PART 1. TRANSPORTATION

TRANSPORTATION OF DETRITUS BY MOVING WATER[1]

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ABSTRACT

The conditions of transport of detritus by moving water constitute one of the most vital problems confronting students of sedimentation. This article by Hjulström summarizes the main aspects of present knowledge of the problem as applied to rivers. Many of the relations for river water apply to ocean water; but the sea differs materially from rivers in at least three ways: the large masses of water involved, the slowness with which the water moves, and the effect of tides. Notwithstanding the fact that these three phenomena modify the picture as portrayed by Hjulström for rivers, the information he presents is of great value to students of sedimentation. This article is a summary of a longer article, which in itself for the most part also is a summary. Consequently in this abstract it seems futile to attempt to present more than a few comments about the main features he describes.

Water moves in two main ways—by laminar flow and by turbulent flow. In laminar flow the water travels in parallel bands; in turbulent flow it moves in pulsations in a variable way. The velocity of water in laminar flow is always low; in turbulent flow it may be low or high. There are several types of turbulent flow, each of which depends mainly upon the velocity. The transport of detritus by moving water is affected by many factors, the most influential of which is the velocity of the water. Particles are transported individually or collectively. Transport of individual particles is in four types: sliding, rolling, saltation (jumping), and suspension. The first three are along the bottom and the fourth is in the water. With increasing velocity the mode of transport ordinarily passes successively through these four states of transport. The particles also may move collectively, that is in masses. In this way are formed such features as ripples, bars, and banks.

The laws governing the different kinds of transportation are complicated. For particles larger than sand (0.5 millimeter) the size of particles that can be put in motion increases as the velocity of the water becomes greater; but for smaller particles the minimum velocity that is required in order to bring them into suspension does not decrease as the particles become smaller; instead it increases. Thus it is easier to move sand off the bottom than silt. Once a particle is in motion it continues to be transported until the velocity of the water decreases to a certain speed. This minimum transporting velocity for particles of sand size or larger seems to be about 30 per cent less than the velocity needed to remove the particles from the bottom; but for progressively smaller particles, the minimum transporting velocity becomes increasingly less in proportion to the velocity required to make the particles go into suspension. (Editor's abstract.)

INTRODUCTION

The sea floor differs considerably from the surface of the land. In addition to its varying morphology, the sea bottom differs widely in physical and chemical composition in different areas, as is pointed out in many of the other articles in this symposium. The activity of living or-

[1] Translated from the Swedish by Parker D. Trask. Manuscript received, July 2, 1938.

ganisms influences materially the composition of the sediments, but aside from that, the motion of the water, particularly its ability to transport material, is the dominant factor. Running water not only facilitates the erosion of the land, but it also transports the eroded material to the sea. Extraordinarily large quantities of detritus are carried to the ocean by water. The Mississippi River, alone, brings some 2 million tons of sediment to the sea each day (36, p. 162).[2] The total quantity of solid material that is brought to the sea from all areas in a given period of time, however, is difficult to estimate. Three processes are involved in the action of running water: 1, erosion; 2, transport; and 3, deposition. These processes are closely inter-related, especially transportation and deposition, but erosion can be separated from transportation only with difficulty.

MOTION OF WATER

The mechanical work accomplished by running water depends upon the character of the water, the nature of the surface the water acts upon, and what is more important, upon the motion of the water. In fact, the dynamics of running water cover a whole science and they involve many interesting and complicated questions that are not yet solved. Water, however, is known to move in several different ways, each of which has special properties. These are briefly described below.

Laminar motion.—The characteristic feature of laminar motion is the parallel way in which the water particles move. The parallel layers do not merge with one another, and no cross-currents develop. The velocity of water, when in laminar motion, generally is low. Each river or current has a certain critical velocity that may not be exceeded if the laminar motion is to be maintained. In ordinary streams this critical velocity is very low—a fraction of a millimeter per second. If the water contains suspended matter the viscosity is increased and the critical velocity becomes somewhat higher. The increase, nevertheless, is small and ordinarily can be neglected (17, pp. 234–37). The hydraulic mean depth also is a factor; the greater the depth, the smaller the critical velocity. However, even in thin sheets, such as flowing rain water, the critical velocity is almost always exceeded (17, pp. 237–43). Thus, water under conditions prevailing in nature, whether in the sea or in tiny sheets of flowing rain water, generally moves in a turbulent way.

Turbulent motion.—When the critical velocity is reached, laminar motion passes over into turbulent motion. Turbulent flow is characterized by a variety of mixed movements, which produce a disturbed eddying

[2] See references at end of article.

motion. In addition to the main flow of a stream, individual masses of particles of water have secondary motions, whose direction may or may not coincide with the main flow of the water downstream. These groups of particles in secondary motion may be large or small, but they exist as separate entities only for a short time and soon mix with the surrounding water. New turbulent masses then develop, exist for a brief period, and merge with the surrounding water; and so the process continues.

The velocity at any point in the water, therefore, varies around an average value. The variations, or pulsations, are most pronounced on the bottom and near the sides of the stream, especially if the average velocity of the stream is low. Experiments of Fage and Townend (*Phil. Mag.*, ser. 7, Vol. 21, 1936, and bibliography in 17) indicate that in the center of a mass of water in turbulent flow in tubes, the intensity of the secondary movements is about the same in all directions, but near the sides transverse movements are weaker or are absent.

The same phenomena are believed to characterize rivers. Fage and Townend were able to show, with aid of an ultramicroscope, that in a brass tube in which water was in turbulent motion, turbulence was present up to within 1/1600 millimeter of the sides of the tube. Immediately overlying the bottom of natural streams a boundary layer with laminar flow may be presumed to exist. This boundary layer affects to a very high degree (27, 55) the transport of detritus in suspension and along the stream bottom.

The nature of turbulence is not yet well known. Thus far the theoretical approach to the problem of the motion of the *individual* particles has yielded only a few results. Oseen, the eminent hydrodynamicist, quite simply, proposed in 1930 to define the condition of motion as turbulent, since it is so complicated that we do not attempt to explain the individual movements but are satisfied with a description of the average movement. In recent years, however, Taylor's statistical studies on the correlation between velocities at pairs of points offer great promise in accounting for the nature of turbulence (published in *Proc. Royal Soc. London*, Ser. A, 1935–1938).

Hitherto the *average* conditions have been the main objects of study. The intensity of turbulence is characterized by a mathematically defined property that is designated variously as: eddy viscosity, "Austauschkoefficient," exchange coëfficient, eddy conductivity, or mechanical viscosity. The laws for the variations in turbulence across the profile of a river are not yet well known. A schematic first approximation has been given by Leighly (25) and his results have been strenghthened by experimental work of the writer (17). According to these investigations the greatest intensity of turbulence in a river that has a symmetrical profile lies on each side of the middle line and a little below half the depth. However, these preliminary results require further studies of the relation between velocity of water and turbulence.

