EROSION OVER TIME ON SEVERELY DISTURBED GRANITIC SOILS: A MODEL

W. F. Megahan

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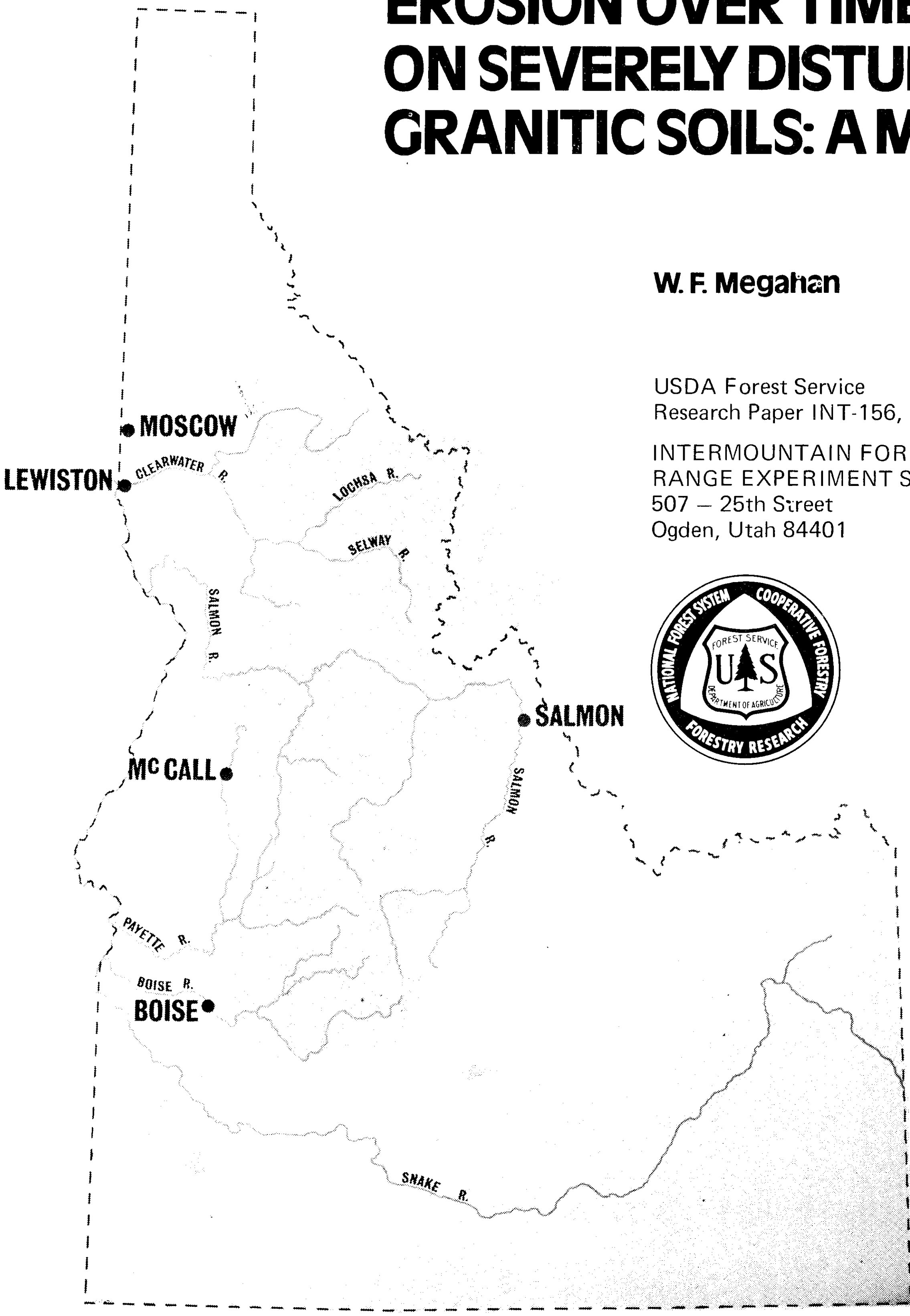
INTERMOUNTAIN FOREST &
RANGE EXPERIMENT STATION
507 — 25th Street
Ogden, Utah 84401



THE AUTHOR

WALTER F. MEGAHAN is Principal Research Hydrologist and Leader of the Idaho Batholith Ecosystems Research Work Unit in Boise, Idaho. He holds bachelor's and master's degrees in Forestry from the State University of New York, College of Forestry, at Syracuse University, and a doctoral degree in Watershed Resources from Colorado State University. He served as Regional Hydrologist for the Intermountain Region of the USDA Forest Service in Ogden, Utah, from 1960 to 1966 and has been in his present position since 1967.

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Roger R. Bay, Director

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ABSTRACT

A negative exponential equation containing three parameters was derived to describe time trends in surface erosion on severely disturbed soils. Data from four different studies of surface erosion on roads constructed from the granitic materials found in the Idaho Batholith were used to develop equation parameters. Rainfall-intensity data were used to illustrate that variations in erosion forces, as indexed by rainfall kinetic energy times the maximum 30-minute rainfall intensity (the erodibility index), were not the cause of the time trend in surface erosion. In addition, although vegetation growth can be an important factor in reducing accelerated erosion, it did not cause the rapid erosion decreases found in the cases studied. The evidence suggests that surface "armoring" was the dominant factor causing the time trends in surface erosion. The significance of time trends in surface erosion is discussed.

