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Techniques and interpretation: The sediment studies of G. K. Gilbert

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ABSTRACT

The laboratory experiments on sediment transport conducted by G. K. Gilbert differed importantly in technique from such studies of more recent date. Gilbert's flume was level and could not be altered in slope. Sediment was introduced at the upper end at a predetermined rate and by deposition built a bed gradient sufficient to transport the introduced load. The adjustment of slope in Gilbert's flume has contributed to the idea widely held by geologists that a river achieves equilibrium by adjusting its slope to provide just the velocity required for the transportation of the supplied load.

In fact, slope adjusts but little to a change in amount of introduced sediment load. The adjustment takes place principally among other hydraulic factors: width, depth, velocity, bed forms, channel pattern, and pool-riffle sequence. Gilbert sensed this complicated adjustment process, but its details are as yet only partially known in quantitative terms.

FLUME OPERATION

One of the most often referenced papers in the large literature on sediment transport is the famous U.S. Geological Survey Professional Paper 86 (Gilbert, 1914) in which Grove Karl Gilbert presented his data on the experiments in sediment transport. Interestingly, although this paper is probably quoted in references more often than nearly any other paper on the general subject, few people seem to have read it carefully. It is true that the analytical part of this long document is complicated, and the approach reflects the fact that at that time many things that are now taken for granted were not known.

The part that is probably not well understood concerns the implications of the methodology used by Gilbert in running the experiment. The most important aspect, and that which seems to be most overlooked, is the fact that his flume was built with a constant slope, a practice that differs from that of modern experimenters who use a more complicated flume in which the slope can be adjusted. The floor of Gilbert's flume was level, and the sideboards that formed the banks of the channel were high near the upstream end and decreased in steps toward the downstream end (see Pyne, this volume, Fig. 4B), Sand progressively built up in the trough, thicker upstream than downstream, until the bed acquired a slope sufficient for the transport of introduced sediment. Discharge was specified, and Gilbert controlled it by an orifice opening. The load also was specified; sediment was put in by gravity through a feed system where the sand was made mobile by having a small amount of water coming in on top of the sediment storage tank. The dependent variable was the slope of the debris bed.

As sediment came from the hopper, deposition occurred in the upstream end of the flume, and a wedge of sediment gradually extended itself downstream until the slope of the debris bed became more or less uniform. In Gilbert's own words:

> Near the head of the trough sand was dropped into the water at a uniform rate, the sand grains being of approximately uniform size. At the beginning of an experiment the sand accumulated in the trough, being shaped by the current into a deposit with a gentle forward slope. The deposit gradually extended to the outfall end of the trough, and eventually accumulation ceased, the rate at which sand escaped at the outfall having become equal to the rate at which it was fed above. The slope was thus automatically adjusted and became just sufficient to enable the particular discharge to transport the particular quantity of the particular kind of sand. The slope was then measured. Measurement was made also of the depth of the current; and the mean velocity was computed from the discharge, width, and depth. [1914, p. 17]

Contrast this method of operation with that now used in the recirculating type of flume. In modern work, great emphasis is placed on achieving a constant depth of water down the length of the flume. As equilibrium conditions are approached, the traveling carriage on the flume sides is run up and down the length of the flume to see that the water surface becomes parallel to the flume rails. Under most conditions it can be assumed that when the water surface is parallel to the rails, the depth of sediment on the bed is uniform and the bed slope, therefore, is also parallel to both rails and the bottom of the trough.

Gilbert did not worry much about the parallelism of water surface and debris bed. In general, he took the slope of the debris bed to be also the slope of the water surface. As Gilbert explained, at the end of the measuring or timing period during which time the sediment was being trapped, the discharge was then stopped, and then "The slope of the channel bed is measured, and the sand caught during the period recorded by the watch is weighed" (1914,

p. 22). In other words, the slope that Gilbert published is for the most part the slope of the debris bed measured after the experiment was completed. He also pointed out that when the debris surface was rough, "it was usually graded before measurement by scraping from crests into adjacent hollows" (1914, p. 25).

Looking at the tabulation of the original data, one can see that the water-surface slope was measured in about one experiment out of ten; therefore, in nine out of ten cases the final published slope was the slope of the debris bed.

The recirculating flume commonly used in modern experiments on sediment transport is a design chosen to eliminate one of the really great disadvantages of the type of equipment used by Gilbert. In the Gilbert flume, when sediment was fed in at the upstream end at a known and chosen rate, the sediment was accumulating downstream in the collection device and had to be removed from the settling tank and physically carried upstream for it to be used again. This required much handling of sediment material, not only necessitating considerable storage space but facilities for drying and moving of sediment.

