~~00193~~

United States
Environmental Protection
Agency

Corvallis Environmental
Research Laboratory
Corvallis, Oregon 97330

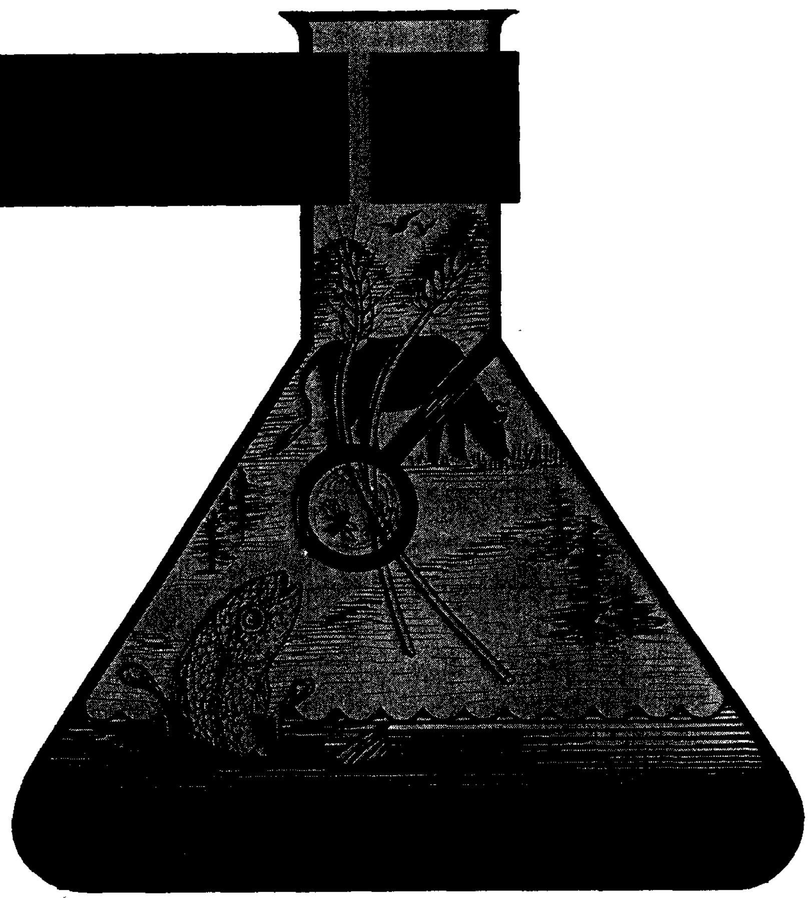
60019782

[redacted]

EPA

BIOLOGICAL SIGNIFICANCE OF FLUVIAL PROCESSES IN THE LOTIC ENVIRONMENT

CERL - 042



BIOLOGICAL SIGNIFICANCE OF FLUVIAL PROCESSES IN THE LOTIC ENVIRONMENT

By: Frederick B. Lotspeich

INTRODUCTION

It has long been recognized by aquatic biologists that the physical nature of a stream bottom directly influences its productivity as an anadromous fishery and the benthic communities comprising the bulk of fish food. Experts concur that optimum fish and fish-food production requires clear, cold water and a gravel substrate free of fine sediments to permit maximum oxygen transfer, provide for removal of metabolic wastes, and allow sufficient pore size for developing embryos and movement of benthic organisms. Aquatic biologists have also observed that within a given area encompassing separate watersheds, some streams consistently produce more fish.

Recent legislation mandates that future attention be given to the effects of nonpoint source pollution - primarily sedimentation - on low-order streams, the same streams that are of prime concern to aquatic biologists. All of these requirements concern the biologist who is asked to devise ways to evaluate stream systems with respect to relative productivity and document how low-order streams respond to sedimentation from nonpoint sources. A distinction must be drawn between low-order streams that are most amenable to control measures within each watershed and those less so but where biological productivity is of prime consideration. In mountainous terrain, first and second-order streams are steep, bedrock is near the surface, and clastic sediments are thin and intermittant. Such streams cannot support a high biological productivity, but because their aggregate linear length constitutes 80 to 90% of total stream mileage, they act as collectors of sediment from nonpoint sources. Sediment from these headwater reaches then moves downstream to third and fourth order streams where productivity is high and excessive sediment degrades the aquatic environment. By controlling sediments in unproductive headwater streams, we can maintain optimum production in higher-order streams which do not act as sediment collectors but are impacted by erosion products from careless management practices in headwater basins.

Therefore, assessing stream quality and evaluating best management practices requires expertise in physical as well as biological sciences. Any evaluation of stream quality demands an understanding of stream dynamics and mechanisms of sediment transport over a wide range of hydrologic conditions. Only with such knowledge, can an environmental scientist provide advice in developing a program of habitat evaluation as best management practices are introduced to control erosion products from nonpoint sources.

For many years, physical scientists have generated information that, when properly applied to aquatic biology, could help biologists evaluate many sedimentation problems associated with nonpoint sources. Geologists specializing in sedimentation have relevant expertise, as do specialists in certain fields of engineering, soil physics, hydrology, and ceramics, to name a few. Collectively, these researchers have amassed a wealth of knowledge on processes and properties of clastic materials that can help solve many problems facing lotic biologists. However, biologists often may not be aware of the related work in other disciplines and the rich literature dealing with natural, clastic materials. This is not to imply that river mechanics are thoroughly understood, especially for low-order streams with gravel beds. Emphasis is, and has been, on sand and silt-bedded streams which are moderately well understood. Gravel-bottomed streams are more difficult to study because current methods of measuring bed movement and grain-size sampling leave much to be desired. A more thorough understanding of these stream types requires improved sampling methods for these two parameters.

However, with present knowledge and application of a few straightforward measurements, streams can be readily evaluated with sufficient accuracy to describe the habitat requirements for a particular use of a stream. In this discussion, only fluvial processes relating to sediment movement will be described; other processes such as meandering, riffle-pool formation, sinuosity, etc., will not be considered.

