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River Morphology at the Meandering River Boundary Layers

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Abstract: The sculpture and degradation of the land are performed partly by shore-waves, partly by glaciers, partly by wind; but chiefly by rain and running water. The last mentioned agencies only will be here discussed. All indurate rocks and most earths are bound together by a force of cohesion which must be overcome before they can be divided and removed. The natural processes by which the division and removal are accomplished make up erosion.

INTRODUCTION

Transportation is chiefly performed by running water. Disintegration is naturally divided into two parts. So much of it as is accomplished by running water is called corrosion, and that which is not, is called weathering.

Stated in their natural order, the three general divisions of the process of erosion are
1) weathering,
2) transportation and
3) corrosion.

The rocks of the general surface of the land are disintegrated by weathering. The material thus loosened is transported by streams to the ocean or other receptacle. In transit it helps to corrode from the channels of the streams other material, which joins with it to be transported to the same goal.

In weathering the chief agents of disintegration are solution, change of temperature, the beating of rain, gravity, and vegetation. The great solvent of rocks is water, but it receives aid from some other substances of which it becomes the vehicle. These substances are chiefly products of the formation and decomposition of vegetable tissues. Some rocks are disintegrated by their complete solution, but the great majority of it is divided into grains by the solution of a portion; and fragmental rocks usually lose by solution the cement merely, and are thus reduced to their original incoherent condition. The most rigid rocks are cracked by sudden changes of temperature; and the crevices thus begun are opened by the freezing of the water within them. The coherence of the more porous rocks is impaired and often destroyed by the same expansive force of freezing water.

The beating of the rain overcomes the coherence of earths, and assists solution and frost by detaching the particles which they have partially loosened. When the base of a cliff is eroded so as to remove or diminish the support of the upper part, the rock thus deprived of support is broken off in blocks by gravity. The process of which this is a part is called cliff-erosion. A portion of the

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water of rains flows over the surface and is quickly gathered into streams. A second portion is absorbed by the earth or rock on which it falls, and after a slow underground circulation reissues in springs. Both transport the products of weathering, the latter carrying dissolved minerals and the former chiefly undissolved. Transportation is also performed by the direct action of gravity.

In corrosions the agents of disintegration are solution and mechanical wear. The mechanical wear of streams is performed by the aid of hard mineral fragments which are carried along by the current. The effective force is that of the current; the tools are mud, sand, and boulders. The most important of them is sand; it is chiefly by the impact and friction of grains of sand that the rocky beds of streams are disintegrated. Streams of clear water corrode their beds by solution. Streams transport the combined products of corrosion and weathering. A part of the debris is carried in solution, and a part mechanically. The finest of the undissolved minerals are held in suspension; the coarsest is rolled along the bottom; and there is a gradation between the two modes. There is a constant comminuting of all the material as it moves, and the work of transportation is thereby accelerated. Boulders and pebbles, while they wear the stream-bed by pounding and rubbing, are worn still more rapidly themselves. Sand grains are worn and broken by the continued jostling, and their fragments join the suspended mud. Finally the minerals are all more or less dissolved by the water, the finest the most rapidly.

In brief, weathering is performed by solution; by change of temperature, including frost; by rain beating; by gravity; and by vegetation. Transportation is performed chiefly by running water. Corrosion is performed by solution, and by mechanical wear. Corrosion is distinguished from weathering chiefly by including mechanical wear among its agencies, and the importance of the distinction will be apparent when we come to consider how greatly and peculiarly this process is affected by modifying conditions.

Conditions Controlling Erosion

The chief conditions which affect the rapidity of erosion are (1) declivity, (2) character of rock, and (3) climate. In general erosion is most rapid where the slope is steepest; but weathering, transportation, and corrosion are affected in different ways and in different degrees. With increase of slope goes increase in the velocity of running water, and with that goes increase in its power to transport undissolved material.

