Land Use and Sediment Yield

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INTRODUCTION

When the vegetal cover is removed from a land surface, the rate of removal of the soil material, at least initially, increases rapidly. So well known is this principle that it hardly needs restatement.

If attention is focused on any individual drainage basin in its natural state, large or small, and inquiry is made as to the rate of denudation, a quantitative answer is not easily obtained. The possible error in any computation of rate of sediment production from any given drainage basin is considerable. Significant variations are found in sediment yields from closely adjacent watersheds which appear to be generally similar. To make a quantitative evaluation of the change in the rate of denudation when the natural vegetation is disturbed is, therefore, even more difficult. Considering the fact that "soil conservation" has been promoted to the status of a science, our lack of ability to answer what is apparently so simple a question may seem surprising. Let us look at some of the reasons.

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METHODS OF MEASURING EROSION RATE

Sheet erosion cannot be accurately measured by observing directly the gradual lowering of the ground elevation as a function of time. The lowering is not areally uniform; on a microscale, erosion here is offset by deposition there. The process is slow in terms of a man's span, even in a badland area (King and Melin, 1955). To judge the amount of erosion in terms of loss of a certain portion of a complete soil profile supposed to have originally existed is crude at best (though widely employed) and hardly satisfies the desire for an objective, quantitative measure.

To measure rate of degradation of a landscape by gully erosion through computation of the volume of the gully network is possible, though few good data exist. But such estimates are plagued by the importance of local deposition (temporary storage) of the eroded material in fans near the mouth of the gully (Hadley, 1954). Furthermore, there is no assurance that at least some of the gullies did not exist prior to the beginning of the period under consideration. Leopold and Miller (1954) have emphasized that many gullies in Wyoming which appear to have been formed since the opening of the West are in fact at least pre-Columbian and may be several thousands of years old.

It is theoretically possible to estimate net rate of removal of soil material from a watershed on the basis of the sediment load of the main stream draining the area. But present techniques are adequate to measure only the suspended portion of a stream's load, and then only if the material is not coarser than sand. There is no practical method at present for measuring that part of the load moving along or close to the bed of the stream. Though the suspended portion of the sediment load may constitute three-quarters or more of the total debris in many streams, the suspended load is still only a portion. The load of gravelly streams cannot be accurately measured in the channel at all.

The rate of sediment deposition in a reservoir provides the best measurement of total load and, therefore, of average denudation rates. Though some suspended sediment does not deposit in the reservoir but passes through the gates or over the spillway, this spill usually can be estimated with an accuracy commensurate with that of other necessary measurements. Currently, some four hundred reservoirs in the United States have been surveyed and have ranges established for resurvey. But this number is hardly adequate to describe the diversity of watersheds in the river basins of the United States. Moreover, reservoir surveys do not furnish information on the relative amounts of debris from various parts of the basin upstream.

Excellent measurements of rates of soil loss are available from experimental plots and watersheds, but the data cover only a small fraction of the many possible combinations of soil type, slope, and vegetal cover. Moreover, it is very difficult to extrapolate from the measurements on small areas to large natural drainage basins.

The scope of the available experimental data dealing with the interrelation of vegetation, soils, rainfall, runoff, and erosion may be judged from a review of federally sponsored research. This represents not all, but the major portion, of such experimentation. A recent survey (Leopold and Maddock, 1954) showed that investigations by federal agencies included work on about 1,700 experimental plots and on some 560 natural watersheds, together comprising 464 experiments. Of the total, 86 per cent of the experiments dealt with areas of less than 100 acres in size. Such experiments provide a quantitative measure of the effect of particular vegetal changes on sediment production only in similar watersheds of like size.

Rate of degradation of a landscape is not measured solely by the movement of discrete particles of debris, for the constituents dissolved in the runoff water may be a significant part of the whole. Measurements of reservoir sediment deposits do not include the dissolved fraction.

Clark (1924) estimated that the annual rate of chemical denudation in the United States is approximately 100 tons per square mile, though this figure needs revision on the basis of new data. From fifty representative records of sediment yield in the United States, chosen by Glymph (1951, Table 1), the median value was 900 tons per square mile annually. It appears from this rough comparison that chemical degradation may be of the order of 10 per cent of the total. In the Wind River Basin, Wyoming (Colby *et al.*, 1955), the dissolved load of streams constitutes about 13 per cent of the total dissolved and sediment load. It is possible that dissolved loads may be more important in landscape reduction than indicated by Glymph.