Recognition of the interdisciplinary nature of lotic biology requires a melding of biological and physical sciences if aquatic ecology is to move effectively to solve environmental problems. Moreover, this can only be attained by establishing a professional rapport among scientists, gaining a better understanding of physical processes and use of conventional physical measurements, using a common classification, and improving communication between biological and physical scientists. The multidisciplinary approach will achieve these goals more efficiently and with greater satisfaction than if each scientist works in isolation.

The primary intent of this paper is to describe the origin, physical processes, and properties of clastic sediments to help biologists understand the fluvial environment and how these factors relate to lotic habitat requirements. In an attempt to provide succinct, brief descriptions, the author uses a minimum of technical "jargon" and no equations. Another objective is to define those essential terms, commonly used by physical scientists, that will enable an multidisciplinary group to share a common vocabulary and thus facilitate communication. A third objective is to describe several methods of stream bed evaluation to help biologists interpret physical data from the field and laboratory in relation to lotic biology when assessing stream quality.

MATERIALS

As used here, materials will include sediments processed while using flowing streams as the transporting agent. The unit controlling the functioning of any stream is the watershed which provides sediments and water to move them and which should be considered as an ecosystem because of the interactions of the physical environment and the life contained within it. Biologists unfamiliar with terms used by physical scientists frequently misuse or coin new terms when describing sediments. To establish a common terminology, several terms that will be used throughout this paper are defined. They are included in the text because it seems appropriate to incorporate them early in the discussion and avoid the inconvenience of searching for a definition in a glossary.

Definitions

Bed transport: The movement of grains or particles (too large to carry in suspension), by rolling, skipping, or sliding on or very near the stream bottom.

Clastic: Fragment of any earth material and present as discrete grains ranging in size from clay-size to boulders; clastic sediments (in our discussion, alluvial) are thus distinguished from other sediments such as chemical, i.e. limestone, cherts, etc.

Competence: The ability of a stream to move the largest grain, i.e. particle, in a given reach.

Fines: "Fines" as used by sedimentologists and soil scientists refer to grains smaller than 100 microns (0.1 mm), anything larger would be sand, gravel, cobbles, etc.

Fluvial: Relating to rivers, conforming to changing course of a stream, produced by river action.

Gradient: The degree of inclination, in the case of a stream it is the water surface or that of specified reaches of the stream bed. Usually expressed as slope or the ratio of vertical distance divided by horizontal distance.

Hydrology: The study of the interrelationships and reactions between water and its environment in the hydrologic cycle.

Lotic: Relating to or living in actively moving waters as in stream currents as opposed to limnic or standing body of water (lakes, ponds).

Median size: Relating to the size-percent accumulation curve; the median size is the grain size (in millimeters) where the 50% accumulation (by weight) intercepts the curve.

Order of stream: A systematic way to classify streams from their headwaters downstream; a first-order stream is the uppermost headwater stream without a tributary, after 2 first-order streams join they are classified second order and so on downstream.

Permeability coefficient: A dynamic property of a clastic sediment that expresses its ability to transmit fluids. The rate of flow depends on the hydraulic gradient, the area of the cross section, the length of the transmitting column, the nature of the porous media, and the viscosity of the fluid. When all factors, except the media, are held constant, the rate is a function of the transmitting sediment and is termed the "permeability coefficient."

Pore space: That space among the grains of a clastic sediment filled with water or air; usually expressed as a percent of the total bulk volume.

Pore space efficiency: A term coined for this discussion to denote the relative efficiency of the interstitial voids of a substrate to support vital biological functions which are corollary to the quantifiable hydraulic properties, permeability coefficient, and specific yield. Pore space efficiency is envisioned as a field habitat description derived from field/laboratory estimates of a specific yield over a time span.

Potential energy of a stream: The energy of a mass of water owing to its position above other similar masses; this is the source of all energy possessed by flowing waters.

Sediment: Geologists define sediments as deposits of solid material on the earth's surface from any medium (air, water, ice) under normal conditions of the surface. Here we will only be concerned with clastic sediments deposited in streams (alluvial sediment); textures range in size from clay to boulders.

Sediment discharge: A time rate of movement of dry weight of sediment through a cross section.

Sorting coefficient: An index derived by sedimentary geologists to describe the size distribution of grains about a median; defined as the square root of the quotient of the grain size at the 75% level divided by the grain size at the 25% level - a perfectly sorted sediment has a coefficient of one.

Specific yield: That amount of water yielded by a saturated sediment under the force of gravity; usually expressed as a percentage of a unit volume of sediment, coarse sediments yield more than fine sediments in a shorter time span, this is a common term used by groundwater hydrologists.

Suspended transport: Fine grains carried by flowing water held in suspension by turbulence or colloidal processes; size of grains held in the water column is primarily a function of velocity.

Clastic materials originate by physical and chemical processes of weathering of all types of rocks. Properties of the clastics are controlled to a large extent by the lithology from which they are derived as weathering products. Processes of erosion and mass wasting move these materials downslope until they reach a stream which then modifies them by fluvial action and they become true alluvial sediments. Fluvial processes continue to modify the clastics by reducing them in size through mechanical abrasion, impact, and hydraulic sorting as they are carried downstream.

Two properties of clastic sediments, porosity and permeability, are of fundamental importance to aquatic biologists and will be discussed later. These two derived properties can in turn be described by five properties of grains comprising a sediment. They are (1) composition, (2) size, (3) shape, (4) roundness, and (5) packing.

(1) Composition is a property derived from the original source rock that determines the grain's mineralogy and how it will behave during fluvial processes. Thus, a grain weathered from igneous bedrock will have a different shape and resistance to abrasion than clastic material from soft sediments or metamorphic rocks. Clastics from massive igneous rocks (chiefly granitic types) tend to be equi-dimensional whereas those from gneisses or schists tend to be tabular or platy.

