# Looking Toward a Quantitative Geology

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For a good many years geologists have been assuming that rock A was resistant and that strata B was erodable. Such an assumption is probably not open to serious question. But we have never been able to say with any certainty *how much* more erodable strata B was than A. This desire for quantitative measures in geology, particularly in relation to erosion, is no new thing. Indeed it seems to have been almost as old as the science itself.

Now desire is becoming a need. Erosion has ceased to be merely an academic study. It has become a threat to our welfare. No one can travel without seeing that fields are losing their fertility and many are turning into gullies. A quantitative geology that can be applied to the control of gullying seems to be developing. But a quantitative geology that is applicable to the morphology of streams in general is still in the distant future.

**Purpose of this report.** It is the purpose of this report first, to review the literature on the quantitative aspects of stream work as it has come to the attention of the writer; second, to attempt to outline the difficulties that confront the student attempting a quantitative geology, in so far as a review of he literature permits; and finally to suggest additional means of approach to the problem.

## Previous Work

There have been two groups of workers that have attacked the problem of how much erosion water can do, the geologists and the hydraulic engineers. Studying their work one is inclined to paraphrase the late Peter Cunne's "Mr. Dooley" who, commenting on the care of the sick by Doctors and Christian Scientists remarked, "If the Doctors had a little more Christianity and the Christian Scientists had a little more science, t'would make no difference who you called, provided you had a good nurse." Similarly one wishes the geologists had a little more engineering and the engineers a little more geology.

## Various Geologic Approaches

One approach to the problem of how much a stream erodes is continued observation over a period of years. Thus Dreyer and Davis[1] reported in the Proceedings of this Academy on the work done by a normal brook in thirteen years.

They listed the disappearance of islands, the cutting off of an oxbow, and lateral erosion, thus making "a broad flood channel". No estimates of the amount of material actually transported are offered.

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[1] Dryer, Chas. R., and Davis, M. K. "The Work Done by a Normal Brook in Thirteen Years." Proc. Ind. Acad. Sci., **20**:147-152. 1910.

The Culbertsons[2] also offered a paper before this Academy that dealt with the retreat of Clifty Falls. Their studies take no account of various factors of stream flow; volume, velocity, etc., but show what has been done by a stream in cutting back a falls over a period of years.

Speaking of falls, none has been more intensively studied than Niagara. Camera lucida sketches were made as early as 1827 and surveys have been made repeatedly since 1842. Estimates based on this work give a present rate of recession of $\frac{7}{10}$ mile per year, "but involve uncertainties that make the figure unreliable."[3]

In this same category of what I term in my own mind the "historical approach", is an article by Ireland[4] in the Journal of Geology in which he describes how erosion over a period of 100 years developed a gully of truly stupendous proportions. But here, as in the work of the Culbertsons, hydraulic data is limited.

Quite a number of similar studies are found in the literature. They are open to the criticism that they do not consider the hydraulic factor in sufficient detail to offer a basis for generalization.

A different geologic approach is the consideration of deposition as a measurable factor. The work of Antevs[5] is a case in point.

If we accept the fundamental premise of the seasonal nature of banded clays we have a record of many centuries of deposition. Moreover, if later discoveries[6] are incorporated with Antevs' work the areal extent of such deposition can be determined. We are, however, strictly limited in even the inferences that may be drawn as to the nature of the streams that caused the deposits.

From the point of view of developing a quantitative study, the work of Brown[7] is of greater value. His "Studies of Reservoir Silting", while little more than a preliminary notice of what is to be done, suggest that when observations have been made over a period of years we may actually know how deposition occurs.

Silting study is a Soil Conservation Service project and hence under federal supervision. We can only hope that such a worthy work can be continued during and after these war years.

Silting has also been approached from another direction by Brown and others. Brown has reported on "Silt Measurements During a Potomac River Flood."[8] This brief note gives a definite estimate (7,200,000 cu. ft.

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[2] Culbertson, J. Archer. "Further Observations of the Erosion of Clifty and Butler Ravines, Jefferson County, Ind." Ind. Acad. Sci. Proc. **37**:117-120. 1927. This paper summarizes a previous paper by the author's father covering observations begun in 1897.

