Yield of Sediment in Relation to Mean Annual Precipitation

W. B. LANGBEIN AND S. A. SCHUMM

Abstract—Effective mean annual precipitation is related to sediment yield from drainage basins throughout the climatic regions of the United States. Sediment yield is a maximum at about 10 to 14 inches of precipitation, decreasing sharply on both sides of this maximum, in one case owing to a deficiency of runoff and in the other to increased density of vegetation. Data are presented illustrating the increase in bulk density of vegetation with increased annual precipitation and the relation of relative erosion to vegetative density.

It is suggested that the effect of a climatic change on sediment yield depends not only upon direction of climate change, but also on the climate before the change. Sediment concentration in runoff is shown to increase with decreased annual precipitation, suggesting further that a decrease in precipitation will cause stream channel aggradation.

Introduction—The yield of sediment from a drainage basin is a complex process responding to all the variations that exist in precipitation, soils, vegetation, runoff, and land use. This study is aimed only toward a discernment of the gross variations in sediment yield that are associated with climate as defined by the annual precipitation. Such a study may contribute to an understanding of the effects of climatic change on erosion and of the regional variations in sediment yield. Data on sediment yields are now available in sufficient number for this kind of study, although still quite deficient in geographic coverage. Two major sources of sediment data exist. Records collected at about 170 gaging stations of the U. S. Geological Survey, where sediment transported by streams is measured, is one source of data; whereas, the other source of data is provided by the surveys of sediment trapped by reservoirs. Both kinds of data are used in this study.

Precipitation data—Precipitation is used as the dominant climatic factor in the study of sediment yield, because it affects vegetation and runoff. However, the effectiveness of a given amount of annual precipitation is not everywhere the same. Variations in temperature, rainfall intensity, number of storms, and seasonal and areal distribution of precipitation can also affect the yield of sediment. For example, *Leopold* [1951] in an analysis of rainfall variation in New Mexico, found that despite the absence of any trend in annual rainfall, changes in the number of storms produced a significant influence upon erosion. Although analyses of these effects are beyond the scope of this study, the effect of temperature, which controls the loss of water by evapotranspiration, can be readily taken into account. As is well known, the greater the temperature, the greater are the evapotranspiration demands upon soil moisture; hence, less moisture remains for runoff. More precipitation is required for a given amount of runoff in a warm climate than in a cool climate. Therefore, instead of using actual figures of annual precipitation, it is preferable to use figures of precipitation adjusted for the effect of annual temperature. However, in lieu of carrying out these extended computations, it appears possible to use the data on annual runoff which already reflect the influence of temperature. Annual runoff data are available for all the gaging station records and for most of the reservoir records. Because of the well-established relationships between annual precipitation and runoff, it is readily possible to estimate precipitation from the runoff figures.

We shall define effective precipitation as the amount of precipitation required to produce the known amount of runoff. Figure 1 shows a relationship between precipitation and runoff based on data given in Geological Survey Circular 52 [*Langbein*, 1949]. This graph has been used to convert known values of annual runoff to effective precipitation, based on a reference temperature of 50°F. In a warm climate, with temperature greater than 50°, the precipitation so estimated would be less than the actual amount of precipitation; in a cool climate, the effective precipitation so estimated would be more than the actual amount. This is the desired relationship.

Sediment-station data—In recent years a number of records of sediment yield, as measured at sediment-gaging stations, have become available. Annual loads were computed for about 100 stations giving preference to the smaller drainage areas in any region. All parts of the country,

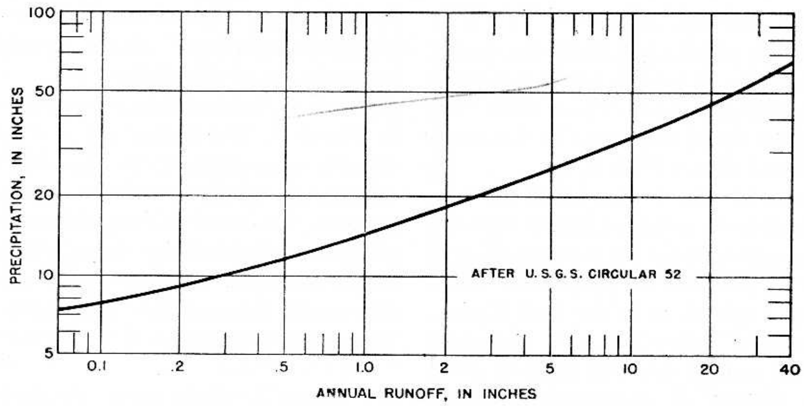

FIG. 1 – Relation between annual precipitation and runoff for a mean temperature of 50° F

where sediment records are collected, are represented.