INTRODUCTION

Surface erosion can be defined as movement of individual soil particles along the soil surface, in contrast to mass erosion, the movement en masse of numerous particles. The subject of this paper, surface erosion, can be expressed as

$$\varepsilon = f(h, p, f), \tag{1}$$

where ε = surface erosion rate; h = inherent soil erosion hazard and includes such factors as soil detachability and slope gradient; p = protection afforded the soil surface by vegetation and litter; and f = force applied by raindrops, overland flow, etc.

Under a relatively stable forest ecosystem, erosion hazards tend to be minimized and protection afforded the soil surface tends to be maximized. Erosion forces vary but, over time, yield some average (or other appropriate measure of central tendency) value for surface erosion, which varies with individual site conditions. This average erosion rate (ε_n) has been termed the "norm" for the site in question (Bailey 1941).

Severe soil disturbance disrupts the ecological balance, thereby increasing h and decreasing p. Consequently, surface erosion rates are accelerated, often to alarming proportions (Anderson 1954; Reinhart and others 1963; Packer 1967; Copeland and Packer 1972). Over time, a new ecological balance is established on the disturbed site that leads to a new erosion norm, which may differ from the original because of permanent changes in site factors. Thus, on a severely disturbed site, the total erosion rate at any time (ε_t) is comprised of two components, the natural norm for the site (ε_n) plus the accelerated erosion due to disturbance (ε_s). Therefore,

$$\varepsilon_t = \varepsilon_n + \varepsilon_s \tag{2}$$

Considering the accelerated erosion component (ε_s), a body of disturbed soil, (S) can be assumed, where disturbance has been severe enough to completely disrupt the original soil characteristics. Such soil is a polydispersed mixture with subsoil and bedrock fragments well graded throughout, with no remnants of the original soil horizons or structural development, and with no surface vegetation or litter. Such disturbances have numerous causes such as road construction, mining, logging, and landslides.

Relation 1 above reduces to

$$\varepsilon_s = f(h) \tag{3}$$

if it is assumed that f is constant and p is zero (i.e., there is no protection available from vegetation, litter, mulches, etc.). Under such conditions, it is logical to assume that the opportunity for erosion is maximum immediately after disturbance and decreases with time. In other words, the erosion hazard decreases with time after disturbance. A number of causal factors might exist. For example, in a polydispersed mixture, the more easily detached and transported particles are most likely to be removed first. Over time, the average erodibility of the surface materials will tend to decrease. This "armoring" or "erosion pavement" phenomenon is commonly observed and is probably the result of an increase in the average size of surface particles, possibly, keying in of surface particles (fig. 1), or both. Other factors, such as compaction of materials as settling occurs and reduction in slope gradients, may also help reduce erosion hazards over time.

If erosion hazards do indeed decrease following disturbance and relation 3 is valid, the rate of accelerated erosion can be assumed to be directly proportional to erosion hazard ($\varepsilon_s \alpha h$). Further, erosion hazard is greatest when the disturbed soil body is greatest and decreases as the body of soil decreases. Thus, erosion hazard appears to be directly proportional to the amount of soil present ($h \alpha S$). Assuming linearity, constants of proportionality can be assigned to the above proportions,

$$\varepsilon_s = k_1 h$$

$$h = k_2 S;$$

so

$$\varepsilon_s = k_1 k_2 S = kS.$$

But, ε_s is simply the rate of change of S,

$$\varepsilon_s = \frac{ds}{dt}; \tag{4}$$

so

$$\frac{ds}{dt} = -kS. \tag{5}$$

The negative constant of proportionality is used to indicate soil loss. By solving for S and integrating,

$$S = S_0 e^{-kt},$$

based on the boundary condition that $S = S_0$ when $t = 0$. Substituting in 4 and 5,

$$\varepsilon_s = -kS_0 e^{-kt}. \tag{6}$$

Figure 1.--Photograph A was taken on a road fill on Interstate 90 in northern Idaho shortly after construction. The same plot is shown in photograph B, 4 months later. Note the increase in average surface particle size resulting from erosion.

In this form, ε_s represents a loss from the body of soil S and so is a negative value. However, this is not consistent with equation 2 where ε_s is positive. Thus, equation 6 is modified to:

$$\varepsilon_s = kS_0e^{-kt} \tag{7}$$

Finally, when equation 7 is substituted into equation 2, the total erosion rate on a disturbed site is

$$\varepsilon_t = \varepsilon_n + kS_0e^{-kt}, \tag{8}$$

where ε_n, S_0 and k are parameters to be determined.

Interpretations of these parameters and the units used in this report are:

ε_n(tons mi^{-2}day^{-1}) = The erosion rate to be expected on the disturbed area after a long period, assuming no new major disturbance. This value is an estimate of the long-term norm for the site.