Streaming and shooting.—Turbulent motion consists of two types, streaming and shooting. The streaming state of motion occurs when the velocity is low and is less than the square root of the depth times the acceleration due to gravity. The critical velocity between these two states of flow is the same as the velocity at which surface waves move. Shooting is further distinguished from streaming in that the effect of any disturbance, such as waves or damming, can not go upstream.

If the velocity increases markedly, other phenomena, such as cavitation, result (17, p. 257). The maximum possible velocity with which the water can flow in natural streams is 23.5 meters per second.

Secondary phenomena.—These states of motion are often accompanied by secondary movements, such as vortices, eddies, rollers, and transverse helical circulations (17, pp. 258–62). The influence of these types of movement on the transportation of detritus, however, is not well understood.

EROSION

The distinctive feature of the transport of detritus is its great variability. The manner of transport changes from instant to instant and the quantity of detritus supplied to the stream varies widely according to geologic conditions. Erosion is also closely related to transportation, because the individual particles come to rest often between the time they are first loosened from bed rock until they reach their final place of accumulation. Consequently, the particles get into a state of motion, that is, are eroded, many times on their way to their final resting place.

Rain wash.—Erosion takes place in two ways: 1, scouring of the river channel; and 2, rain wash in the drainage area of the river; these two types of erosion in part act in different ways and according to different laws even though the boundary between them is vague. The erosion of the bed of a river requires a greater force, because the cohesiveness of the particles on the stream bottom must first be overcome. Interfluvial erosion ordinarily takes place more easily, because in addition to the action caused by moving water, the weathering processes facilitate the loosening of the particles from the soil and bedrock. In most streams the material transported is derived to a larger extent from material eroded from the interfluvial areas than from the bottom of the stream. Many factors such as vegetation, cultivation of land, and climate, influence the amount of material eroded from any interstream area. Relatively few data, however, are available as to the amount of material eroded in this way in a given time, as well as to knowledge of the nature of this kind of erosion.

Erosion of stream bed.—On the other hand, considerable information concerning the direct erosion of the stream bed is available from laboratory studies and from investigations of natural rivers. One of the difficulties with previous experimental work, however, is that the investigators studied varying types of material of varying grade size, before the behaviour of uniformly sorted materials had been ascertained.

Erosion, like transportation of the bedload, depends upon the work of running water on its bed. The forces that act, among others, are mainly pressure and suction. The velocity of the water can be considered as the dominant factor. Subsidiary factors are the velocity gradient and the physical characteristics of the water and particles of sediment. Accordingly, the main factor that should be studied is the motion of the water. Such a study, however, is difficult because the rapid fluctuations in velocity and direction of flow must also be considered; the momentary extremes in velocity have undoubtedly a greater influence than the average velocity (17). In practice it has therefore been necessary to use the more easily available data, such as slope, depth, and roughness. Shulits and Corfitzen (41) distinguish 5 different types of formulas and experimental data for determining the erosion (the stable channel bottom profile of equilibrium) in streams of given slope. Among these is a formula for the critical tractive force, whose effect, among other things, has been pointed out in recent papers by O'Brien (31, 32). The reliability of this formula, however, has not yet been proved for fine-grained material. The alternative theories of the force required to move particles on a stream bed have been recently discussed by Rubey (55).

Erosion velocity.—As a result of recent investigations of the erosion of different types of material, the writer has prepared a chart (Fig. 1) which shows the relations between the *average* velocity across a transverse profile of a river and size of particles for the three states—erosion, transportation, and deposition (17, Figs. 17, 18; and also 7, 8, 46). It follows, however, from what has been said above that the choice of the average velocity as an independent variable must be regarded as a temporary substitute until more data are available. Greater accuracy is not possible at present. In the future similar curves may be prepared for sediments of varying size distribution rather than for the uniformly sorted grades given in Figure 1. Also it may be possible to present data showing the effect of stream gradient and depth. These factors are not considered in preparing the chart, except that the depth should be greater than 1 meter. The velocities near the bottom of the stream would be approximately 10 to 20 centimeters per second less than those given on the chart (15). Owing to the uncertainty of the data, curve A in Figure 1 is presented as a series of bands rather than as a single line.

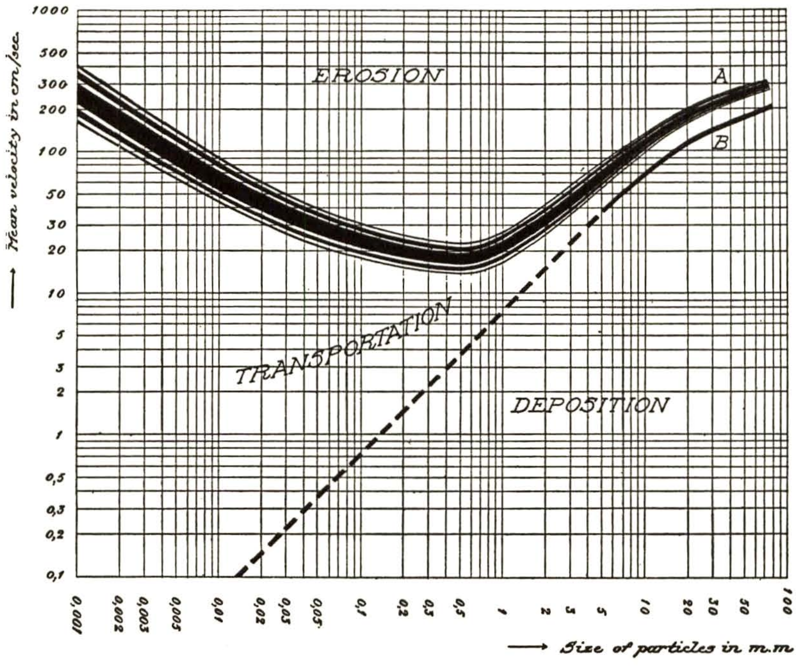

FIG. 1.—Approximate curves for erosion and deposition of uniform material (Logarithmic scale.)

Curve A in Figure 1 indicates that for uniformly sorted material having a diameter greater than 0.5 millimeter the erosion velocity increases with increase in size of particles. The requisite mean velocities for eroding particles of this dimension are about 20 centimeters a second. For particles of a size of 25 centimeters the velocities are about 200 centimeters a second. However, for particles smaller than 0.5 millimeter the erosion velocities increase and for clays are fairly high. Thus, fine sand, which has a diameter of 0.3 to 0.6 millimeter is the easiest to erode, whereas both silt and clay on the one hand and coarse sand and gravel on the other, require higher velocities.