Changes in water quality as a result of successive use by irrigation are well known, and in the Wind River Basin, for example, Colby *et al.* (1955, p. 192) believe that irrigation "is greatly accelerating the normal processes of erosion and transport of water-soluble minerals from the Wind River formation, alluvial terraces, and associated soils." Such effects of human activity generally apply to only portions of the drainage basin. We are forced, however, from both lack of data and lack of personal knowledge, to restrict the present discussion to landscape degradation products carried by streams as sediment.

EFFECT OF HUMAN USE

The relative extent to which human use has increased sediment yield probably varies inversely with the rate of the original yield. This is suggested by measurements and appears logical from general considerations. Brune's (1948) estimates of increase for areas in the north central states are much larger than those of Rosa and Tigerman (1951) for areas in the Colorado River Basin. The eastern edges of the prairie and the hardwood associations of the upper Mississippi were originally characterized by nearly complete vegetal cover, whereas large areas in the West and Southwest included badlands, poorly vegetated scarps, and generally low vegetation density. The well-vegetated mountain areas, though contributing most of the water, comprise only a minor part of the total drainage area.

The presettlement sediment yield of drainage basins in the West is particularly difficult to evaluate. The original density of vegetation in woodland and semidesert shrub association was characteristically low even in presettlement times. However, this low density need not necessarily be interpreted as coincident with high sediment yield. The species composition now extant is often quite different from that originally found over great areas, even where vegetation *density* has not changed appreciably. Furthermore, in the Southwest the relatively good observational record of early American exploration came only after two centuries of land use by the Spanish (Leopold, 1951). The Spanish were poor observers of natural history, and their records are of little use in reconstructing original conditions.

There are but few good accounts of vegetation as it affects sediment yield in areas essentially untouched until white exploration. The Lewis and Clark journals are among the best. From them we learn that the Missouri was certainly high in sediment load. But even the best expedition accounts do not provide a clear picture of where the sediment originated. Bank-cutting on the Missouri was described as an active source, but bank-cutting is usually a process of sediment-trading—erosion in one place and deposition in another.

Even in Montana, where vegetation on the plains areas is generally far more dense than that in comparable topography of the Southwest, Lewis and Clark (Coues, 1893, p. 347) made the following observation near the foot of the Bear Paw Mountains:

> A high, level, dry, open plain . . . [constitutes] the whole country to the foot of the mountains. The soil is dark, rich, and fertile; yet the grass is by no means so luxuriant as might have been expected, for it is short and scarcely more than sufficient to cover the ground. There are vast quantities of prickly-pears, and myriads of grasshoppers. . . .

In the same place during a rain, they observe (*ibid.*, p. 348) that they

> found the bed of a creek 25 yards wide at the entrance, with some timber, but no water, notwithstanding the rain. It is indeed astonishing to observe the vast quantities of water absorbed by the soil of the plains, which, being opened in large crevices, presents a fine rich loam.

A thorough review of the methodology and of the results of attempts to determine the total sediment yield from natural watersheds would be out of place in the present discussion. A few examples will, however, provide some picture of the difficulties involved and the possible order of magnitude of the effect of human activities on land degradation.

One technique is illustrated in a study by Brune (1948), using primarily rates of accumulation of sediment in reservoirs. By modifying these results with supplemental suspended sediment records and experimental data from plots and small watersheds, Brune derived figures on the rate of annual sediment movement from some particular drainage basins of various sizes. It is generally recognized that the sediment yield is a function of drainage-basin size even in an area of relatively uniform characteristics. But the figures on sediment yield for basins of a given size in the Brune study showed a variation of approximately a hundred times between minimum and maximum sediment yield. He attempted to relate this variation to land use as well as to physical characteristics of the individual basins. The first step was to segregate the data in terms of land use. Three categories were used to represent the percentage of the drainage area which was in cultivation. An adjustment for effect of soil type, degree of slope, length of slope, and type of rotation was made on the basis of a somewhat subjective classification of the whole area into zones chosen to represent relative uniformity in respect of these variables. A further step was to apply a factor to the sediment yield to represent the mean annual runoff.