S_0(tons mi^{-2}) = the amount of material available to be eroded at time zero after disturbance.

k(day^{-1}) = an index of the rate of decline of erosion following disturbance. This can be thought of as an index of the recovery potential for the site in question.

By measuring erosion rates on disturbed sites over time, values can be assigned to these parameters. However, measurements of instantaneous erosion rates are extremely difficult to obtain. Most studies of erosion depend upon periodic measurements of on-site soil losses or of accumulations of eroded material at some downslope point. Such data provide a measure of erosion integrated over time. Accordingly, equation 8 must be integrated in order to develop parameter estimates from periodic measurements of erosion. Integration of equation 8 with respect to time yields the model to be fitted,

$$\varepsilon_t = \varepsilon_n t - S_0[e^{-kt} - 1], \tag{9}$$

where ε_t is in units of tons mi^{-2} and t is the days of elapsed time since disturbance.

EXPERIMENTAL RESULTS

The Forest Service has been studying the effects of severe soil disturbance on surface erosion and sedimentation in the Idaho Batholith for a number of years. The Idaho Batholith is an extensive mass of granitic rock (16,000 mi^2) covering a large portion of Idaho and parts of Montana (fig. 2). Various types of granitic rocks are found; however, quartz monzonite predominates. The bedrock exhibits wide variation in degree of weathering and fracturing (Clayton and Arnold 1972. The area is almost entirely mountainous and forested. Typically, shallow, coarse-textured soils are found on steep slopes that often exceed 70 percent gradient. Soils of this type are extremely erodible (Anderson 1954; André and Anderson 1961). Localized, high-intensity rainstorms of short duration are common during the summer season. At other times of the year more general storms occur, often in conjunction with melting snowpacks. Following soil disturbance, the combination of steep topography, high-soil erodibility, and high-climatic stress often results in dramatically accelerated surface erosion rates (Megahan and Kidd, 1972).

Data available from four different studies (fig. 2) conducted in the Idaho Batholith provide insight into the time trends in surface erosion following road construction. Two studies in the Deep Creek and Silver Creek study areas present data for erosion from the entire road prism (cut slopes + roadbed + fill slopes). The other two studies, located on double-lane forest roads in the Bogus Basin and Deadwood River areas, were designed to measure erosion on road fill slopes only.

Road Prism Erosion

Deep Creek Study:--In the Deep Creek study (fig. 2), about 0.2 mile (providing a total area disturbed of 1.1 acres) of low-standard logging-access roads was constructed in two small, ephemeral drainages totaling 5.2 acres. Slope gradients in the drainages average about 70 percent. Material eroded from the entire road prism was trapped in sediment dams located about 300 feet downslope. Data from the sediment dams were collected twice a year: following the snowmelt period (about June 1) and near the end of