(2) Size is controlled by source rock, weathering processes, how far the grains have been transported, and degree of sorting. Clastics from tabular rocks (schists, gneisses, laminated sediments) cleave at linear planes and are reduced to smaller grains in a shorter distance than are the massive rocks. Sand-sized and smaller grains tend to be monomineralic whereas larger grains are composed of several minerals derived from the parent rock.

Although sedimentologists have been using a standardized classification scheme for decades, biologists have never seemed to be aware of it during their discussions of sediments. The most widely used scheme is that of Udden-Wentworth, which is presented in this paper, and is based on the millimeter as the central unit. Sediments are usually classified by dry sieving for coarse separates (> 0.062 mm) silt size and by some wet procedures for < 0.062 mm. Grains larger than 1 mm are classed by doubling each sieve opening and those less than 1 mm by halving each class interval as shown in Table 1.

(3) Shape of grains in a sediment is a property controlled primarily by grain lithology. The shape of clastic grains causes them to behave in a variety of ways during transport and imparts various properties to the resulting sedimentary deposit. Four basic shapes describe clastic grains:

(a) equant or grains whose three "principal or orthogonal" axes are nearly the same length (tend to be spherical).

(b) tabular, or disc shape, where two axes are near the same length with the third much shorter; such a shape characterizes clastics from schists and gneisses.

(c) bladed, where all three axes vary considerably in length from one another giving a rectangular shape in two directions with a short axis at right angles.

(d) cylindrical, where two short axes are about the same length with the third much longer giving a rod shape to the grain.

(4) Roundness, as a descriptive property of clastic grains, is not related to shape. Roundness is that condition that gives curvature to angles and tends to obliterate surfaces caused by cleavage or fracture planes; thus a blade-shaped clastic can be just as rounded as an equant grain but will behave differently during transport and deposition. Roundness, or its opposite, angularity, imparts certain characteristics to a sediment that controls derived properties. Orientation influences derived properties and is strongly influenced by shape during the deposition process. Clastics with similar shapes tend to take the same orientation during deposition.

(5) Packing refers to the arrangement and closeness of grains in a sediment. This property is strongly influenced by shape which, in turn, strongly influences porosity, pore size distribution, and permeability. The total appearance and relationship to one another of all structural elements of a clastic sediment is its "fabric." Derived properties will be discussed under processes and properties because these are of prime importance to life in the lotic system.

SEDIMENT TRANSPORT

Flowing water derived from a watershed through groundwater and surface runoff is the transporting agent that moves clastic sediment during fluvial processes. The nature of flow, such as seasonal distribution, quantity, and rate of flow, depends on the local climate, geology, and stage of watershed maturity. The only energy source of flowing water is the potential energy of gravity as water moves from higher to lower reaches. Thus, energy to transport sedimentation in a given reach is a function of its gradient. Fine sediments are transported by suspension which is a function of turbulence or eddies as velocities change in various reaches and cross sections of a flowing stream. Coarse grains move as bed load by skipping, rolling, or temporary suspension during high water and the processes of moving depends on stream power which is a combination of downstream force and hydrodynamic lift as water flows past large grains. The relative proportion moving by either mechanism is primarily a function of grain size although velocity and turbulence are also important.

Suspended fine materials move with about the same speed as the flowing water whereas grains moving along the bed move at a slower rate and may be stationary at times, moving as pulses. Engineers and hydrologists have developed equations to estimate sediment discharge for both transporting modes but all are qualitative, especially those for the coarse sediments moving on the bed. Sediment discharge is also a function of available supply and, for fine grains, the supply is usually much less than the stream can transport. On the other hand, the supply of coarse grains is usually greater than the stream can transport, hence they accumulate as gravel deposits. Velocities in a stream are not uniform through the vertical water column but are highest at the water surface and decrease to near zero at the bed surface, hence, the ability to move grains is lowest on the stream bed. Competence of a stream is its ability to move the largest grain in a particular reach, for large grains can only occur during flood or other times of high discharge.

Clastic sediments are coarser in the upper reaches of a stream, even though its competence is higher because of steeper gradients, because most of the sands and finer grains have been flushed out to reaches where gradients are lower. As flood stage decreases most of the coarse material lags behind as finer material passes through a given reach and thus is called lag gravel which generally contains very small amounts of sand and fines. As gradients decrease downstream, clastic sediments decrease in grain size primarily because of hydraulic sorting but also as a result of continued grinding action of large grains as they tumble and roll during transport.

THEORETICAL PROPERTIES OF CLASTIC SEDIMENTS WITH SPHERICAL GRAINS

Discussion of the two derived properties of clastic sediments, porosity and permeability, was deferred to examine some relevant work demonstrating how they are affected by the five fundamental properties described in the previous section. Since these two properties determine the quantity of fluid in a deposit, and how it will yield on pumping, petroleum engineers and groundwater hydrologists have a vast interest in them. Ceramic and highway engineers use this information to obtain maximum compaction with minimum porosity and, by using spheres as an ideal standard, have developed appropriate criteria. These criteria also are useful to lotic biologists. Porosity is that percent of a volume of sediment that is not occupied by solid grains and which, when under water, is filled with water or air and water.

Spheres of uniform size can be arranged in space by six packing arrangements, ranging from cubic with most open packing (porosity of 47.6%), to the rhombohedral with closest packing (porosity of 26.0%). Thus, merely by arrangement in space, porosity can be altered by 21.6% without changing grain shape or size. Theoretically, the same porosity is possible, with the same systematic packing, regardless of the size of grain, assuming all are the same size. Although the grain shape is uniform, the shape of pores is highly irregular, from wide interstitial spaces to very thin channels or throats, but is repetitive in space for a given packing. For closest packing of a given grain size, it is possible to calculate grain sizes that will just fill interstitial pores to introduce secondary, tertiary, quaternary, and quinary grains that fill voids to produce a total pore space of only 14.9%. It is such calculations that permit engineers to select optimum grain-size distribution to give minimum porosity with maximum strength of material.