On the basis of such analysis, Brune showed that on the average, for a drainage area of 100 square miles, in north central United States, as an example, basins within which one-third of the total area is cultivated or "idle" are characterized by a long-term sediment concentration in runoff equal to .015 per cent by weight. He concluded that the concentration is increased by six and one-half times when cultivated and "idle" land represents one-third to two-thirds of the drainage area. It is increased by thirty-five times when more than two-thirds of the drainage area is cultivated or "idle." Brune estimated that the present rate of sediment production in the Ohio and the Great Lakes drainage basins is roughly fifty times the geologic norm. He stated further (*ibid.*, p. 16) that "in the upper Mississippi River drainage basin where about 42 per cent of the land is now cultivated or idle, the present rate of sediment production and erosion is approximately seventy-five times the geologic norm."

Another approach to the problem is illustrated in a study by Gottschalk and Brune (1950). A multiple correlation was used to express the relationship between total sediment accumulation in a reservoir (considered a dependent variable) as a function of net watershed area, age of the watershed in years, rate of gross erosion, and the ratio of reservoir capacity to watershed area. The regression is greatly influenced by the value of the parameter used to represent the rate of gross erosion. Estimates of this factor were obtained by adding results of two kinds of measurements. Gully erosion was determined by field observations, using rate of gully development measured on successive aerial photographs. Sheet erosion was estimated by an empirical interrelation among average length of slope, average degree of slope, and type of cultivation, based principally on the results of plot and small-watershed experimentation.

The nature of the problem unfortunately necessitates this kind of roundabout analysis. Any studious attempt to correlate the many variables is commendable; nevertheless, we should not gloss over the fact that the results obtained can be considered nothing better than general approximations.

Still another type of methodology is illustrated by the study of Rosa and

Tigerman (1951), who attempted to estimate the sediment contribution from various portions of the Green and Colorado drainage basins. These workers began by restricting their attention to surface runoff from storms, separating out base flow. The sediment load obtained from daily averages of suspended sediment was correlated with mean daily discharge during the passage of individual hydrograph rises. Using forty such flood occurrences, a relation between sediment load and daily discharge was derived. For a given discharge the sediment load was then correlated with vegetal cover types on the watershed to which approximate values of cover condition had been assigned. It was found that there was good agreement between the estimates of sediment yield so derived and estimates based on a subjective classification map of erosion conditions compiled from general field observation. The same authors studied six small drainage basins which had different vegetal covers under varied land use. The watersheds were mapped and categorized by subjective field observations which attempted to take into account vegetal cover, erosion, soils, slope, and other factors. Sediment measures so derived were compared with analyses based on suspended-load sampling in the Boise River Basin.

Rosa and Tigerman made further comparisons with measurements on the amount of sheet erosion from infiltrometer studies where water is sprinkled onto plots varying in size from 12 by 30 inches to 6 by 12 feet. They concluded (*ibid.*, p. 17) that "if all watersheds could be improved from fair to a good condition [of vegetal cover], sedimentation rates might be expected to be reduced to about one-half of the present rate from large drainage basins. . . . If it were possible to restore all poor watershed areas to a good condition the future sedimentation would be only one-third to one-fourth the existing rate." It should be realized, however, that such a statement can apply only to areas of uniform characteristics.

Experimental data indicate that changes in land use have a greater effect on sediment yield than on either total runoff or runoff intensity (Leopold and Maddock, 1954, p. 81). Yet it must be admitted that available data do not permit quantitative generalizations about the effect of human activity on landscape degradation. Both cultivation and grazing have, without question, for a time increased sediment yield over that obtaining in the natural or original condition, but the amount is variable and highly dependent on local conditions.

This cursory description of attempts to generalize relations of geology, topography, vegetation, and climate to sediment contribution can do no more than indicate the complexity of the problem. All the methods used are, basically, forms of correlation between observed sediment yields and several controlling factors. In any such correlations an unexplained variance remains, and this margin of error may be quite large. It is clear, therefore, that any attempt to estimate the change in sediment yield resulting from a change of the controlling variables depends for validity on the relative magnitude of the anticipated consequences of and the error inherent in describing the original condition.

