Effects of Water Temperature on the Discharge of Bed Material

GEOLOGICAL SURVEY PROFESSIONAL PAPER 462-G

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By B. R. COLBY *and* C. H. SCOTT

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

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A study of the theoretical and observed effects of changes in water temperature on the transportation of bed material

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EFFECTS OF WATER TEMPERATURE ON THE DISCHARGE OF BED MATERIAL

By B. R. Colby and C. H. Scott

ABSTRACT

Changes in water temperature and consequent changes in viscosity affect bed-material discharge (for this paper, the discharge of particles larger than 0.062 mm) in complex ways. These ways may be explained in terms of three separate effects. One effect is on the thickness of the laminar sublayer, and this effect is usually the smallest of the three. A second effect is on the vertical distribution of suspended bed material. It is a large effect that causes, according to several somewhat inexact computations, an approximate doubling of bed-material discharge if water temperatures are decreased from 80° to 40°F and if mean velocities, depths, and sizes of the bed sediments are the same for the two water temperatures. This second effect seems to be the most consistent and predictable of the three. The third effect is on the bed configuration and, hence, on the resistance to flow. It is a seemingly erratic and somewhat indeterminate effect that is sometimes large and sometimes small.

Temperature effects on bed-material discharge may be of several kinds, and they require careful classification if their different possible meanings are to be understandable.

Experimentally defined temperature effects on bed-material discharge usually require classification in terms of the flow characteristics that were kept constant, the variables that were involved in the analysis of the data, and the way in which the data were analyzed. These effects for flume flows may seem to be considerably different from those for field flows. Part of the difference is due to the shallow flows, variable energy gradients, wide range of bed configuration, and relative lateral and longitudinal uniformity of the flume flows as compared with field flows. Part is due to differences in the kinds of temperature effects that are generally defined. That is, in flume flows, the bed-material discharges may be measured at constant flow, constant depth, variable energy gradient, and two or more different water temperatures. The bed-material discharges may then be plotted against shear, and a temperature effect may be determined on the relation between bed-material discharge and shear. For flows at a cross section of a natural stream, the bed-material discharges per foot of width at approximately constant energy gradient may be plotted against mean velocity to define an average relation. The individual departures of observed bed-material discharges from the average relation may be plotted against water temperature to show any general effect of temperature in causing bed-material discharge to depart from the average relation. Such a general effect might be much different from the temperature effect on the relation between bed-material discharge and shear in flume flows.

Experimental defined temperature effects on the relation of bed-material discharge to mean velocity for three rivers indicate an average increase of about 75 percent in bed-material discharge for a decrease of water temperature from 80° to 40°F. This average increase together with some other experimental data and theoretical computations is the basis of a graph that is given to show the approximate temperature effect on the relation between bed-material discharge and mean velocity. The graph shows an increase in the percentage of this temperature effect with increase in depth of flow.

High concentrations of fine sediment increase the apparent viscosity of a water-sediment mixture. The addition of 20,000 parts per million of bentonite to distilled water has an effect on viscosity that is about the same as the effect on distilled water of a reduction in water temperature from 60° to 34°F (Simons, Richardson, and Haushild, 1963, fig. 6). The equivalence of a particular concentration of fine sediment to a particular temperature change and some observed bed-material discharges for the Rio Puerco in New Mexico largely define the given graph of approximate effect of high concentration of fine sediment on the relation of bed-material discharge to mean velocity.

Of course, effects of temperature or of concentrations of fine sediment on the relation of bed-material discharge to mean velocity are not directly applicable to the relation of bed-material discharge to any factor or variable other than mean velocity.

INTRODUCTION

A general increase of bed-material discharge with decrease in water temperature has been reported for the Missouri River (U.S. Congress, 1935, p. 1089–1092), the Colorado River (Lane, Carlson, and Hanson, 1949), the Middle Loup River (Hubbell and others, 1956, p. 54), and the Niobrara River (Colby, 1956, p. 31–32). However, some flume experimenters have reported a decrease and some an increase of bed-material discharge with decrease in water temperature (Hubbell and Al-Shaikh Ali, 1961).

The purposes of this paper are (1) to explain at least qualitatively three different temperature effects that are due to changes in viscosity of the water, (2) to indicate reasons why temperature effects for flume flows may seem inconsistent or somewhat contradictory, whereas temperature effects for field streams seem to be relatively consistent, and (3) to give a rough idea of the temperature effect on the relation between bed-material discharge per foot of stream width and mean velocity. Although changes in water temperature may affect somewhat the discharge of fine sediment (silt and clay), most streamflows can transport at any temperature their supplied amounts of fine sediments. Hence, this paper deals mainly with temperature effects on bed-material discharge, which for this paper is defined as the discharge of particles larger than 0.062 mm. The paper is based on some field and flume studies and on theoretical computations of the temperature effect. It is not comprehensive enough to be much more than a reconnaissance report on the whole field of temperature effects on bed-material discharge.

First, three temperature effects are explained individually, and some idea of the general magnitude of each is given; next, overall temperature effects as reported for flume and field studies are discussed; and finally, an approximate quantitative effect of water temperature on the relation between bed-material discharge and mean velocity is given.

TEMPERATURE EFFECTS THROUGH VISCOSITY CHANGES

Both the specific weight (or the density) and the viscosity of a liquid change as the temperature changes. The change in specific weight of water is small (fig. 1) for the usual range of temperature in natural streams. The change in viscosity of water (fig. 1) is much greater than the change in specific weight. The effect on sediment discharge of changes in the specific weight of water is so small that it generally can be disregarded, but the effect on sediment discharge of changes in viscosity may be large enough to be very significant, especially for some particle sizes.

Viscosity changes that result from changes in water temperature have three effects on sediment discharge. The first to be discussed is the effect on the thickness of the laminar sublayer; the second, the effect on the fall velocity of suspended sediment and hence on the vertical distribution of suspended sediment in turbulent flow; and the third, the effect on the bed configuration.

EFFECT ON THICKNESS OF THE LAMINAR SUBLAYER

Changes in thickness of the laminar sublayer because of temperature changes are generally small but should not be completely disregarded. Like other temperature effects, the effect on bed-material discharge of changes in this thickness depends not only on the flow and the bed sediment but on the factors, other than temperature, that also control bed-material discharge or are correlated with bed-material discharge. This effect is complex and difficult to evaluate except in terms of some selected relations that may not be generally accepted. (No one relation or set of relations is generally accepted as satisfactory for computing either bedload discharge or bed-material discharge.) The effect is discussed here in terms of a particular relation of bedload discharge (the discharge of particles on or within a few particle diameters of the streambed) to mean velocity (Colby and Hubbell, 1961, pls. 1, 2). The relation involves $(RS)_m$, a quantity that has the physical dimensions of a

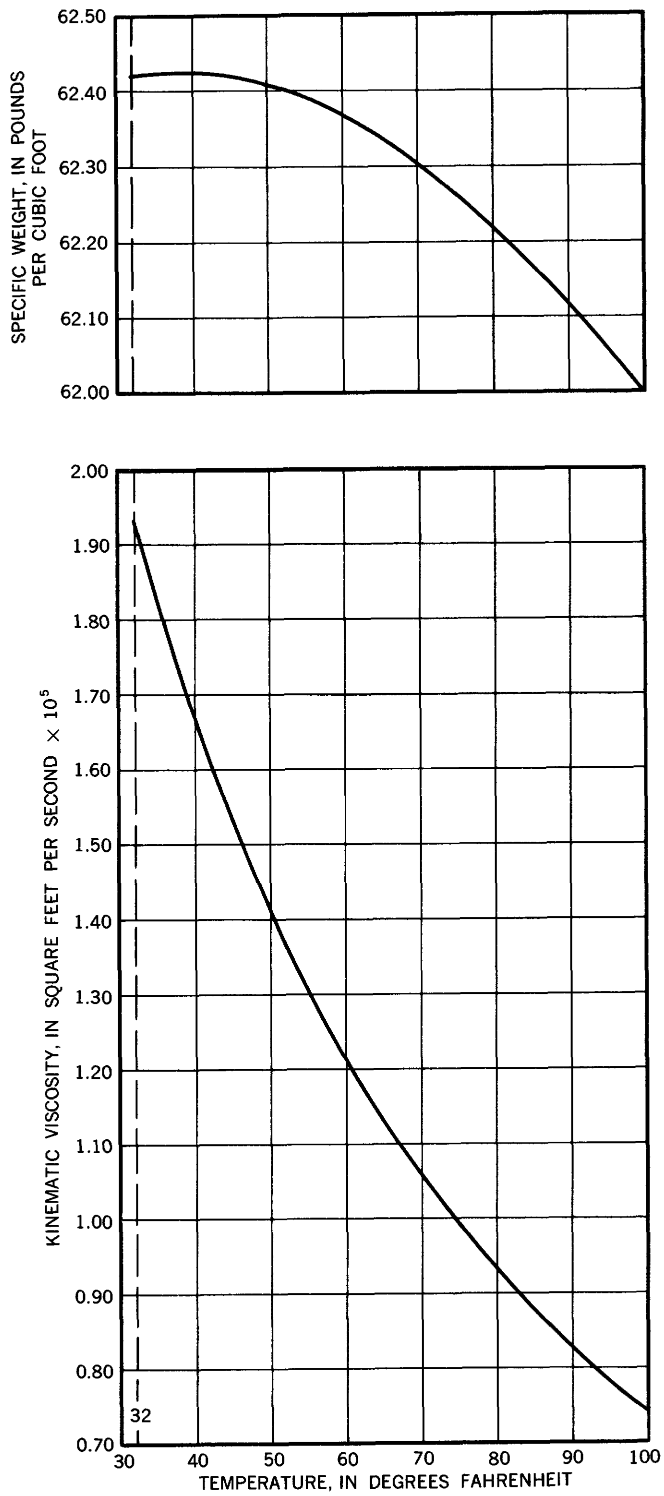


FIGURE 1.—Specific weight and kinematic viscosity of distilled water.

length and that is equal to the effective shear on the bed sediment divided by the specific weight of the water-sediment mixture. This relation was used for this paper in computing bed-material discharge at the same mean velocities, depths, and size distributions of bed sediments, but at different water temperatures. Of course, other relations may be preferred by many persons, but the one used here should give at least a rough idea of the possible changes in bedload discharge and bed-material discharge when the thickness of the laminar sublayer varies as a result of changes in water temperature.

A change in thickness of the laminar sublayer affects the relation between mean velocity $\bar{u}$ and effective shear on the bed sediment $\gamma_f(RS)_m$. This effective shear is the product of γ_f, the specific weight of water-sediment mixture, and $(RS)_m$, a quantity that is computed from known mean velocity and a mean-velocity equation. The quantity γ_f is approximately constant, and $(RS)_m$ is roughly equivalent to $R'S$, the product of the hydraulic radius with respect to the grains as used by Einstein (1950) and the energy gradient. For a hydraulically rough boundary, the ratio of $\bar{u}$ to $\sqrt{(RS)_m}$ or to $\gamma_f(RS)_m$ does not change as water temperature changes. Also, if 1,000 $k_s\bar{u}/(\nu\cdot 10^5)$ is less than about 5, the relative effect of a change in water temperature is less at high ratios of $\bar{u}$ to $\sqrt{(RS)_m}$ than at low ratios. (See fig. 2.) The amount and the direction of the temperature effect on the ratio are determined by the quantity 1,000 $k_s\bar{u}/(\nu\cdot 10^5)$, in which k_s is the diameter of bed sediment for which 65 percent by weight is finer and ν is the kinematic viscosity of water. Except for shallow depths and low mean velocities (the lower left corner on fig. 2), even an increase of temperature from 32° to 100°F changes the ratio of $\bar{u}$ to $\sqrt{(RS)_m}$ by only 10 percent or less. Figure 2 is based on an evaluation of fixed boundary roughness by Keulegan (1938) and in particular on his equation 38 for a rectangular channel of infinite width and on his figure 3.

The method given by Colby and Hubbell (1961) for computing bed-material discharge from mean velocity is based mainly on the procedure formulated by Einstein (1950). The method implies the assumptions that the relation of bedload discharge to $(RS)_m$ is independent of water temperature and that the bed-material discharge is proportional to the bedload discharge if the depth of flow and the relative vertical distribution of suspended sediment remain constant. If these two assumptions are correct, changes in thickness of the laminar sublayer because of temperature changes should not affect the relation between bed-material discharge and effective shear on the bed sediment. The changes should, however, affect somewhat the relation between bed-material discharge and mean velocity for a given depth unless the boundary is hydraulically rough. The effect of a particular temperature change on the relation between bed-material discharge and mean velocity should sometimes be in one direction and sometimes in the other. (See fig. 2.) Fortunately, it should be small enough to be insignificant in comparison to the larger effects of water temperature on the vertical distribution of suspended sediment and on the bed configuration.

EFFECT ON VERTICAL DISTRIBUTION OF SUSPENDED SEDIMENT

Basically, the vertical distribution of suspended sediment depends on a ratio between two quantities—the fall velocity of the sediment particles in a turbulent water-sediment mixture and the effective turbulence of the flow for suspending sediment. Neither quantity has a well-defined effect that can be expressed in simple and exact mathematical terms.

THEORETICAL EQUATION FOR VERTICAL DISTRIBUTION

The usual equation for the vertical distribution of suspended sediment of a single fall velocity or a narrow range of fall velocities in turbulent flow between a water surface and a streambed that are plane and parallel was given by Rouse (1937):

$$\frac{c_y}{c_a}=\left(\frac{d-y}{y}\frac{a}{d-a}\right)^z. \qquad (1)$$

By definition

$$z=w/(ku_*) \qquad (2)$$

in which

- d is the depth of flow;
- a and y are distances above the streambed;
- c_a and c_y are concentrations at distances a and y above the bed;
- w is the fall velocity of sediment particles of one size or of a representative particle from a narrow range of sizes;
- k is the turbulence constant; and
- u_* is the shear velocity and equals $\sqrt{gRS}$, which is the square root of the product of the gravity constant, the hydraulic radius, and the energy gradient.

According to equation 2, z is inversely proportional to the product of k, a measure of the rate of change of velocity with depth and hence a measure of turbulence, and u_*, a measure of shear on the streambed and hence, too, a measure of turbulence. Also, for a given turbulent flow, ku_* is constant and z varies directly with fall velocity according to equation 2. Unfortunately, equation 2 is rather inaccurate.

