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Chapter F

FLUME STUDIES OF THE EFFECT OF TEMPERATURE ON THE MECHANICS OF FLOW IN ALLUVIAL CHANNELS

by

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ILLUSTRATIONS--LONG LIST

ILLUSTRATIONS--LONG LIST (Continued)

TABLES

Rough Draft

INTRODUCTION

One of the variables that affects the flow resistance and the sediment discharge in alluvial channels is water temperature. Although the role of temperature has been studied by a number of investigators, its multiple effects are not understood well. Data from previous studies, seemingly, have not been consistent. As a result, conclusions about the effects of temperature changes have been contradictory. The only generally agreed upon conclusion seems to be that the effects of temperature changes can be very significant.

In an effort to reconcile previous experimental differences and to gain additional information, the effects of temperature changes on flow resistance and sediment transport were investigated in a laboratory flume.The investigation was made as a part of a general study on fluvial mechanics that is being conducted by the U. S. Geological Survey at Colorado State University (Simons and others, 1961; Simons and Richardson, 1961).

Fortunately, previous studies in an 8-ft flume and a 2-ft. flume on the effect of fine sediment on flow phenomena (D. B. Simons, E. V. Richardson, and W. L. Haushild, written communication, 1961) have provided some insight into the nature of temperature effects.

Definitions

In this study, the only sediment present in the experimental system was the bed material, which was sand. Thus, the suspended sediment concentrations and the total sediment concentrations were derived entirely from the bed material. Ordinarily, such concentrations would be designated as suspended-bed-material concentrations and total bed material concentrations, respectively, in order to differentiate them from the fine sediment concentrations (wash load concentrations) and total sediment concentrations. However, for briefness in this report the prefix "bed material" has not been used. The reader should bear in mind that the data and findings pertain only to bed material concentrations. Whenever the data and findings are discussed in terms of natural streams and data from other investigators are used and discussed, the prefix "bed material" has been included as a part of the terms.

Definitions of some of the important terms used in this report are as follows:

Sediment: Fragmental material that originates from weathering of rocks and that is transported by, suspended in, or deposited by water.

Sediment concentration: The ratio of the weight of sediment to the weight of water-sediment mixture, in parts per million.

Suspended sediment: Sediment that at any given time is moving in suspension in a fluid and is maintained in suspension by the upward components of turburlent currents or by colloidal suspension.

Total sediment: A prefix for the terms concentration and discharge to denote totality, regardless of the mode of transport of the sediment or its source.

Ripples: Small, triangular-shaped sand waves on the channel bottom that are similar to dunes, but that have much smaller and more uniform amplitudes and lengths.

Dunes: Triangular-shaped sand waves on the channel bottom that have a gentle upstream slope and a steep downstream slope.

Plane bed: A bed form in which there are no sand waves on the channel bottom and the bed relief is flat.

Standing waves: Curved, symmetrically-shaped sand waves on the channel bottom that remain virtually stationary. With standing waves the water and bed surfaces are roughly parallel and in phase at all times.

Antidunes: Curved, symmetrically-shaped sand waves on the channel bottom that move upstream. With antidunes, the water and bed surfaces are roughly parallel and in phase except at times when the water-surface waves build up, then break like surf.

Lower flow regime: A category for flows having bed forms of ripples, ripples on dunes, or dunes.

Upper flow regime: A category for flows having bed forms of plane bed with sediment movement, standing waves, or antidunes.

Equal transit rate: A method of sampling suspended sediment in which a sampler that collects water-sediment mixture everywhere at stream velocity is traversed, at a constant rate, throughout most of the depth of verticals equally spaced across the flow. Concentrations determined from samples collected by the ETR method are velocity-weighted mean concentrations.

EQUIPMENT AND PROCEDURE

A schematic drawing of the flume and recirculation system used for this study is shown in figure 1. The flume is 60 ft long, 2 ft wide and 2-1/2 ft deep, and has 1/2 in. clear-plastic walls and a 1/4 in. stainless-steel plate bottom. The water-sediment mixture is recirculated by pumping from the tailbox through a pipe back to the head box. The flow enters the head box through a manifold diffuser and then passes through a lattice and screen arrangement which decreases the size and energy of the turbulent eddies. At times when it was necessary, a wave dissipator was used at the flume entrance.

Figure 1. — Schematic diagram of the flume.

The depth of flow in the flume was controlled with a vertical, adjustable tailgate when the flow was in the lower regime. When the flow was in the upper regime, a weir was placed at the exit of the flume to control both the depth of sand in the flume and the depth of flow.

A carriage that moves along rails on the flume was used for supporting various measuring instruments. The carriage is built so that the instruments can be moved transversely as well as longitudinally.

Cold water and steam were used to vary the water temperature in the flume and circulation system. For the low-temperature runs, a constant temperature was maintained by continually adding water from the main and allowing some recirculated flow to drain off. For the high-temperature runs, a constant temperature was maintained by adding steam to the system at the tail box.

The bed material used in this study was sand having an average median standard fall diameter (Federal Inter-Agency River Basin Committee, 1957A) of 0.31 mm and a size distribution as shown in figure 2.

Figure 2. -- Composite size distribution of bed material.