The recirculating flume eliminates these difficulties by having the sediment returned to the upstream end through the return pipe, but it also means that the sediment becomes a dependent rather than an independent variable.

The implication of this apparently modest difference in technique is immense. One might say that, in a broad sense, the sediment engineer and modern hydraulician have paid too little attention to the implications of the techniques used by Gilbert. By the same token, the geologist and geomorphologist have probably paid too much attention to the results of the Gilbert experiments without giving adequate attention to the implications of the technique itself. The reason for saying this is that the geologist, without really knowing it, has been led to apply in his mind the major results of the Gilbert experiments despite lip service to the interdependence of the variables. To be more specific, the geologist has tended to follow closely the reasoning summarized at length in the paper by J. Hoover Markin, who stated and expanded on the idea that slope of the stream is adjusted to accommodate the discharge and load. Specifically, he said that his study of the subject "tends to confirm the standard geologic view that streams readjust themselves to new conditions primarily by adjustments in slope, and only in minor degree by modification of the channel section" (1948, p. 508).

It is logical to reach this conclusion when one looks at the Gilbert experiments in that the discharge and load were specified or chosen in advance, and the depositing sediment on the bed of the flume built up a slope sufficient to transport the imposed load under the conditions of discharge and width chosen as the fixed parameters of the particular experiment.

FIELD EXAMPLE OF THE GILBERT FLUME IN ACTION

Practically no exactly similar situation exists in nature except for the one described by Leopold and Bull (1979) at the Loop of the San Juan River in Utah, an abandoned meander of the river. In that geologic accident, the abandoned loop of the river, having a very flat slope, built a wedge of sediment within the confines of the canyon until, as in the Gilbert flume, the slope was sufficient to carry the debris derived from the drainage area under the conditions determined by drainage area and climate.

Neither in the paper dealing with the Berkeley experiments nor in the paper on hydraulic-mining debris did Gilbert imply that he would expect the natural river to act in the same manner as he found in the flume. That is, he did not infer from the experiments that when the debris load was increased the slope would increase, as Mackin would explain. This is the problem of whether an increased load will cause aggradation or whether it will cause the stream to alter its slope. In the paper on the laboratory experiments, Gilbert expressed it in the following way:

> Whenever and wherever a stream's capacity is overtaxed by the supply of debris brought from points above a deposit is made, building up the bed. If the supply is less than the capacity, and if the bed is of debris, erosion results. Through these processes streams adjust their profiles to their supplies of debris. The process of adjustment is called gradation; a stream which builds up its bed is said to aggrade and one which reduces it is said to degrade. [1914, p. 219]

Gilbert explained the process of a stream adjusting to a change in load in slightly different terms in the paper on hydraulic mining. He said:

> If a stream which is loaded to its full capacity reaches a point where the slope is less, it becomes overloaded with reference to the gentler slope and part of the load is dropped, making a deposit. If a fully loaded stream reaches a point where the slope is steeper, its enlarged capacity causes it to take more load, and taking of load erodes the bed. If the slope of a stream's bed is not adjusted to the stream's discharge and to the load it has to carry, then the stream continues to erode or deposit, or both until an adjustment has been effected and the slope is just adequate for the work. [1917, p. 26]
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> Any change of conditions which destroys the adjustment between slope, discharge, fineness, and load imposes on the stream the task of readjustment and thus initiates a system of changes which may extend to all parts of the stream profile. The mining debris disturbed the adjustment of streams by adding to their load. Reclamation of levees disturbs it by increasing the flood discharge in certain parts of the river channels.
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> The law of adjusted profiles applies to streams with mobile beds—alluvial streams. Streams with fixed beds are normally underloaded. . . . This process works toward an adjustment of slopes, but with exceeding slowness, and the factors involved are different from those of alluvial streams. [1917, p. 27]

DOES A CHANGE IN LOAD CAUSE SLOPE TO CHANGE?

The crux of the matter is the extent to which slope will alter if sediment load changes. The near parallelism of terraces with present streambeds implies that, in most situations, change in load-discharge relationships in a given basin results in aggradation or degradation with nearly no change in channel slope. In those cases where a change of slope, as well as aggradation or degradation, is observed, it will usually be also associated with a change in the size or size distribution of the sediment load.

The deposition of a valley fill or aggradation through a long reach of channel results from the introduction into the channel system of more sediment than can be transported through the system. The gradient of the deposited fill is the result of the interaction of the adjustable or dependent variables in the hydraulic process: width, depth, velocity, and the elements contributing to hydraulic resistance (roughness). These include sediment size and size distribution, bed forms, channel slope and pattern, bank undulations, curvature, and pool-riffle formation.