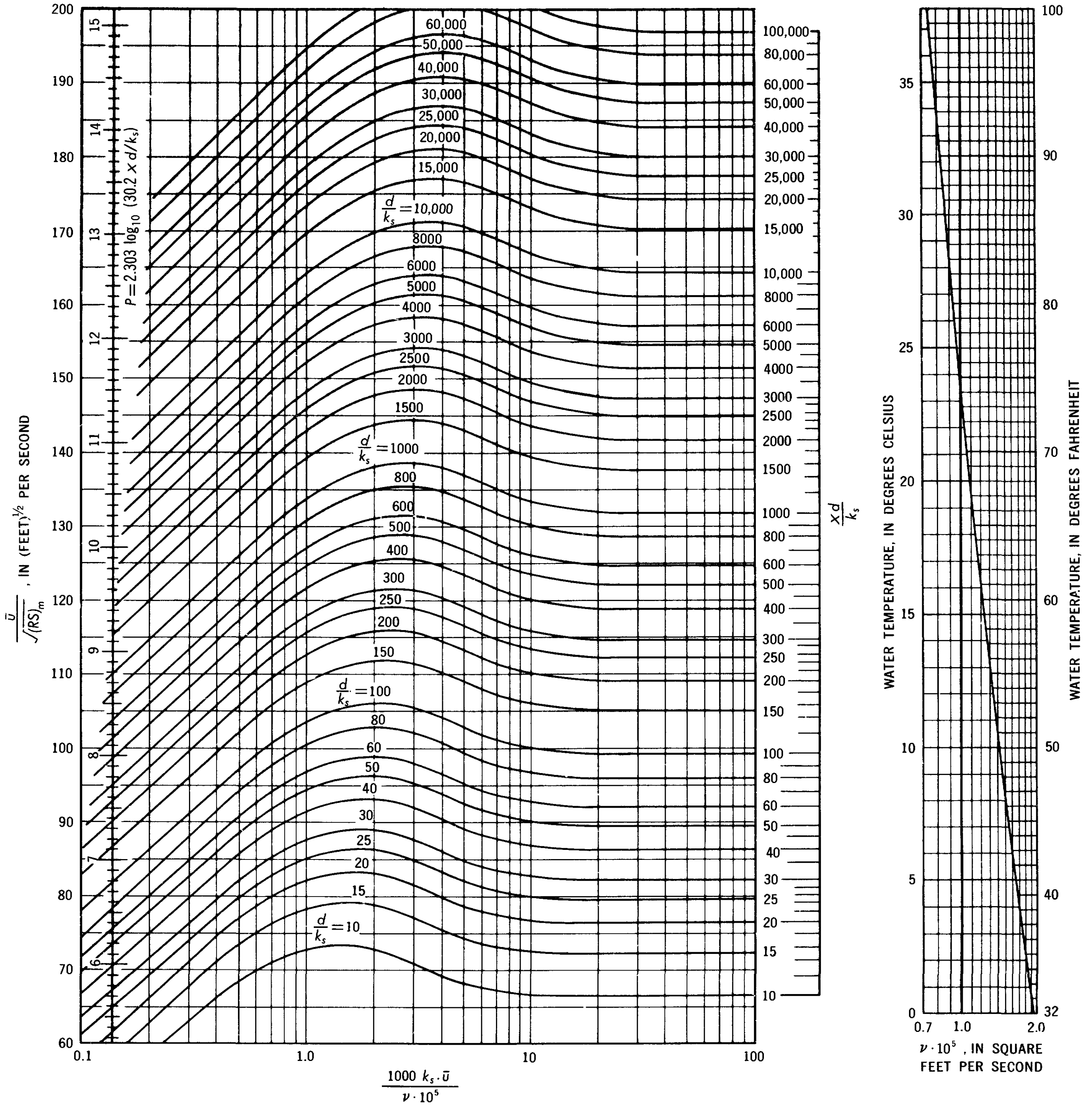


FIGURE 2.—Nomograph for ratio of mean velocity to $\sqrt{(RS)_m}$.

The quantity ku_* is an uncertain measure of turbulence. The turbulence constant k is commonly assumed to be about 0.40 for clear-water flow and to be somewhat lower for sediment-laden flows because of an effect of sediment on the vertical distribution of velocity (Einstein and Chien, 1954, fig. 12). For flow over dunes, the assumptions on which the turbulence constant k was originally based do not apply satisfactorily, and k as computed from a vertical-velocity curve varies widely as position of the vertical changes with respect to the crest of a dune. Hubbell and Matejka (1959, p. 71) found k's much higher than 0.40 for flows over sand dunes. Besides the uncertainty and variation of k, the use of u_* has also been questioned. Einstein (1950, p. 28, 59) used u_*', which may be much less than u_* for some flows, in the computation of z.

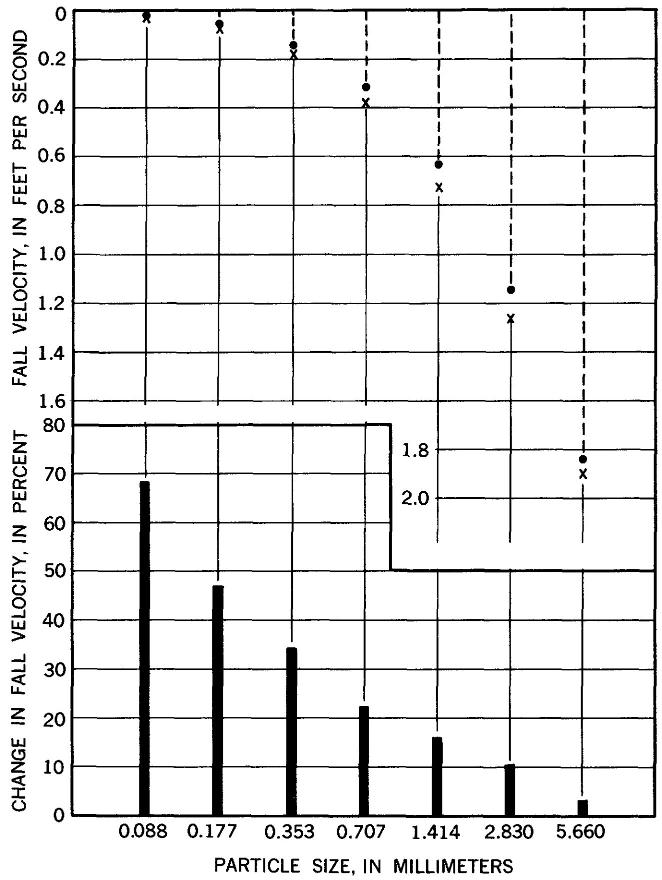
The numerator of the right-hand side of equation 2 may be about as uncertain as the denominator. Experimentally determined z's (often called z_1's) for different size ranges of sand within a given flow (Anderson, 1942) do not necessarily increase so rapidly as the 1.0 power of the fall velocity. Experimental z's for some streams increase as about the 0.7 power of fall velocities that are based on equations given by Rubey (1933, p. 332), according to Colby and Hembree (1955, p. 69–71) and Hubbell and Matejka (1959, p. 70–72). Of course, a defined relation between experimental z's for different particle sizes and fall velocities depends not only on the z's but also on the uncertain fall velocities that are assumed to apply. Particle sizes may be either sieve sizes or fall diameters. The effective fall velocities in a given turbulent flow are not known; the fall velocities used are based on laboratory experiments in relatively still water.

RELATION OF FALL VELOCITY TO TEMPERATURE

The temperature effect on the fall velocities of sediment particles is different for different sizes. The resistance to fall of a particle through a fluid is due mainly to viscous forces for particles that are small and that fall slowly and is due mainly to turbulent forces for particles that are fairly large and that fall rather rapidly. The fall velocities of sands (particles whose diameters are from 0.062 to 2.0 mm) in water are affected by both viscous and turbulent forces, but to different relative degrees for different particle sizes. Fall velocities of sediment particles have been discussed at length by Schulz, Wilde, and Albertson (1954) and by the U.S. Inter-Agency Committee on Water Resources (1957).

The variable effect of water temperature on the fall velocities of quartz spheres of different sizes in water is indicated on figure 3. The percentage effect for the change in temperature from 40° to 80°F is greatest for the quartz spheres in the size range of very fine sand and decreases progressively as the particle size and the fall velocity increase. The greatest absolute increase in fall velocity for the temperature change from 40° to 80° F is for quartz spheres whose median diameters are about 2 or 3 mm.

The percentage change in bed-material discharge that accompanies a particular temperature change is generally small for particles of 1 mm or larger. The fall of particles as large as 1 mm is resisted much more by the generation of turbulence, which does not vary appreciably with water temperature, than by viscous drag. The fall velocity of particles finer than sand is low no matter what the temperature may be, and a large percentage change in the low fall velocities may not affect the carrying ability of the stream for these sizes to a significant degree.



Explanation

×, 80°F ●, 40°F

Geometric mean size (mm)	Geometric mean size (ft)	Size range of spheres (mm)
0.088	0.00029	0.062–0.125
.177	.00058	.125– .250
.353	.00116	.250– .500
.707	.00232	.500–1.000
1.414	.00464	1.000–2.000
2.830	.00928	2.000–4.000
5.660	.01856	4.000–8.000

FIGURE 3.—Effect of a change in water temperature from 40° to 80°F on the fall velocity of quartz spheres of several sizes (U.S. Inter-Agency Comm. on Water Resources, 1957, table 2).

COMPUTED TEMPERATURE EFFECTS ON BED-MATERIAL DISCHARGE

The effect on bed-material discharge of changes in vertical distribution of suspended sediment can be roughly evaluated at stream verticals from a few computations of bed-material discharge at different water temperatures. These computations are based partly on theoretical and partly on empirical relations. Even though the computed bed-material discharges are inaccurate, perhaps largely because of inaccurate z's, the ratio between the computed bed-material discharge for one water temperature and that for another may be reasonably representative of actual temperature effects on bed-material discharges. The computed bed-material discharges should at least indicate the general way in which the temperature effect, mainly due to changes in vertical distribution of suspended sediment, varies with changes in particle sizes, depths of flow, and mean velocities.

Computations were made for three size distributions of bed material (fig. 4), at mean velocities of 2, 5, and 10 feet per second, for depths of 1 (or 4) and 10 feet, and at water temperatures of 40°, 60°, and 80°F. In a general way, the computations were based on the procedure by Einstein (1950); however, the bedload discharge per foot of width, $i_B q_B$, was computed from a graph given by Colby and Hubbell (1961, pl. 2), and $\sqrt{(RS)_m}$ was taken from figure 2. The bed-material discharges, which include both bedload and suspended sediment of the appropriate particle sizes, were computed from $i_B q_B(PI_1+I_2+1)$; P is from figure 2, and I_1 and I_2, which is always a negative quantity, were taken from curves given by Einstein (1950, figs. 1 and 2). For mean velocities of 10 feet per second, a depth of 4 feet—rather than 1 foot—was used to avoid Froude numbers greater than 1.0. (The Froude number equals $\bar{u}/\sqrt{gd}$.)

The computations of bed-material discharge included the effects of water temperature on both the thickness of the laminar sublayer, through the use of figure 2, and the vertical distribution of suspended sediment, through the use of the I_1 and I_2 curves. Because of the uncertainty of equation 2, the z's that were used to determine I_1's and I_2's were computed from the simple and partly arbitrary equation

$$z=4.0\,w^{0.7} \tag{3}$$

The equation was based on an examination of experimental z's for the Niobrara River near Cody, Nebr., and for the Mississippi River near St. Louis, Mo.

The fall velocity w for equation 3 was based on a table given by the U.S. Inter-Agency Committee on Water Resources (1957, p. 26, table 2). Accurate fall velocities are not necessary for this equation because the computed temperature effect is based mainly on change in fall velocity rather than on absolute fall

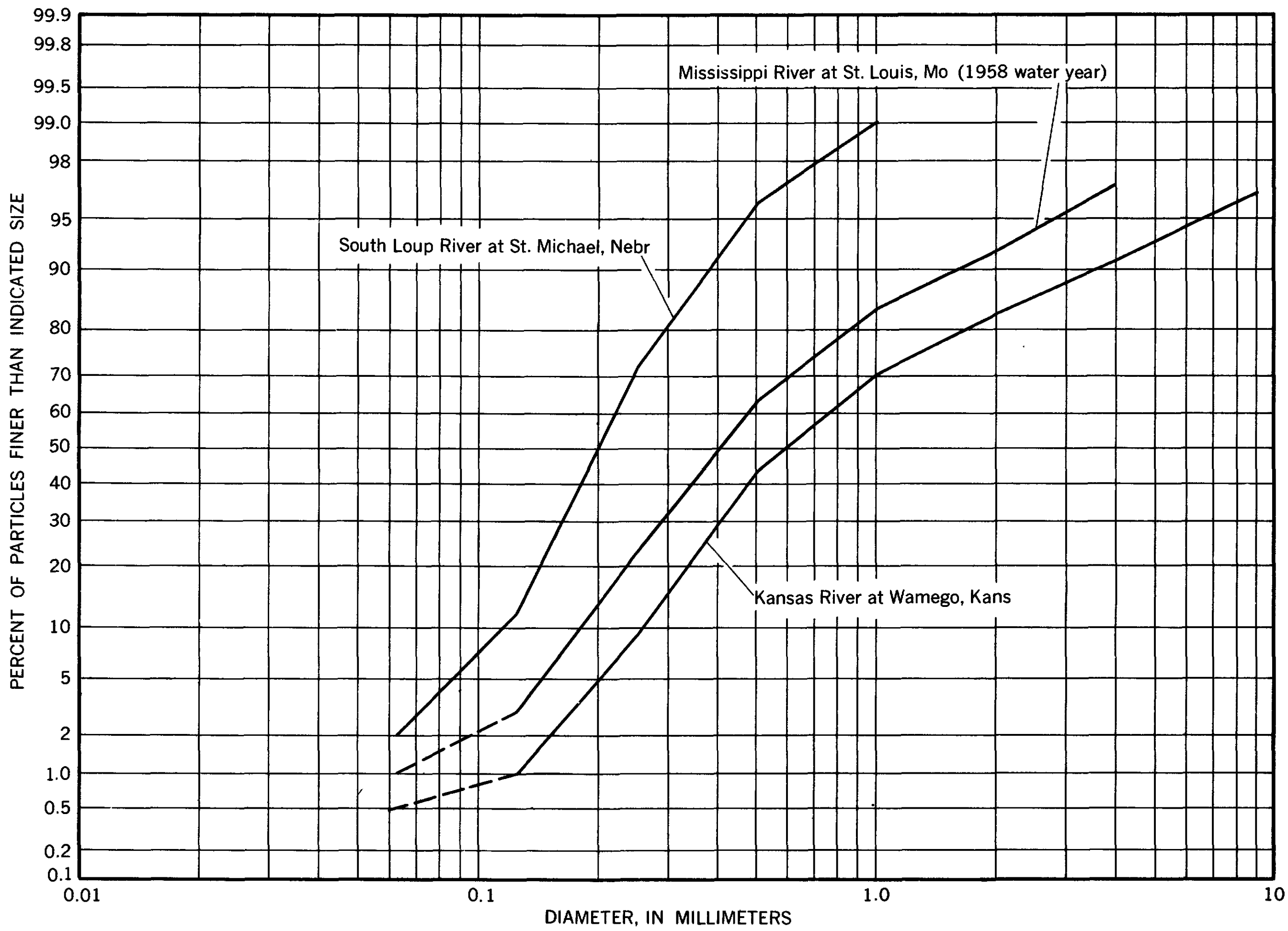


FIGURE 4.—Size distributions of bed sediments for computing temperature effects.

velocity. Similarly, the accuracy of equation 3 is not particularly significant because the computations are intended to indicate mainly a relative temperature effect on the discharge of bed material instead of absolute discharges of bed material.