The relative resistance of clay to erosion has been pointed out by Fortier and Scobey (15). Cohesion, as has been mentioned by many workers, is one of the factors that makes clay hard to erode. Perhaps turbulence also has little effect in eroding clay particles.

> The resistance in unconsolidated material is a direct function of the mass of individual particles and an inverse function of the size of interstices among them. In fine material, the interstices are so small that movement among the particles is laminar practically from the wetted surface of the bed inward. Hence the familiar stability of clay banks of streams (Leighly, 25, p. 21).

Stiff clays containing colloids can bere garded as a difficultly erodible type. Large immovable stones mixed with sand on the other hand can be thought of as increasing erosion owing to the swirling motion they are likely to cause by sticking up in the water.

Erosion with silt-laden water.—The detritus suspended in the water tends to lessen the eroding power of the stream. The decrease in eroding power is particularly strong if the suspended matter consists mainly of colloids. Fortier and Scobey (15) report that for fine-grained material, the maximum permissible velocities without erosion in canals are decidedly greater for water containing silt than for pure water. For sand and gravel the permissible erosion velocities are doubled. Colloids "will make the bed all the more tough and tenaceous, increasing its resistance to erosion" (15).

If the suspended matter consists of sand, gravel, or rock fragments, the difference from pure water becomes less, and under certain conditions may lead to the erosion of particles, especially if colloidal material is present. Stiff clays, alluvial silts, ordinary farm loam, and volcanic ash are eroded easier in water of this type than in the purely artificial conditions that prevail in a flume.

Wright (53) obtained practical results in experiments with typical Colorado River sand from Yuma, Arizona. He was able to increase the critical velocity for erosion by adding fine clay in amounts of 10 to 25 per cent of the weight of the suspended matter.

> A heavy load of suspended silt in the water lays down a protecting mat of cohesive particles which fill the interstices at the top of the bed and thus enable it to resist scour. However, in the experiments with the asphalt sand and the coarser undispersed kaolin, when this mat was once broken through by the water, a greater scour resulted with the muddy water than with the clear water. Nevertheless in general it was found that the clay tended to restrict scour (53).

Similar studies should be made for particles other than sand. Lane (23) reports that the silt content may be the cause of the high erosion velocity when the material is fine-grained. However, the greater eroding velocities for fine particles indicated by Figure 1 also apply to wind erosion (Bagnold, 2). This suggests that this increased eroding velocity for finer constituents holds for all fluids.

DEPOSITION

When particles are torn from the bed they remain in motion as long as the velocity of water is maintained and usually also if it is somewhat lower. However, when the velocity decreases to a certain point—the lowest transportation velocity—the particles are deposited. The available observations on the relation between eroding velocity and lowest transportation velocity are somewhat contradictory (17, pp. 320–22). The relations certainly are different for different size of particles. For fine clays the differences between these two types of velocity may be very great. Very fine particles may remain in suspension for extremely small velocities, at least as long as the water is in turbulent motion, and perhaps even longer, if the particles can be raised by the hydrodynamic upthrust. Curve B, in Figure 1, corresponds to the lowest transportation velocity according to the work of Schaffernak.

Following Gilbert (16, p. 35) the term "competency" is used for the particular power of running water to carry detritus. It is usually expressed in terms of size of particles. Curve B therefore indicates the competency.

For gravel the ratio between eroding velocity and lowest transportation velocity seems to be 1.4 to 1. Thus, the erosion velocity can be decreased about 30 per cent before deposition begins. The data, however, are somewhat uncertain, but nevertheless it follows that once particles have been eroded, especially those that have gone into suspension, they can be transported even though the velocity of the water decreases somewhat. For given velocities and for particles ranging between 2 and 30 millimeters in diameter, the particles that can be transported are about double the diameter of those that can be eroded.

TRANSPORT

Gilbert in his classic studies on the transportation of débris was the first to distinguish between motion of individual particles and collective motion. The motion of individual particles can be classified into four groups: sliding, rolling, saltation, and suspension. The first three refer to motion along the stream bed, the fourth to motion in the water. The differences between sliding, rolling, and saltation are gradual; and it is difficult to determine when one leaves off and the other begins. Consequently, the limits between them are arbitrary.

INDIVIDUAL MOTION

Sliding.—Sliding is a very minor factor in a river's work. It is rarer in rivers than in laboratory experiments.

Rolling.—Rolling is the usual state of transportation. The moving particle is acted upon by a greater force on its upper part—where the velocity is greatest—than on its lower part. The swirling motion of the water where the flow lines converge also causes a sucking action. As a result the particles are overturned and start to roll. The influence of sucking is fairly great and also affects sliding. Even flat stones are lifted on end and start rolling.

Pebbles with prolate spheroidal shapes, or with one long dimension and two shorter, roll parallel to the longest axis and ultimately come to rest in that position, laboratory studies showing this rule to be almost universal. Furthermore, pebbles placed on a sand bottom in a current too weak to transport them, rotate through washing of sand beneath them until they attain a position with their longest axis perpendicular to the current, the median axis at the same time acquiring a position that dips up-current (45, p. 36 from an unpublished thesis by Hunzicker, University of Wisconsin, 1930).

The size of particles and the roughness of the stream bed influence materially the nature of the motion. Large particles are more readily moved by currents than small particles, partly because of their larger surface area and partly because they stick up higher in the water, where the motion of the water is greater. If a large grain of sand lies on the surface of a bed of well sorted fine-grained sand, the transportation velocity is higher and the roughness is relatively less than if the bottom consists entirely of even-sized large grains. On the other hand, on a rougher bottom the velocity of a sand particle is often increased by a swirling motion caused by the protruding grains or blocks. The wind exhibits similar relations; sand is much more easily blown across gravel than over a sand surface.

Rolling grains move more slowly than the water. The writer in an experiment with the transportation of sand in water moving at a rate of about 50 centimeters a second obtained the following velocities for different size of particles.

Diameter of Particle Millimeters	*Velocity Centimeters per Second*
5	30
2	25
1	15

When the velocity is increased so that the water can transport also larger particles, these will roll faster than the others, if once started. Nor do the large particles stop now and then, but roll incessantly. The small particles have a comparatively greater friction to surmount in the crowd of particles of the same size, and will have a short moment of rest now and then included in the velocity figures above (17, p. 301).

If the particles rise over an obstacle and above the bottom layers of water they come into a zone of faster moving water and often lose contact with the stream bed and make a small hop. This phase of motion is a transition to saltation.