[3] Schuchert, C., and Dunbar, C. O. "Textbook of Geology, pt. 2 Historical Geology." John Wiley and Sons, 1941, p. 438.

[4] Ireland, H. A. "Lyell" Gulley, A Record of a Century of Erosion. Jour. Geol. **47**:47-63. 1939.

[5] Antevs, Ernst. "The Recession of the Last Ice Sheet in New England." Am. Geog. Soc. ser. No. 11, New York, 1922.

[6] Flint, R. F. Glacial Geology of Connecticut." Conn. Geol. and Nat. Hist. Survey, Bull. 47. 1929.

[7] Brown, Carl B. "Studies of Reservoir Silting." Soil Conservation **1**:1-5, 14. 1936.

[8] Brown, Carl B. "Silt Measurements During a Potomac River Flood." Soil Conservation **7**:14. 1936.

per hour) for the rivers silt bed. The author believes this to be low rather than an excessive estimate.

The most complete study of silting that has come to my attention is that of the New River Watershed.[9] There are four reservoirs on the New River, the oldest of which was 33.5 years at the time the study was made. These reservoirs have not retained all the sediment carried by the New River, but certainly during the earlier years they must have been very effective in settling the mechanical load of the river.

Be that as it may, the average annual accumulation per acre of drainage area is determined. The nature of the sediment is described as to size, color, and composition. The vegetable cover of the watershed is noted. Furthermore, though not considered by Brown and Barnes, hydraulic data are available for the river, as the U. S. G. S. maintains a gauging station at Ivanhoe on the New River. Reports from the station give a clear picture of amount, intensity and distribution of rainfall and flood waters. It would seem that here we have many of the variables measured and that a coherent picture of the rate and way of erosion can be determined. Such is the case as it applies to the New River. However, it is not yet possible to apply the results of these observations generally.

## The Hydrodynamic Approach

Present day consideration of the way a stream carries debris as well as the amount carried is founded on the work of Gilbert.[10] He gave us the concept of suspended and tractional load, as well as the concept of competent slope and competent discharge. Turbulence as a means of lifting the suspended load of a stream was not recognized as such; though a result of turbulence—the rippling of any surface of discontinuity—was described as the "rhythmic forming of dunes."

Furthermore, a series of equations for capacity, that is the maximum load of a given kind of debris which a given stream can transport, in relation to slope (defined in per cent grade), discharge (cubic feet per second), and fineness (computed as a function of both the mean diameter of the particles and the number of particles in a unit volume of debris), is set forth. The equations all fall in the same form, that is $C = k(F\text{-}f)^n$, letting C equal capacity, F equal the factor in question (slope or discharge or fineness), f equal the competent factor, that is a limiting value below which movement does not occur. In any series of observations k, n are constants found empirically and varying widely. Thus in the slope formula, k constant, n varied from .93 to 2.37, "values being greater as discharges are smaller or debris coarser." Similarly in the discharge formula n varied from .81 to 1.24, "values being greater as slopes are smaller or the debris is coarser." In the fineness formula n varies from .50 to .62, "values being greater as slopes and discharges are smaller."

[9] Brown, Carl B., and Barnes, F. F. "Reservoir Silting in the New River Watershed." Soil Conservation **2**:95, 106-107. 1936.

[10] Gilbert, G. K. "Transportation of Debris by Running Water." U. S. G. S. Prof. Paper 86. 1914.

It is this important parameter (n) that has been the stumbling block in any application of the formulae to natural streams and has been a challenge to all subsequent students.

Gilbert also finds that capacity varies as the 3.2 to 4th power of the mean velocity, values of the power "being greater as slope, discharge and fineness are less."

Of these later works which have come to my attention, that of Leighly presents most clearly the reasons for questioning the capacity-velocity relation of Gilbert. Leighly[11] shows by observation and equation that there are three parts in a stream. Region 1 is an axial region of maximum velocity and moderate turbulence, and contains only such silt as is diffused to it from adjacent regions; in other words low to moderate silt load. Part 2 consists of two flanking regions each side and below region 1. Here turbulence is high, velocity moderate, and suspended load greatest, the maximum load within this region being below and to each side of the axial region. Part 3 consists of two lateral regions lying beyond the flanking regions and impinging on the sides and bottom. The lateral region has low turbulence and low velocity. It receives suspended material from the flanking region but tends to deposit it. The flanking area is apparently one of high silt concentration and low velocity.