Using spheres, these interstitial grain sizes are given as ratios of the radius of the primary or framework grain. The sizes to just fill voids without forcing primary grains apart is called the "critical ratio of occupancy." Thus in any clastic sediment with known size of primary grain, a grain size to fit the voids can be estimated. Another size, called "critical ratio of entrance," permits a determination of grain size that can enter interstitial spaces without disturbing the packing. Such calculations permit estimating what size of clastic grain may freely enter a deposit if the size of primary grain is known. Adding interstitial grains without disturbing the primary grains always decreases porosity. Although in systematic packing of spheres, total porosity is independent of grain size, in random packing (such as occurs in clastic sediments) total porosity always increases with decrease in grain size because of bridging, but individual spaces decrease in size. This relationship has a significant influence on biological "pore space efficiency" and on corollary permeability which is the property that defines intragravel flow.

Unlike porosity, which is a static property dependent on size and arrangement of grains, permeability is a dynamic property dependent, in addition to size and arrangement of grains, on potential force measured by hydraulic head. Permeability may be defined as the ease with which a fluid moves through a porous material, in this case clastic sediments. It has been found experimentally that for a given cross section of material, the rate of flow is directly proportional to the hydraulic head in the direction of flow and inversely proportional to the viscosity of the fluid. Thus, in stream deposits, intergravel flow (permeability) is directly dependent on stream gradient, the only energy source available to move the fluid. Sediments with large pore spaces, i.e., coarse grained, have high permeabilities under a given head. As pore size decreases, by having interstitial spaces filled with smaller grains or an overall decrease in primary grain size, permeability decreases. Shape and size of pores control permeability because it is the minimum size of pore that determines the rate. A pore that varies in shape and size is controlled in its rate by the smallest cross section of pore.

FLUVIAL PROCESSES IN SEDIMENT FORMATION

Obviously, stream gravels are not spheres nor are they of uniform size. However, even with these limitations, concepts of porosity, pore shape, and how these affect the really basic parameter, permeability, are useful to biologists working in natural habitats. Many of the fluvial processes, acting on clastic sediments, form structural units that have properties similar to those described for the ideal case.

Although stream gravels can never reach the ideal as to shape (spheres) and sorting (one size class), processes in the stream cause clastics to trend toward ideal shapes with properties that are predictable enough to be useful to aquatic biologists. Size of the clastics ranges from coarse (e.g. boulders) in the headwaters where competence is high to finer sand and silt as stream order increases in lower reaches with lower gradients and velocities to decrease competence. A given large grain becomes rounded in a few miles of downstream travel but its size tends to be rather stable. Few streams have competence enough to move boulders through reaches with low gradients. Smaller grains are flushed out by flow that cannot move the largest grains and are distributed downstream by hydraulic sorting. A perfectly sorted sediment is composed of grains of one size and is extremely rare in nature; most deposits contain several size classes. Upper reaches contain the coarsest grains because most fines are flushed out by hydraulic sorting in these steep reaches. Intermediate reaches frequently have a mixture of grains too large for the normal competence of that reach; many times these are added to the master stream from tributaries with higher competence. Fines contained in gravels are usually added after coarser grains are deposited as flow decreases during hydrograph recession. The higher the degree of sorting for a given size range, the higher the permeability.

Shape and roundness affect permeability because certain shapes tend to be oriented differently than others and roundness tends to cause fewer eddies as water flows past individual grains. Oblate grains tend to be deposited with the long axis parallel to the flow and, if one end is blunt, the larger end is upstream because this orientation offers the least resistance to flow. Flat grains tend to take an imbricated or shingled orientation with their flat surface facing upstream, dipping into the current at right angles to flow direction. The downstream edges of these grains are higher than upstream edges. When viewing imbricated deposits from upstream all grains appear flat with the upstream edge lower than that downstream; as viewed from downstream one is looking at the upper edges of individual grains. Deposits with this orientation indicate the direction of flow at the time of deposition. Permeability of such deposits depends on the direction of flow with maximum flow parallel to the bedding and minimum flow across the flat surface. Highly angular (low roundness) grains tend to collect fines at lower flows but not at higher flow because of turbulence caused by sharp angles. Such grains also tend to interlock with adjacent grains and resist further movement.

Packing of clastic sediments in a river is far more complex and diverse than for the ideal case because of the wide range in grain size and conditions under which deposition occurs. One physical fact important in the study of this phase of river phenomena is that most grains, when immersed in water, weigh about 38% less than their weight in air. Density of most rocks and rock-forming minerals is near 2.65; since water is close to 1 at all temperatures, immersion allows such material to be moved with less energy than if dry. Such a reduction in immersed density results in a more open packing arrangement, even with uniform shape and size of grains, because gravity is less effective as a packing force.

With an ample supply of clastics of all sizes, reaches with various competencies will have gravel sizes that reflect the competence of each individual reach. As river competence decreases, larger grains will drop out and, if in ample supply, will form a more or less random packing arrangement that constitutes the basic framework of the deposit for that reach. In nature, packing is somewhere between cubic (very unstable) and closest packing which is most stable. Smaller grains continue downstream until they encounter a reach with low velocities where they drop out. If a supply of smaller grains, upstream from a coarse deposit, continues to be available, many of the void spaces of the coarse framework will be filled with these smaller grains if they are not too large to enter the structure. Thus, the natural hydraulic sorting action forms a framework of coarse grains with subsequent filling of voids as competence decreases. It is at this second stage that the "critical ratio of entrance" may become important; if the size of these secondary grains exceeds the pore space available, they cannot enter the framework, and must be carried further downstream or be deposited on top. Thus, many voids of the primary framework may remain unfilled, resulting in higher permeability for a given grain size. Since riffles fit these conditions, high competence with a rapid decrease as the flowing water enters a pool, they tend to have random, open packing with maximum permeability. Because hydraulic sorting is continuously operating, clastics initially tend to be deposited with a narrow range of grain size; finer materials enter later to form a matrix which decreases permeability.