The ratio of computed total discharge of bed material at 40°F to the computed total discharge of bed material at 80°F averaged roughly 2:1 (fig. 5). The ratio always increased as the depth of flow increased. The ratio tended to decrease, at least slightly, as either mean velocity or median particle size increased. The decrease in ratio may not be significant, however, except for the change in median size from 0.40 to 0.60 mm.

The relations of computed total discharge of bed material to depth are not necessarily straight lines on log-log paper, but straight lines should be satisfactory approximations on figure 5 for connecting computed points.

Although the computed total discharges of bed material are inexact, they probably are realistic enough to make the computed temperature effects reasonable approximations of actual temperature effects on bed-material discharges at a stream vertical. However, a further check was made to see if a large change in computed z's might give a much different indicated temperature effect.

The check was made by arbitrarily dividing the z's from equation 3 by 2.0 and then recomputing the total bed-material discharges for a depth of 10 feet, a mean velocity of 10 feet per second, the bed sediment whose median diameter is 0.40 mm, and water temperatures of 40°, 60°, and 80°F. Although the recomputed bed-material discharges were about seven to nine times the original bed-material discharges (fig. 5), the indicated temperature effect was reduced only about 25 percent. Thus, the recomputations indicate that large absolute errors in computing total bed-material discharges may not change greatly the indicated temperature effect.

The relative consistency of the temperature effect (fig. 5) may be misleading unless the computed bed-material discharges are shown for individual size ranges and for the water temperatures of 40° and 80°F. (See figs. 6–8.) The percentage temperature effect indicated by the computed bed-material discharges is largest for the size range from 0.125 to 0.25 mm. The percentage effects for the two size ranges from 0.062 to 0.125 mm and 0.25 to 0.50 mm are about equal, and they are next largest to the effect for the 0.125- to 0.25-mm-size range. The percentage temperature effect on bed-material discharge decreases markedly as the particle size increases above 0.50 mm and would be small if all bed material transported by a flow were larger than 0.50 mm. Especially for the two finer bed sediments (figs. 6 and 7), nearly all the computed bed-material discharges were of particles finer than 0.50 mm. For any one depth, the percentage temperature effect is reasonably constant for all the flows and bed sediments for which computations were made, but this relation may be due partly to the use of equation 3 for all flows. This effect generally increases as the depth of flow increases, particularly if the temperature effect is appreciable as it is for the fine sand.

The computed differences in bed-material discharge for different water temperatures were due mostly to changes in the vertical distribution of the suspended sediment rather than to changes in the thickness of the laminar sublayer. According to the computation procedure, only the bedload discharge is affected by changes in thickness of the laminar sublayer, and any percentage change in the bedload discharge will cause an equal percentage change in the bed-material discharge. The bedload discharge of all particle sizes for the 0.20-mm median diameter, at a depth of 1.0 foot and a mean velocity of 2.0 feet per second, was about 11 percent more at 40° than at 80°F. For this size of bed sediment and this assumed flow, the bedload discharges for two of the individual size ranges were about 20 percent more at 40° than at 80°F. For all other computations, the differences in bedload discharge for individual size ranges or for total bedload discharge were never more than a few percent for the change in temperature from 40° to 80°F. Some of these small changes in bedload discharge were plus and some were minus for the stated change in temperature. Minus changes in bed-material discharges, because of changes in the thickness of the laminar sublayer, exceeded the computed plus changes in vertical distribution of suspended sediment for the two coarsest size ranges of the 0.40-mm sand for a mean velocity of 5 feet per second. That is, the computed bed-material discharg increased rather than decreased for a change in temperature from 40° to 80°F. (See fig. 7.)

EFFECT ON BED CONFIGURATION

The sand bed in a laboratory channel may have several distinctive kinds of bed configurations and widely different resistances to flow (Simons and Richardson, 1961). The configurations are related to some measure of flow, and physical size of the bed sediment has a complex and sometimes large effect on bed configuration (Simons and Richardson, 1961, fig. 3; 1962, fig. 2). A change caused in the fall velocity of sediment of a given physical size by a change in viscosity probably affects bed configuration and resistance to flow in much the same way as a similar change in fall velocity caused by a change in physical size.

Because bed configuration is difficult to define quantitatively and to express mathematically especially for

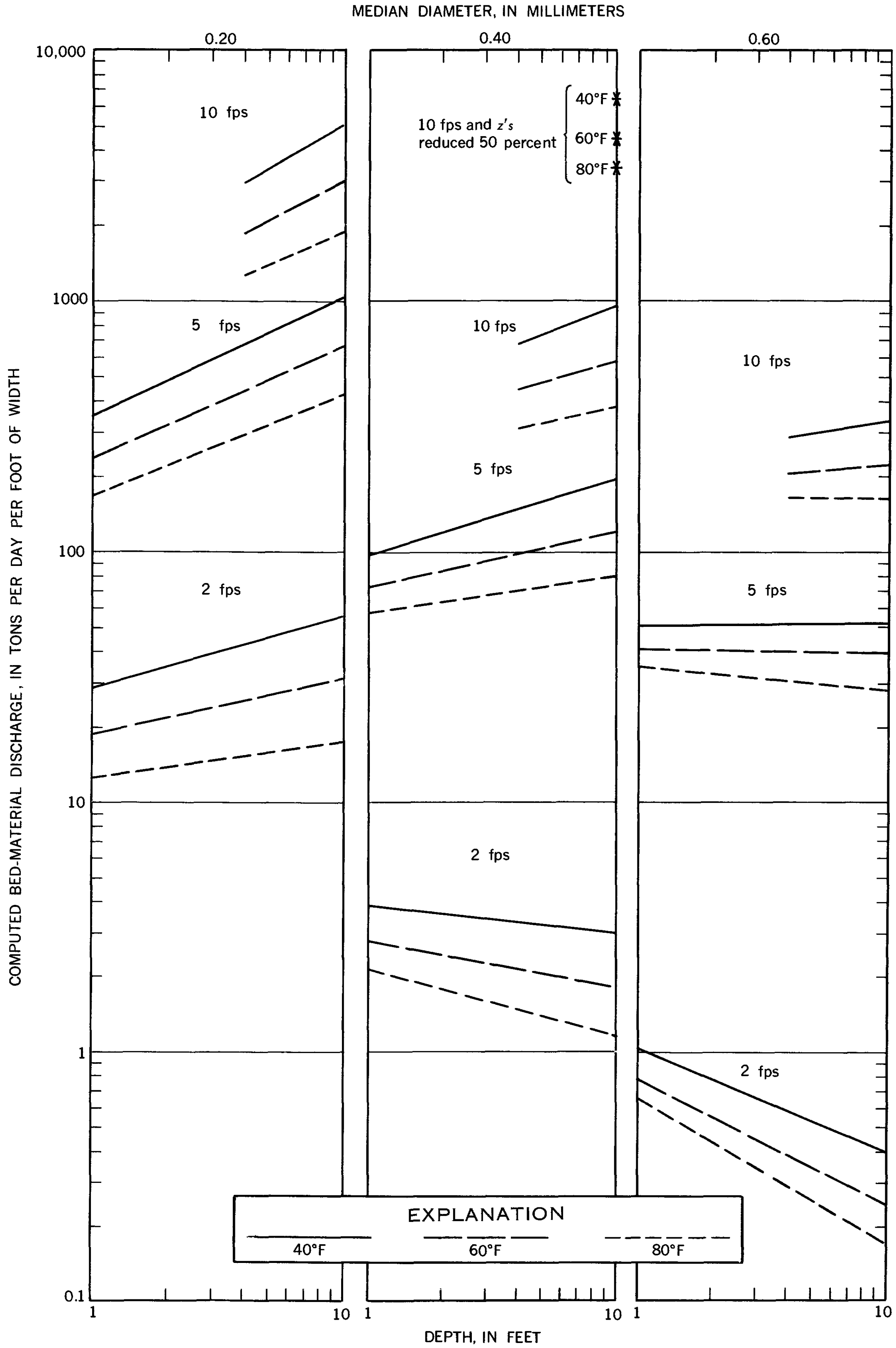


FIGURE 5.—Computed effect of water temperature on the relation of bed-material discharge to mean velocity.

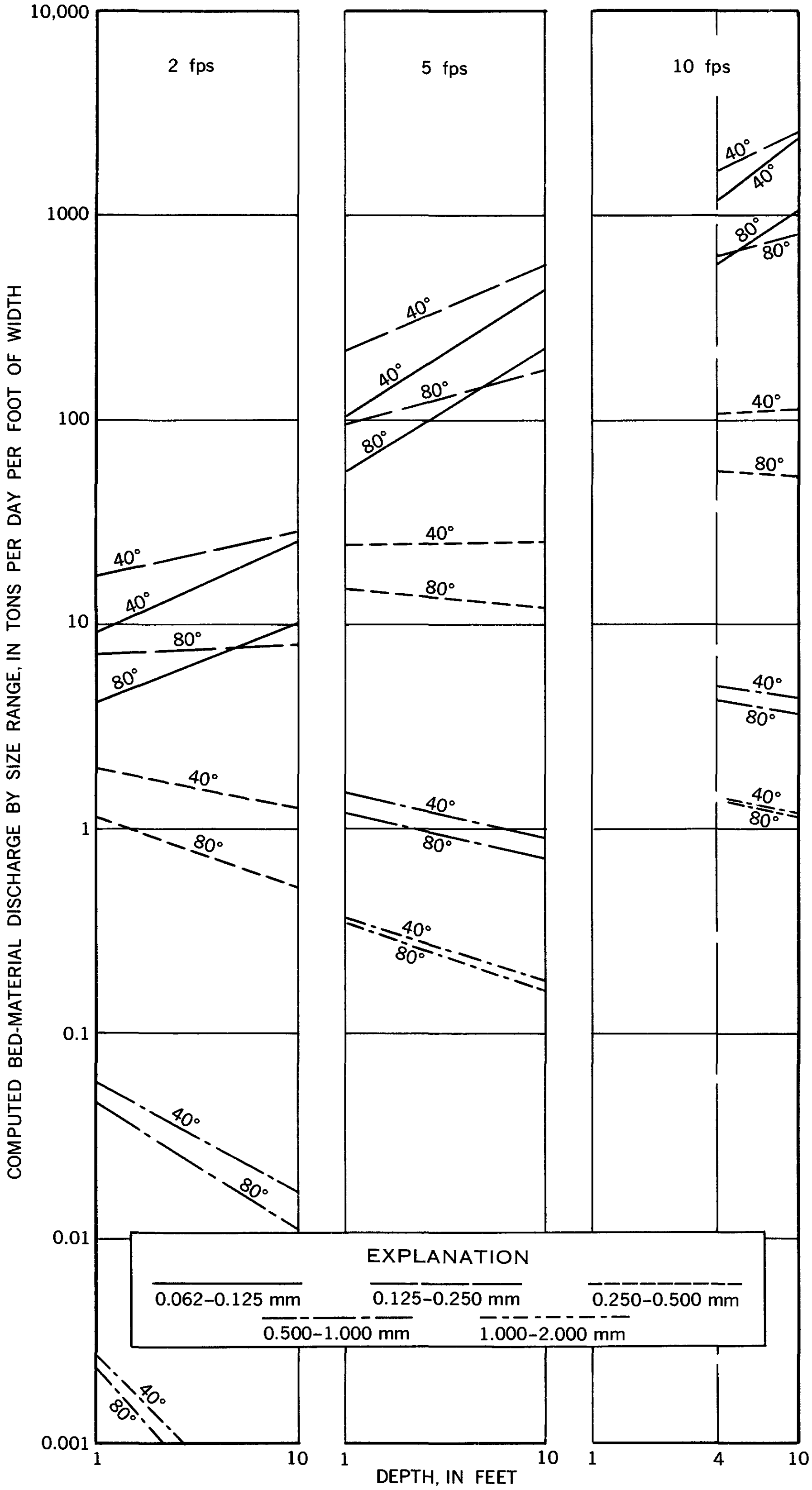


FIGURE 6.—Computed sediment discharges by size ranges for a bed sediment whose median diameter is 0.20 mm. Temperatures are on the Fahrenheit scale.