Saltation.—Saltation, like rolling, is a common type of motion of particles along the stream bed. Saltation is a jumping motion. The particles are lifted from the bottom by the suction forces mentioned above. Jeffreys describes the mechanics of the motion in the following way.

the pressure is greater below the solid than above it, and provides a force tending to lift the solid. If it is greater than the weight of the solid (after allowing for the buoyance of the liquid), it will lift the solid off the bottom. But if the solid is denser than the liquid it will not stay off the bottom. The classical flow breaks down in time, vorticity is formed behind the solid, and a force arises accelerating the solid in the direction of the stream. If it reached the velocity of the stream in its neighborhood the difference of velocity would no longer be available to produce an upward force, so that there would be nothing to hinder gravity from bringing the solid down again. Actually of course gravity overcomes the force due to the difference of velocity before this has quite vanished. So the solid descends and again strikes the bottom. The shock when this happens destroys most of the velocity of the solid down stream, and the original conditions are restored. Thus the solid jumps off the bottom again. In a stream with a suitable velocity, therefore, a solid body that is not too large can be carried along the stream, its progress consisting of a series of jumps (11, p. 144).

In places, depending upon the nature of the bottom, saltation is interrupted by a rolling phase for a considerable distance. The direct bouncing described by Bagnold as a characteristic of wind driven sand is now known for sand moved in water.

Saltation is more typically characteristic of groups of grains than for individual grains on a solid surface. When assembled grains move, the motion of the particles often is concentrated in a zone near the bottom.

Viewed from the side, the saltation was seen to occupy at the bottom of the current a space with a definite upper limit . . . the distribution of flying grains was systematic, the cloud being dense below and thin above, but not perceptibly varying from point to point along the bed . . . . When, in looking from the side, attention was directed to the base of the zone, it was easy to watch grains that travelled half by rolling and half by skipping, and these moved quite slowly; but higher in the zone the motions were so rapid and diverse that all was a blur (16, p. 27).

The nature of the motion of the water in this zone of moving sand grains is practically unknown, though owing to the heavy load, it may be presumed to be laminar or only slightly turbulent.

The above hydrodynamic explanation of this type of transport is based on the premise of laminar motion, because only in this state of motion does the velocity gradient become relatively high. The direct picture of saltation, however, gives an impression of turbulence, and the question as to whether it is caused mainly by laminar or turbulent flow remains open. When individual particles flow over a solid surface turbulence has a very strong influence, owing to the presence of upward streams of such force and frequence that saltation passes easily over into suspension. A similar process occurs also when the motion is collective, but only if the velocity of the water increases above a certain limit.

Suspension was visible in the flume as soon as saltation began. When saltation was strong and accompanied by dune formation of the bed material, bands of particles were lifted vigorously and dispersed into suspension (8, p. 1729).

The velocity of particles in saltation, as in rolling, is less than that of the water. Only in a part of the paths of motion does the velocity of the saltating particles approach the velocity of the water. On the other hand, in places they decrease in velocity and take on a rolling motion. No data are available for the velocity of saltation, although it would be very useful to determine the difference in velocity between water and particles transported in this way. The velocity of transported silt is usually assumed to be the same as that of the water (2, p. 410). This is true for fine-grained material, such as suspended clay and silt, but not for sand. According to Leighly (25, p. 19) it is probable that definite measurements of the silt content of rivers that show very large proportions of silt to water near the bottom have been made on samples taken from a thick entrained layer. However, if the measurements extended as deep as the zone of saltation, the results as computed perhaps were several times too large.

COLLECTIVE MOTION OF BED LOAD

When particles are moved together in masses over the river bed, new features result which are different from those associated with the motion of the individual particles. In some places rhythmic features are developed. In others a mixing of sand and water occurs, in which the motion of the water is influenced by the movement of the sand and vice versa.

Current ripples.—When the velocity of a stream flowing over a smooth bed gradually increases, first a small number of grains start to slide and roll along the stream bed (7, pp. 3, 4). If the velocity is raised slightly, the quantity of particles of the same size that are moved increases greatly. These particles at first move fairly uniformly, but after a short time and usually suddenly they orient themselves in a series of more or less regular waves and hollows, or ripples.

These ripples have a well defined but unsymmetrical form. They consist of two types—current ripples and linguoid ripples (4, 20, 45).

> Where developed over large surfaces by a current of uniform direction, as on tidal flats, current ripples consist of numerous essentially parallel, long, narrow, more or less equidistant ridges, trending in straight or gently curved lines at right angles to the current, anastomosing frequently . . . . Where confined to a narrow channel, the current ripples are more or less crescent-shaped, the convex side directed down stream, often not extending across the whole channel (4, pp. 153–54).

The wave length ordinarily is between 1.5 and 30 centimeters. The more fine-grained the sediment, the more well developed are these current ripples (for particles smaller than 0.4 or 0.5 millimeter, according to 7, p. 56). If the particles are coarser, linguoid ripples may be formed (Bucher, 4, p. 164). Linguoid ripples are tongue-shaped and vary considerably in outline. Other types of ripples are rhomboid ripples (54) and a series of more complex forms, which are of minor importance.

Motion in the form of ripple marks is rhythmic. The movement is rhythmic not only in time, but also in space. The particles of detritus alternate between a state of rest and motion; and masses of particles continually change their position in the ripples (17, p. 338). The sand grains move up the comparatively gently inclined sides of the ripples, which face upstream, and then roll down the more steeply inclined downstream sides, where they become buried until the ripples move by, when they again flow over the surface; and so on. The load of rolling material increases on the upstream side from the lowest to the highest point. If the form of the ripples is to remain unchanged the same amount of matter must be carried away per unit from every surface unit of the upstream side of the ripple. Consequently it follows that this type of transportation represents a state of equilibrium; erosion counterbalances deposition. However, if the bed is eroded the transportation seems to take place in a uniform layer (17, pp. 338–343).

The physical explanation of the origin of ripple marks is unknown. Many workers have expressed the view that the phenomenon is a wave formation of the same type that occurs in the boundary surface between two media of different density and state of motion. The laws governing such wave formations therefore should control the distance between the crests of the ripples. The writer (17, pp. 335–38), using Taylor's (44) data on the effect of variation in density on the stability of superposed streams of fluid, found that calculations based on a reasonable assumption about the differences in velocity and content of sediment gave wave-lengths similar to those found in nature. This relationship holds just as well for transport by rolling as for rolling combined with saltation. The thickness of the zone of saltation influences the length of the waves materially. Whether or not the agreement between the results of the theory and the observations also implies some physical relationship is not yet understood—the almost instantaneous formation of ripples on a plane surface gives the impression that pulsations of the water play a major role (1, p. 24; 17, pp. 333–34).