The ability of a stream to corrode by solution is not notably enhanced by great velocity; but its ability to corrode by mechanical wear keeps pace with its ability to transport, or may even increase more rapidly. For not only does the bottom receive more blows in proportion as the quantity of transient material increases, but the blows acquire greater force from the accelerated current, and from the greater size of the moving fragments. It is necessary however to distinguish the ability to corrode from the rate of corrosion, which will be seen further on to depend largely on other conditions.

Weathering is not directly influenced by slope, but it is reached indirectly through transportation. Solution and frost, the chief agents of rock decay, are both retarded by the excessive accumulation of disintegrated rock. Frost action ceases altogether at a few distance below the surface, and solution gradually decreases as the zone of its activity descends and the circulation on which it depends becomes more sluggish. Hence the rapid removal of the products of weathering stimulates its action, and especially that portion of its action which depends upon frost. If however the power of transportation is so great as to remove completely the products of weathering, the work of disintegration is thereby checked; for the soil which weathering tends to accumulate is a reservoir to catch rain as it reaches the earth and store it up for the work of solution and frost, instead of letting it run off at once unused. In brief, a steep declivity favors transportation and thereby favors corrosion. The rapid, but partial, transportation of weathered rock accelerates weathering; but the complete removal of its products retards weathering.

Rate of Erosion and Rock Texture

Other things being equal, erosion is most rapid when the eroded rock offers least resistance; but the rocks which are most favorable to one portion of the process of erosion do not necessarily stand in the same relation to the others. Disintegration by solution depends in large part on the solubility of the rocks, but it proceeds most rapidly with those fragmental rocks of which the cement is soluble, and of which the texture is open. Disintegration by frost is most rapid in rocks which absorb a large percentage of water and are feebly coherent. Disintegration by mechanical wear is most rapid in soft rocks. Transportation is most favored by those rocks which yield by disintegration the most finely comminuted debris.

A stream of water flowing down its bed expends an amount of energy that is measured by the quantity of water and the vertical distance through which it descends. If there were no friction of the water upon its channel the velocity of the current would continually increase; but if, as is the usual case, there is no increase of velocity, then the whole of the energy is consumed in friction. The friction produces inequalities in the motion of the water, and especially induces subsidiary currents more or less oblique to the general onward movement. Some of these subsidiary currents have an upward tendency, and by them is performed the chief work of transportation. They lift small particles from the bottom and hold them in suspension while they move forward with the general current. The finest particles sink most slowly and carried farthest before they fall. Larger ones are barely lifted, and are dropped at once. Still larger are only half lifted; that is, they are lifted on the side of the current and rolled over without quitting the bottom. Finally there is a limit to the power of every current, and the largest fragments of its bed are not moved at all.

There is a definite relation between the velocity of a current and the size of the largest boulder it will roll. It has been shown that the weight of the boulder is proportioned to the sixth power of the velocity. It is easily shown also that the weight of a suspended particle is proportioned to the sixth power of the velocity of the upward current that will prevent its sinking. The true inference is, that the velocity determines the size-limit of the material that a stream can move by rolling, or can hold in suspension. Every particle which a stream lifts and sustains is a draft upon its energy, and the measure of the draft is the weight of the particle, multiplied by the distance it would sink in still water in the time during which it is suspended. If for the sake of simplicity we suppose the whole load of a stream to be of uniform particles, then the measure of the energy consumed in their transportation is their total weight multiplied by the distance one of them would sink in the time occupied in their transportation. Since fine particles sink more slowly than coarse, the same consumption of energy will convey a greater load of fine than of coarse. Again, the energy of a clear stream is entirely consumed in the friction of flow; and the friction bears a direct relation to its velocity. But if materials be added to the water, then a portion of its energy is diverted to the transportation of the load; and this is done at the expense of the friction of flow, and hence at the expense of velocity. As the energy expended in transportation increases, the velocity diminishes. If the material be composed of uniform particles, then we may also say that as the load increases the velocity diminishes. But the diminishing velocity will finally reach a point at which it can barely transport particles of the given size, and when this point is attained, the stream has its maximum load of material of the given size. But fine material requires less velocity for its transportation than coarse, and will not so soon reduce the current to the limit of its efficiency. A greater percentage of the total energy of the stream can hence be employed by fine material than by coarse.