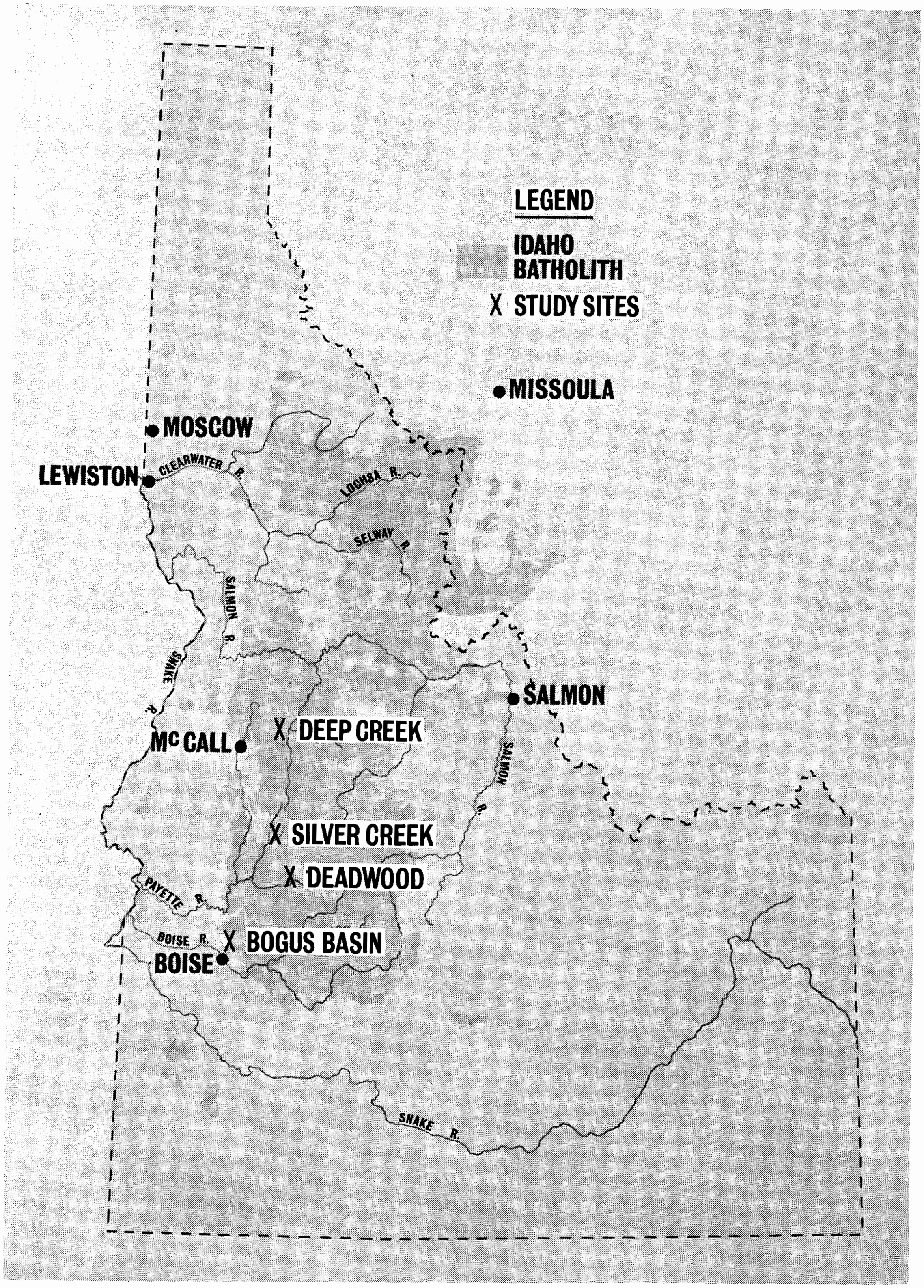


Figure 2.--Location of study sites in the Idaho Batholith.

the water year (about September 30). Sediment accumulations behind the dams were surveyed by using a grid of closely spaced cross sections. The study was designed so that road erosion could be segregated from erosion occurring on unroaded portions of the drainages (Megahan and Kidd 1972). The roads were constructed in November 1961; collection of postconstruction data was continued on schedule until September 1967. Twelve measurement periods were sampled during the 6-year study.

Accumulated surface erosion data are plotted in figure 3. Notice that eroded material accumulates rapidly immediately after disturbance, but that the rate of accumulation decreases with time. Equation 9 was fitted to the data by using a nonlinear least-squares procedure (Marquardt 1963). The fitted regression line and the derived equation are shown on figure 3. The relation has a standard error of 502 tons mi^{-2} and an r^2 value of 0.98. Nonlinear confidence limits for model parameters indicate that all parameters are significantly greater than zero at the 95 percent level.