The annual sediment loads were first arranged according to effective precipitation. They were next assembled into the class groups shown in Table 1, and the arithmetic averages were then computed for each group. Within any group the loads may vary tenfold, reflecting geologic and topographic factors not considered in this study. Each group mean is subject to a standard deviation of about 30 pct. The group averages are plotted in Figure 2. The curve shown was fitted to the data, subject to the condition (1) that it did not depart more than one standard deviation (30 pct) from any of the plotted group means, and (2) that it show zero yield for zero precipitation.

There is considerable opportunity for bias in the figures for load, because the relatively few records prohibit any high degree of selectivity. Few of the rivers drain areas in their primeval environment and moreover, land use can greatly affect the sediment yield. Farming, grazing, road construction, and channelization tend to increase sediment yield; reservoirs impound and, therefore, delay the movement of sediment. If these effects are uniform countrywide, then the overall results might be free of bias in the statistical sense, even though the absolute magnitudes may not be representative of primeval conditions. However, there is considerable variation, particularly with respect to intensity of agricultural operations, which perhaps are most intensive in the midcontinent region. The effects of various kinds of land use upon erosion vary with climate, physiography, soil type, and original vegetation. One surmises that the effect of cultivation is greater in the humid region, where effective precipitation is more than about 30 inches, because of the great contrast between original forest cover and tillage. The erosive reaction of some soil types to cultivation is evident for some small drainage basins in the humid region, which have sediment yields that approach or exceed those usual even in the arid country and are far above those to be expected within their particular range of annual precipitation. For example, sediment

TABLE 1 – *Group averages for data at sediment stations*

Range in effective precipitation	Number of records in each group	Average effective precipitation	Average yield
inch		inch	tons/sq mi
Less than 10	9	8	670
10 to 15	17	12.5	780
15 to 20	18	17.5	550
20 to 30	20	24	550
30 to 40	15	35	400
40 to 60	15	50	220

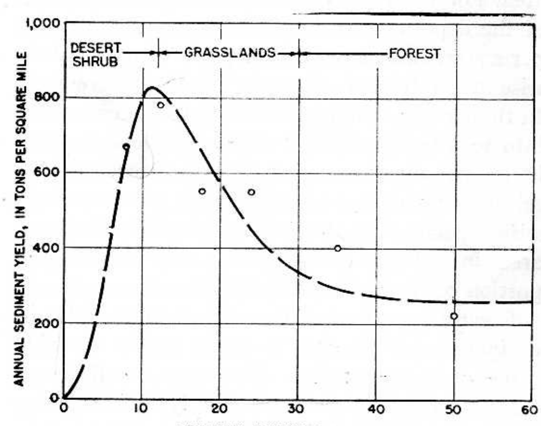

FIG. 2 – Climatic variation of yield of sediment as determined from records at sediment stations

yield from small drainage basins (0.1 to 1.0 sq mi) in the loess hills of Iowa and Nebraska is very high, largely because of poor conservation practices on wind deposited soils. These rates "are among the highest found anywhere in the country" [*Gottschalk* and *Brune*, 1950, p. 5].

Another source of bias is the relatively non-uniform distribution of sediment-gaging stations. Most are in the central part of the country, whereas virtually none is available in the Pacific Coast Region, in New England, or in the Gulf Region.

Reservoir sediment data—Although preference was given to the smaller drainage areas in using gaging-station records of suspended sediment, opportunities for choice in this regard were severely limited. Fortunately, surveys of sedimentation in reservoirs are more numerous, so that there was opportunity to be more selective in choosing reservoirs below small drainage areas, which on that account were presumed to be more indicative of sediment yield nearer the source. Data on reservoir sedimentation were compiled by the *Federal Inter-Agency River Basin Committee* [1953]. Rates of sedimentation were obtained from surveys of sediment accumulation, expressed as an annual rate in acre feet or tons per square mile of drainage area. For those reservoirs where the bulk density of the deposits was determined, the annual rates per square mile are given in terms of tons, otherwise the rates are given in terms of acre feet. In these cases, volumes in acre feet were converted into tons by assuming a density of deposit of 60 lb/cu ft, an average of reported densities. In selecting reservoirs, preference was given to those with capacities exceeding 50 ac ft/sq mi of drainage area, in order to select those which trap a large portion of the sediment that enters the reservoir.

Reservoirs with less than five square miles of drainage area appear to have highly variable rates of sedimentation. For very small areas, rates of sediment yield are greatly influenced by details of land use and local features of the terrain [*Brown*, 1950]. For this reason, reservoirs having drainage areas between 10 and 50 sq mi were used. Because no reservoirs in desert areas were listed in the Inter-Agency compilation, data for desert reservoirs were obtained from unpublished records collected by the U. S. Geological Survey. However, because these reservoirs were on drainage areas of ten square miles or less, rates of sediment yield for these desert reservoirs were adjusted downward to obtain equivalent rates from drainage areas of 30 sq mi, according to the 0.15 power rule explained below. The sediment data were arranged according to effective precipitation and grouped as shown in Table 2.