Concept of the Graded River

Grade is a condition of equilibrium in streams as agents of transportation. The validity of the concept has been questioned, but it is indispensable in any genetic study of fluvial erosional features and deposits.

A graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and the prevailing channel characteristics, just the velocity required for transportation of all of the load supplied from above. Slope usually decreases in a down valley direction, but because discharge, channel characteristics, and load do not vary systematically along the stream, the graded profile is not a simple mathematical curve. Corrosive power and bed rock resistance to corrosion determine the slope of the ungraded profile, but have no direct influence on the graded profile.

River engineering has been faced for river accumulation which is sometimes inadequate for reliable prediction of river behavior, while on the other hand, there has been little attempt at systematic quantitative evaluations to discover identity in difference. The purpose is to review certain principles which afford a rational derivation of the profile of river beds and to test the results on several rivers.

Derivation of Equation of river-bed profile

As particles of bed-load move downstream, their size or weight is reduced by abrasion or wear, collision, and solution. The most important of these factors is abrasion, for which it was developed a law that has been verified experimentally by SCHOKLITSCH (1933). The reduction in weight of a stone or particle, as it travels downstream, should be proportional to the work done against friction along the bed. If P is the weight of the stone and y the coefficient of friction, the frictional resistance to motion is at any instant yP. The work against friction in a very short distance dx is yPdx. Let dP be the resulting decrease in weight. Then it can be said that

$$-dP = c\ yPdx \tag{1}$$

in which c is a constant of proportionality. The minus sign indicates that P decreases as x increases-that is, - dP goes with + dx. Integration yields

$$P = P_o\ e^{-ax} \tag{2}$$

or

$$\log_{10}P = \log_{10}P_o - ax\ \log_{10}e$$
$$= \log_{10} P_o - 0.434\ ax \tag{3}$$

with cy replaced by " a " and $\log_{10}e$ by 0.434. In this equation, the Sternberg abrasion law, P is the weight of a stone after traveling a distance of x miles downstream from the starting point where the initial weight was P_o while e is the base of natural logarithms. The quantity "a" is called the coefficient of abrasion or wear of the bed-load material and represents the loss in weight of a stone weighing one pound after traveling one mile; the units of "a" are pounds per pound per mile or mile^{-1}.

KRUMBEIN (1937) measured the average pebble-size along the beach, and found empirically that the size-variation with distance along the beach followed an exponential law like that in equation (2). Since the bed-slope of a river and the size of bed-load material are known to decrease from source to mouth, it is not far-fetched to assume the slope proportional to the size of bed-load material. Mathematically expressed

$$S = kP_o e^{-ax} \tag{4}$$

where S is the bed-slope and k is another constant of proportionality. At the starting point where x = 0, $S = S_o$, so that $kP_o = S_o$ and

$$S = S_o\ e^{-ax} \tag{5}$$

or

$$\log_{10}S=\log_{10}S_o - 0.434\ ax \tag{6}$$

which is the equation of the slope of river profiles. $S = S_o\ e^{-ax}$ is a rationally deduced formula, based on reasonable or at least plausible assumptions and not on measured data. There is no compulsion for a measured, actual bed-profile to conform to it. But if profiles can be shown to have an equation of this form, the inference must be that Equation (5) is reliable and valid. If the data from an actual river yield a linear relation on semi-logarithmic paper, then $S = S_o\ e^{ax}$ is justified.

Application to practical problems has shown that a slight variation in the form of above slope-distance equation is convenient.