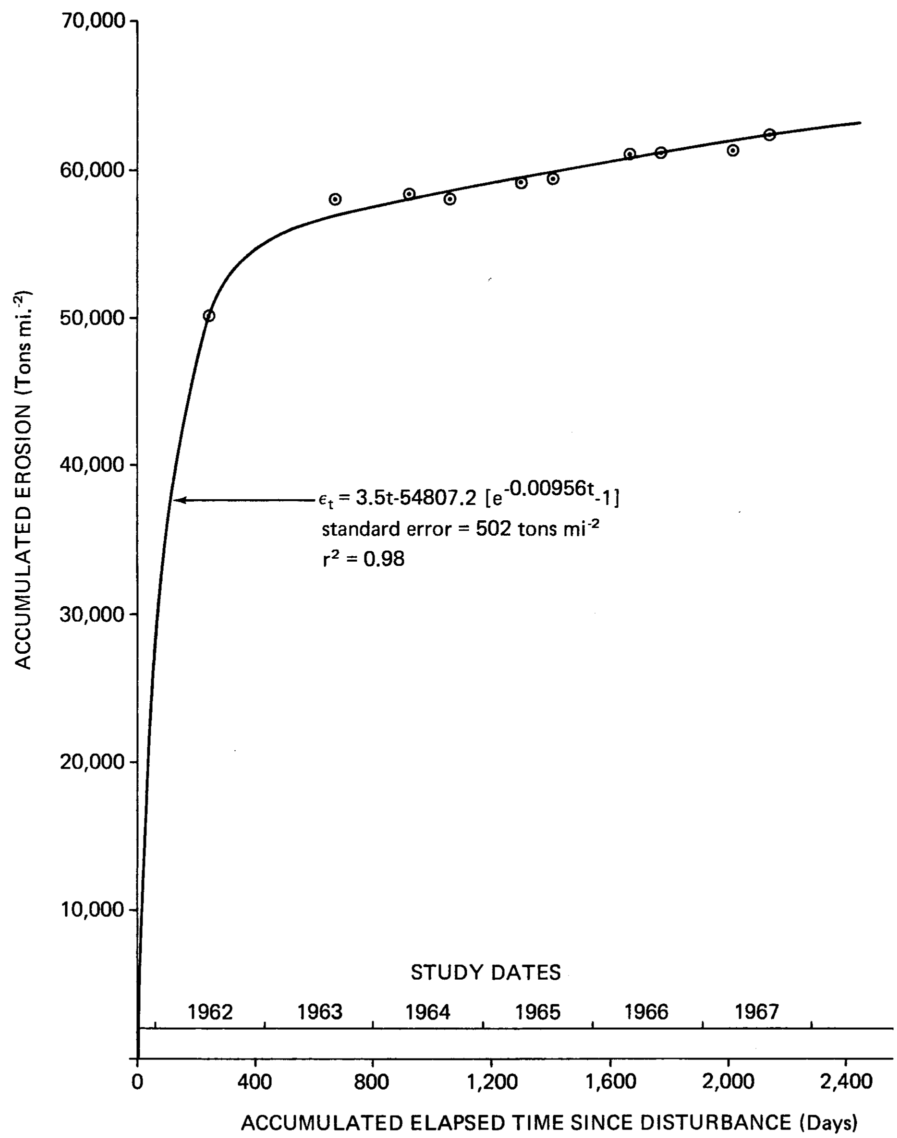


Figure 3.--Accumulated surface erosion over time--Deep Creek Study area.

Silver Creek Study:--Other study data are available to check the validity of the long-term erosion rate (ε_n) determined from the Deep Creek data. Beginning in 1965, annual sediment production data have been collected from each of seven study watersheds in the Silver Creek area of the Payette River drainage (fig. 2). Six of the study watersheds are essentially undisturbed; the seventh, Ditch Creek, contains a low-standard forest road about 2 miles long that was constructed in 1933. The road is comparable to the Deep Creek road in that it is low standard, narrow, closely fitted to the landscape, and traverses similar topography for most of its length.

Average sediment yields for Ditch Creek are greater than for any other watershed in the Silver Creek study area. However, based on watershed characteristics, Ditch Creek should rank approximately in the middle of the seven watersheds in terms of sediment production. No doubt, the increased sediment yields in Ditch Creek are due to erosion on the Ditch Creek road. This statement is borne out by inspection on the ground; erosion is occuring on the road tread, on the cut slopes, and in isolated instances on the fill slopes (Megahan 1972).

Logically, the undisturbed sediment yields from the 0.41-mi^2 Ditch Creek drainage would fall between the sediment yields from the two watersheds that flank it (Cabin Creek, 0.40 mi^2, and Eggers Creek, 0.51 mi^2), because it is intermediate in respect to forest cover, sideslope gradient, channel gradient, and watershed size. Thus, the average of sediment yields from the two undisturbed drainages provides a reasonable estimate of what the sediment yield for Ditch Creek would be if the watershed were in the undisturbed state. This amount can be subtracted from the measured sediment yield to obtain an estimate of the sediment yield caused by the old road. Finally, this amount can be prorated back to the area actually disturbed by road construction to provide a measure of annual road erosion. Based upon 7 years of data, annual road erosion ranges from 0.4 to 9.7 tons mi^{-2} day^{-1} and averaged 3.5 tons mi^{-2} day^{-1}. The average erosion rate for this 37-year-old road is equal to the value of ε_n derived from the Deep Creek study. Such values would be expected to vary with site conditions. Consequently, such good agreement is likely to be more coincidence than fact, but it does illustrate that the ε_n value predicated from the Deep Creek study is reasonable.