The theoretical and mathematical aspects of Leighly's paper are considered by O'Brien, whose findings tend to confirm Leighly's. O'Brien[12] is, however, careful to add that further observations are required to establish a sound basis for calculations.

Just how necessary such qualifications prove to be is brought out by a report of Love[13] on suspended matter in small streams. First of all, it appears that a few days of high water carry most of the load of a stream. Second, it appears that during one period of flood the West Fork of Deep River near High Point, N. C., showed a load of 100 tons per hour suspended matter at discharge rates of 470, 670, 900 sec. ft. Worse still, spring and fall high water on the same stream showed different loads at the same discharge rates. A falling stream characteristically showed a lighter load than a rising one at the same discharge rate. That is, a small stream is cleaned out by a vigorous flood. Less is then carried until a new supply of debris accumulates. The mathematical approach has to date ignored this fact, so far as I have been able to discover.

So much for hydrodynamics. Let us now look at the last and probably most expensive field of study of this problem of erosion, the use of scale models.

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[11] Leighly, John. "Turbulance and the Transportation of Rock Debris by Streams." Geog. Rev. **24**:453-464. July, 1934.

[12] O'Brien, M. P. "Notes on Transportation of Silt by Streams." Am. Geophys. Trans. **17**:431-436. 1936.

[13] Love, S. K. "Suspended Matter in Several Small Streams." Am. Geophys. Union Trans. **17**:447-452. 1936.

## The Terrain Model Approach

The use of scale models[14] constructed of material taken from the area being studied, or of material believed to be erodable in some ratio to that of the area represented, seems to have been practiced extensively by the Germans. One meets numerous references to their findings in most theoretical reports. During the past decade the Corps of Engineers, U. S. Army, have constructed numerous models in connection with channel and silt control of the Mississippi and Columbia Rivers, as well as harbor works on our east and west coasts.

Reports on much of this work have not been made available to the public by the U. S. Engineers. Fortunately a report by Vogel[15] of the Waterways Experiment Station, Vicksburg, Miss., gives a clear picture of the set-up and working of these models. The models are made with considerable distortion of vertical to horizontal scale. In a model described, horizontal scale was 1/1000 while vertical was 1/125. Further, the erodable material composing the bed of the model is not necessarily the same as that of the stream being studied. Vogel further points out that if the exaggerated slopes of the distorted model are not sufficient to make streams flowing over the model assume the velocities desired, the model is further distorted by tilting the whole thing.

In defense of these models it can be said that these distortions are held in a logical mathematical relation and the relation of the force required to move one kind of material to that force required to move another is predetermined by flume observations.

So far as I can discover, no effort has been made to apply the specific studies of small areas of stream to the larger field of morphology of the river; and properly not, since it has always been a fallacy to argue from the particular to the general. The usefulness of the model lies in the fact that here we have a way of controlling the many variables in erosion, so that the effect of each may be determined separately, though the combined effect may not be—in fact is not—a simple summation.

The criticism of models as a means of learning about erosion seems to be chiefly that *runs* over the model are usually just long enough to determine whether or not a specific change in control works will produce the effect desired. They have been used, as some author puts it, as a way of solving the complex mathematical equations involved in the play of natural forces in an area. Is that a way of saying that the model is a means of taking care of the unknowns in the complex mathematical equations, without which the equations are unsolvable? It is the unknown factor, not the known, that prevents our progress towards a quantitative geology.

## The Difficulties Involved

**Laboratory Control.** The laboratory study of stream erosion as exemplified in the bed-model just described is confined to study of limited areas and specific problems connected with stream control within

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[14] The earliest use of hydraulic models seems to have been by Osborne Reynolds in 1885 for the development of regulating works along the Mersey.

[15] Vogel, Herbert D. "Movable Bed-Models." Am. Geophys. Union. Trans. **14**:509-512. 1933.

the limited area. It does not give an over-all picture. Indeed, findings in connection with a particular stretch of river are not applicable to another area of river even a short distance away, much less to rivers in general.