Group averages of the reservoir data are plotted in Figure 3. The general shape of the resulting curve is quite similar to the one obtained from the records of suspended sediment measured at river stations. The most evident difference is that the yields are about twice those indicated by the sediment-station records. There are significant differences between the two kinds of records. The sediment-station records do not include bed

TABLE 2. – *Group averages for reservoir data*

Range in effective precipitation	Number of reservoirs in each group	Average effective precipitation	Average yield	Remarks
inch		inch	tons/sq mi	
8–9	31	8.5	1400	15 reservoirs in San Rafael Swell, Utah, and 16 in Badger Wash, Colo.
10	38	10	1180	26 reservoirs in Twenty-mile Creek basin, Wyo., 7 in Cornfield Wash, N. Mex., and 5 general.
11	12	11	1500	General
14–25	18	19	1130	General
25–30	10	27.5	1430	General, including debris basins in Southern Calif. considered as one observation.
30–38	20	35.5	790	General
38–40	11	39	560	General
40–55	18	45	470	General
55–100	5	73	440	General

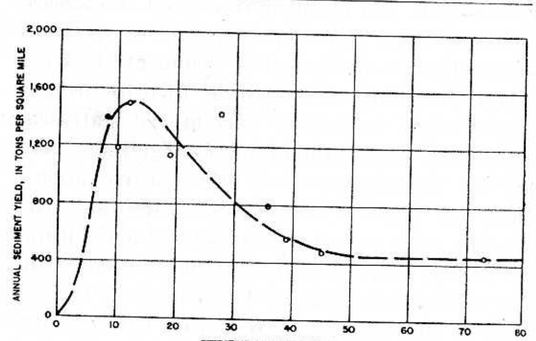

FIG. 3 – Climatic variation of yield of sediment as determined from reservoir surveys

load, which, being the coarser fraction of the load, is trapped by a reservoir. The effects are variable depending on relative amounts of bed and suspended loads at gaging stations and on the trap efficiency of the reservoirs. Moreover, reservoirs are generally built in terrain that offers favorable sites, which means drainage basins with steep slopes and hence higher rates of net erosion. However, in the comparison made here most of the difference is probably due to the effect of size of drainage area. Several studies have shown that sediment yields decrease with increased drainage area, reflecting the flatter gradients and the lesser probability that an intense storm will cover the entire drainage basin. Assuming that the graphs shown by *Brune* [1948] are correct for this effect, rates of sediment yield are inversely proportional to the 0.15 power of the drainage area. Noting that the drainage areas used for Figure 2 average about 1500 sq mi and those for Figure 3 about 30 sq mi, the sediment yields for reservoir data should average about $(1500/30)^{0.15}$, or 1.8 times that for the sediment-station data. This correction applied to the reservoir data would very nearly account for most of the difference between the curves of Figures 2 and 3.

Figures 2 and 3 appear to show a maximum sediment yield at about 12 inches annual effective precipitation, receding to a uniform yield from areas with more than 40 inches effective precipitation. The lack of data for climates with less than 5 inches of annual precipitation makes it difficult to determine the point of maximum yield with accuracy. Available data indicate, however, that it is at about 12 inches or less.

In a similar study of erosion rates and annual precipitation for large rivers of the world (Fig. 4), *Fournier* [1949] notes that the drainage basins are located on a parabolic curve in relation to their climatic character. For example, the upper limb of the parabola (greater than 43 inches) is formed by rivers typical of a monsoon climate: Ganges, Fleuve Rouge (Hung Ho), Yangtze, and some basins of southeastern United States; the middle segment of the curve between 24 and 43 inches of rainfall is formed by drainage systems located in regions with essentially equally distributed annual rainfall, as the Atlantic coastal rivers of the northeastern United States; the lower limb of the curve below 24 inches is formed by rivers draining regions of the more continental steppe or semiarid climates: Vaal, Indus, Rio Grande, Hwang-Ho, Tigris, and Colorado. Fournier concluded that the regions of maximum erosion are those in which monthly rainfall varies greatly, the monsoon and steppe climates.