In discussing the laboratory experiments, Gilbert made a separate analysis of the effect of various hydraulic parameters on capacity to carry load. The factors include discharge, slope, velocity, depth, form-ratio, and roughness, the roughness being treated less completely than any of the others. Gilbert certainly did not imply that any of these parameters could, in a natural stream, be treated separately, and his whole discussion indicated that he visualized an interdependence in which all were being mutually adjusted, just as Mackin stated. Mackin, however, made the further assertion, not to be found in Gilbert's work, that slope was the primary manner in which a stream adjusted to changed conditions, and that the effect of the adjusted slope was felt primarily in velocity, which Mackin stated was the principal determinant of the stream's capacity to carry sediment load.

RELATION OF GILBERT'S IDEAS TO MORE RECENT FINDINGS

Three important ideas have developed since the Gilbert experiments of which, of course, he had no knowledge. The first was the result of the Shields experiments, in which a relationship is expressed between sediment size and flow characteristics at the beginning or initiation of motion.

The second main idea is the hydraulic geometry: in any stream cross section, width, depth, and velocity vary with increasing discharge in a specific and conservative way. Similarly, as discharge changes downstream, the width, depth, and velocity change in a progressive manner.

The third main idea toward which Gilbert was reaching but did not at that time see is that the various dependent factors adjust mutually toward a most probable state—the concept of minimum variance.

However, when one looks at the present major computational scheme for estimating sediment load, the principal factor, now fairly well agreed upon by most workers, is stream power. This was well known to Gilbert, but its importance was apparently not completely apprehended by him. That he considered stream power important is indicated by the fact that it appears in the abstract of his paper. He said:

> The energy of a stream is measured by the product of its discharge (mass per unit time), its slope, and the acceleration of gravity. In a stream without load the energy is expended in flow resistances, which are greater as velocity and viscosity are greater. Load, including that carried in suspension and that dragged along the bed, affects the energy in three ways. 1) It adds its mass to the mass of the water and increases the stock of energy pro rata. 2) Its transportation involves mechanical work, and that work is at the expense of the stream's energy. 3) Its presence restricts the mobility of the water, in effect increasing its viscosity, and thus consumes energy. For the finest elements of the load the third factor is more important than the second; for coarser elements the second is the more important. For each element the second and third together exceed the first, so that the net result is a tax on the stream's energy. Each element of load, by drawing on the supply of energy, reduces velocity and thus reduces capacity for all parts of the load. This principle affords a condition by which total capacity is limited. Subject to this condition a stream's load at any time is determined by the supply of debris and the fineness of the available kinds. [1914, p. 11]

Gilbert was ahead of his time in several important respects. His experimental technique, when viewed in terms of modern hydraulic laboratories, was simple. The present generation apparently has not benefited from this early example of simplicity, for the complications of current experimental techniques have added less than one might suppose. No other experimenter has been willing to take the time to deal with such a large variety of sediment sizes as did Gilbert, and the fact that Gilbert's experiments have not been duplicated and extended now poses one of the serious problems in availability of laboratory data.

Furthermore, most modern experimenters have not yet seen the theoretical difference between the results obtained from recirculating flumes and those obtained from a sediment-feed flume such as Gilbert used. Until the work of Maddock (1969) and Langbein (1964), it was not visualized that the results would be slightly different if the sediment was fed as an independent variable or if the sediment load was a dependent variable as in a recirculating flume. In fact, most hydraulicians at the present time have not become convinced that this difference exists, but both theory and practice indicate that the results depend on which parameters are dependent and which are independent.

Gilbert was unwilling to estimate how, in a natural stream, these various hydraulic and sediment factors interact to produce the actual stream conditions. In this respect Mackin's (1948) well-known paper took a step beyond what Gilbert was willing to take, and in retrospect it was a misleading one. Mackin's emphasis on the change of slope in response to a change in load has misled geologists for three decades. Until the concept of minimum variance was put forward, the geologist accepted, apparently without question, that slope governs velocity and velocity governs sediment load; new work indicates that that is correct neither in theory nor in practice.

One of the problems Gilbert cited still remains as a major block to the advance of knowledge of natural streams, that is, the availability of sediment. The new measurements of bedload in natural streams made with the Helley-Smith sampler indicate that the results are highly dependent upon the sediment available to the stream for transport (Emmett, 1976, p. 12).