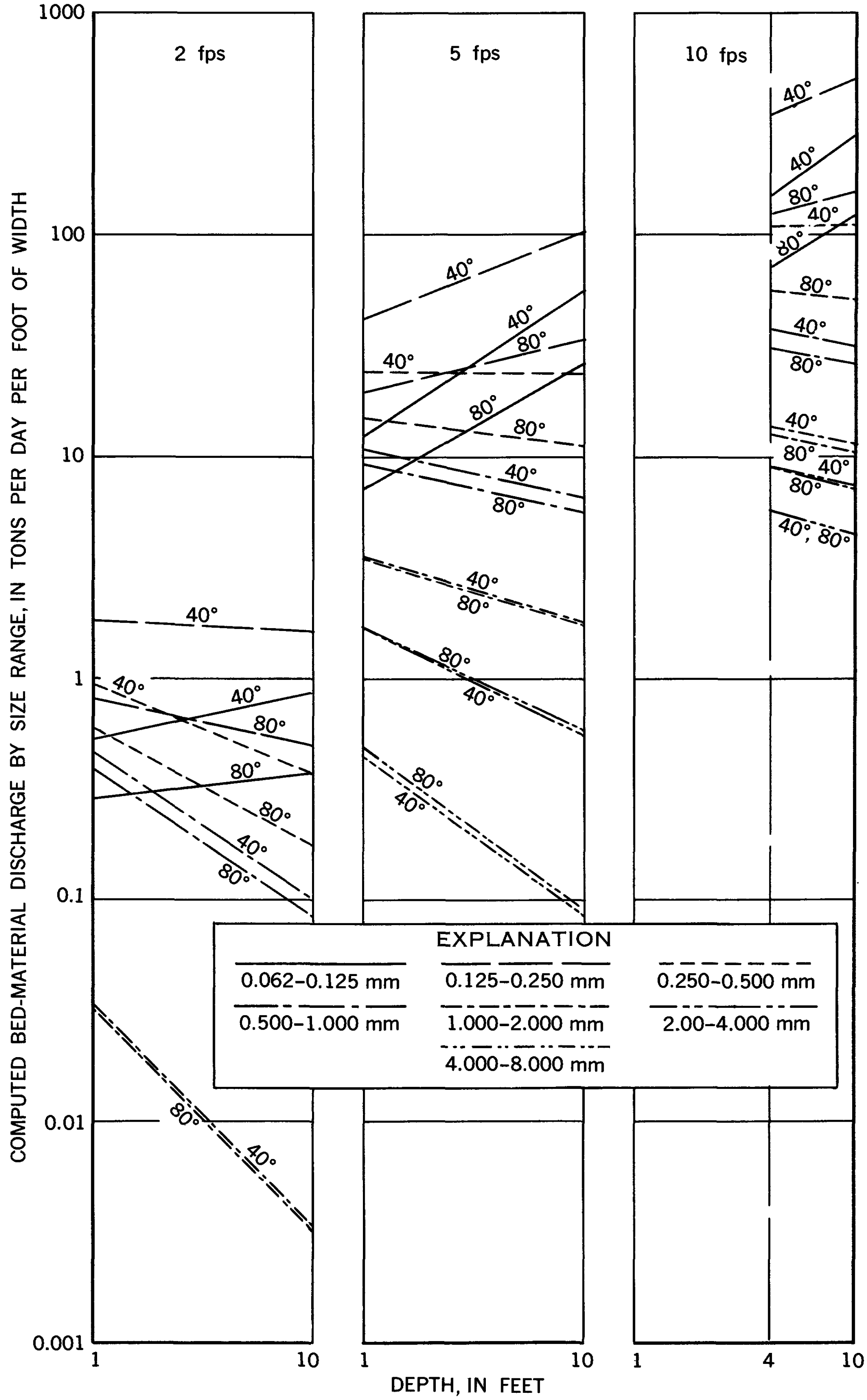


FIGURE 7.—Computed sediment discharges by size ranges for a bed sediment whose median diameter is 0.40 mm. Temperatures are on the Fahrenheit scale.

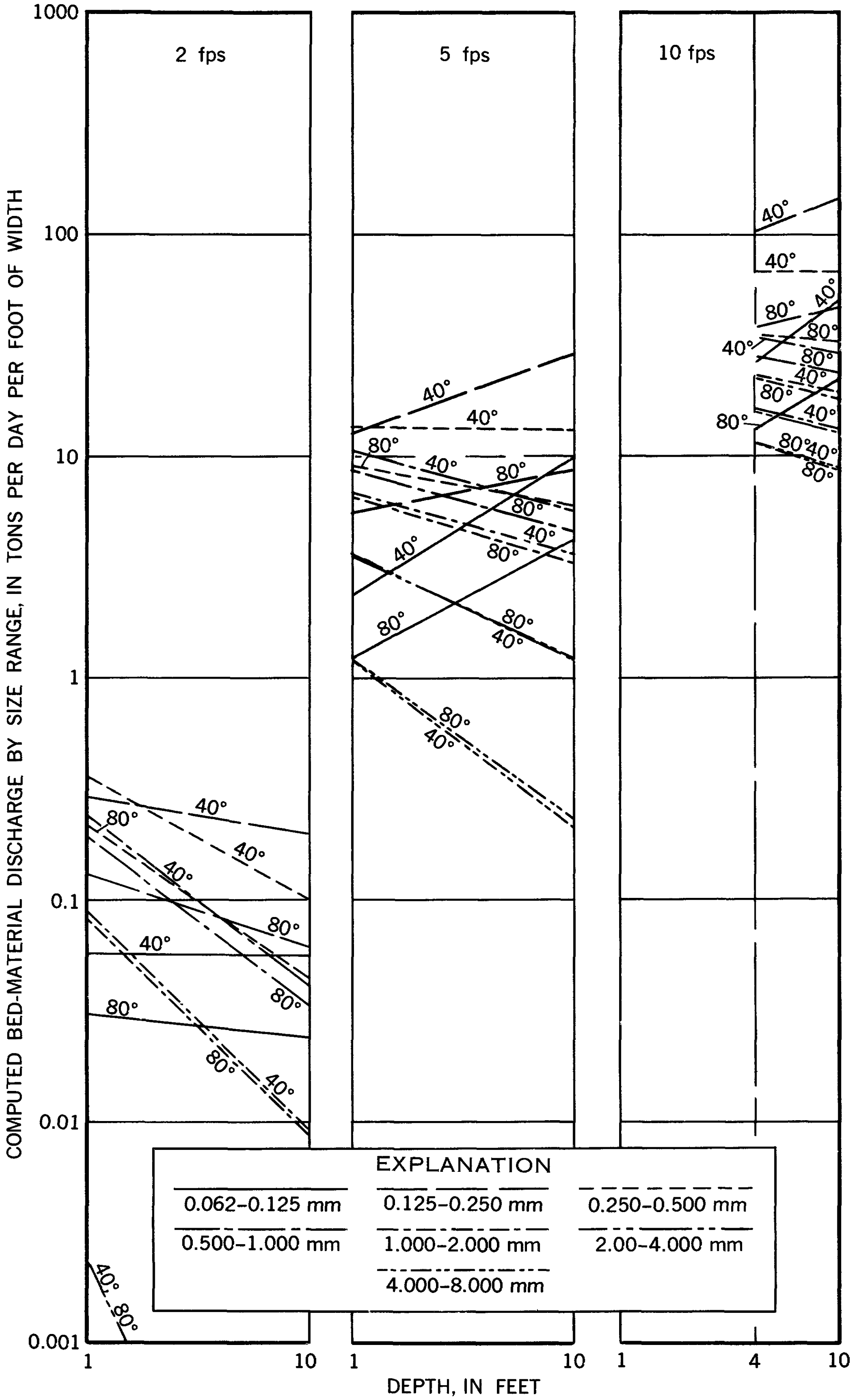


FIGURE 8.—Computed sediment discharges by size ranges for a bed sediment whose median diameter is 0.60 mm. Temperatures are on the Fahrenheit scale.

field streams, resistance to flow generally is used in this paper as an indication of bed configuration. The use of resistance to flow should be fairly satisfactory because of the comparatively large effect of bed configuration on resistance to flow (Vanoni and Brooks, 1957, p. 93–94), though sediment in the flow tends to decrease the resistance to flow for a given bed roughness (Vanoni and Brooks, 1957, p. 93–94). Furthermore, if the streambed is fairly smooth, the resistance to flow seems to vary as the median diameter of the bed sediment changes (Dawdy, 1961, p. C14).

Persons who study mainly flows in laboratory flumes are likely to have concepts of bed configuration somewhat different from those of persons who study mainly field flows. Part of the difference is due to differences in the methods of study and observation and part to differences in behavior of the streambed in small flumes and in field streams.

A worker with laboratory flumes may define a dune in terms of the dune shapes and the particle movements that he can readily see. On the other hand, the shape of the dunes and the movements of sediment particles over the dunes are difficult to observe in field streams, but the characteristic softness of the dunes and the general irregularity of a dune-covered streambed are well known to a worker with field streams. Such a worker is likely to define the dunes in terms of the observations that he has made of the softness and irregularity of the bed. A flume worker usually thinks in terms of a wide range of bed configurations from a plane bed without sediment movement to violent antidunes at a high Froude number, perhaps as high as 2.0. The field worker realizes that neither the plane bed without sediment movement nor the antidunes at Froude numbers as high as 2.0 have much field significance; he concentrates his attention on bed configurations that range from ripples to perhaps a narrow band of antidunes down the middle of a field stream whose cross section seldom has a Froude number that even approaches 1.0.

A significant difference in bed configurations in laboratory flumes to those in field streams is that the bed configurations in flumes are usually about uniform over the bed during most runs, whereas the bed configurations in field streams may differ greatly both laterally and longitudinally. Even though the entire bed of a field stream may be covered with dunes, the size of the dunes is likely to vary from place to place. The nonuniformity of bed configurations in field streams results mainly from variations of depth, average velocity at a vertical, and particle size from place to place in a channel reach. A change of flow with time may cause a certain change in bed configuration at one place but a different change at another place in a field stream. In general, the changes in bed configuration and in resistance to flow in field streams tend to average out to some degree over even short reaches and to be more gradual and less distinct and extreme than those in laboratory flumes.

FIELD STREAMS

The effects of temperature changes on bed configuration and on resistance to flow are difficult to determine for field streams. Flows usually fluctuate widely, sometimes during short periods of time, and changes in flow may cause changes in bed configuration. Large changes in water temperature usually occur gradually and over longe periods of time. Hence, the effects of such temperature changes are not so clearly indicated as they would be if the changes occurred rapidly and if variations in flow and possibly in size of the bed sediment were small during the temperature changes. Even fairly large changes in temperature probably sometimes cause little change in resistance to flow if, for example, the stream has ripples or sand dunes on the bed throughout the range of flow. Furthermore, many field sites where flow and resistance to flow are observed are a short distance upstream from a gravel bar or a riffle that is more effective than bed configuration in controlling depth and velocity of flow.

The Middle Loup River at Dunning, Nebr., which has unusually constant flow throughout most years, has generally lower Manning's n's when the water temperature is low than when the temperature is high (Hubbell and others, 1956, p. 54 and fig. 23). Although the computed n's scatter considerably from the average relation on figure 9, the trend is fairly clear. Hubbell and others (1956, p. 3, 5) also noted a general absence of sand dunes at some cross sections during the winter, when n's were commonly low.

Observations with an ultrasonic depth sounder confirm the change of bed roughness of the Middle Loup River at Dunning from summer to winter for approximately equal flows. (See fig. 10.) Three longitudinal

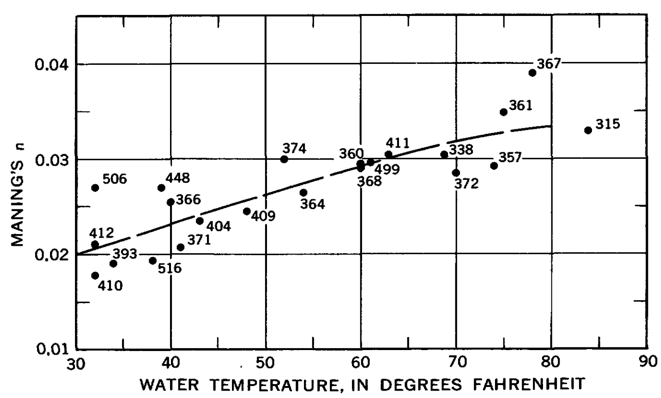


FIGURE 9.—General variation of Manning's n with water temperature for Middle Loup River at Dunning, Nebr., section C_2. Numbers beside points indicate flow, in cubic feet per second.

profiles were defined for a summer day and three for a winter day. Each profile was selected as at least roughly representative of the streambed for one-third of the width of the flow. Each profile for June 25 indicated dunes of about the same size as the dunes indicated by the other two profiles. The dunes extended throughout the lengths of the sounder runs. The bed on December 5 was definitely smoothest at the left profile and roughest at the right profile, but even the right profile was smoother than any of the three profiles for June 25. The bed configurations of figure 10 indicate major decreases in Manning's n from summer to winter and are considered to be representative for the flows and temperatures at which they were defined.

The ultrasonic sounder was described by Richardson, Simons, and Posakony (1961). The field use of the sounder in the Middle Loup River at Dunning, Nebr., was explained by D. W. Hubbell, C. H. Scott, and J. V. Skinner (written commun., 1960).