The preceding discussion dealt with the problem of ascertaining the present rate of sediment production from natural watersheds. To summarize, one of the most satisfactory methods of measuring sediment yield consists of successive measurements of deposition in reservoirs adjusted for outflow of sediment on the basis of suspended-load measurements. Such measurements are available on only a small number of streams relative to the total number in the continent. The values of sediment yield may vary markedly even between basins which superficially appear similar. Some of this variation can be quantitatively accounted for by differences in type and condition of plant cover, soil, slope, and other factors. This variability, however, causes most estimates of sediment yield under virgin conditions to be quite imprecise. It is difficult, then, to know how much reliance may be placed on the computed values of sediment yield under virgin conditions. Subject to this error, the magnitude of which is unknown, the estimates available indicate that in the areas for which studies have been made human activity has increased sediment production from as little as twice to as much as fifty times the original value. These figures are meant only to indicate orders of magnitude.

EVALUATION

With this background in mind, let us examine some of the over-all implications of changes in sediment yield.

The first and most obvious economic reason for an interest in sediment yield relates to erosion on the land. So extensive is the literature on this subject that no review is attempted here. In the present context the rate of sediment removal from a watershed should not be assumed to be in direct ratio to loss of land productivity. Crop yield as it is affected by soil removal is also distinct from loss of "irreplaceable" topsoil. Baver (1950) provided a commendable way of thinking about the erosion problem when he indicated that some topsoil is replaceable. The seriousness of a given amount or rate of erosion depends on the thickness of the regolith, the kind of rock from which it is derived, and the profile characteristics—in other words, on many local factors.

That soil erosion tends to reduce soil productivity is not disputed. Gully erosion may in many places be of even greater importance than sheet erosion by reducing channel storage of runoff water and by the physical dissection of arable land. It is generally believed that sheet erosion is more important, on the average, as a sediment source than is gullying.

No extensive comment is necessary on the effects of reservoir sedimentation. The recent survey of sediment deposits in Lake Mead showed that in the first fourteen years of operation sediment deposits comprised 5 per cent of the reservoir capacity below spillway-crest elevation. The sediment weight is computed to be about two billion tons (Gould, 1951). A particularly interesting result of this survey was the information that about half of the weight of sediment deposit, or 64 per cent of the volume, consists of fine-grained material transported by turbidity currents. This indicates the importance of the fine-grained portion of the total load. Again, we can merely speculate on the question of whether soil erosion which results primarily from human use would result in increased or decreased percentage of a particular size fraction of the load.

The Lake Mead survey provides a specific example of the difficulties in interpretation of reservoir accumulation data. The allocation of the sediment to various portions of the upper Colorado Basin can be made only roughly, and it is virtually impossible to ascertain what percentage of the measured sediment yield can be attributed to effects of land use. Methods such as those described earlier represent the only available bases for estimating this quantity.

RELATION OF CHANGES IN SEDIMENT LOAD ON RIVER CHANNELS

The literature on rates of reservoir sedimentation is extensive. The economic aspects of this problem are patent.

I wish to direct attention to an aspect of the effects of sediment yield which is less well known and more speculative than the problems of accelerated erosion and reservoir sedimentation. This is the change in stream channels produced by change in sediment yield. The river channel is constructed by the river itself. The channel system is the route by which runoff and erosion products are carried from the land to the ocean or to some intermediate basin. As such, it is logical to suppose that any channel system would be of such configuration and size that it is capable of performing this function. Considerable speculation has been directed at the question of how efficient the channel net is for this function. Natural channels generally have a larger width-to-depth ratio than a semicircle, which is known to be the most efficient hydraulic cross-section for discharge of water. The fact that natural channels carry erosion products, as well as water, appears to be the underlying cause of observed channel shapes.