Thus the same problems enunciated by Gilbert still confront us: the amount and type of adjustment that occur among the individual parameters in a stream as a result of a change in imposed conditions. Gilbert grappled with the problem of the interrelationship between velocity, depth, slope, and discharge but was apparently not sensitive to the relationship between these and hydraulic resistance. This quandary is illustrated in the following discussion:

> When depth is increased without change of slope (or width or grade of debris), its increase is effected by increase of discharge, with the result that capacity is increased, so that capacity is an increasing function of depth. When depth is increased without change of discharge, its increase is effected by reducing slope, with the result that capacity is reduced, so that capacity is a decreasing function of depth. When depth is increased without change of velocity, its increase requires increase of discharge accompanied by diminution of slope; and as these changes have opposite influences on capacity, it is not evident a priori whether capacity will be enlarged or reduced. The experimental data show that it is slightly reduced, so that capacity is a *decreasing function of depth.*
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> When depth is reduced without change of slope, and the reduction is continued progressively, a stage is eventually reached in which the velocity is no longer competent for traction. . . .
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> Reduction of depth without change of discharge involves increase of velocity, and it is evident that compentence does not lie in that direction. But increase of depth involves reduction of velocity, and leads eventually to a competent velocity. The limiting depth corresponding to competence is therefore a great depth instead of a small one. . . .

> When depth is reduced without change of mean velocity, the efficiency of the mean velocity is enhanced and competence is not approached. When depth is increased, the efficiency of the unchanged mean velocity is diminished and a [large] competent depth may, under some conditions, be realized. [1914, p. 166]

PROBLEMS OF THE PRESENT

These are the types of questions for which field data are needed to estimate quantitatively the reaction of a natural river system to changes imposed by man's activities. And the effect of man is the major river problem of the present day, just as it was in Gilbert's time.

Let us assume that as a result of man's activities, the incoming sediment load to a reach of river is altered as in the case of hydraulic mining. The work of Leopold and Bull (1979) suggested that slope is going to be the least adjustable of the factors. This stands in contrast to the conditions imposed by the construction and operation of the Gilbert flume. In the latter case the slope was the principal manner in which the adjustment took place, and the slope was altered until it was competent to carry the load that was imposed. The amount of adjustment made in velocity, depth, and roughness to such new conditions is as yet unknown, and new data are needed. After these adjustments have been made to the new conditions, the stream will aggrade if the load cannot be carried, or if the available load is insufficient to fulfill the needs of the adjusted conditions, the stream will degrade. If the size distribution of sediment remains constant, the aggradation and the degradation will probably take place with little or no change in river slope.

What slope a given reach of river will adopt apparently depends primarily on discharge and size of bed material but is also influenced by other factors "such as channel cross section and amount of load (Hack, 1957, p. 59)." But because there are not merely two but several factors interacting, the empirical relation between slope, bed material size, and discharge, such as that of Hack (1957, eq. 2), cannot forecast how a channel reach will react if the amount of introduced load is changed. Present knowledge admits merely that there are many interacting factors that mutually adjust toward a condition of dynamic equilibrium. This has been variously described, but perhaps best by Hack (1960).

> The concept (of dynamic equilibrium) requires a state of balance between opposing forces such that they operate at equal rates and their effects cancel each other to produce a steady state, in which energy is continually entering and leaving the system (p. 86).
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> It is assumed that within a single erosional system all elements of the topography are mutually adjusted so that they are downwasting at the same rate (p. 85).

Hack considered this dynamic equilibrium as alternative to and different from the concept of the graded stream. He preferred to use the word "grade" or "graded" to refer to the smooth curve or smooth profile of any stream or reach of stream.

Leopold and Bull (1979) described a graded stream as follows:

> A graded stream is one in which over a period of years slope, velocity, depth, width, roughness, pattern and channel morphology delicately and mutually adjust to provide the power and the efficiency necessary to transport the load supplied from the drainage basin without aggradation or degradation of the channels. The threshold of critical power is passed and the stream is not graded when the volume of load supplied is insufficient or is too large to be transported and the channel bed degrades or aggrades.

Hack considered this definition too restricted to have value because many streams have beautifully regular profiles but, in his opinion, would not fit the above definition. An example is the Middle River, Virginia, which he has shown to be littered with boulders plucked from the bed and therefore, he argues, must be degrading.

But neither the concept of dynamic equilibrium nor any definition of a graded stream indicates even qualitatively the degree to which slope adjusts in response to a change in sediment load.

The slowly accumulating field data suggest that the load supplied by the drainage basin affects a reach of channel both by its volume-per-unit *time and by its size and size distribution.* It appears that if size does not change but volume changes, the effect on channel slope will be minor, and aggradation or degradation will reflect the volume change. If size and its distribution are changed, the channel will tend to alter its slope by deposition and erosion. Debris size appears to have its principal influence through its effect on hydraulic roughness.

Yet these statements are not expressed in such quantitative terms that they can be used to forecast the results of changes now being quickly wrought by man's alterations of natural river systems. Thus, the slight improvement in concepts that has been made in the six decades since Gilbert's work is insufficient to solve present problems. A comprehensive program of field study comparable to the Gilbert approach to laboratory data is vitally needed.

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