Biologists frequently refer to a given grain size as being critical to emergence or survival of young fish. This statement is only true for a given size of primary grain with whatever packing is caused by shape and grain distribution. Using the reasoning developed in this paper, based on findings from related disciplines, other grain sizes may offer similar restrictions, depending on the size of primary grains. Sizes of critical space needed can be estimated for a given framework of known grain size distribution and whether the "critical ratio of entrance" allows these sizes to enter the structure. Thus, the filling of "living room or space" by one size of grain without considering the entire deposit, or different deposits with another grain size distribution, may unduly restrict options or alternatives in the management of these resources. The coarsest gravel in which a given species of salmonid can prepare a redd, bearing in mind the reduced density of natural grains when immersed, offers the optimum permeability to give adequate reaeration, provide living space, and have sufficient pore size for emergence. A coarse deposit can tolerate a higher percentage of the "so called" critical size than a finer grained deposit and still provide living space. Each deposit has its own limiting grain size depending on the grain size distribution from the primary framework through other class sizes.

PHYSICAL PARAMETERS AS BIOLOGICAL INDICES

The preceding section dealt exclusively with physical processes in the lotic environment. This section will describe some physical measurements and observations that should assist aquatic biologists in evaluating stream quality. It was suggested at a sedimentation workshop—held at Seattle, WA in March 1977—during a discussion of nonpoint sources of sediment, that stream bed composition be used as criterion of stream quality; the exact measurements to make and interpretations of the data were not explained. A simple technique to classify stream beds has been used by aquatic biologists at the University of Idaho. The method consists of four elements from which an index number is derived to classify the bed surface as it appears to an observer. The method is simple, rapid, and, from personal communications with those who have used it, surprisingly accurate when applied by an experienced observer. Stream beds deemed desirable for aquatic life using this method have also been observed to reflect the underlying sediments so its utility extends to some depth in assessing habitat conditions.

The four elements observed in using this tool consist of estimating the size of the predominant material, the next dominant material, material surrounding the dominant grains, and the degree of embeddedness of each of the predominant grains. Size of grains is divided into several classes each of which is assigned a number. The same process is followed to determine degree of embeddedness. The sum of these numbers constitutes a suitability index of the observed site as a habitat for aquatic life. An experienced observer can classify a site in several minutes, hence, several sites on transects across a stream or longitudinal traverses in a stream can be quickly assessed to obtain reliable samples of a given reach.

Two additional observations are suggested when using this subjective tool. One of these is shape of grain since shape is important as a factor in intragravel flow and also gives some indication of source of sediment. The second is roundness, a factor in intragravel flow and stability of sediments in place. It also gives some indication of sediment source. By using these six parameters when observing a stream bed, an experienced biologist can quickly gain considerable insight on classifying a stream for its potential to produce fish or fish food. If the water is clear, this method can be used to a depth of two to three feet without additional equipment. However, because this technique is subjective, relying on individual judgment, it alone cannot form the basis for legally accepted habitat criteria, regulation of watershed management practices, or scientific communication via the literature.

More quantitative evaluation of stream quality requires gravel sampling by more sophisticated methods than visual observation. To get a quantitative estimate of stream bed quality, a sample of the stream bed must be physically removed and analyzed for grain size distribution. It is at this stage that some differences of opinion may arise on what constitutes a representative sample for the parameter or variable being tested. Statisticians hold that sampling should be completely random. This requires an unrealistic number of samples to meet the criterion for a representative sample. Some compromise must be reached between the statistical significance of a sample and physical significance of a relatively few samples whose numbers are determined by physical constraints on sample collection and analysis. The following discussion will point out that completely random sampling is unrealistic and unnecessary, except in a restricted sense.

A fundamental point must be made here: the distribution of sediment grains in a stream is not random but is the result of cause and effect, as discussed previously. Therefore, reliable sampling of a stream depends more on the investigator's knowledge of the sampling objective and the fluvial mechanisms of grain movement, deposition, and entrainment than on absolute randomization to obtain a representative sample. These concepts become especially important when sampling low-order streams (1 through 3) that are narrow, steep, and have a very coarse substrate. These low-order streams are of prime importance when dealing with nonpoint sources of stream degradation because it is on these headwater basins that best management practices can control erosion and prevent sedimentation of higher order streams with their greater biological productivity.

When assessing the need for sampling these streams, some judgment is required to decide what and how intense an effort is needed to meet the stated objective. It may be that bed sampling is not necessary; visual evaluation may be sufficient. On low-order streams, it is impossible to collect a statistically sound sample without disrupting a significant part of the stream. The alternative is to select sampling sites that correlate with the biological objectives of a study, accept the samples as representative, replicated if possible, and make as careful an analysis as is justified. Usually the analytical portion of the process is the most accurate part of the operation. With these headwater streams, it is better to systematically sample a site by collecting several smaller samples, such as with a freeze-core method, than one or two larger samples that disrupt a major portion of a given site in the small streams.

To meet the objectives of a given study, sampling site selection and determining the number of samples needed to represent the site requires the expert judgment of those who fully understand stream mechanics. During the sedimentation workshop at Seattle, the point was made that considerable variation among gravel samples can be eliminated by sampling at the same environmental site by persons familiar with given stream systems. In other words, do not mix samples from different environmental sites (pools - riffles - runs, etc.) because the physical processes at each are different. Stream bed composition at a cross section is a continuous variable resulting from hydraulic events that form a continuous series in terms of both time and spacial effect. Stratified sampling is one technique for dealing with heterogeneous natural materials such as stream gravels. By selecting strata that are fairly homogeneous from a heterogeneous population, greater precision is accomplished over simple random sampling and results can be treated statistically.