Antidunes.—If the velocity of the water increases considerably over the stage when current and linguoid ripples are formed, the ripples are destroyed and the bottom becomes flat again. The effect of transportation is strong and the whole mass of sand and water is placed in a state of motion, such that the finer grains go into suspension and the coarser ones start to roll or jump (saltate). According to Kramer (21, p. 19) the velocity at which this obliteration of the ripples begins, lies slightly over the boundary velocity between streaming and shooting, as indicated by Gilbert's data. Casey's (7) experiments in a flume 40 centimeters wide showed that when the inclination of the bottom is relatively steep and the water is comparatively shallow, longitudinal corrugations or ripples are formed on the bottom, provided discharge remains constant. The distance between the corrugations is about twice the depth of water. These longitudinal ripples, according to Casey (7), are caused by a sort of transverse current motion—helical movements in the water. This motion may be similar to the helical motions induced by the wind, which occur in the upper water layers in seas and lakes (Langmuir, 24). These longitudinal ripples described by Casey do not seem to have been mentioned in other publications.

Another type of ripple, the antidune (16) or regressive sand wave (4, p. 165) resembles transverse current ripples and linguoid ripples. The profile of these antidunes is symmetrical, their crests are weakly rounded, and the wave length ranges between 23 and 600 centimeters. They lie transverse to the stream and move slowly upstream, "some of the sand being scoured from the downstream face . . . and deposited on the upstream face" of the next following wave (16, p. 32). These types of surface features are less stable than stream ripples.

In this connection another primary form of transportation should be mentioned, namely sand waves or reefs. These occur in deep parts of large rivers where, owing to their large size and variable position, they are dangers to navigation. The wave length varies greatly and ranges from 0.6 to 229 meters. The amplitude similarly varies widely. Its range is 0.07 to 5.58 meters (4, p. 171). These sand waves are irregular in shape, but occupy a generally transverse position and move downstream. According to Bucher, they occur only where the velocity of the water is high and where a large amount of material is in suspension. Wittman (51) has shown how gravel banks in the Rhine carry a part of the bed load and how they are influenced by the variations in the discharge of water: for rising water the velocities are 1.27 to 1.93 times those for falling water.

Critical velocity.—The above discussion has shown how the transport of the bed load varies with the velocity. The velocity may be grouped into at least three different phases. These phases are limited by certain critical velocities. Though the data are not plentiful, these velocities seem to vary for different conditions, among other things, upon the type of material, depth of water, stream gradient, and friction, as is indicated by recent laboratory studies. Current ripples have been studied by many workers (7, 21, 46), but the data obtained are conflicting, owing to the different conditions of study and different types of sediment.

Variations in transportation.—The intensity of transport is not the same over the whole bottom. The zone of transport is usually restricted to a belt of greater or lesser width, and it does not always lie in the middle of the river. Moreover, for the same river it varies with the discharge. In general it is believed to follow the position of the zone of maximum velocity and the bordering zone of maximum turbulence. Eventually deposition takes place along the sides of this belt of transport (26, p. 463). The transportation, however, is rather irregular at bends in the streams (12, 28, 30, 52). Mülhofer's studies of the River Inn in Tyrol show that for low water stages all of the bed load is transported in the deepest parts of the river at the bends; at high water no transportation occurs there, but only at the inside bank. Whether this phenomenon is caused by purely local conditions or is of general occurrence is unknown. Experiments at Vicksburg (52) show that turbulence causes transport of sediment from places of greater turbulence to places of lesser turbulence (25); and hence little agreement can be found in the movement of water and sediments near the bottom.

Motion near the bottom.—When the force of the moving water is sufficiently large, as for example in the stage when the current ripples are being obliterated, the bottom of the stream itself moves. A fairly regular transition downward from water laden with silt to a poorly defined immobile lower boundary surface may be assumed (21, 25). The study of these transition zones near the bottom is complicated. The bottom layers are relatively dense owing to the presence of the bed load, thus influencing the motion of the currents. In fact the water near the bottom may have little or no turbulent motion. Under some conditions a relatively thick boundary zone may be present, which is characterized by comparatively little turbulence or by laminar flow. This thick boundary zone particularly seems to exist under conditions of erosion. This condition, moreover, influences the velocity of the water, the slope of the surface of the water, and the friction. Observations from the Nile (6), for example, indicate that the slope decreases when the content of silt increases.

SUSPENDED MATERIAL

Exchange process (*Austausch*).—The transportation of suspended material depends on the turbulent motion of the water and the friction between the silt particles and the water. The physical laws governing the suspension of particles may be considered as solved theoretically by Schmidt's basic work (37, 38). It is assumed that in a stream characterized by water moving in turbulent flow, particles of water are continually moving upward and downward, owing to the nature of the turbulent flow previously described. On the average these upward and downward motions counterbalance one another. Therefore over an extended period of time the vertical motion in a horizontally flowing stream must be zero. It is possible, however, that the water moving upward may have a greater silt content than that moving downward, with the result that sediment is transported upward in the stream.

Each particle that is forced upward has its own particular settling velocity. Thus the position of the particles in the water is determined by the net result of these two opposing factors, the turbulent motion which causes the particles to rise and the force of gravity which makes them sink. A theoretical formula is available for calculating this net result (31, 38). By means of this formula the distribution of particles with respect to height above the bottom can be estimated. However, sufficient data to apply it to field or laboratory studies have not yet been obtained.

The theoretical distribution of grain size to height above the bottom is given in Figures 2 and 3 (17). The Austausch coëfficient, which is a

