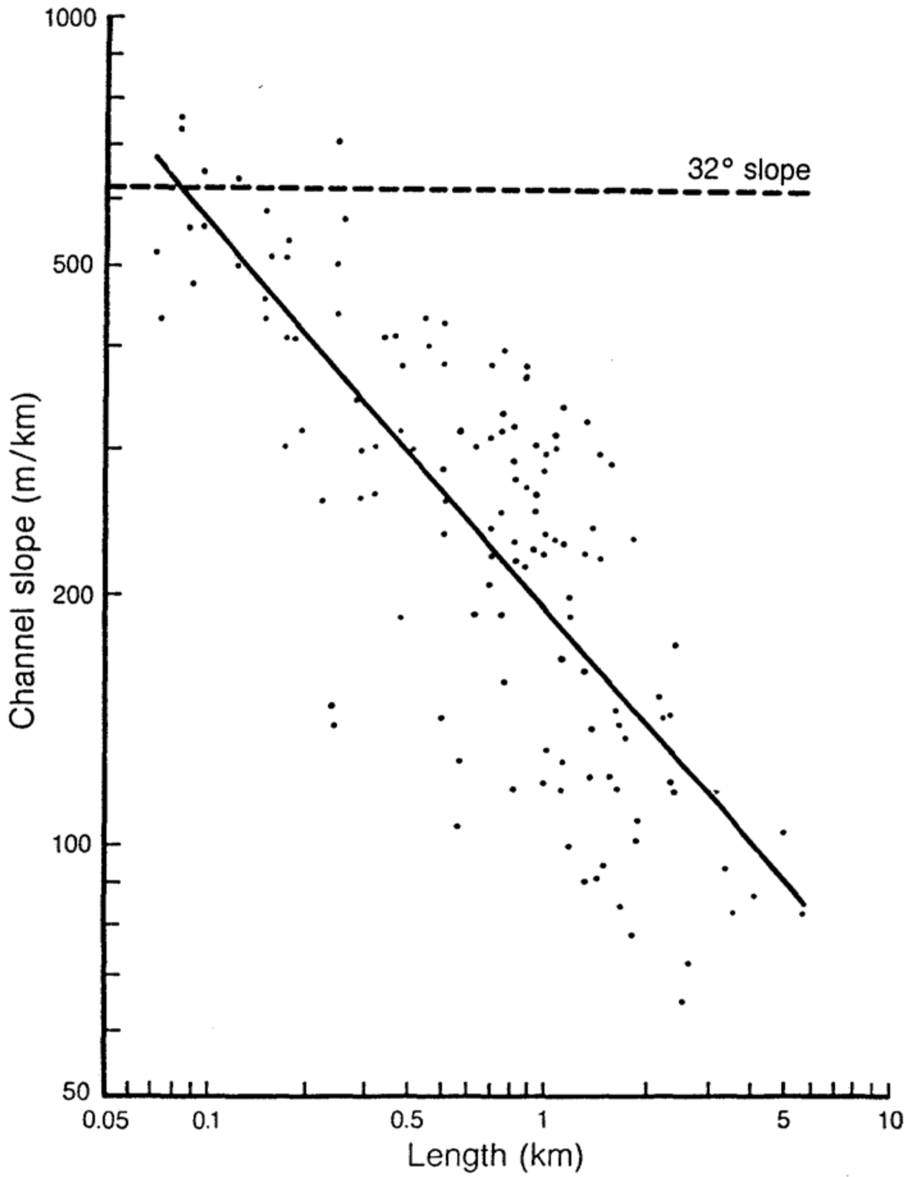

Fig. 4. Relationship between channel slope and length of randomly selected streams on three granitic batholiths of the Klamath Mountains.

of the soil mass on the slope. Rapid drainage promotes stability of slopes although it may destabilize swales particularly if subsurface blockages occur (Pierson, 1983)

Harvesting trees has promoted landslides in some areas. Changes in resisting or driving forces may reduce the safety factor to less than 1. Resisting forces change predominantly because of loss of root strength (Gray and Megahan, 1981); driving forces may also be modified by increased water inputs to the soil that result from: (1) higher-than-normal antecedent moisture conditions due to decreased evapotranspiration and (2) additional input associated with rain-on-snow events in clear-cut areas. Landslides are commonly associated with rain-on-snow events in western Oregon, where clear-cutting may increase water input by 10 or even 25% (Harr, 1981). The result is greater subsurface flow that promotes slope instability (Gray and Megahan, 1981).

GEOMORPHIC IMPLICATIONS

Trees can reduce the resisting forces for all three types of erosion by subsurface drainage-chemical, physicochemical and physical. Trees not only accelerate long-term chemical weathering. They also increase the detachability of material by providing organic anions that mobilize cations, disperse colloids, and generate zones of low relative density that promote spring sapping and landslides. These processes explain how subsurface drainage can shape forested granitic terrane, particularly swales.

Trees indirectly control the driving forces of erosion by providing hydrologic pathways that channel water drainage. Drainage water provides destabilizing seepage forces in all three types of erosion, but the forces needed for transport differ substantially. Dissolved solids and collids move even with the negative heads of unsaturated conditions. In contrast the threshold for movement of soil by piping or landsliding occurs with saturated conditions.

Due to these differences in threshold driving forces, the timing and frequency of erosion processes differ. Chemical erosion is perennial and occurs even during drier periods with unsaturated soils. Physicochemical erosion is more ephemeral or intermittent, while physical erosion occurs during high storm flows and is episodic.

This erosion model has some implications for forest management. Trees accelerate the breakdown of minerals. Because the critical slope angle for failure decreases with weathering, trees can be influential in bringing a slope to its critical angle., The beneficial influence of trees on cohesion and piezometric levels may prevent slope failure; however, timber harvesting may change the safety factor sufficiently to allow failure.

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