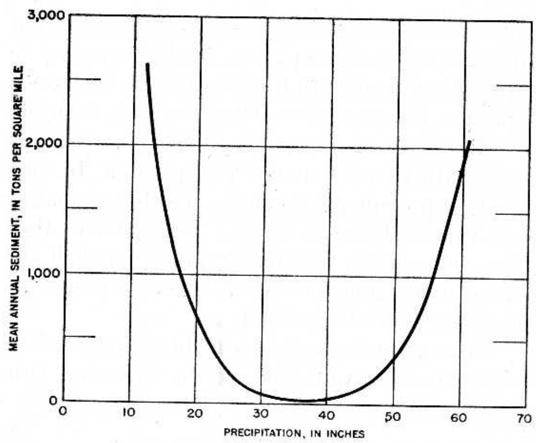

FIG. 4 – Relation of sediment yield to precipitation [after *Fournier*, 1949]

The midpart of his curve shows an annual yield of only five to seven tons per square mile which Fournier attributes to basins in which rainfall is uniform throughout the year such as those in the northeastern United States. These figures are much below that indicated by the few available records in that region which range from a minimum of about 40 tons/sq mi for Scantic River in Connecticut to 370 tons/sq mi for Lehigh River in Pennsylvania.

The lower limb of Fournier's curve terminates at a precipitation of about 12 inches, reaching an annual yield of about 2500 tons/sq mi. Although rates as high and even higher occur in many areas in the arid country, the figure of 2500 tons/year seems somewhat high as an average. The upward trend cannot continue if there is zero sediment yield (in rivers) for zero precipitation; the curve seemingly must reverse its upward trend and swing downward towards the origin.

The upper limb of Fournier's curve (above 43 inches precipitation) shows sharply increasing sediment yield with increasing precipitation, a trend that is not evident in Figures 2 and 3. However, it is possible that additional information in such areas of great rainfall as northern California and the Pacific Northwest may introduce an increasing trend in this part of those graphs.

Analysis of the climatic variation in sediment yield—The variation in sediment yield with climate can be explained by the operation of two factors each related to precipitation. The erosive influence of precipitation increases with its amount, through its direct impact in eroding soil and in generating runoff with further capacity for erosion and for transportation. Opposing this influence is the effect of vegetation, which increases in bulk with effective annual precipitation. In view of these precepts, it should be possible to analyze the curves shown in Figures 2 and 3 into their two components, the erosive effect of rainfall and the counteracting protective effect of vegetation associated with the rainfall.

These opposing actions can be represented by mathematical expressions of the following form

$$S = aP^m \frac{1}{1 + bP^n} \qquad (1)$$

in which S is annual load in tons per square mile, P is effective annual precipitation, m and n are exponents, and a and b are coefficients. The factor aP^m in the above equation describes the erosive action of rainfall in the absence of vegetation. The die-away factor $1/(1 + bP^n)$ represents the protective action of vegetation. The factor aP^m increases continuously with increase in precipitation, P, whereas the factor $1/(1 + bP^n)$ is unity for zero precipitation, and decreases with increases in precipitation.

Eq. (1) can not be evaluated by the usual least-squares method. Hence it was evaluated by trial and error, graphical methods yielding the following approximate results.

$$S = \frac{10P^{2.3}}{1 + 0.0007P^{3.33}}$$

for sediment station data and

$$S = \frac{20P^{2.3}}{1 + 0.0007P^{3.33}}$$

for reservoir sediment data.

The factor $P^{2.3}$ describes the variation in sediment yield with constant cover. Analyses of measurements of rainfall, runoff, and soil loss made on small experimental plots operated by the Department of Agriculture [*Musgrave*, 1947], indicate that, other factors the same, erosion is proportional to the 1.75 power of the 30-minute rainfall intensity. However, it is rather difficult to draw a connection between the intensity of 30-minute precipitation and annual precipitation. Inspection of *Yarnell's* [1935] charts indicates one relationship exists in the eastern part of the country and another in the western areas. However, in both areas 30-minute intensities vary with annual rainfall to some power greater than unity. Hence, one can conclude that erosion will vary regionally to some power of the annual precipitation greater than 1.75.

The second factor, $1/(1 + 0.0007\ P^{3.33})$, equals $S/aP^{2.3}$. This function, as graphed in Figure 5, purports to isolate the variation in sediment yield caused by differing degrees of vegetative cover. This function varies as shown in Table 3.