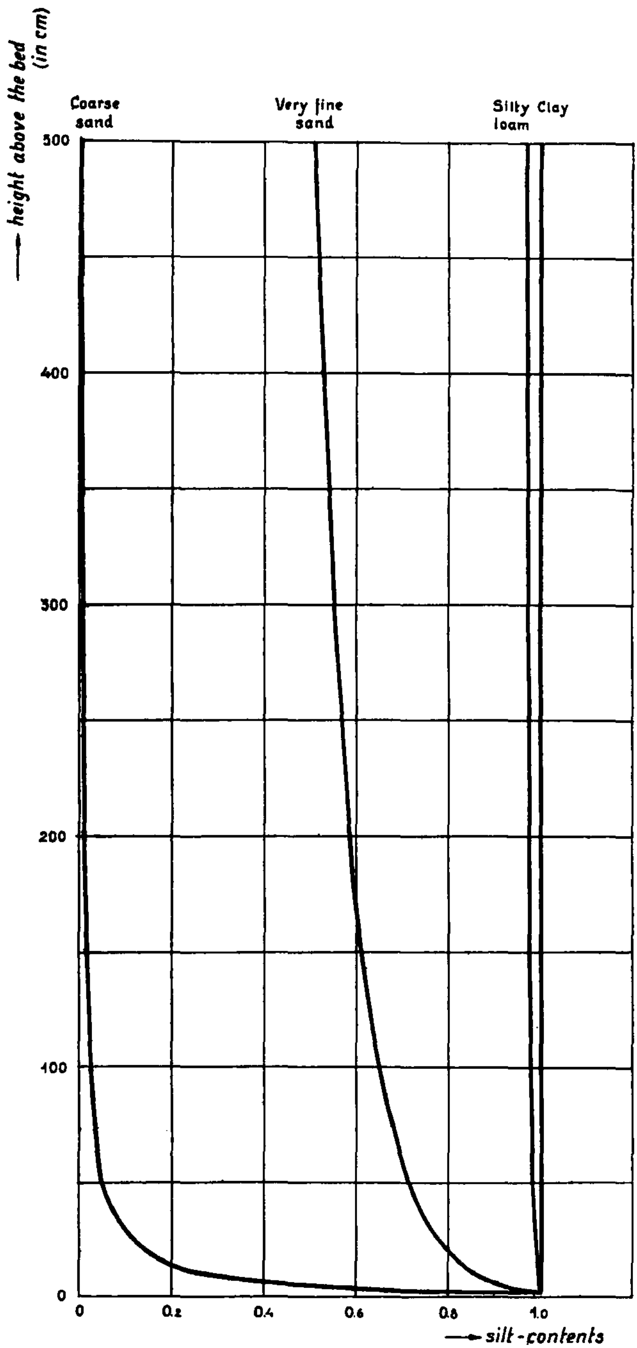

FIG. 2.—Distribution of sediment (silt content) in stream or current with respect to height above stream bed, as computed from Schmidt's formula (38).

measure of the intensity of the exchange processes, in this figure is assumed to vary according to the formula $A = A_1 \cdot Z^{7/8}$, where A is the Austausch coëfficient, A_1 is value of A at a height of 1 centimeter above the bottom and Z is the height of the particle above the bottom. The data refer to average conditions.

Influence of settling velocity.—Figure 2 shows the distribution of silt content for different heights when $A_1 = 10$. The concentration of sediment at a height of 2 centimeters is given as 1 for all four size groups represented in the figure—coarse sand, fine sand, silty loam (silt), and clay. The clay in this figure, which corresponds to particles having a diameter of 1 micron, has a settling velocity of .000892 centimeter a second or 1.98 centimeters per 24 hours at a temperature of 20°C. For silty loam of a size of 20 microns the settling velocity is 0.0357 centimeter per second; for very fine sand having a diameter of 0.1 millimeter the settling velocity is 0.778 centimeter per second; and for coarse sand having a diameter of 1 millimeter the settling velocity is 6.662 centimeters per second.

It is evident from the figure that the bulk of the coarse sand is concentrated near the stream bed. At a height of 30 centimeters above the bottom, only 10 per cent as much coarse sand is present as at a height of 2 centimeters; and at a height of 5 meters only 0.3 per cent as much as at 2 centimeters. At this height of 5 meters, approximately one-half as much fine sand and 97 per cent as much silty loam is in suspension as at a height of 2 centimeters. No noticeable difference is noted for clay throughout the entire height of 5 meters represented on this figure. The more fine-grained constituents therefore are fairly uniformly distributed throughout the stream, whereas the coarser particles are located mostly near the bottom. Mechanical analyses of the suspended matter at different depths therefore indicate different size distributions of the particles.

Settling velocity.—The factors influencing the settling velocity have been summarized adequately by Wadell (47 and 48). The size, shape, and specific gravity of particles and the specific weight, temperature, and viscosity of the medium through which they settle, all affect the settling velocity. As a decrease in temperature lessens the settling velocity, sediments are transported more easily in winter than in summer. The content of suspended matter in the water is also a factor that influences the settling velocity. The presence of significant amounts of suspended fine particles decreases the rate of fall of large particles perceptibly. Finally should be mentioned the difficulty of obtaining satisfactory data on settling velocity by the usual method of determining the rate of fall in *still* water, as the presence of turbulent motion may unduly affect the results, particularly if the particles are not spherical in shape (35).

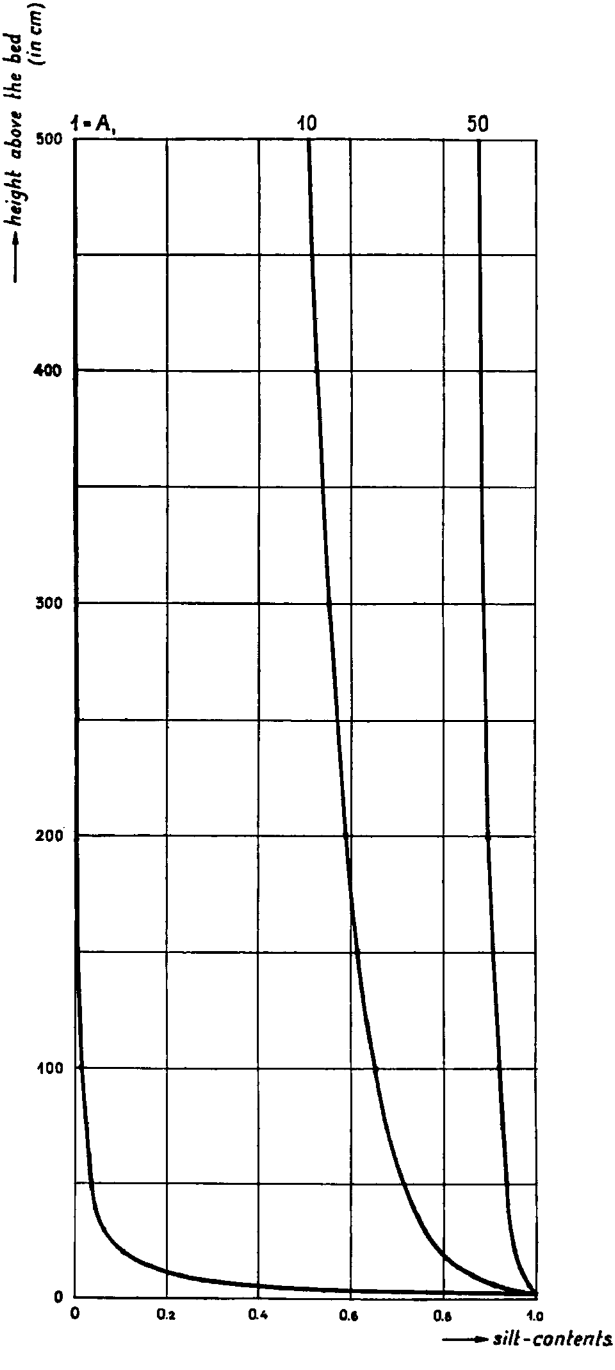

FIG. 3.—Distribution of very fine sand in suspension at different heights above bottom for different degrees of turbulence. Numbers at top of figure refer to exchange (Austausch) coëfficients: the higher the number the greater the degree of turbulence.