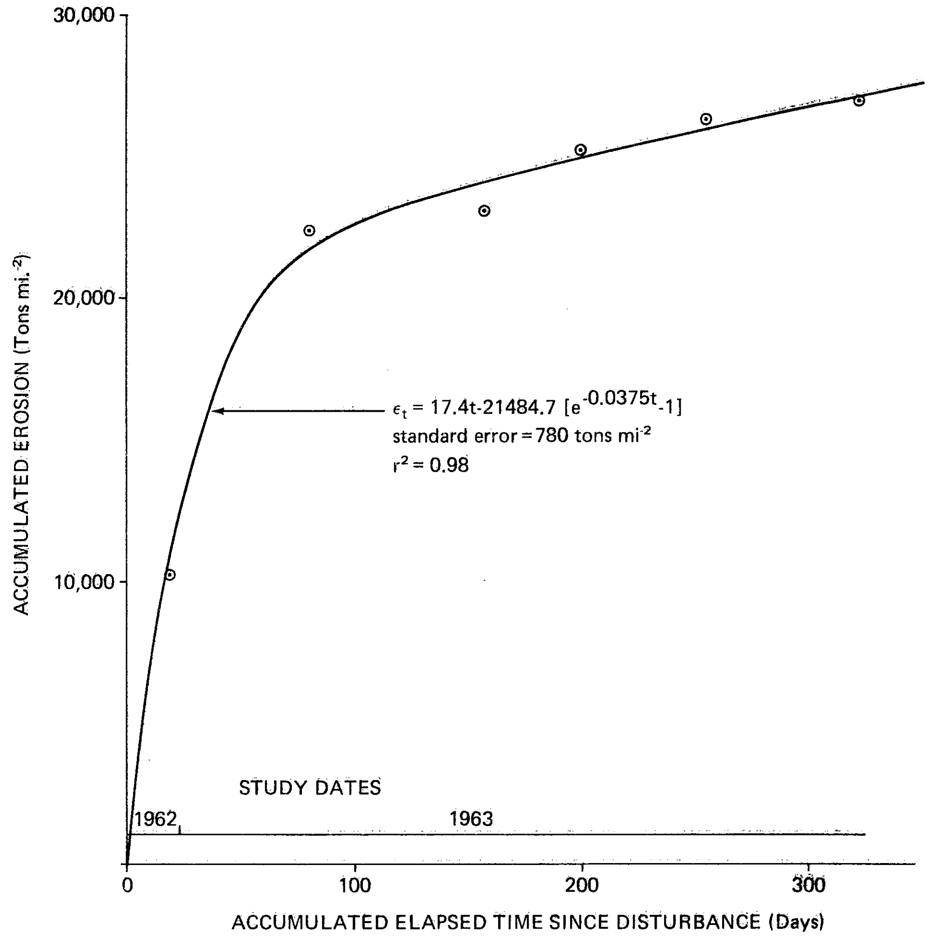
Road Fill Slope Erosion

Bogus Basin Study:--Other studies on granitic materials in the Idaho Batholith support the time-trend results reported above. These were designed to measure erosion rates on plots installed directly on steep road fills. One study was established in the fall of 1962 on the newly constructed Bogus Basin highway leading from Boise, Idaho, to the Bogus Basin Ski Resort (fig. 2). The study was designed to evaluate the effectiveness of various kinds of erosion-control measures and included a 1/100-acre unvegetated control plot that received no treatment. Erosion data were collected during the first year after construction: the first measurement was taken at 17 days and the last at 322 days (Bethlahmy and Kidd 1966).

Accumulated erosion data are summarized in figure 4. These data appear to fit the postulated erosion model; consequently, nonlinear regression was used to fit equation 9 to the data. The fitted regression model has a standard error of 780 tons mi^{-2} day^{-1} and an r^2 value of 0.98. All model parameters are significant at the 95 percent level of confidence.

Deadwood River Study:--Additional data (unpublished, USDA Forest Service, Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory, Boise, Idaho) are available to check the value for ε_n determined from the Bogus Basin data. These were collected on another road erosion study conducted on the Deadwood River drainage (fig. 2). The study was installed on the Deadwood road on a fill slope where site

Figure 4.--Accumulated erosion vs. time--Bogus Basin Study Area.



conditions were similar to those on the Bogus Basin road. Numerous attempts to revegetate this road fill by reseeding were unsuccessful because of harsh site conditions. Three unvegetated, 1/200-acre control plots were available on this study to compare to the Bogus Basin study. However, the Deadwood road fill was constructed in 1957; thus, the erosion data collected during the 1968-1972 sample period represent erosion rates expected from a 12- to 15-year-old unvegetated road fill. The average of these data should provide an approximate check on the ε_n value computed from the Bogus Basin data. The 3-year annual erosion average on the Deadwood plots is 9.1 tons mi^{-2} day^{-1} as compared to the ε_n value on the Bogus Basin plot of 17.2 tons mi^{-2} day^{-1}. The lower value for the older study area could be caused by site differences, a tendency for erosion rates to continue to decrease beyond the time period used to fit the regression line, or both. In any case, considering the large variability usually associated with erosion data, the value for ε_n is again reasonable.

Role of Rainfall Energy and Vegetation

The derivation of the erosion model was based upon the assumptions that the erosive forces are constant over time and that no surface protection is available from vegetation and litter. Obviously, erosive forces are not constant over time in nature; consequently, the time trend in erosion may in fact be due to time trends in erosive forces.

Wischmeier and Smith (1958) showed that the erodibility index, defined as the kinetic energy of rainfall (foot-tons per acre-inch of rainfall) times the maximum 30-minute rainfall intensity (inches per hour) was a reliable index of the forces available for surface erosion. In addition, they developed a procedure for calculating the erodibility index that utilized rainfall-intensity data. An intensity rain gage was operated from early spring to late fall directly on the Deep Creek site for the entire study. During the remainder of the year, an intensity rain gage was operated at a similar elevation about 2 miles east of the Deep Creek study area.

The rainfall-intensity data were used to develop erodibility-index values for all storms occurring during the course of the Deep Creek study. No calculations were made when a snowpack existed because the erodibility index is irrelevant during such times. A degree-day procedure was developed for predicting the daily fluctuation of the snowpack at the study site. This procedure was based upon a detailed analysis of 6 years of snow-cover data collected monthly throughout the winter at eight sites in the vicinity of the study area. Wet adiabatic lapse rates were used to adjust the mean daily temperatures at the climatic station in the town of McCall, about 20 miles southwest of the study area, to those at the study site. Finally, a computer program was developed to predict daily snow accumulation and melt at the study site based upon daily precipitation and temperature.

The average erodibility index for each erosion-measurement period used in the study was computed by summing the erodibility indices for each rainstorm that occurred during snowless days and dividing by the number of days in the period. These data were then compared to the average rate of erosion for each measurement period (fig. 5).