Some other streams show less consistent decreases in Manning's n with decrease in water temperature. Manning's n's given by Beckman and Furness (1962, table 2) for the Elkhorn River near Waterloo, Nebr. (fig. 11), show no clear-cut reduction in n as the temperature decreases at either low or high flows. However, the few n's for low temperatures average considerably lower than the n's for high temperatures at flows between 2,500 and 5,000 cfs (cubic feet per second). Somewhat

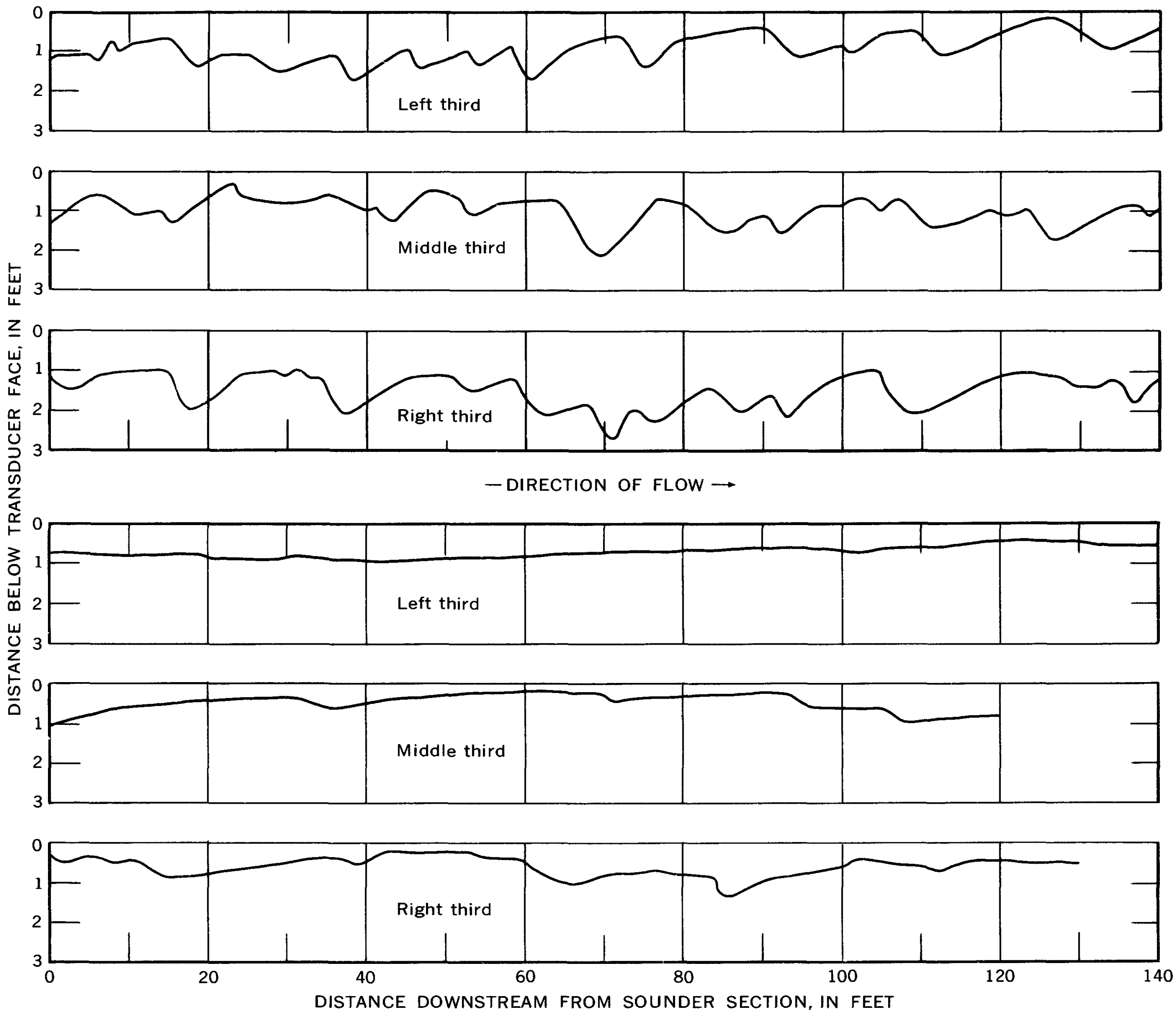


FIGURE 10.—Longitudinal profiles of streambed at different water temperatures, Middle Loup River at Dunning, Nebr. Upper set of graphs shows variations in streambed for June 25, 1959 (flow, 350 cfs; temperature, 83°F). Lower set of graphs shows variations in streambed for December 5, 1959 (flow, 360 cfs; temperature, 39°F).

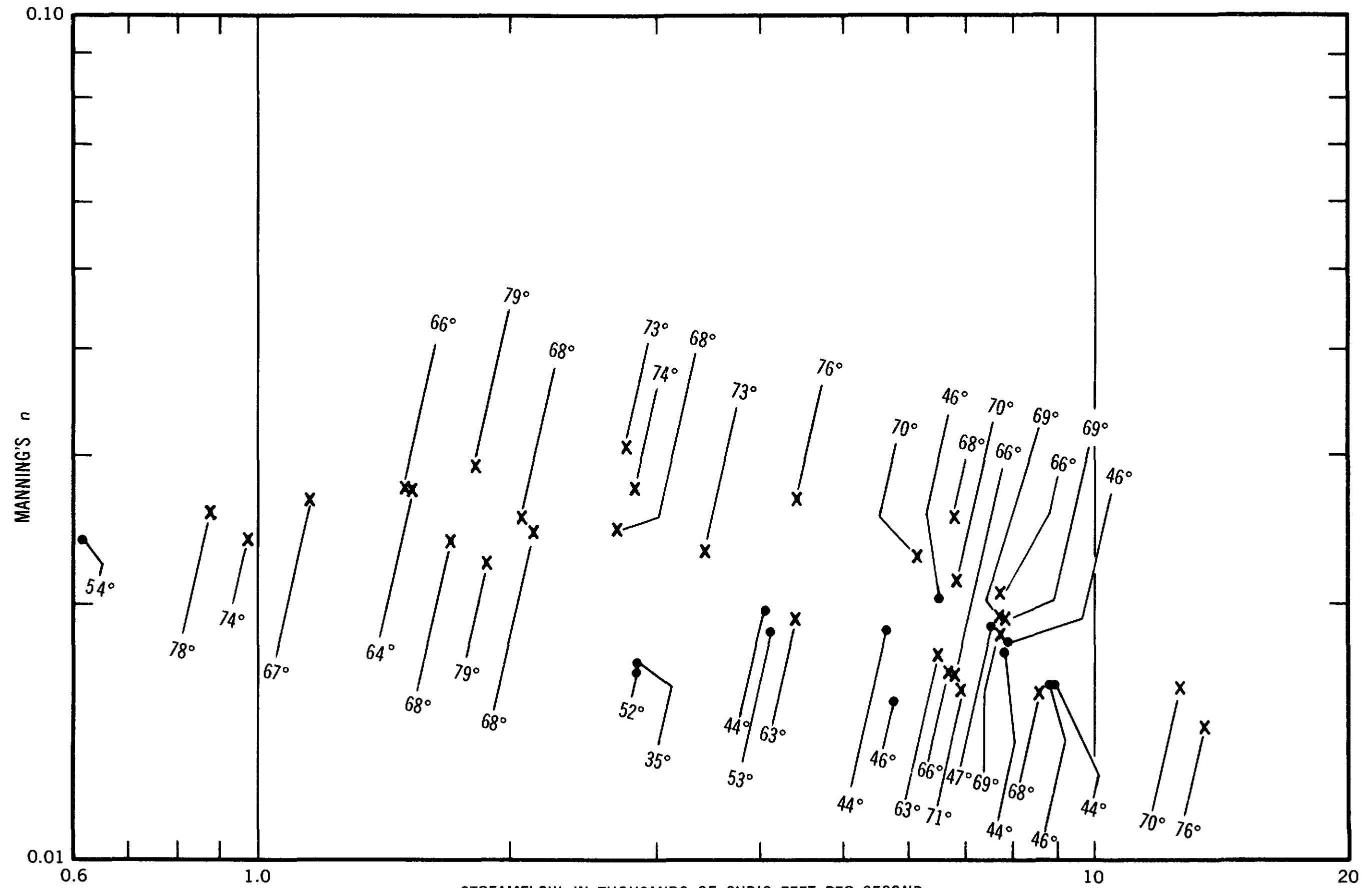


FIGURE 11.—Variation of Manning's *n* with streamflow and water temperature for Elkhorn River near Waterloo, Nebr. ×, 60°F and above; ●, below 60°F. (Data from Beckman and Furness, 1962, table 2.)

similarly, the *n*'s given by Jordan (1965, table 2) for the Mississippi River at St. Louis, Mo., generally decrease as the flow increases (fig. 12); but, except perhaps for flows of more than 400,000 cfs, *n*'s do not seem to vary significantly with temperature (fig. 13).

The *n*'s for the three rivers probably indicate that water temperature has an appreciable effect on the resistance to flow only within certain ranges of flow, and these ranges are different for different streams. The flow of the Middle Loup River seems to be generally in the range for which a decrease in temperature may cause an appreciable decrease in *n*.

FLUME FLOWS

For some experiments in laboratory flumes, water temperature may have no consistent effect on resistance to flow (fig. 14). The data on which figure 14 is based were reported by Hubbell and Al-Shaikh Ali (1961, fig. 301.1) for a bed sediment whose median standard-fall diameter, as defined by the U.S. Inter-Agency Committee on Water Resources (1957, p. 13, 14), was 0.31 mm. Probably the information on figure 14 is insufficient to justify many conclusions except that of apparent inconsistency. Perhaps a tendency should be noted for a particularly high or a particularly low resistance to flow at either high or low temperatures to change toward more moderate resistances whether the temperature is increased or decreased, but the tendency may not be significant.

A set of flume experiments by Straub, Anderson, and Flammer (1958) was made to determine a temperature effect on bed-material discharge for bed sediment from the Missouri River. The stated median sieve diameter of the bed sediment was 0.163 mm, and runs were made at the same water discharge and at six different water temperatures. Depth of flow apparently depended on the volume of water in the experimental equipment. A 9-percent reduction in depth as the temperature decreased from 86° to 34°F was, of course, accompanied by a 10-percent increase in mean velocity. The combined effect of the increased velocity and the decreased temperature was insufficient to change the bed configuration appreciably under the conditions of the experiments. The resistance to flow did increase somewhat as the temperature decreased. The energy gradient was permitted to adjust freely.

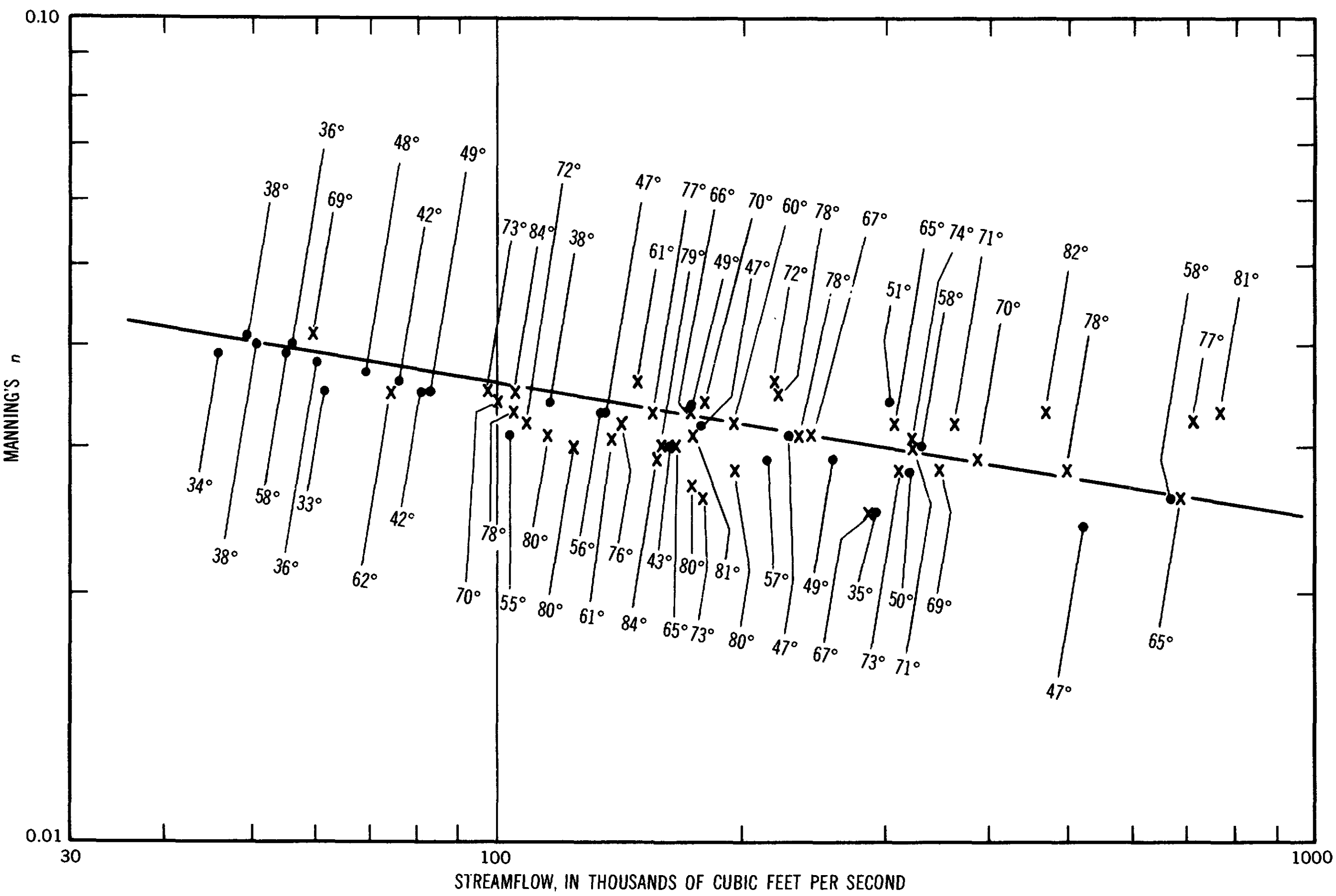


FIGURE 12.—Variation of Manning's *n* with streamflow and water temperature for Mississippi River at St. Louis, Mo. ×, 60°F and above; ●, below 60°F. (Data from Jordan, 1965, table 2.)

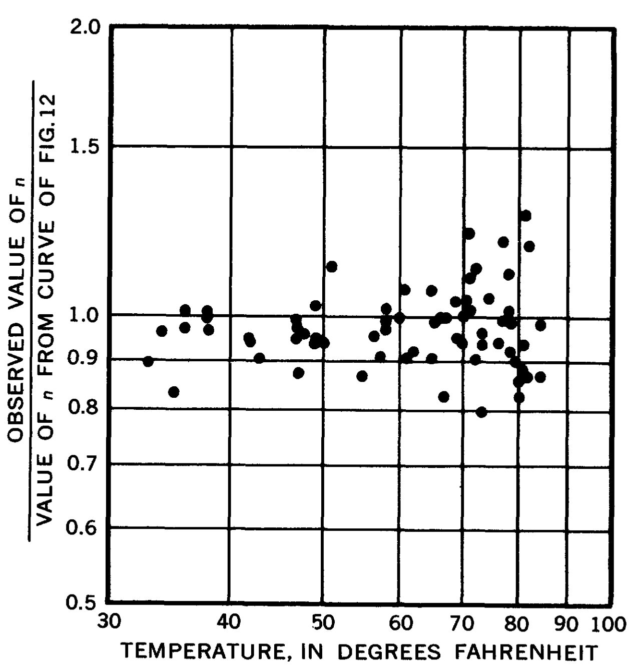


FIGURE 13.—Ratios of observed values of *n* to values of *n* from average curve of figure 12 plotted against water temperature.

In spite of the wide differences in resistance to flow (fig. 14), the observed changes in bed-material concentration reported by Hubbell and Al-Shaikh Ali (1961, fig. 301.1) were not particularly large (fig. 15). The greatest increase of concentration at low temperature over the concentration at high temperature was 73 percent, and the greatest decrease was 29 percent. The changes were much less than those for the Middle Loup River at Dunning, Nebr. (Hubbell and others, 1956, fig. 23), or those for the Missouri River bed sediment (Straub, Anderson, and Flammer, 1958, p. 8).