Increasing attention recently has been devoted to the problem of explaining river-channel characteristics. Studies of channels in general led to the conclusion that a quasi-equilibrium tends to exist between the discharge and sediment load emanating from a drainage basin and the natural channel which carries these products (Leopold and Maddock, 1953). Detailed study of a channel system of a single drainage basin confirmed this generalization and demonstrated that such quasi-equilibrium tends to characterize small headwater tributaries in youthful topography as well as the major stream channels (Wolman, 1955). A generally similar tendency for quasi-equilibrium was shown to typify even ephemeral headwater channels and rills in a semiarid area (Leopold and Miller, 1956).

The river flood plain is a particularly important feature in the equilibrium picture. The level area bordering a stream is built by the stream itself and at such a level that it is overflowed during high stage. Of greatest interest is the concept that the frequency of such overbank flow is essentially constant for small rivers and large ones in the same basin and between rivers of different basins (Wolman, 1955; Wolman and Leopold, 1956). This similarity in frequency of overflow of the flood plain, which in essence is also the frequency of the bankfull stage of the river, is a consequence of the characteristics of sediment load and sediment action in flows of various magnitudes. Small flows carry small sediment loads and are essentially ineffective in scour and deposition. The greatest floods are the most effective in shaping the channel and altering existing shape, but these extreme flows are so infrequent that, in the long run, they are less important than the lesser floods. The level of the river flood plain is, therefore, controlled primarily by floods of such magnitude that they are capable of significant erosion and deposition but still frequent enough to have cumulative effects of importance. This combination appears to characterize flows of that magnitude which recur about twice each year (Wolman, 1955; Wolman and Leopold, 1956).

This apparent consistency in the recurrence interval of bankfull floods in combination with the concept of a river channel in quasi-equilibrium lead to a provocative hypothesis: If a change occurs in the relation of sediment yield to water discharged from a drainage basin, forces exist which would, over a long period, tend to readjust the height of the flood plain, so that the frequency of the flood stage would remain constant. If activities of man, therefore, tend to increase markedly the sediment yield relative to discharge characteristics of a drainage basin, the river channel will, given sufficient time, adjust its channel in such a manner that floods over the flood plain will recur at about the same frequency which originally prevailed.

This concept has its first and primary application to the field of flood control through land management. Programs for land-use improvement generally anticipate marked reduction in sediment yield from a drainage basin. It should be expected that a consequence of this reduction of sediment would be a channel readjustment. This readjustment may be such that overbank floods do not, in the long run, occur any less seldom than originally.

However, man's work directly on river channels has been and probably will continue to be a far more important determinant of future channel conditions than the natural operation of river mechanics in response to man's changes on the watershed. It is probable that long before the effects of the latter can occur, river conditions will have been so altered by dams that the latter will be the primary factor in controlling river-channel characteristics. The degradation of the channel of the Colorado River after the construction of Hoover Dam is a well-known example of one type of change. There will probably be extensive changes of a more subtle nature distributed widely over rivers in this country as the dams, already planned, are built. Bank-cutting, channel-shifting, and other effects not so obviously connected with reservoir construction as bed degradation should be expected. In the Mississippi Basin alone ninety-six new dams are contemplated even at this time (Leopold and Maddock, 1954). This figure indicates the trend in river work. This trend can probably be expected to continue at least until the best reservoir sites have been utilized and for as long as there remains economic justification for hydroelectric and irrigation development.

Projects are considered justifiable, under present laws, if the computed benefits exceed the costs. Most projects will yield benefits equal to costs during their economic life, but there will come a time when great lengths of major river valleys will consist of reservoirs more or less filled with sediment. When that time comes, the problems of water control and of water use will be of a distinctly different character from those which concern us today, though this will not occur until several generations hence.

SUMMARY

In summary, then, we may conclude that man's use of the land can have a marked effect on sediment yield. Because of the difficulties of measurement of the initial conditions, it is extremely difficult to evaluate quantitatively this effect. Although increased erosion affects soil productivity, this effect is influenced by many variables in the dynamics of soil formation. The effects of high sediment yields on reservoir capacity are well known and have obvious economic implications. Less well known are the effects on river channels of changes in sediment yield. The present trend is toward ever increasing numbers of dams on the rivers of the United States. The effect of these structures on changes in the channels greatly overshadows the effects due to varying proportions of sediment to water produced by man's use of the land.

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