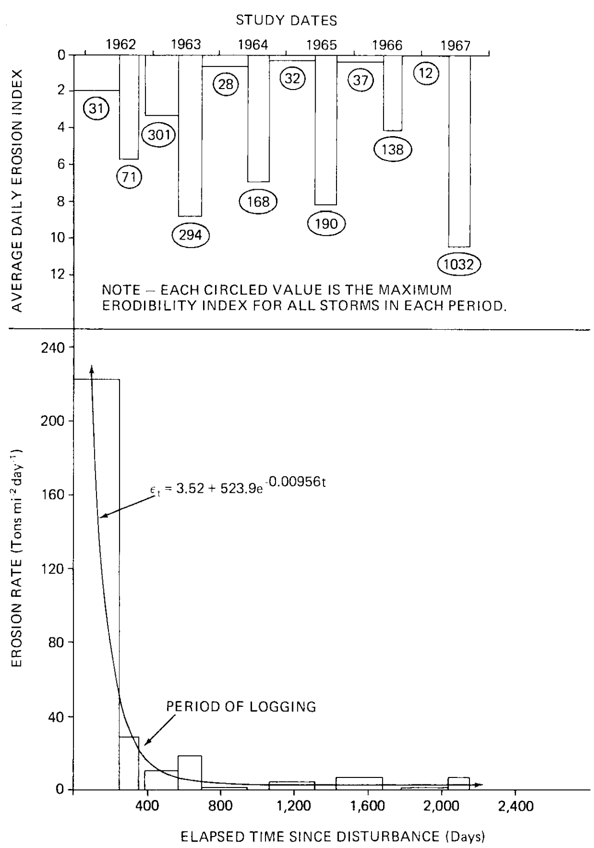


Figure 5.--Variations in erodibility indices and erosion over time--Deep Creek Study Area.

The instantaneous rate of soil erosion is also shown as a continuous curve on the figure. This rate was developed by differentiating the nonlinear regression fit of equation 9. Notice there is no time trend in the erodibility index similar to that shown for erosion in figure 5. The maximum erodibility index for all storms in each period is also shown on the figure; again no time trend is evident. These data suggest that variation in erosive forces did not have a primary influence on the time trend in erosion found on Deep Creek.

As one might expect, all vegetation within the area affected by road construction on Deep Creek was obliterated at the time of construction. Because of limited natural revegetation, the road remained essentially in this condition until after the study watersheds were logged a year later in 1962. At this time, standard postlogging erosion-control measures (water bars and grass seeding) were installed on the roads (fig. 5). Because of the time of year (November), no appreciable vegetation growth occurred until the following growing season: almost 2 years after construction. Notice in figure 3 that erosion had receded considerably by the end of the first year after construction, an indication that vegetation growth and installation of water bars was not the primary cause of the recession.

Unfortunately, no recording rain gage was operated at the Bogus Basin study area. However, climatic data are available from two nearby stations (Deer Point and Boise Airport) on each side of the study site. Data from these stations were adjusted to the elevation of the study site to develop erodibility indices for snowless days for each erosion-measurement period in the study (fig. 6). Snowless days were determined by using a procedure similar to that used on the Deep Creek study area. Note there is no time trend in either the average or the peak erodibility index that corresponds to the time trend found for erosion. Vegetation growth on the Bogus Basin plot was not a factor because essentially no vegetation growth occurred on the plot surface during the course of the study.

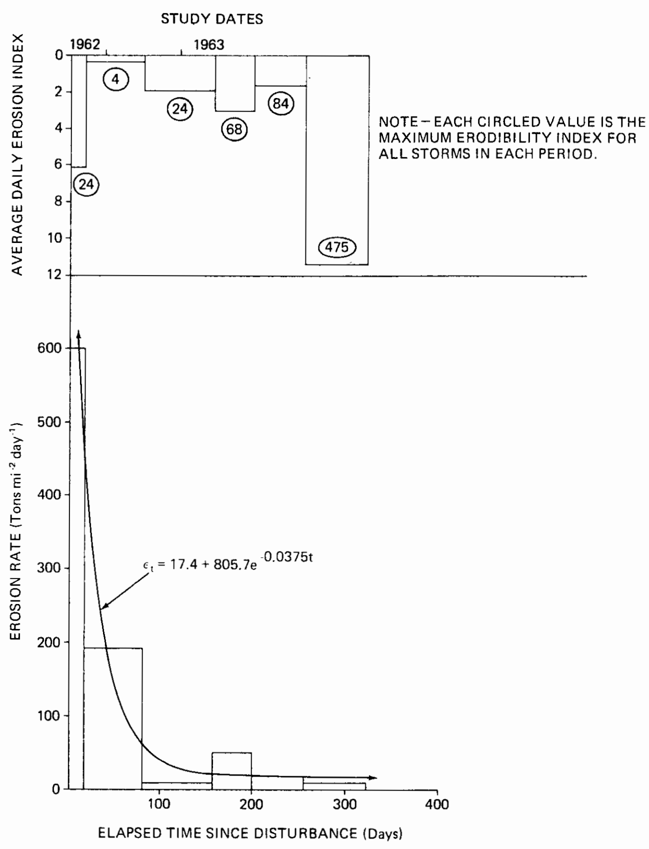


Figure 6.--Variations in erodibility indices and erosion over time--Bogus Basin Study Area.