Influence of turbulence.—Figure 3 illustrates the theoretical distribution of very fine sand in suspension at different heights above the stream bed for different conditions of turbulence. The conditions are the same as in Figure 2. The data shown on Figure 3 indicate that the effect of turbulence is large. When the turbulence (A_1) increases, the distribution of silt for any given height above the stream bed is more nearly uniform. When the turbulence is low, as indicated by the left-hand line, most of the fine sand is concentrated near the stream bed; when the turbulence is high, as indicated by the right-hand line, almost as much fine sand is in suspension at a height of 5 meters as at a height of 2 centimeters above the stream bed. In fact, the quantity in suspension at a height of 5 meters is 88 per cent of that at a height of 2 centimeters when A_1 is equal to 50; whereas when A_1 is equal to 1, only 2 per cent as much sand is in suspension at a height of 1 meter as at a height of 2 centimeters.

What factors are the most dominant for these relationships? Without going into the hydrodynamic relations, it may be stated that the velocity of the water and the roughness of the stream bed are the most important. The exchange coëfficient seems to increase a little faster than the square of the velocity. The effect of temperature might also be mentioned, as the turbulence increases slightly with increase in temperature.

Distribution of silt with respect to erosion and deposition.—The relations discussed above represent deviations from a point of equilibrium between the effects of exchange and gravity. If erosion is dominant the concentration of particles near the bottom is greater than for conditions of equilibrium, and if deposition is dominant the concentration of particles near the bottom is less than for conditions of equilibrium. Therefore by determination of the distribution of silt with respect to height above the stream bed it might be possible to ascertain whether the stream is eroding its bed, is transporting sediment without erosion or deposition, or is depositing sediment. In practice, however, this method is difficult to apply (17, pp. 277–280). Straub (42) has found that

> in a unit width of cross section of a stream, the quantity of sediment transported in suspension per second could be determined quite accurately by measuring the sediment concentration at two points, namely at two-tenths and eight-tenths the depth of the stream from the water surface.

Data from direct observations.—Only a few data are available as to the distribution of detritus in moving water, either in the laboratory or in natural streams, at least not with respect to the content throughout all parts of the body of moving water at any given instant (5, 6, 14, 17). The accompanying table indicates a typical distribution of silt in a small river, which has a low gradient (17, p. 406). The distribution is seen to be somewhat irregular, though a concentration with depth is noticeable. No effect of helical flow is indicated by the data. In fact helical flow seems to have little influence in natural rivers.

DISTRIBUTION OF DETRITUS IN DIFFERENT POINTS IN PROFILE

Vertical section number	I	II	III	IV	V	VI	VII	VIII	IX
Total depth of water in meters	1.8	2.9	3.3	3.6	3.7	3.6	3.5	3.9	1.9
Depth of Sample in Meters	*Content of Detritus in Water—in Mg./Lit.*								
0	15.6	16.0	15.0	15.8	16.3	16.5	13.4	19.3	14.0
1	—	13.4	18.8	16.0	16.9	14.9	18.2	18.1	24.8
1.5	16.1	15.0	15.6	15.1	17.2	16.7	12.1	18.1	19.6
2	—	18.1	16.1	19.0	18.1	19.1	18.1	15.4	—
3	—	—	17.1	19.1	19.1	19.4	18.1	—	—
0.3 meter above stream bottom	—	19.8	18.1	20.0	20.7	19.8	18.5	19.1	19.6

Many factors may account for the deviation from the estimated theoretical distribution of silt indicated by Figures 2 and 3. The distribution of turbulence may be different than postulated by Schmidt. Turbulence does not seem to vary according to the exponent 7/8 but instead it more likely varies according to some logarithmic law near the bottom. As was mentioned above, an irregular distribution of turbulence has been found experimentally, where two maximum values for the turbulence were observed on each side of the median line of a profile across a body of moving water (17, 26). Richardson (35) has found empirically that "the factor in question is found to increase in direct proportion to height at first but rapidly reaches a constant value in the main stream." It should be mentioned that Richardson determined mean values for the exchange coëfficient for a horizontal line across the entire river channel, and not at different points along that line.

The content of silt in the water generally varies considerably from moment to moment, at least for the fractions that are not sufficiently fine-grained to be uniformly distributed in the entire body of the water. Consequently the transportation of suspended matter is no more constant than the rhythmic transportation of the bed-load. The silt seems to be transported in the water in the form of clouds.

ACTUAL LOAD OF SOLID MATTER

The different modes of transport of detritus have been described *per se* above. The total transport of solid material, that is the load, takes place under different conditions. A river may only transport suspended matter providing the river is actually scouring its bed entirely in clay. More rarely, the river may only transport the bed load, as for instance when pure water runs over sand or gravel and the velocity is insufficient to cause suspension of the sand.

The bed load and suspended matter are believed to be transported more or less together, owing to the complex nature of the material that

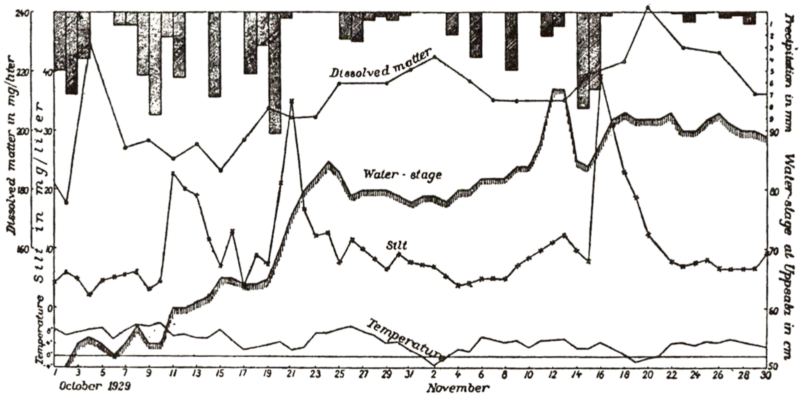

FIG. 4.—Content of suspended and dissolved matter in water from River Fyris at Upsala, Sweden during October and November, 1929, with respect to water stage, precipitation, and temperature at Upsala. (After Hjulström 17, 18.)

is moved. The relations between the different types of transport are different for different rivers and for different places in the course of an individual river. In the lower parts of the course of large rivers the quantity of suspended matter may be as much as 10 to 50 times the bed load. For the Mississippi according to Dent (quoted in 36) it is 20 times the bed load. On the other hand, in streams that have great fall, as for example, alpine streams, the bed load may form a relatively large proportion of the total transported matter. In the Rhone near Villeneuve, the ratio of suspended load to bed load is 7 to 1; for the Linth near Walensee, 3.5 to 1; and for the Sarine near Kallnach, 3.4 to 1(10).