Presumably a main purpose of flume experiments should be to obtain information that may be applied to the behavior of field streams. In such streams, the temperature effects that usually have the most meaning are those at a cross section or within a short reach of stream. If the cross section is representative of a fairly long reach of the stream, the energy gradient, at least at steady flow, does not change appreciably as the temperature changes. That is, the energy gradient of a long reach of stream channel is generally constant over long periods of time. Hence, if a temperature change could increase appreciably the energy gradient at one place along the reach, it would necessarily decrease the energy gradient at some other place. Therefore, flume studies of temperature effect on bed configuration and on bed-material discharge might be more meaningful for field streams if they were made at constant energy gradient.

If width and energy gradient are constant during a set of experiments with flume flows, the relations among other variables probably are more nearly restricted to the relations that exist in fairly uniform field channels. Any change in resistance to flow requires changes in both depth and mean velocity if the flow is constant. Any change in resistance to flow at either constant depth or at constant mean velocity requires a change in flow. If the bed configuration varies when water temperature varies, the change in bed configuration generally depends on which of the variables—flow, depth, or mean velocity—is kept constant. Perhaps fairly consistent temperature effects on bed configuration could be defined regardless of which of these three variables was kept constant while the temperature changed.

If energy gradient is fairly constant, a progressive increase in depth and flow may cause successively a plane bed without sediment movement, ripples, dunes, a transition phase, plane bed with sediment movement, standing waves, and antidunes to form on a sand bed

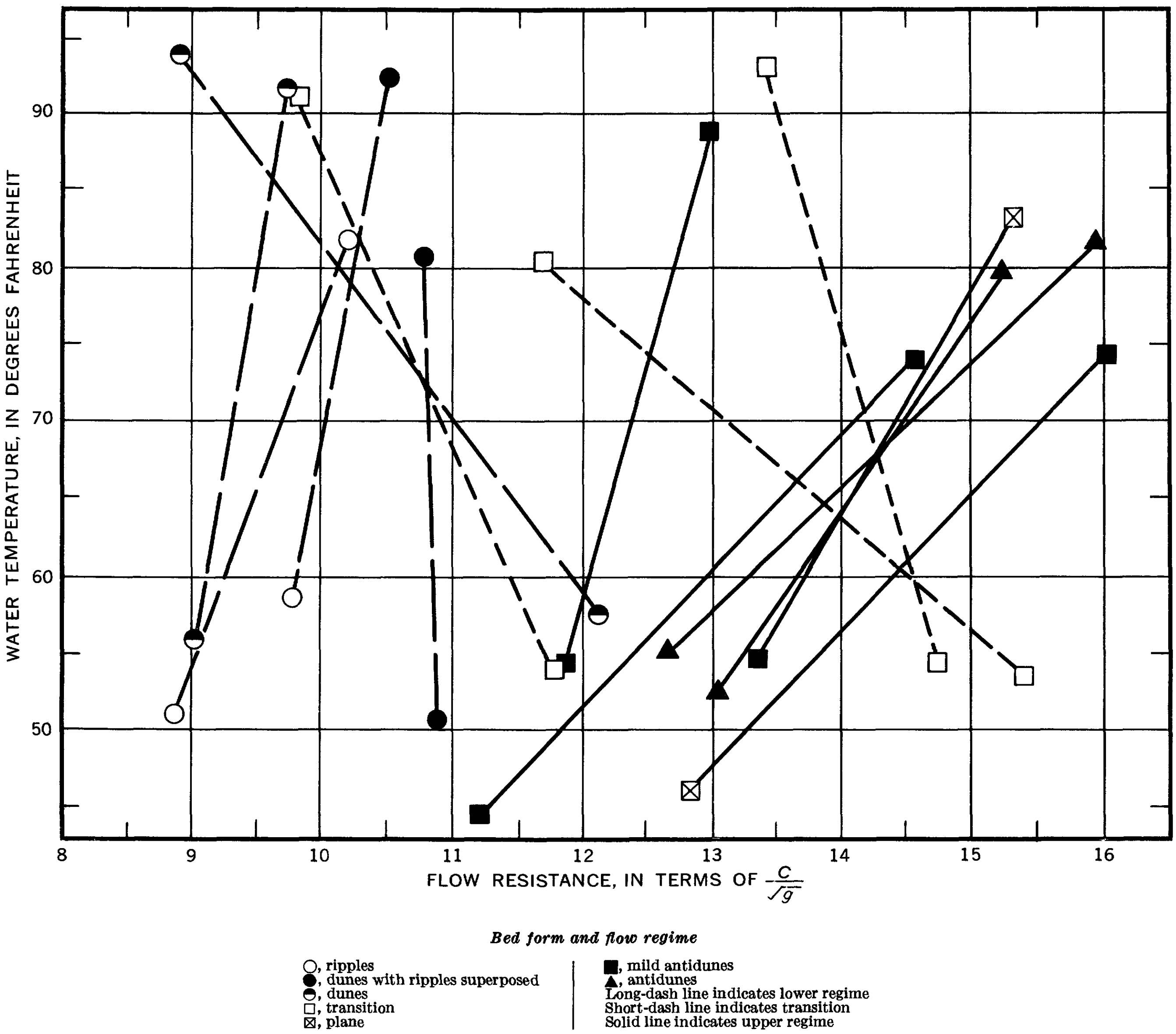


FIGURE 14.—Differences in resistance to flow for pairs of flume runs at high and low water temperatures (after Hubbell and Al-Shaikh Ali, 1961, fig. 301.1).

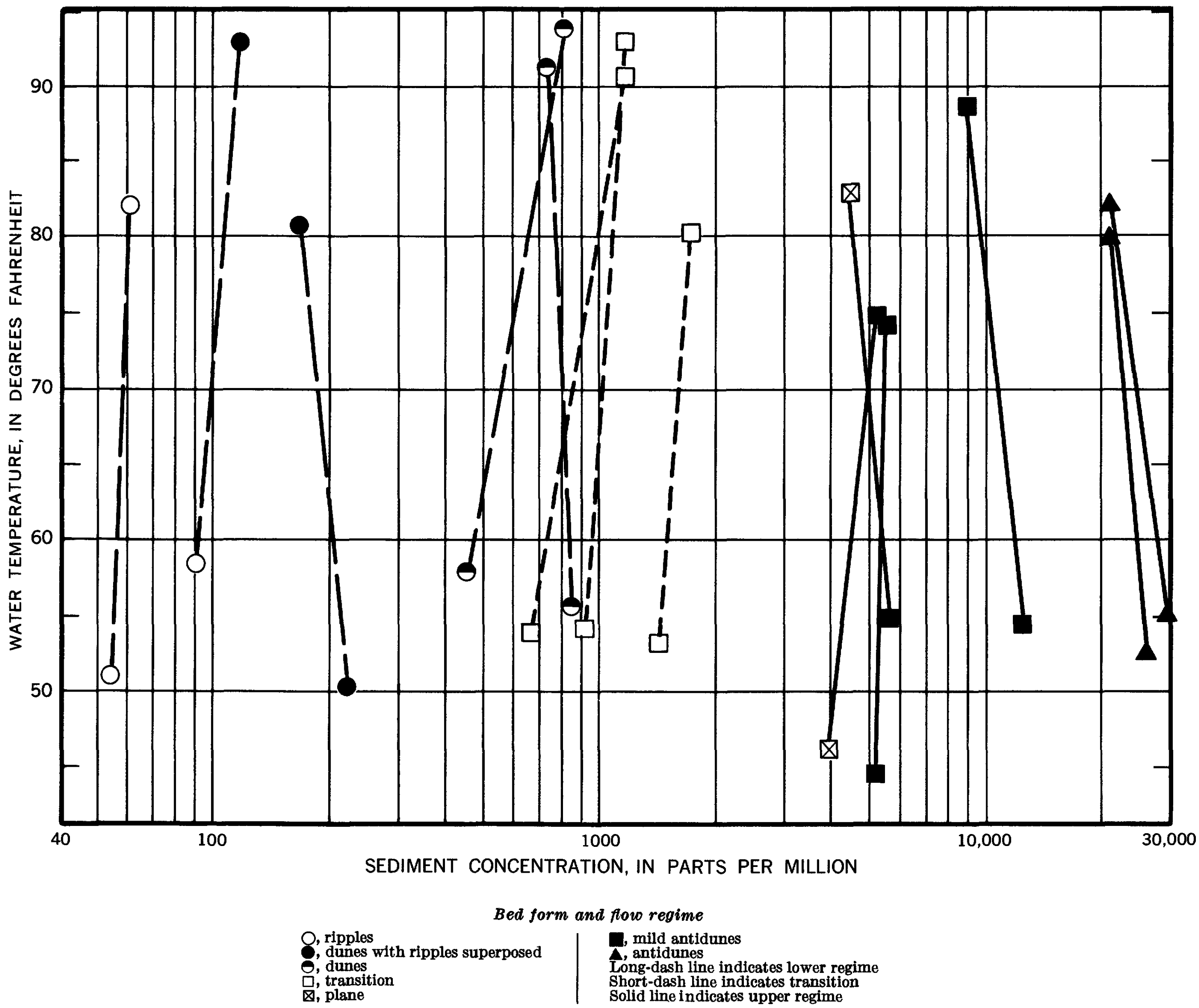


FIGURE 15.—Differences in bed-material concentration for pairs of flume runs at high and low water temperatures (after Hubbell and Al-Shaikh Ali, 1961, fig. 301.1).

(Simons and Richardson, 1960, p. 77). However, the change in flow would have to be very large to produce all these kinds of streambed at constant energy gradient. A small change in flow may have a much larger effect on bed configuration at some ranges of the progressive increase than at other ranges.

Experiments at constant energy gradient should show a reasonably understandable temperature effect on the succession of bed configurations as the flow increases. In general, a decrease of fall velocity because of a decrease in temperature should have much the same effect on bed configuration as an appropriate increase in flow at constant energy gradient. In other words, the effect produced on the bed configuration by a particular temperature change should be about reproducible by the proper change in flow at constant temperature.

OVERALL TEMPERATURE EFFECTS ON BED-MATERIAL DISCHARGE

In the preceding discussions, three temperature effects that changes in viscosity cause on flow and on bed-material discharge have been considered. These effects—on the thickness of the laminar sublayer, on the vertical distribution of suspended sediment, and on the bed configuration—are the ones that might be included in a theoretical computation of bed-material discharge. Although theoretically computed bed-material discharges are generally inaccurate, a study of these three effects provides a background for evaluating and interpreting available field and laboratory information on the overall effect of water temperature on bed-material discharge.

Overall temperature effects, as the term is used here, are those that are based on experimentally determined bed-material discharges. They require careful classification mainly in relation to the other independent variables that were used as measures of bed-material discharge and to the manner in which the effects were determined rather than in relation to the theoretical temperature effects. Temperature, as compared to mean velocity or to shear, has a relatively minor effect on bed-material discharge, and the relation of bed-material discharge to factors that have major effects partly controls the residual temperature effect. For example, an experimentally defined temperature effect on bed-material discharge might be for a constant flow and mean velocity and a variable energy gradient, for a constant mean velocity and energy gradient and a variable flow, or for a constant flow and energy gradient and a variable mean velocity. A temperature effect might be obtained by a regression study that involved such other statistically independent variables as median particle size of the bed sediment, shear, and depth of flow. The effect on the relation between bed-material discharge and total shear might be considerably different from the effect on the relation between bed-material discharge and mean velocity; either of these effects usually is different for deep flows than for shallow flows, and for fine bed sediment than for coarse bed sediment. Briefly, any defined or definable overall temperature effect has little specific meaning unless it is carefully identified and clearly stated.

DIFFERENCES BETWEEN FLUME FLOWS AND FIELD STREAMS

Overall temperature effects for flows in laboratory flumes may appear to be considerably different from those for flows in field streams for at least five somewhat related reasons. These reasons are (1) the relative shallowness of flume flows, (2) the wide range of Froude number and of bed configuration for flume flows, (3) the general uniformity of bed configuration over the effective part of the flume bed at most times, (4) the variability of energy gradients for flume flows, and (5) the difference in types of data analysis for flume data and for field data. Because temperature effects are small as compared with some other effects on bed-material discharge, they usually are observed and defined for field streams at a cross section of a fairly uniform reach of channel in which the particle sizes of the bed sediment and the energy gradient remain fairly constant.

The relative shallowness of flume flows has considerable bearing on the observed temperature effects. In particular, the percentage effect, which is reasonably consistent, of water temperature on bed-material discharge because of changes in fall velocity and in vertical distribution of the suspended sediment is less in shallow flume flows than in deep field flows (fig. 5). In contrast, the highly variable effect of water temperature on bed configuration and on resistance to flow (fig. 14) is just as large and probably more noticeable in shallow flume flows than in deep field flows.

The wide range of Froude numbers and of bed configurations for flume flows leads to a strong emphasis on the variable effect of water temperature on bed configuration and on resistance to flow. In contrast, most canals and many large field streams that flow over beds of sand are in the dune range of flow nearly all the time. For example, the Mississippi River at St. Louis, Mo., seldom has a Froude number greater than about 0.20 for a cross section and probably always has dunes on at least part of its bed even at the highest flows. (Of course, the Froude number for the whole cross section is only a very rough guide to bed configuration, but a low Froude number does indicate a narrow range of possible bed configurations.) Thus, the range of bed configuration of the Mississippi River at St. Louis may be only from dunes everywhere to dunes on part of the streambed and washed out dunes or perhaps a plane bed on other parts of the bed. For this range, a decrease of water temperature at a particular flow should always tend to reduce the resistance to flow, if it causes any appreciable effect.

The general uniformity of the bed configuration from place to place in a flume flow provides a better chance for observing the effect of water temperature for distinctly different bed configurations than does the usually less uniform bed configuration of natural streams. In field streams, most observations of temperature effect are made for a bed that is partly or wholly covered with dunes. Overall temperature effects on bed-material discharge have probably never been clearly defined for a natural stream that had one consistent bed configuration, other than dunes, throughout a reach at both high and low temperatures. (A natural stream does not include canals or artificially improved stream channels.) Many field streams may also have bars or riffles of coarse sand or of gravel. The surfaces of these bars or riffles may not change configuration or resistance to flow appreciably as the temperature changes.