Statistical analyses are useful in evaluating results of a samplng program. However, it must be remembered that the ultimate objective is not to achieve maximum accuracy in a sampling program, but make it "sufficiently accurate" to meet the stated objectives. It can well be that certain variabilities are tolerable because the errors do not skew data or alter decisions based on data interpretations. Assuming that good judgment is used when selecting a sampling site, statistics is a valuable tool in establishing variability among individual samples, detecting errors in the analytical procedures, and providing some measure of whether results from one site can be extrapolated to a similar site with a predicted degree of reliability.

Once sites have been selected and samples collected, the next step in achieving credible results is to analyze the samples using the best standardized procedures. Dry sieving is recommended for classifying stream gravels using size classes based on the Udden-Wentworth scale (Table 1). Grains bigger than large cobbles can be hand-picked and weighed if the sample is not large; grains less than 0.062 mm can be reported as all material passing this sieve, even though some finer classes will be present. Because of its chemical activity, clay as a component of the $<$ 0.062 mm separate can be important even when present in low percentages. However, in most low-order streams, clay percentage is usually very low and need not be separated from silt, a procedure requiring specialized equipment.

One of the most meaningful methods of displaying results from gravel analyses is by a size-percent accumulation graph where the logarithm of the size (in mm) is plotted on the "X" axis and percent accumulation by weight is plotted on the "Y" axis. From such a graph, the median grain size of the sample can be determined and a measure of the size distribution around the median size calculated, i.e., sorting coefficient. Thus, with two small numbers derived from the overall analysis the biologists can, with some prac-

TABLE 1. SCALE SIZE FOR CLASTIC SEDIMENTS (BASED ON THE UDDEN-WENTWORTH SCHEME). After Colby; 1963.

Class	Millimeters (mm)	Inches (in.)
boulders	> 256	> 10
large cobbles	256 - 128	10 - 5
small cobbles	128 - 64	5 - 2.5
gravel		
very coarse gravel	64 - 32	2.5 - 1.3
coarse gravel	32 - 16	1.3 - 0.6
medium gravel	16 - 8	0.6 - 0.3
fine gravel	8 - 4	0.3 - 0.16
very fine gravel	4 - 2	0.16 - 0.078
sand		
very coarse sand	2.00 - 1.00	0.078 - 0.039
coarse sand	1.00 - 0.50	0.039 - 0.020
medium sand	0.50 - 0.250	0.020 - 0.0098
fine sand	0.250 - 0.125	0.0098 - 0.0049
very fine sand	0.125 - 0.062	0.0049 - 0.0024
silt	< 0.062	< 0.0024
clay	< 0.004	< 0.00015

tice, interpret the graph in relation to the biological significance of the substrate.

Figure 1 displays five curves from grain size analysis ranging in size from 0.1 to > 100 mm. Median size is shown to the left of each curve and the sorting coefficient on the right. These curves illustrate a few of the many possible conditions that may be found in natural streams with substrate textures ranging from sandy to coarse gravels.

Starting with curve #1, it can be seen that the median size is 0.21 mm and the sorting coefficient is 1.3 with a maximum grain size of 0.5 mm and a small percent < 0.1 mm. This sand is very well sorted, as shown by the small coefficient and the steepness of the curve. Biologically this sediment has a high, uniform porosity but permeability is low because pores are uniformly very small and stream gradients, which provide energy for flow, are low with such streams. Thus, merely with this one curve, an experienced field scientist can draw several, biologically significant, inferences about the substrate environment and the nature of the streams in which it is found.

Curve #2 shows that texture is becoming coarser but is still dominated by small gravel and coarse sand. Median size is 1.5 mm (coarse sand) with a sorting coefficient of 2.0, indicating that there is a wider range in grain sizes than for curve #1. This in turn means that many large pores contain smaller grains that impede intragravel flow. Maximum grain size exceeds 10 mm (0.5 in.) and very small grains (< 0.2 mm) are essentially absent. Although this sediment is much coarser than that shown in curve #1, biologically it is still not a desirable habitat for salmonids or other benthic life because pores are small and permeability is low because of poor sorting. Such a deposit also indicates moderate to low gradients which also tend to cause low rates of intragravel flow. Comparing curves 1 and 2, it may be inferred that, although 2 is much coarser than 1, its biological environment is not too much different because of its poor sorting which causes many larger pores to be filled with interstitial grains.

Curve 3 illustrates a substrate with a well-sorted, medium texture whose median size is 14.5 mm with a coefficient of 1.1. Although the maximum size is only 50 mm (about 2 in) its minimum grain size is 2 mm which constitutes very little of the total sediment. Moreover, only 6% of the total is < 9 mm in size. The biological significance of such a size distribution curve