There is a good deal of information on the relation between different vegetal covers and rates of erosion in a given climate. However, most of this information deals with cultivated lands and

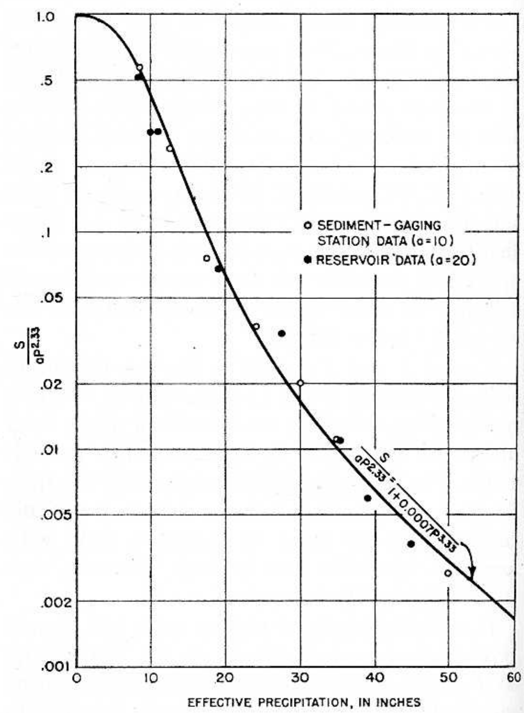

FIG. 5 – Decrease in relative sediment yield with increasing precipitation

TABLE 3 – *Variation in sediment yield associated with vegetative cover*

Effective precipitation	Vegetative cover[a]	$\frac{1}{1 + 0.0007\ P^{3.33}}$
inch		
7	Desert shrub	0.69
13	Desert shrub	0.23
20	Grassland	0.06
30	Grassland	0.017
40	Forest	0.006
50	Forest	0.003

[a] Associated with effective precipitation.

few of the vegetal data are in quantitative terms. *Musgrave* [1947] attempted a quantitative evaluation of relative erosion based on data collected at experimental watersheds in the Pacific Northwest. The results agree quite well with the results given in Table 3.

Cover	Relative erosion
Row crops or fallow	1.0 to 0.60
Small grains, grass hayland, crested wheat grass	0.05
Pasture, excellent condition, and forests	0.01 to 0.001

Formula (1) may be generalized as

$$S \propto R/V \qquad (2)$$

where R is annual runoff, and V is mass density of vegetation. In any given region the two factors operate separately; thus, sediment loads may vary with runoff depending on land use and vegetal conditions. For example, *Brune* [1948] shows that, for a given land condition in the Midwest, sediment yield increases with runoff, and that, for a given runoff, sediment yield varies enormously with percent of tilled land. The present study, however, treats of the broad climatic variation in which both runoff and vegetation are each uniquely related to effective precipitation.

With increasing precipitation, sediment yield varies as shown on Figures 2 and 3, but runoff increases as shown on Figure 1. The ratio between sediment yield and runoff is a measure of the concentration. This quantity is generally reported in parts per million (ppm) by weight and may be computed by dividing sediment yield in tons per square mile by runoff computed in tons per square mile. Figure 6 shows results of this computation for the data in Table 2. The concentration decreases sharply with increasing precipitation.

Annual precipitation, as indicated by the annual runoff, is used as the sole climatic measure. We have considered differences in precipitation intensity and its seasonal distribution only so far as these influences are reflected in the amount of annual runoff. For example, low precipitation regimes are characteristically more variable than those of humid regions [*Conrad*, 1946], and, indeed, the short-period excesses in intensity show up in the runoff. However, we repeat, as we wrote in our introduction, that although climatic influences on sediment are more complex, a good deal can be learned from consideration of the annual precipitation.

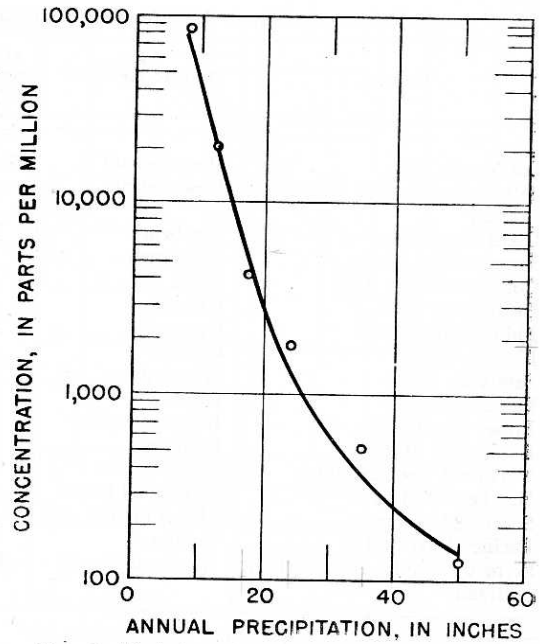

FIG. 6 – Variation of concentration with annual precipitation

Precipitation and vegetation—There can be no question of the highly significant effect of vegetation on erosion. For this reason, we have assembled information on climatic variation and vegetal bulk. The information on vegetal bulk contained in Table 4 was obtained mainly from published sources, ranging in reliability from carefully weighed quadrats to forest statistics and two estimates based on examination of photographs (for references, see Table 4). However, considering the more than 1000-fold variation in vegetal weight, as between desert shrubs to forests, great precision does not seem to be needed for the rough kind of study that seems possible at this time. Some of the data on vegetal weights were given directly in pounds per acre or equivalent. The forest data were obtained by dividing the reported cubic-foot volumes of saw-timber and pole-timber trees, given in millions of cubic feet for each state, by the respective forest area in acres. Unit weights of 45 lb/cu ft were used for hardwoods, 35 for soft woods, and 40 for mixed forests.