The variability of energy gradients for flume flows introduces a complicating factor that is largely avoided for field flows by studying temperature effects at one cross section or within one short reach. The same sort of complicating factor might be included in studies of the temperature effect for field streams if these studies were attempted by comparing bed-material discharges from cross sections of different streams whose energy gradients differed greatly. Because energy gradients usually are permitted to vary widely in flume experiments, flow is not closely related to either mean velocity or depth alone. In field streams on the other hand, streamflow, mean velocity, and depth are likely to be closely interrelated except, perhaps, for a narrow range of discontinuity (Dawdy, 1961) if the reach has relatively uniform lateral and longitudinal distributions of velocity, depth, and particle size. Because of the interrelations, the temperature effect at a constant flow has a more definite meaning for a field stream than for a flume flow, and fewer variables may need to be included in an analysis of the temperature effect in a field stream.

Methods of analyzing temperature effects for flume studies may be much different from those for field studies. As noted above, somewhat different temperature effects are likely to be stressed and observed for flume flows than for field flows, and different data may be measured for the two types of flow. For example, energy gradient—or at least water-surface slope—is nearly always determined for flume flows, whereas it may not be determined at all or may be very inaccurate for field flows. On the other hand, mean velocity is nearly always known for field flows, but it is usually not determined directly for flume flows. Thus, workers with flume flows are inclined to base their analyses of data on such factors as shear or stream power that require a knowledge of energy gradient; workers with field flows are more likely to base their analyses on mean velocity or on discharge per foot of stream width. The use of mean velocity largely bypasses the rather indeterminate effect of water temperature on bed configuration. Flume workers, however, may reject mean velocity as a basic measure of bed-material discharge because it is a poor measure, according to A. A. Bishop (Sediment transport in alluvial channels: a critical examination of Einstein's theory: Colorado State Univ. Ph. D. thesis, 1961), at the high Froude numbers at which many flume experiments are run. Actually, few field streams have Froude numbers as high as 1.0 even for short periods of time.

Some difficulties in applying flume results to field streams are illustrated by the flume experiments for the Missouri River bed sediment (Straub, Anderson, and Flammer, 1958). Because the depth of flow was permitted to decrease 9 percent as the temperature decreased, the mean velocity at constant flow per unit width increased 10 percent. If both the energy gradient and the flow had been kept constant, the indicated increase in resistance to flow with decrease in temperature from 86° to 34°F would have required a decrease in mean velocity rather than an increase. Because bed-material discharge is likely to increase as perhaps the third power of the mean velocity at constant temperature, an appreciable part of the reported 200-percent increase in bed-material discharge may have been due to experimental conditions that were somewhat inconsistent with conditions at a representative cross section of a sand-bed stream.

The confirmation of the experimental temperature effect (Straub, Anderson, and Flammer, 1958, p. 10, 11, and fig. 16) for the Missouri River sediment through computations of suspended sediment by the Einstein procedure (1950) was based on z's somewhat inconsistent with observed z's for field streams. Generally, vertical distributions of suspended bed material in rivers (Einstein and Chien, 1954, fig. 1; Colby and Hembree, 1955, p. 69–77; Hubbell and Matejka, 1959, p. 70–72) show that z changes less rapidly than theoretical z's, which vary directly as the first power of the fall velocity. If Straub, Anderson, and Flammer had used z's that changed less rapidly than the first power of the fall velocity, the differences between the computed bed-material discharges would have been smaller for each temperature change.

Briefly, the overall temperature effect observed on bed-material discharge in flumes is generally due largely to changes in bed configuration and resistance to flow. On the other hand, the overall temperature effect on the relation between bed-material discharge and mean velocity in deep field streams is due mainly to changes in vertical distribution of the suspended bed material.

ROUGHLY DEFINED EFFECT FOR FIELD STREAMS

Even though the effect of water temperature on bed-material discharge cannot be defined accurately, a rough idea of the amount of the effect on bed-material discharges in field streams should be generally helpful. A first step in determining the effect is to decide which other factors should be included as measures of bed-material discharge. As already indicated, the effect of change in water temperature on bed configuration and on resistance to flow is not well known but seems to be erratic and to depend on the antecedent bed configuration, whereas the effect of water temperature on the relation of bed-material discharge to mean velocity (fig. 5) may be fairly consistent. Hence, mean velocity may be a suitable major factor to use as a dominant measure of bed-material discharge, and a defined temperature effect on the relation of bed-material discharge to mean velocity may be meaningful and helpful.

An average relation between bed-material discharge (equivalent to discharge of sands for this site) per foot of stream width and mean velocity shows a rapid increase of bed-material discharge for the Niobrara River near Cody, Nebr., with increase in velocity. (See fig. 16.) The ratios of the individual bed-material discharges to the average bed-material discharges from the curve of figure 16 can be plotted against water temperature (fig. 17) to define a rough experimental effect of water temperature on the relation between bed-material discharge and mean velocity. Of course,

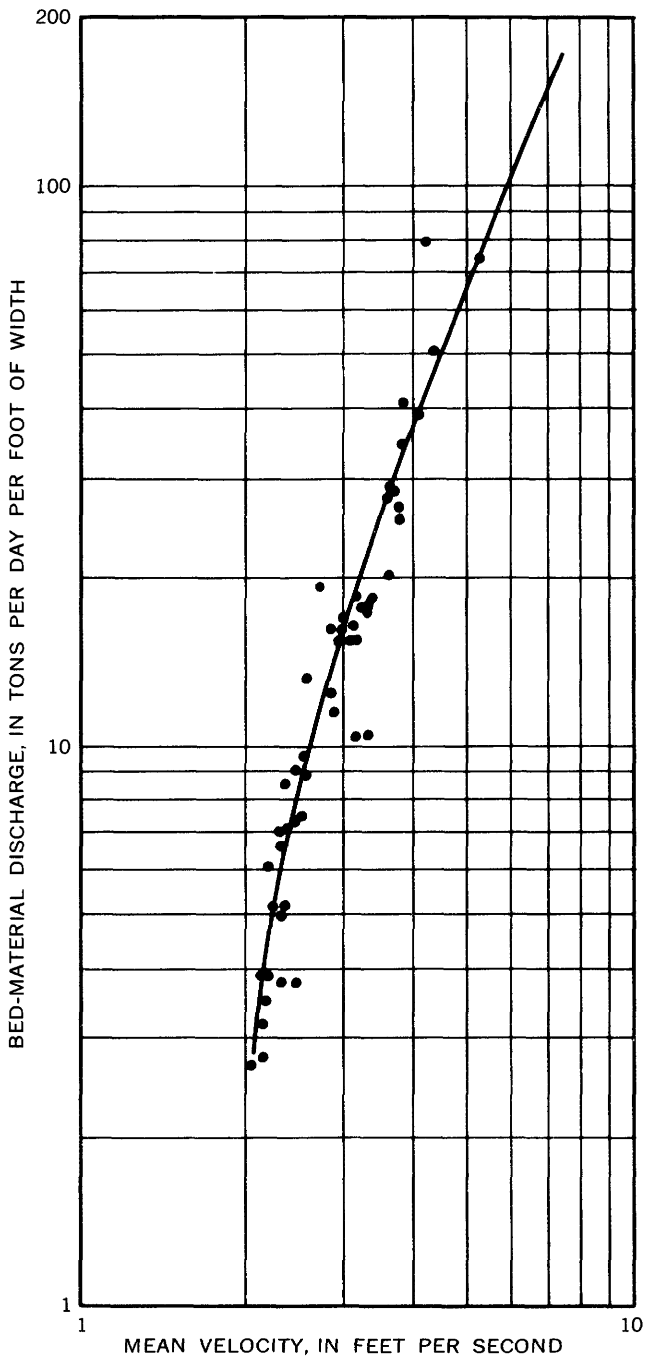


Figure 16.—Relation of bed-material discharge to mean velocity for Niobrara River near Cody, Nebr. (from Colby, 1964, fig. 7).

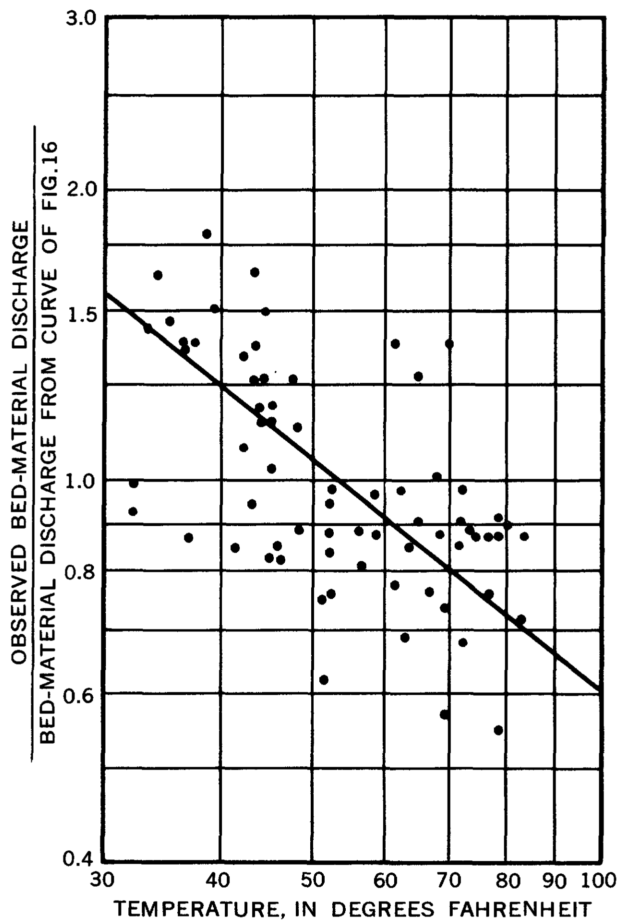


Figure 17.—Approximate relative effect of water temperature on the relation between bed-material discharge and mean velocity for Niobrara River near Cody, Nebr. (from Colby, 1964, fig. 22).

scatter of points from the curve of figure 17 is due partly to experimental error and to factors whose effects have not been eliminated. Hence, the effect of water temperature should be more consistent than figure 17 seems to indicate.

Temperature effects on the relation of bed-material discharge to mean velocity were similarly defined for the Middle Loup River at Dunning, Nebr., and for the Mississippi River at St. Louis, Mo. The three experimentally determined effects are surprisingly consistent (see the slopes of lines on fig. 18), perhaps partly by chance. They provide a rough idea of the probable temperature effect for field streams. The slopes of the lines on figure 18 indicate a change of bed-material discharge that is fairly consistent with the computed temperature effects of figure 5.

The relation of bed-material discharge to mean velocity for the Niobrara River (fig. 16) was based mainly on measurements that were made when the water was at least moderately warm. The streamflow and the depth generally increased as the mean velocity increased. The question might be raised whether the relations shown by figures 16 and 17 can be applied to a stream such as the Middle Loup River at Dunning, Nebr., in which the size of the bed sediment is about the same as that for the Niobrara River at Cody but in which the sediment discharge and the resistance to flow may change rather widely without much change in streamflow (Hubbell and others, 1956, fig. 23).

Bed-material discharges computed from figures 16 and 17 (table 1) seem to explain adequately the increase of sediment discharge, mostly bed-material discharge, that accompanied a decrease in Manning's n, according to Hubbell and others (1956, fig. 23). The total bed-material discharges were computed from information given by Hubbell and others (1956, table 1) for section D at which substantially the total sediment discharge was measured. Water temperatures, mean velocities, and stream widths for computing bed-material discharges from figures 16 and 17 were also given by Hubbell and others (1956, tables 1 and 4).

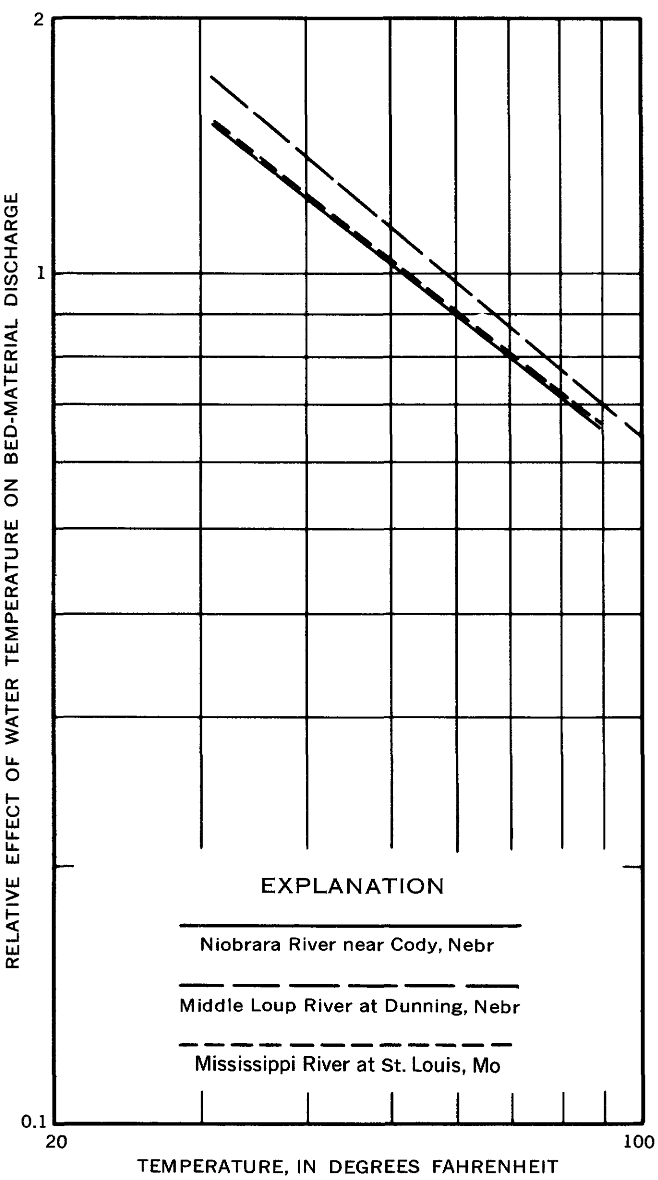


FIGURE 18.—Approximate relative effect of water temperature on the relation between bed-material discharge and mean velocity for three rivers (after Colby, 1964, fig. 23).