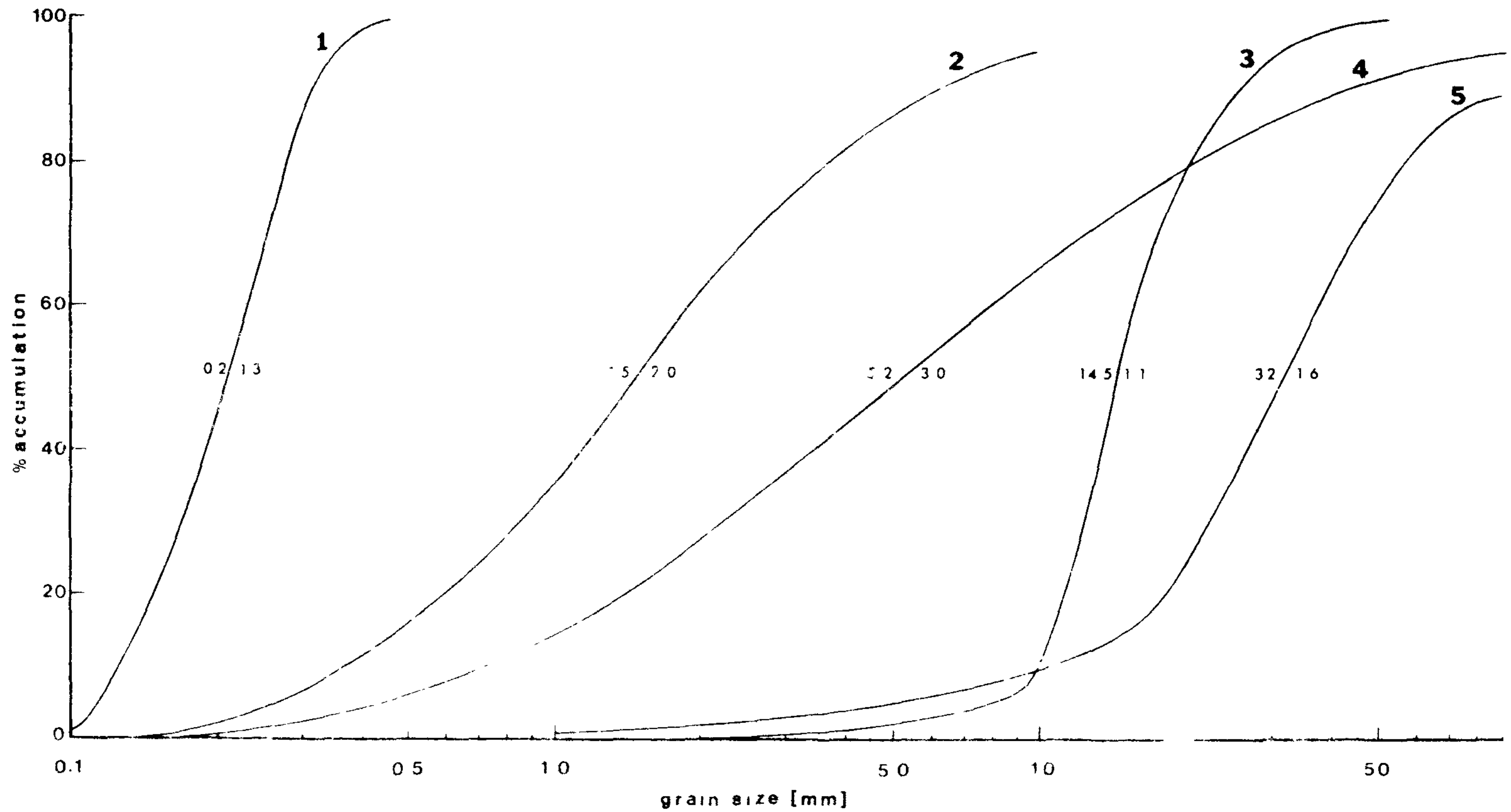


Figure 1. Grain Size Accumulation Curves of 5 Sediments.

implies high porosity with uniform pores and high permeability because the extensive sorting eliminates interstitial grains that might fill large pores. Such a substrate should provide an optimum environment for all forms of aquatic life and, because gradients are moderately high, intragravel water flow should be nearly ideal to sustain life.

Curve 4 illustrates another set of grain-size distribution. In this example, median grain size is only 5.2 mm even though maximum size is > 100 mm (about 4 in) because of the very poor sorting with a coefficient of 3. Total porosity of this sediment is high but, because of the wide range in grain size, many pores are filled with interstitial grains of diminishing size because grains are available to fill even small pores. Although no grains < 0.2 mm are present in this sediment, 14% of the total is 1 mm or less in size. Such a sediment should have a moderate to good biological potential, but permeability will only be moderate to low for the reasons given above. Such a grain-size distribution implies moderate to high gradients and an ample source of sediment of all grain sizes.

Curve 5 portrays the coarsest sediment of the entire group and illustrates a somewhat different set of environmental conditions. Although sorting is poorer than for curve 3 (1.6 compared to 1.1), porosity, size of pores, and permeability should provide a substrate that is biologically as good or better than 3 because of the greater overall grain size. Only 4% of the grains are < 4 mm in size and almost none are less than 1 mm. About 10% of the larger grains are > 100 mm in size and the curve suggests that there are some larger grains, probably being supplied from a different source than the main stream. The larger grains are probably being supplied by a tributary with a higher gradient giving it competence to transport larger grains than can the main stream, itself a high gradient stream.

The five curves presented here represent a range of potential biological productivity from low (curve 1) to median (curves 2 and 4) to good for curves 3 and 5. No conclusions seem final without evaluation by biologists to attain a stated objective. Since it appears that potential productivity increases as grain size increases with good sorting, it might be argued that the coarser a sediment the higher its biological productivity. This probably is not true. A stream substrate composed of 10 in. boulders is not as likely to be as productive as one with smaller grains, lower gradients, and some interstitial grains. Some combination of median grain size, sorting coefficient, gradient porosity, and permeability in the median range for all parameters ought to give optimum productivity, and not extremes at either end of the spectrum for these factors. An assessment process is suggested in the next section.

Specific yield of a sediment, defined earlier, can be used to estimate the efficiency with which a substrate yields water under the force of gravity. The time needed to drain a given volume of sediment from saturation to equilibrium with gravity is an estimation of the permeability coefficient which depends on the nature of the porous medium, here stream gravels. Combining the two is a measure of "pore space efficiency." A sediment that yields a large volume of water in a short time has a high pore space efficiency. A high efficiency implies that pores are large, fine grains are minimal, and permeability high. Such a sediment would provide an optimal environment for all forms of aquatic life, i.e. pores large enough for movement in any direction and intragravel movement of water for reaeration and removal of metabolic wastes.