Table 4 also includes data on mean annual precipitation and temperature applicable to each case. The climatologic data were not usually given in the references cited and were obtained from U.S. Weather Bureau reports.

Figure 7 shows a plot of precipitation against

TABLE 4 – *Climatologic data and data on weight of vegetation*

Location	Type of vegetation	Mean annual precip.	Mean annual temp.	Weight of vegetation	Reference for vegetal bulk
		inch	°F	lb/ac	
Las Vegas, Nev.	Desert shrub	5	65	100	*McDougal* [1908, pl. 28]
Salt Lake Desert, Lakeside, Utah	Desert shrub	8	50	400	*McDougal* [1908, pl. 24]
Clark Co., Idaho	Sagebrush	12	40	891	*Blaisdell* [1953]
Fremont Co., Idaho	Sagebrush	12	40	1,273	*Blaisdell* [1953]
Coconino Wash, Ariz.	Grass	15	45	1,886	*Clements* [1922]
Burlington, Colo.	Grasses	17	52	2,251	*Weaver* [1923]
Phillipsburg, Kans.	Grasses	22	52	3,230	*Weaver* [1923]
Lincoln, Nebr.	Grasses	27	51	4,467	*Weaver* [1923]
Sandhills, Nebr.	Wheat grass	18	49	4,000	*Smith* [1895]
Lincoln, Nebr.	Grasses	27	51	6,224	*Kramer* and *Weaver* [1936]
Fraser forest, Colo.	Lodgepole pine	25	32	43,000	*Wilm* and *Dunford* [1948]
Rocky Mt. States	Conifers	28	38	54,000	*U. S. Forest Service* [1950]
Northeast Central States	Mixed forest	30	43	64,000	*U. S. Forest Service* [1950]
Northeast States	Hardwood forest	42	45	55,000	*U. S. Forest Service* [1950]
Southeast States	Mixed forest	51	60	48,000	*U. S. Forest Service* [1950]
Pacific Coast States	Conifers	64	47	150,000	*U. S. Forest Service* [1950]
Serro do Navio, Amapa Terr., Brazil	Hardwood forest	120		870,000	Field estimate by M. G. Wolman, 1956

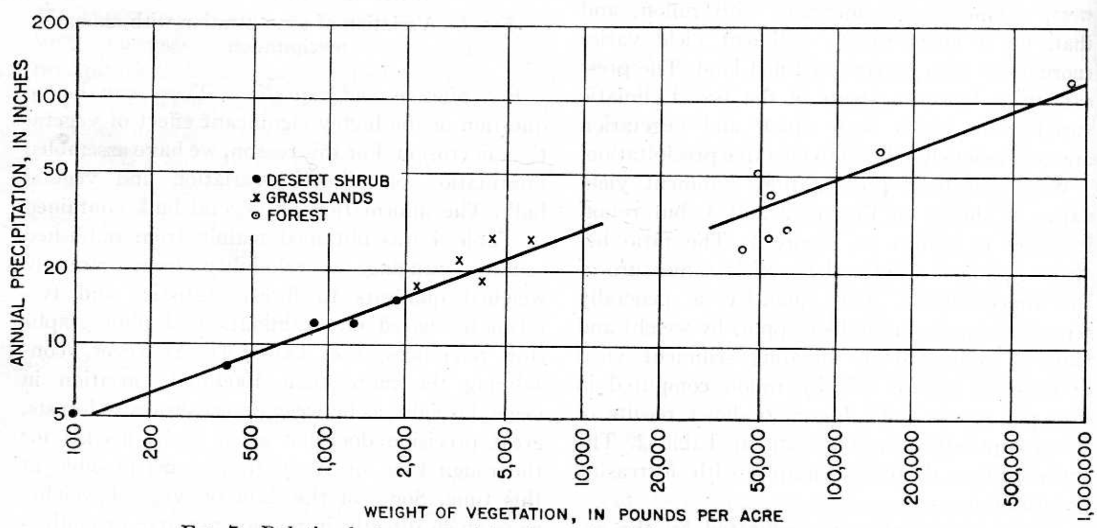

FIG. 7 – Relation between precipitation and weight of vegetation per unit area

vegetation weight. For the data available, the correlation seems quite high with a decided break between forest and nonforest types. The graph indicates that for equivalent rainfall, forests have about five times as much weight as grasses. With a longer life span, trees should understandably show greater total weight in place, although perhaps the annual growth (= annual decay for equilibrium) would be less than for grasses.