TABLE 1.—*Measured and computed bed-material discharges for Middle Loup River at Dunning, Nebr.*

[Basic data from Hubbell and others, 1956, tables 1 and 4]

Date	Section	Temperature (° F)	Bed-material discharge (tons per day)	
			Measured at section D[1]	Computed[2]
1955				
Nov. 24	B_1	38	2,550	2,300
Nov. 24	C_2	35	2,550	3,100
1956				
Jan. 7	C_2	32	2,850	3,400
Jan. 8	C_2	32	2,790	2,800
Mar. 7	C_2	39	2,970	2,800
Mar. 8	B_1	32	3,200	3,900
May 8	A	55	1,830	1,100
May 8	E	64	1,290	1,300

[1] Practically the entire sediment discharge is in suspension and can be measured at section D.
[2] Based on relations shown by figures 16 and 17 and on mean velocities, widths, and water temperatures for sections other than section D.

The generally satisfactory agreement (table 1) between bed-material discharges measured at section D and those computed for sections other than D from mean velocities, widths, water temperatures and figures 16 and 17 implies some significant findings. (The agreement for section A, May 8, 1956, is not good, but section A is more than a mile upstream from section D and is usually a poor section for either measuring or computing bed-material discharge.) One point is that figures 16 and 17 may be applicable to streams other than the ones for which they were defined. Another point is that the increase in bed-material discharge that accompanies a decrease in resistance at almost constant flow is explainable in terms of the effect of the increased mean velocity on the bed-material discharge. A consequent point is that the erratic and difficult-to-define temperature effect on bed configuration and resistance to flow (figs. 11, 12, and 14) probably can be avoided by using mean velocity as a measure of bed-material discharge.

If mean velocity is accepted as a logical major factor that correlates with bed-material discharge, an inexact but probably logical and practical graph can be defined for indicating the general effect of water temperature on the relation of bed-material discharge to mean velocity. The slopes of the curves of figure 18 can be used as experimental measures of the temperature effect for bed sediments whose median diameters are about 0.2 to 0.3 mm. Unfortunately, these curves were based on data (fig. 17) that were not sufficiently exact to define a difference between the temperature effect at one depth and that at another. However, the probable relative effect of water temperature on the relation between bed-material discharge and mean velocity can be approximated for different depths from the curves of figure 5. Thus, information, partly theoretical and partly experimental, can be combined to define roughly the temperature effect that is indicated by the main graph of figure 19, a figure that was given by Colby (1964, fig. 24). Of course, the relation is not well defined and gives only an approximate idea of the effect that might be expected for different depths and water temperatures. The effect is defined for, and is directly applicable to, only those bed sediments whose median diameters are about 0.2 to 0.3 mm. The effect is on the relation between bed-material discharge and mean velocity. The temperature effect might be considerably different on, for example, the relation of bed-material discharge to total shear or to stream power. Hence, the temperature effect indicated on figure 19 should always be understood and designated as an effect of water temperature on the relation of bed-material discharge to mean velocity.

Of course, the temperature effect varies somewhat as the size distribution of the bed sediment changes even though the median diameter remains constant. It also varies as the depth or the mean velocity changes. A complete definition of the complex temperature effect on the relation of bed-material discharge to mean velocity obviously is not now possible. Even if a complete definition were possible, it probably would be very complicated, and its application for many flows might not appreciably improve the accuracy of computed bed-material discharge.

Because the effect of water temperature on the relation of bed-material discharge to mean velocity varies as the median particle size of the bed sediment changes, the effect indicated by the main graph of figure 19 should be decreased as the bed sediment sizes become either much smaller than 0.2 mm or much larger than 0.3 mm. (See figs. 5–8.) A very rough idea of the possible change in temperature effect with change in median diameter was given by Colby (1964, fig. 24) and is shown on the small graph of figure 19. The indicated decrease of the temperature effect as the median particle size of the bed sediment increases above 0.3 mm may be too rapid. The decrease depends considerably on the size distribution as well as on the median diameter and has not yet been experimentally defined. Of course, an adjustment coefficient of 1.20 from the main graph would become 1.16 (1.00+80 percent of 0.20) rather than 0.96 (80 percent of 1.20) for an 80-percent effect from the small graph. Thus, the effect on computed bed-material discharges of large errors in the small graph generally will be small as compared to other possible errors in computing bed-material discharge, except for very high concentrations of fine sediment.

EFFECT OF CONCENTRATION OF FINE SEDIMENT

The effect of high concentrations of fine sediment, particularly of some clays, is discussed briefly here for two reasons. First, this effect, like the temperature effect, seems to be mainly through an increase in the apparent viscosity of the water-sediment mixture (Simons, Richardson, and Haushild, 1963). Second, the effect of high concentrations of fine sediment may be much greater than the effect of water temperature and may obscure the effect of temperature in some field flows.

If the effect of the fine sediment on bed-material discharge is due almost wholly to the change that the fine sediment causes in the apparent viscosity of the water-sediment mixture, the effect should be similar to a change in water temperature. According to Simons, Richardson, and Haushild (1963), the addition to distilled water at 60°F of 2 percent or 20,000 ppm (parts per million) by weight of a commercial bentonite had the same effect on the apparent kinematic viscosity as a change in water temperature from 60° to 34°F. This general equivalence of concentration of bentonite to change in temperature was used by Colby (1964, fig. 24) as the basis for estimating the effect (fig. 19) of concentrations as high as 20,000 ppm of fine sediment that is mostly bentonite. Extensions of the effect to higher concentrations of fine sediment were based on rough proportioning from the lower concentrations and on some determinations of bed-material discharge, mostly determinations for the Rio Puerco near Bernardo, N. Mex. A given concentration of bentonite has a greater effect on apparent viscosity than the same concentration of kaolin (Simons, Richardson, and Haushild, 1963).

Recently, C. H. Scott (U.S. Geol. Survey unpub. data, 1964) measured the fall velocities of three small samples of sorted sands in distilled water and in dispersions of Wyoming bentonite in distilled water. The nominal diameters of the smallest and the largest of the sorted sands were 0.48 and 3.20 mm, and the maximum concentration of bentonite was 17,500 ppm. At this maximum concentration, the fall velocities of the 0.48- and 3.20-mm sands were about 39 and 5 percent less, respectively, than in clear distilled water. The 3.20-mm sand is large enough to have its fall controlled much more by turbulent forces than by viscous forces. The relatively small effect of the bentonite in suspension on the fall velocity of the coarse sand is consistent with the assumption that fine sediment probably af-

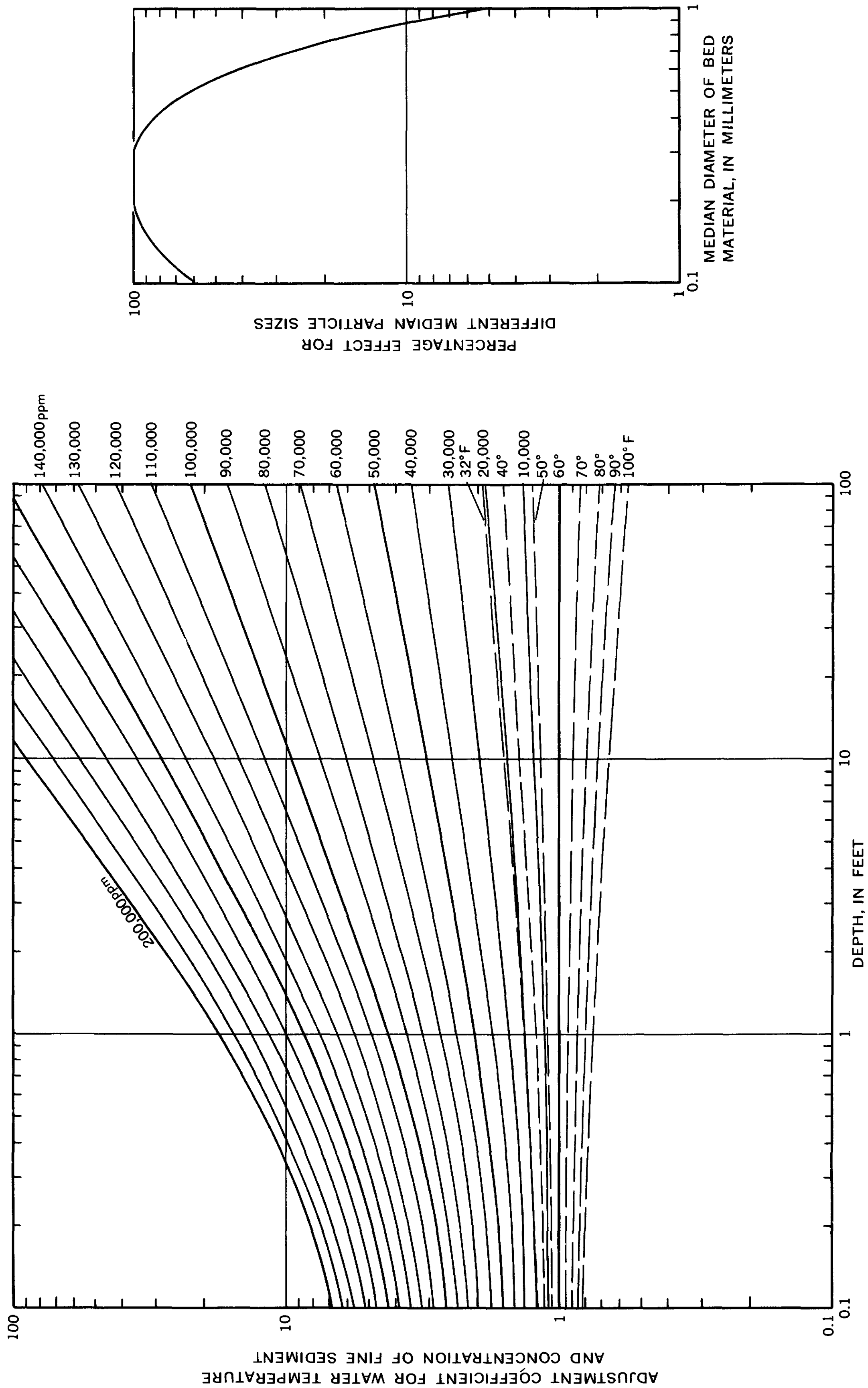


Figure 19.—Approximate effect of water temperature and concentration of fine sediment on the relation of bed-material discharge to mean velocity (from Colby, 1964, fig. 24).

fects fall velocity mainly by changing the apparent viscosity of the water-sediment mixture rather than by directly interfering with the settling of the course particles.

However, Scott found that the fall velocity of the 0.48-mm sand decreased much more rapidly with increasing concentration of bentonite than the fall velocity of the 0.47-mm sand that was used by Simons, Richardson, and Haushild (1963). The reasons for the difference in effects are not clear, but the difference may be due, at least partly, to differences between the commercial bentonites that were used in the dispersions. J. C. Mundorff (written commun., 1960) has shown that both concentration and characteristics of the suspended material have a significant effect on the fall velocities of sands and that, in general, bentonite has the most pronounced effect.

Of course, care should be used in interpreting laboratory experiments on the effects of bentonite or other fine sediment on the fall velocities of sands. Differences in the kinds and concentrations of dissolved solids in the water-sediment mixture, in the exchangeable ions on the clay particles, and in turbulence all may have appreciable effects on the relation of the concentration of fine sediment to the fall velocities of the sands.

Presumably, the small graph of figure 19 can be used in a similar manner for adjustments for the effect of fine sediments and for the effect of water temperature. Of course, the indicated effect of the concentration of fine sediment is an effect on the relation of bed-material discharge to mean velocity and should not be used directly as an effect on any other relation of bed-material discharge to a factor that controls bed-material discharge.

CONCLUSIONS

Changes in water temperature have at least three effects on bed-material discharge as the result of changes in the viscosity of the water.

One effect is on the thickness of the laminar sublayer. A change in this thickness affects the relation between mean velocity at a given depth and the effective shear on the bed sediment. For most flows, the change in the relation is only a few percent for usual temperatures in natural streams.

A second effect is on the vertical distribution of sediment concentration because of changes in fall velocity. Several computations of bed-material discharge for different depths, average velocities, median particle sizes, and water temperatures of 40°, 60°, and 80°F gave reasonably consistent temperature effects on bed-material discharges for a stream vertical. The computed bed-material discharges were roughly twice as large for the temperature of 40° as for the temperature of 80°. Effects of changes in the thickness of the laminar sublayer were included in the computations, but they were small as compared with the effects of changes in fall velocity. The computed temperature effect on bed-material discharge varied little as the velocity changed, but it did increase somewhat as the depth increased. The percentage effect differed widely from one size range to another and was small for particles coarser than 0.5 mm.

A third effect is on bed configuration and resistance to flow. It seems to be rather erratic, at least for flume flows, and presumably affects field flows significantly when the bed configuration is close to a critical point of change to another configuration. This poorly defined temperature effect on bed-material discharge can be largely eliminated by using mean velocity as a dominant measure of bed-material discharge for field streams.

A temperature effect is rather meaningless unless it is carefully defined and clearly designated. Not only are there the three general types of temperature effect mentioned above, but each type of analytical study and each set of experiments may define a different sort of temperature effect because different variables are kept constant or different variables are included in the study.

Temperature effects observed in flumes may be considerably different from those defined at a cross section of a field stream. As compared with field streams, flume flows generally are shallow, have energy gradients that are frequently adjusted, and may cover a wide range of Froude numbers and bed configurations, but the bed configuration at any one time is likely to be relatively uniform laterally and longitudinally. Furthermore, the type of analysis used for flume data may be different from that used for field data.

A temperature effect was roughly defined for field streams whose bed sediments have median diameters of about 0.2 to 0.3 mm. For each of three rivers, an average curve was prepared of bed-material discharge per foot of stream width against mean velocity. The indicated scatter of each bed-material discharge from the average curve was then plotted against water temperature to define experimentally an average effect of water temperature on the relation of bed-material discharge to mean velocity for the river. The three resultant curves of temperature effect and the computed increase of percentage temperature effect as the depth increases (fig. 5) were used as the principal bases for a graph of approximate temperature effect on the relation between bed-material discharge and mean velocity.

High concentrations of fine sediment may have an effect on the apparent viscosity of a water-sediment mixture that is generally similar to and may obscure the effect of water temperature. A graph of probable effect of concentrations of fine sediment that is mostly bentonite was based partly on the graph for the temperature effect and partly on some bed-material discharges for the Rio Puerco in New Mexico. Although the graph is inexact, it indicates a possibly very large effect of high concentrations of fine sediment on the relation of bed-material discharge to mean velocity.

Only a general idea is given in this paper of the different temperature effects and of the quantitative effect of water temperature on the relation of bed-material discharge to mean velocity. Much further study is required before the many different and complex temperature effects can be defined satisfactorily.

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