Another Form of the Profile Equation

A variation of the bed-profile equation, in terms of elevation and horizontal distance, can be derived from $S = S_o\ e^{ax}$. Let z_o be the elevation at x = 0 where the slope is S_o, and let z be the elevation at any point x where the slope is S. If dz is the change in elevation in a very short horizontal distance dx, then the slope S = dz/dx and equation (5) becomes

$$S = dz/dx = S_o e^{ax} \tag{7}$$

or

$$dz = S_o e^{ax} dx \tag{8}$$

which can be integrated to

$$z - z_o = (S_o / a)(e^{ax} - 1) \tag{9}$$

If the elevation is taken through the origin, $z_o = 0$ and Equation (9) can be simplified to

$$z = (S_o/a)(e^{ax} - 1) \tag{10}$$

It must be remembered that Equations (9) and (10) are merely derivations from $S = S_o e^{ax}$ and not independent formulas. They are more directly applicable to profiles and therefore more interesting to the river engineering. This different form of equation is not suited to an easy check of the basic principles, though a profile can be computed if the wear-coefficient, a, is known. GANDOLFO (1940) tried Equation (9) on the San Juan River in Argentina and found agreement of practical adequacy between actual and computed values of the river profile in a stretch of the river for which comparisons could be made. The coefficient was computed from the mechanical composition curves of the bed-material in a manner similar to that suggested by SCHOKLITSCH (1933), which space requirements prevent from explaining here. GANDOLFO'S (1940) investigation is therefore another verification of the general method. The semi-logarithmic slope-distance plots (the straight-line approximation) and the resulting value of the wear-coefficient give good elevation profiles. The gradient of the line on the slope – distance diagram cannot be changed too much and still be sensibly acceptable; but the small possible shifts of the line would not alter the computed elevation profile appreciably and the calculated profile is well within reasonable limits of accuracy.

For rivers all the variables in Equation (10) are easily determinable except the wear-coefficient a. This coefficient is not a constant for a given rock or bed-load material: It increases with the one-fourth power of the particle velocity, is proportional to the diameter of the material over which the particle rolls, and depends on the pebble-shape. The coefficient should vary for different parts of a river and the reduction in weight per pound per mile decreasing downstream in general. This difficulty is circumvented for river engineering purposes by computing an overall coefficient for the entire stretch of river under consideration; the shorter the reach, the more representative the coefficient. This method yields useful results even for a 1000 mile continuous stretch of river. Where it is not practicable to work from profile data, a value of the wear coefficient can be estimated for the type of mineral in the river from experimentally determined values (SCHOKLITSCH, 1933).

The choice of S_o, the slope at the starting point, x = 0, is slightly troublesome. It is best to determine S_o from the semi-logarithmic chart. The intersection with x = 0 of the straight line through the plotted points yields a good value of S_o for the purpose.

General remarks on applicability and limitations

Plots of other streams do not always show the regularity of the application of the formulas, but in many cases careful inspection of the stream gives a physical interpretation of seeming discrepancies: Rock outcrops, dams, flashy tributaries, debris-cones, local overloading of the stream-capacity for solids transport, etc., may disturb the wear-phenomena on which the ideas are predicated. In such instances the profile can sometimes be approximated by a series of lines calculated with locally varying coefficients. Steep headwaters in mountainous regions may not fit the framework since collision more than wear might be the predominating agent.

RESULTS

The wear-phenomena offer a rational approach to river-bed-profile morphology. The inference is that the bed-load plays a very important role in forming the river-channel. The caution is indicated, the rational instrument offered here for the analysis of river-profiles gives a practical means for expressing the vertical shape of a river-bed so that the morphologic effect of man-made measures can be studied. The usefulness of $S = S_o e^{ax}$ and $z = (S_o/a)(e^{ax}-1)$ lies in the fact that they formulate the equilibrium-profile, that which will prevail ultimately or after complete morphologic development. Hence, if the regimen of a river is altered by regulation, a practical prediction of the final form can be ventured, with more rational basis for the estimate. Another possibility is the establishment of a relation between an overall wear-coefficient like "a" and the watershed geology that would permit fluvial or physiographic predictions in a manner to the use of flood-formulas.

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