The seeming fact that desert shrubs are on the lower continuation of the line defined by the grasses seems anomalous. In arid and semi-arid regions the increase in vegetal bulk with rainfall rather simply reflects increasing opportunity for a greater number of plants, greater opportunity for each plant to reach maximum development for the species environment, and opportunity for growth of larger species. However, this does not explain the variation of forest bulk with rainfall greater than needed to satisfy optimum evapotranspiration demands for the climate. Forests are areas of water surplus in the climatic sense, yet vegetal density seems to vary with precipitation and temperature. Among the eastern states, for example, the vegetal bulk per unit area in Maine and North Carolina are about the same. The lesser annual precipitation in Maine appears to be compensated by a lesser temperature; whereas, in North Carolina higher annual precipitation is compensated by a higher temperature. The forested areas of Washington, Oregon, and California have about the same temperature; the forest densities seem to follow precipitation as follows:

State	Precipitation inch	Vegetation lb/ac
Washington	80	177,000
Oregon	60	158,000
California	53	120,000

The variation in unit weight shown in Figure 7 is made up of two components, one due to variation in weight among different communities of the same vegetation type, and that due to variation in weight among different types. The latter is very likely the dominant factor in the relationship on Figure 5. Beyond a certain limiting precipitation, say that for which precipitation is adequate to meet all evapotranspiration requirements, differences in vegetal bulk may reflect not so much growth factors as differences in plant types or associations. The heavy vegetal bulk in the Pacific Northwest, for example, may be the reflection of a difference in plant type rather than a direct effect of precipitation on growth.

We are considering here only gross relations, ignoring rather important variations that might be due to differences in species, topographic setting, or moisture conditions that might favor or discourage growth. For example, there are patches of timber in the valley bottoms, in the Great Plains, with weight densities far exceeding that of the grasslands. The data used to define this relationship are admittedly crude and subject to bias. The forest statistics, for example, generally exclude bark, leaves, flowers, fruit, and most branches. The ratio of these parts to the whole tree decreases with age. The existing data are for stands in various degrees of maturity, and most existing data exclude roots. The ratio of roots to aboveground growth is variable among different kinds of plants and may be a large source of error.

Then again, although one might conceive that the maximum amount of plant material should theoretically be correlative with climate, other factors such as aspect, depth, and nature of soil are of major influence. Ideally, vegetal densities should be studied locally to arrive at a normal density for the regional climate. However, this kind of study would be beyond the scope of this discussion. Only the evident fact that vegetal densities are so variable over the range of climates experienced in this country makes it at all possible to use the existing data.

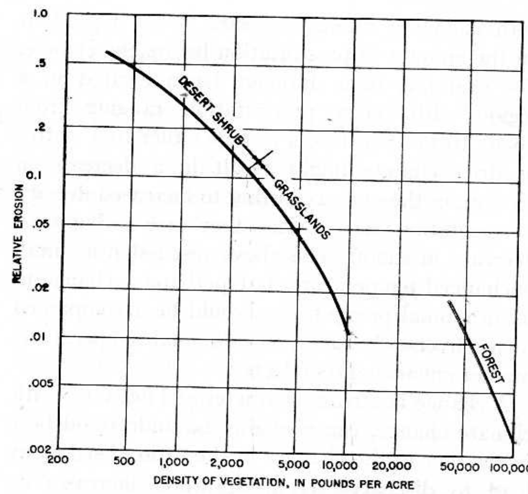

FIG. 8 – Relative erosion compared with density of vegetation

Interpreting the graph in Figure 5 as an indication of relative erosion associated with vegetation, as shown on Figure 7, the relationship shown on Figure 8 can be drawn. According to this graph, a relative change in vegetal density is effective on erosion throughout the climatic range, although the break between trees and grass suggests that per pound, grass is more effective in retarding erosion than trees.

Erosion and climate change—Examination of Figures 2 and 3 may be useful in visualizing not only variations in rates of net erosion between climatic zones in the United States but also the probable change in rates of erosion and stream activity during a climatic change.

Within the 0- to 12-inch precipitation zone an increase in annual rainfall would apparently be followed by an increase in erosion and vice versa; whereas, between about 12 to 45 inches of rainfall, erosion should decrease with increased precipitation. Above 45 inches of precipitation, erosion should remain about constant with increased precipitation, although Fournier's curve (Fig. 4) shows a marked increase in sediment yield above 43 inches of precipitation.