**Factors Involved.** Little is known of the factors involved in erosion. Nichols[16] considers that "The whole field of the hydraulics of erosion is practically untouched". In this he includes entrainment, bed load, suspended load, sorting and deposition. H. H. Bennett[17] comments even more strikingly on the variable when he says, "Not only are the interdependent processes of absorption, run-off, and erosion profoundly affected by slope, climate, soil, and cover of vegetation and vegetative litter, but by the condition of the surface soil resulting from various methods of utilization, and, subsequently, by the condition and character of the different sub-layers successively exposed by planation. These and other factors introduce . . . . an almost inconceivable number of highly pertinent variables."

It is the lack of knowledge of these variables that inhibits our progress toward a true understanding of the quantitative aspects of erosion. Nowhere can one find a comprehensive summary of the known factors. Data on run-off is assembled by one group, that on soil loss by another, while yet a third gathers information on the silting of reservoirs. Moreover, few if any of these studies are undertaken on a long period basis. Weather bureau studies are just beginning to bear fruit after 80 years of observation. And while one would not say that meteorology is less complex than geology, certaintly it is not more so.

Specifically, it seems to me that there are certain details of erosion that are especially lacking. For example, the relation of stream load to velocity is subject to much mathematical speculation by relatively little actual measurement of samples, due to the expense of analysis. The concept of the overloaded stream has been invoked to explain certain phenomena. Apparently we need the concept of an underloaded stream as well. Is this an explanation of the very swift, often crystal clear, mountain stream? If so, what does it mean to the overall picture of erosion? We are woefully lacking in knowledge of what part of the stream does the major part of the carrying of either suspended or traction load. In fact, are these separate or gradations of a single process?

It is perhaps presumptuous to attempt to enlarge on the variables involved in the erosion process beyond what has already been offered. Nevertheless I shall attempt to set before you a systematic arrangement of what is known.

A stream can do three things; corrode and corrade its bed, transport its load. These acts are in some mathematical relation to the stream's velocity. Though what that relation can be in view of the work of Love[18] is difficult to see.

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[16] Nichols, Mark L. "Research Problems in Conservation Engineering." Soil Conserv. 5:183-185. 1940.

[17] Bennett, H. H. "Dynamic Action of Rains in Relation to Erosion—etc." Amer. Geophys. Union. Trans. 15:474-488. 1934.

[18] Loc. cit. p. 6

Velocity varies in some relation to the slope, volume load, and bed form. Each of these in turn have variables that affect them, which we can briefly enumerate in outline and without discussion. Slope is not merely a matter of degrees inclination from the horizontal but involves also length, roughness, vegetation, and material (i.e., soil, gravel, rock, etc.). Volume depends on precipitation with intensity, total amount, seasonal distribution, state—i.e. snow or rain, and evaporation as factors. The effect of volume further depends on absorption by soil, by vegetation with its attendant litter, and slope. Finally volume is a relative term, dependent on cross-sectional shape and capacity of the bed. Load factors are debris fineness and available amount, turbulance—both self generating as evidenced by ripples, and that induced by bed irregularities—, depth of water, and volume. Bed-form factors are cross-sectional shape, roughness, sinuosity, and are related in turn to slope and volume and load. In each of these categories there may be additional unknown and known factors. But at least this outline serves as a guide and suggests the great complexity of the problem.

One need not consider that this problem of a quantitative geology is so complex as to be unsolvable. However it is doubtful whether an individual in a lifetime could assimilate all data now available. As a group project it would not present unsurmountable difficulties. Certain data are needed, particularly in relation to varying loads in the different parts of a single stream, as well as a continuous record of sediment transported past some point determined as average for the stream. This we can now consider.

## A Means of Approach

The Geological Survey maintains a host of gauging stations recording the run-off of streams. At these stations are current meters which give us continuous records of stream flow past the point of observation. At some stations silt samples are collected at various times and analyzed. At a few stations aliquot samples of water are taken continuously and the silt load determined. This does not seem sound. The aliquot sample requires the drawing off of water from the side of a flume. It may or may not represent an average. The same is true of other sampling methods.

It is therefore suggested that a device be designed by which a continuous record of silt load may be recorded. Furthermore this device, like a current meter, should be designed to record at varying depths and distances from shore.

It is to be regretted that details of this device cannot be offered at this time, but war work and other demands upon the time of the laboratory that has agreed to assist in the design of the apparatus has delayed making it.