Variation in load.—Variations in the quantity of material transported are much greater and more frequent and sudden than in the discharge of water. Figure 4 shows the relations between climatic factors and the amount of sediment carried by the River Fyris in Sweden. This river is a gently flowing stream and has no bed load. Though during the time illustrated by the figure, the discharge varies 5-fold, the percentage of silt in the water varies as much as 17-fold and the total quantity of silt transported per day no less than 35-fold. Nevertheless the variations in this river are less than in many other rivers. Moreover if part of the material is transported along the bed, the variations become even greater than indicated in Figure 4. This kind of transportation postulates a minimum velocity. When at rising water this critical value is attained the movement of the bed load begins; and each rise in velocity then causes a very great increase in bed load.

The climate, particularly rain water and melting snow, influences materially the transport of detritus. Rain obviously works in the following way. As soon as it falls on the dry ground it immediately washes away much of the easily erodible material (17, 18). After the ground becomes soaked, the constituents of the soil stick together and the erosion due to run-off decreases. The run-off water gradually collects in the drainage system and the streams begin to swell. The transport of silt is no longer at its maximum as it would be if the silt came from the bed of the water course. The dissolved materials in the river become less owing to the dilution of the river water by rain water, but later the content of soluble material increases. The subsequent increase in dissolved matter in the stream probably represents the effect of ground water, which reaches the stream some time after the rain and which has dissolved substances in its passage through the ground. There are three different maxima at different times: first, in silt content; second, in water stage; and third, in content of dissolved matter.

The quantity of material eroded likewise varies during different times of year. In cold-temperate regions of Northern Europe and America the transport is likely to be greater in spring and fall than in summer or winter. In summer the ground is covered with vegetation and in winter it is frozen. In spring and fall, the land is apt to be plowed, thus tending toward a state of greater transportation. In fact, the total load of rivers seems to be increasing in late decades, thus perhaps indicating the effect of man on transportation.

Computation of total load.—Owing to the large number of factors involved, the computation of total load is very difficult. Straub (42) has put forward a relationship between water discharge and sediment transported in suspension which agrees well with available quantitative data.

The equations, however, are "very different for every river" (42, p. 376). A large number of formulas for computing the bed load have been described by several authors (7, 8, 21, 29). Direct measurement in rivers is the best way to obtain results. The methods of measurement, however, raise some difficulties. Attention should especially be given to the determination of the average quantity of both suspended matter and bed load rather than the quantity at any given instant. The water samples must also be analyzed carefully owing to the colloidal material present (17). The bed load is more difficult to determine, though in recent studies the determinations are better than formerly (13, 19, 30, and 49). Even when the data are obtained by apparatus placed in the stream, the measurements may be unreliable owing to the effect of the apparatus on the motion of the stream, particularly because of currents induced by water flowing around the instruments which may deflect the detrital particles transported by the water (17, p. 399).

Problem of capacity.—How much material can a river transport? In the literature on the transportation of débris by running water, the term capacity is used in the sense defined by Gilbert, namely, the maximum load the stream can carry. The application of the term in this sense to natural streams is subject to several complications, because of the wide range in grain size that is or may be carried. Moreover, streams in nature can scarcely ever become saturated with detritus in the same way they can be for salt. All gradations are found between pure water and mud flows.

PROBLEMS THAT SHOULD BE WORKED UPON

Many problems remain to be solved before man can answer the questions as to how detritus is transported by moving water and also as to the quantity carried. Some of the problems that await solution are here given.

1. Determination of the velocity, or tractive force, with which material of similar or dissimilar grain size is eroded. In other words, a careful determination of curve A in Figure i. Similar curves should be determined for different stream gradients and other hydrographic features.

2. Same determinations as in 1, but in silt-laden water.

3. Determination of relations between minimum eroding velocity of water and the lowest transportation velocity for different types of material. In order to accomplish this, curve B in Figure 1 will have to be determined more reliably.

4. Careful determination of the content of detritus and the velocity of flow across a profile of a river at given instants of time.

5. An international coöperative enterprise for direct measurement of the transport of detritus during a period of at least a year for a large number of rivers on the earth according to some particular method. In this way perhaps it might be possible to ascertain the total amount of material transported in a given time to the sea. At the same time, similar determinations should be carried on extensively in the sea.

The main difficulty in the determination of the different details of transportation is the fact that the present state of knowledge of hydrodynamics is still too defective. Some important problems that need to be solved were suggested at the General Sessions of the International Union for Geodesy and Geophysics at Edinburgh in 1936 (27, pp. 610–23).

6. Determinations of the intensity of turbulence in different directions and at different places throughout a transverse profile of a stream with respect to different velocity, different depth, different roughness of bottom, different types of profiles, for straight and for crooked stretches in streams, and for convergence and divergence. This type of an investigation could be approached along many different lines. It should be started with laboratory studies and followed by investigations in rivers and in the sea.

7. The nature of the bottom layers of a stream should be studied with respect to their thickness (27) and state of motion, and to the transportation of bed load at different concentration gradients (17, p. 331). Such an investigation is very much needed, though relatively little work has been done yet. The introduction of salt solutions into fresh water should be very helpful in indicating the motion of the water in such a study. According to unpublished work of the late Wilhelm Schmidt, Vienna, communicated in a letter, in such investigations the introduction of salt solutions is more suitable than the use of salt crystals.

8. Determination of helical flow of water, especially during straight stretches in the course of a river. This problem could be worked upon in connection with point 6. Helical flow may affect materially the transportation of débris, but its nature and explanation are very poorly understood at present.

9. Determinations of content of detritus and velocity at given instants in a transverse profile of a stream simultaneously at many different points in the profile at short intervals of time. Such a study would yield much information upon mode of transport of suspended silt and motion of water. The relations of the pulsations in turbulent flow could be understood better by such a study. Analogy from studies of the structure of wind (39) might be helpful.

10. Conditions of collective movement of particles, such as ripples.

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