Specific yield can be quickly estimated in the field by saturating a known volume of stream gravel, weighing it, draining the gravel from below under gravity until it reaches a defined equilibrium, and then weighing the drained sediment. The difference in weight is the volume yielded to gravity from which specific yield can be calculated. If the time elapsed from start of draining to equilibrium is noted, a measure of the permeability coefficient is obtained. As an aquatic scientist gains experience with a range of substrate textures he can soon learn to equate biological indices which, in some fashion, measure productivity with those physical indices that control or influence biological activity. By combining those various, relatively simple, measurements an aquatic scientist can quickly evaluate a stream for probable biological potential with respect to the substrate environment.

DISCUSSION

The significance of fluvial processes and physical indices to lotic biology have been discussed and the utility of this understanding in evaluating stream systems has been emphasized. During their training aquatic biologists usually are not exposed to physical sciences that explain the physical processes involved with stream mechanics. This deficiency becomes evident when reading biological reports on how physical parameters affect aquatic life, especially grain size and grain-size distribution. Often the terminology is different than that used by physical scientists to describe the same process or measurements. This frequently creates confusion and illustrates the need for a common vocabulary. These observations apply equally to physical scientists who must expand their knowledge of biology to meet the common objective of both disciplines. An understanding of stream mechanics and evaluation of stream quality can best be attained by small interdisciplinary groups working toward common objectives in an atmosphere structured to foster group excellence.

Three methods have been described for evaluating the biological significance of the physical environment. They may be used separately or in combination. For a quick survey, visual observation might be used. However, for a more rigorous evaluation, all three methods will probably be needed, even though this requires considerably more resources. Early assessment efforts usually result in a more extensive sampling program than may be needed. However, as an evaluation group, or individuals, gain experience in an area and become familiar with the various classes of streams, relatively few samples may verify or authenticate visual observations or quick methods of measuring "pore space efficiency." It is always wise to collect more than enough samples to meet an objective rather than have gaps that can only be filled with conjecture.

The overall objective of stream quality assessment is to provide guidelines for developing regulations that will implement a system of best management practices to benefit life in a stream and those who make use of its watershed. Although problems of stream degradation are in the field, not in an office or laboratory, standards regulating watershed management practices must be based on criteria that can only be acquired by field and laboratory research. Sound criteria must have broad, universal application because every stream cannot justify a separate study. Reliable scientific data from which to develop criteria for best management practices must be based on the premise that a watershed and its waters constitute an ecosystem. If credible results are to be achieved and accepted by those who regulate and enforce standards for watershed use, research to establish these criteria must be designed and conducted as an integrated effort of those with the best scientific expertise available.

ANNOTATED BIBLIOGRAPHY

This annotated bibliography replaces the usual text references and gives selected sources of the rich literature dealing with sedimentary processes as described by professionals in the earth sciences. Most entries are descriptive with enough equations for an interested biologist to benefit from their findings and conclusions and apply them to the stream environment.

1. Bjornn, T. C., M. A. Brusven, M. P. Molnau, J. H. Milligan, R. Klamt, E. Chacho, C. Schaye. 1977. Transport of Granitic Sediment in Streams and its Effect on Insects and Fish. Research Tech. Comp. Rpt., Proj. B-036-IDA., Univ. of Idaho, Moscow, Idaho.

   This report describes the use of the embeddedness and substrate index in relation to aquatic life and also shows that the Meyer-Peter, Muller equation was reliable in predicting bed movement of bottom sediments derived from the Idaho batholith as verified by the Helley-Smith sampler.

2. Blatt, Harvey, Gerald Middleton, and Raymond Murry. 1972. Origin of Sedimentary Rocks. Prentice-Hall, Inc., 634 pp.

   This recent text brings together in a readable manner, the current thinking of most authorities in the field. Chapter 3, on the Sedimentary Textures, and 4, on Sediment Movement by Fluid Flow, are especially useful to the nonspecialist.

3. Colby, Bruce R. 1963. Fluvial Sediments - A Summary of Source, Transportation, Deposition, and Measurement of Sediment Discharge. U.S. Geological Survey Bull. 1181A, 47 pp.

   Although concerned primarily with sand and silt textured sediments, this summary acts as a primer describing the theory and observations of fluvial processes involved in stream sedimentology.

4. Fraser, H. J. 1935. Experimental Study of the Porosity and Permeability of Clastic Sediment. Journal of Geology 43:910-1010.

5. Graton, L. C. and H. J. Fraser. 1935. Systematic Packing of Spheres - With Particular Relation to Porosity and Permeability. Journal of Geology 47:785-909.

Although more than 40 years old, these two works are still quoted and their findings are still valid; they present equations and discuss in detail packing, porosity, and permeability of clastic sediments for the ideal case.

6. Koski, K. Victor. 1975. The Survival and Fitness of Two Stocks of Chum Salmon (Ohcorhynchus Keta) from Egg Deposition to Emergence in a Controlled-Stream Environment at Big Beef Creek. Ph.D. Thesis, University of Washington, Seattle, Washington.

This thesis is a thorough study of the controls over emergence and the effects of grain size on productivity; includes a thorough literature review that includes nearly all published works dealing with gravel substrates from the biological requirements; no geological evaluations included.

7. Leopold, Luna B., M. Gordon Wolman, and John P. Miller. 1964. Fluvial Processes in Geomorphology. W. H. Freeman and Co. 522 pp.

Probably the most modern treatment of fluvial processes. Chapter 6, on Water and Sediment in Channels, and Chapter 7, Channel Form and Process, are especially pertinent to the fishery biologist.

8. Pettijohn, F. J. 1957. Sedimentary Rocks. Harper and Brothers (2nd Ed.) 718 pp.

This is one of the bibles of sedimentary rocks, the chapter on texture is especially informative to the nongeologist.

9. White, H. E. and S. F. Walton. 1937. Particle Packing and Particle Shape. Journal of Amer. Ceramic Soc. 20:155-166.

These men developed the equations to calculate secondary, tertiary, quaternary, and quinary sized particles to fit interstitial spheres that can be used for clastic grains of any size class.