The direction of a change in sediment yield with changing rainfall appears to be dependent on the amount of precipitation before the change. For example, in a drainage basin located in a region with mean precipitation ranging from about 10 to 15 inches, a change either to a wetter or drier climate might result in a decrease in erosion, in the one case owing to increased density of vegetation and in the other case owing to a decrease in runoff. The above discussion assumes unchanged temperature, but perhaps a change in mean annual precipitation would be accompanied by an inverse change in mean annual temperature, further enhancing its effects.

A change in stream character and activity, with climate change, can probably be understood best in relation to the changes in the ratio of sediment load to discharge as precipitation increases or decreases. Referring to Figure 6, it is apparent that as annual precipitation decreases, the concentration of sediment per unit of runoff increases. This suggests quite strongly that, other factors being the same, the increasing sediment loads associated with increasing dryness will cause aggradation, in an amount depending on the magnitude of the climatic change. *Mackin* [1948, pp. 493–495] has summarized changes to be expected in stream activity with changes in load and discharge. In every case, an increase in load or decrease in discharge with constant load results in aggradation and vice versa.

The decrease in annual runoff with decreased precipitation will necessitate an adjustment of stream gradient and shape according to established principles [*Leopold* and *Maddock*, 1953], such that the width and depth of the channel should decrease and gradient increase. These changes are consistent with aggradation. Of course, an increase in precipitation might be expected to result in degradation as sediment concentration decreases. The increased discharge will result in an increase in channel width and depth and a decrease in gradient. Numerous exceptions to the above generalizations can be cited, especially when glaciation, deforestation, cultivation, or a change in base level become important.

References

Blaisdell, J. P., Ecological effects of planned burning of sagebrush-grass range on the Upper Snake River Plains, *U. S. Dept. Agr. Tech. Bul. 1075*, 1953.

Brown, C. B., Effects of soil conservation, *Applied sedimentation*, P. D. Trask (ed), pp. 380–406, John Wiley and Sons, 707 pp., 1950.

Brune, Gunnar, Rates of sediment production in midwestern United States, *Soil Cons. Serv. TP-65*, 40 pp., 1948.

Clements, F. E., Destruction of range by prairie dogs, *Carnegie Inst. Washington Yearbook 21*, 1922.

Conrad, V. A., *Methods in climatology*, Harvard Univ. Press, 1946.

Federal Inter-Agency River Basin Comm., *Summary of reservoir sedimentation surveys for the United States through 1950*, Subcommittee on Sedimentation, Sedimentation Bul., 31 pp., 1953.

Fournier, M. F., Les facteurs climatiques de l'erosion du sol, *Bul. Assn. Geogr. Francais 203* (Seance du 11 Juin 1949), 97–103, 1949.

Gottschalk, L. C., and G. M. Brune, Sediment design criteria for the Missouri Basin loess hills, *Soil Cons. Serv. Tech. Pub. 97*, 21 pp., 1950.

Kramer, J., and J. E. Weaver, Relative efficiency of roots and tops of plants in protecting the soil from erosion, *Nebr. Univ. Cons. & Surv. Div. Bul. 12*, p. 94, 1936.

Langbein, W. B., Annual runoff in the United States, *U. S. Geol. Surv. Circ. 52*, 11 pp., 1949.

Leopold, L. B., Rainfall frequency: An aspect of climatic variation, *Trans. Amer. Geophy. Union*, **32**, 347–357, 1951.

Leopold, L. B., and T. Maddock, Jr., The hydraulic geometry of stream channels and some physiographic implications, *U. S. Geol. Surv. Prof. Paper 252*, 57 pp., 1953.

Mackin, J. H., Concept of the graded river, *Bul. Geol. Soc. Amer.*, **59**, 463–512, 1948.

McDougal, D. T., Botanical features of North American deserts, *Carnegie Inst. Washington Pub. 99*, 1908.

Musgrave, G. W., The quantitative evaluation of water erosion—A first approximation, *J. Soil Water Cons.*, **2**, 133–138, 1947.

Smith, T. G., Forage conditions of the prairie region, *U. S. Dept. of Agr., Yearbook*, 1895.

Weaver, J. E., Plant production as a measure of environment, *Carnegie Inst. Washington Yearbook 22*, 1923.

Wilm, H. G., and E. G. Dunford, Effect of timber cutting on water available for streamflow, *U. S. Dept. of Agr. Tech. Bull. 968*, 12–14, Nov. 1948.

Yarnell, D. L., Rainfall-intensity frequency data, *U. S. Dept. Agr. Misc. Pub. 204*, 67 pp., 1935.

U. S. Forest Service, Basic forest statistics of the U. S. as of Jan. 1945, Sept. 1950.

U. S. Geological Survey, Washington, D. C. (W.B.L.) and U. S. Geological Survey, Denver Federal Center, Denver, Colorado (S.A.S.)

(Communicated manuscript received April 25, 1958.)