DISCUSSION

Based upon experimental data on granitic materials from four different study sites, the derived exponential model for surface erosion over time appears to be appropriate. The model is useful to persons working in the area because it provides an estimate of the quantity and timing of surface erosion following disturbance. The need for such estimates is appreciated when surface erosion rates on disturbed lands are compared to those on undisturbed lands. Availability of a considerable body of sediment-yield data makes possible an estimate of the average erosion rate for undisturbed lands similar to the lands disturbed by road construction in these studies (Megahan 1972). The erosion rate for undisturbed lands averages about 0.07 ton mi^{-2} day^{-1}. For the first year after disturbance, erosion rates per unit of area involved in road construction are three orders of magnitude greater than those on similar undisturbed lands; after almost 40 years, they are still one order of magnitude greater. The potential for damage by such accelerated erosion should be apparent.

Fortunately, accelerated erosion of this magnitude need not be accepted as an inevitable consequence of severe soil disturbance because it is possible to reduce the erosion with a variety of treatments. However, surface erosion follows an exponential relationship such that by far the largest percentage of soil loss occurs within 1 to 2 years after disturbance. Thus, erosion-control measures must be applied immediately after disturbance to be effective. A common approach is to reseed disturbed areas. However, seeding alone will have minimal effect because of slow initial growth responses; additional protection must be provided on the soil surface during the critical high-erosion period. Studies have shown that treatments such as mulching and transplanting on granitic road fills can reduce total soil losses dramatically. For example, Bethlahmy and Kidd (1966) reported that soil losses on the Bogus Basin study plots were not reduced at all by grass seeding alone, but were reduced about 70 and 98 percent when seeding was accompanied by mulching and mulch plus netting, respectively. Soil losses from erosion plots on the Deadwood road were reduced 98 percent by combining ponderosa pine planting with a straw mulch plus netting.

As with most studies where results are related solely to time, the true causes of the time trends are not identified. The studies reported here simply were not designed to evaluate the causes of time trends in erosion, but they were conducted in a manner that helps eliminate some likely causal factors. Obviously, variations in erosive forces will tend to modify erosion rates over time. However, these studies suggest that a widely used index of erosive forces (the erodibility index) was not well related to the time trends in erosion, at least during the initial period of rapid recession. Time trends in other erosive forces, such as wind or seepage flows, are a possibility, although no such effects were noted. Numerous studies attest to the ability of vegetation and mechanical measures to reduce erosion. Such treatment measures were applied late in Deep Creek and not at all on the road fill studies, which eliminates them as a cause of the rapid decrease in erosion. The foregoing suggests that variations in erosive forces (f) and protection (p) as defined in equation 1 did not cause the time trend. Therefore, it is postulated that the dominant causal factor was "armoring" of the erosion surface.

Wischmeier and others (1971) developed a procedure for estimating soil losses from farmland and construction sites based upon the universal soil-loss equation. No time trends in erosion were indicated by these studies. However, the study procedure and the fact that soil disturbance was not severe enough to include underlying parent material may have affected the results. Studies by other researchers suggest that time trends in erosion do occur under other soil and geologic conditions. Vice and others (1969) reported such trends following suburban highway construction in a 4.54-mi^2 drainage basin in Virginia. In this case, soil disturbance ultimately included about 11 percent of the study drainage. Anderson (1972) found decreasing time trends in sediment from poorly logged areas in California following severe flooding. Such areas contained logging roads next to channels and landings in draws. Sedimentation resulting from surface erosion on logging roads in Oregon decreased rapidly after an initial high rate following construction (Fredriksen 1970).

As is true of the Idaho studies reported here, the actual processes causing the erosion decreases with time were not evaluated. However, one additional study in West Virginia was more definitive; Reinhart and others (1963) found that sedimentation increases following logging resulted from erosion on skidroads. They observed the erosion process over time and reported:

> The impact on water quality was greatest during and immediately after the logging operation.... Repeated disturbance during logging continually brought to the road surface a new supply of fine soil particles. Erosion decreased rapidly after logging, due first to the development on our soils of a partial erosion pavement (a surface cover of small stones) and later to vegetation growth on roads.

Obviously, the coefficients developed for the studies in Idaho will not apply elsewhere, but apparently the form of the basic time trend relationship is appropriate. It is important to note that the relationship applies only to surface erosion *following* disturbance: any additional disturbance will initiate a new surface erosion cycle. Furthermore, it applies only to *surface* erosion, not mass erosion.

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1974. Erosion over time on severely disturbed granitic soils: a model. USDA For. Serv. Res. Pap. INT-156, 14 p., illus. (Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.)

A negative exponential equation containing three parameters was derived to describe time trends in surface erosion on severely disturbed soils. Data from four different studies of surface erosion on roads constructed from the granitic materials found in the Idaho Batholith were used to develop equation parameters. The evidence suggests that surface "armoring" was the dominant factor causing the time trends in surface erosion. The significance of time trends in surface erosion is discussed.

OXFORD: 116:116.3. KEYWORDS: surface erosion, vegetation, erosion energy, erodibility index, disturbed soil, soil erosion.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field Research Work Units are maintained in:

- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)
- Reno, Nevada (in cooperation with the University of Nevada)