The sand, which was obtained from the bed of the Elkhorn River near Waterloo, Nebraska, originally had an average median fall diameter of 0.28 mm; however, because of its previous use in an 8-ft wide flume, the material had coarsened somewhat. The gradation coefficient of the bed material σ_b , (see p.) as determined from a composite of all samples collected during this study was 1.57.

Throughout the study, two runs, one having a high water temperature and the other having a low water temperature, were made for each discharge, basic flume slope, and tail gate setting. In the first run of each pair of runs the desired discharge and water temperature (high or low) were established, the tail gate was adjusted to produce a depth of flow of about 0.55 ft, and the slopes of bed and water surface were allowed to adjust to accommodate the resultant hydraulic and sediment conditions.

During the period of time required for the system to reach equilibrium, the tail gate was adjusted to maintain the required depth. After equilibrium was reached, the final measurements were made. A run was considered to be in equilibrium when the bed configuration remained essentially the same over the length of the flume, except near the entrance and exit, and when the slope was relatively constant with respect to time. For the second run in each pair of runs, only the water temperature was changed and the system was allowed to reach equilibrium, usually, without the flow being turned off.

To limit the number of variables affecting sediment transport and bed roughness, the depth was kept essentially constant throughout the study. However, as previously mentioned, the depth in only the first run of each pair of runs was regulated.

DATA COLLECTION

With a rough movable boundary, uniform steady flow exists only in a statistical sense because of the instantaneous changes in both the magnitude and direction of the velocity of flow. As a result, representative average values for all the basic variables had to be obtained by making successive measurements during relatively long periods of time after equilibrium was reached. The frequency and the time period over which the measurements were taken depended mainly on the bed form. For example, a few slope measurements over a short time were sufficient to give a reliable average when the bed form was ripples; but, many measurements over a long time were required when the bed form was dunes.

The basic data for this study were collected from thirty equilibrium runs that represent different bed forms (Simons and Richardson, 1961) from plane bed and no sediment movement to antidunes. Fifteen were low-temperature runs, and the other fifteen were high-temperature runs.

The basic data are listed in table 1 and the methods used to measure or compute the basic variables are explained in the following sections.

Water-Surface Slope

Water-surface slopes were determined from point-gage measurements of the relative water-surface elevation at various places along the flume. When the water surface was smooth, or relatively smooth, single measurements were made every two feet along the flume. When the water surface was rough and fluctuating, many measurements were made at three stations along the flume.

A slope was determined from each set of measurements by graphing water-surface elevation versus distance and drawing an estimated mean line. When all the graphs for a run were well defined, the average of all slopes was used as the average slope for that run; whereas, when the graphs were not well defined, the slope was determined by a combination of the graphical method and the least square method. Only the slope measurements that were taken after equilibrium conditions had been attained were used to establish the average slope. Also, water-surface elevations that reflected non-uniform flow at the entrance and exit of the flume were discarded.

On the average, 5 slope measurements were taken during each run. The number of individual measurements depended on the condition of the flow.

Discharge

Discharge was measured with a calibrated orifice meter and water-air manometer. On the average, 8 readings were used to compute the mean discharge. The maximum difference in discharge between the runs of each pair of runs was 0.03 cfs.

Water Temperature

Water temperature was measured with a mercury thermometer. Usually about 6 temperature readings were used in determining the mean temperature of each individual run. For the high-temperature runs, temperatures varied from 23.4 to 34.3°C and averaged 29°C; for the low-temperature runs, they varied from 7.0 to 14.7°C and averaged 11.6°C. The maximum difference between the temperature of any low-temperature run and the average temperature for all such runs was 39.6 percent; the maximum difference was 18.3 percent for the high-temperature runs. Also, on the average, the variation in temperature during the runs was 1.4°C.

Depth

Individual depths were determined at one-foot intervals along the center line of the flume by computing from point-gage measurements the difference in elevation between water and bed surfaces. The average depth, in turn, was computed from the individual depths. Only those depths measured in the part of the flume where the flow was steady and uniform were used to establish the average depth. Because of the rapid changes in water-surface elevation at a point and the softness of the bed especially during the runs in the upper flow regime, many depth measurements had to be made to obtain accurate average depths.

Generally, about 80 depth measurements were used in computing the average depth for the runs in the lower-flow regime and about 120 were used for the runs in the upper-flow regime. The average depth for the thirty runs was 0.61 ft, and the maximum deviation in the average depth for any run was 22 percent from this overall average.

Mean Velocity

Mean velocity was computed by dividing the mean discharge by the average flow area (mean depth times the width of the flume). Mean velocities ranged from 0.86 to 5.73 fps.

Total Sediment Concentration

Samples of the water-sediment mixture were taken with a width-depth, integrating, total-load sampler at the flume exit to establish the velocity-weighted total sediment concentration. In general, 10 samples, each of which consisted of about 86 pounds of water-sediment mixture, were taken during a run. For runs in the lower flow regime, the samples were collected throughout an average period of 10 hours; for the runs in the upper flow regime they were collected throughout an average period of about 4 hours. Total sediment concentrations ranged from 0 to 29,600 parts per million (ppm).

Suspended-Sediment Concentration

Suspended sediment was sampled at the middle of the flume with a depth-integrating sampler. The sampler consisted of a 3- x 1/4-inch brass nozzle that was connected to a vacuum pump and attached to a wading rod. The vacuum pump was used to achieve a nozzle velocity that was approximately equal to the mean velocity of the flow. About 0.9 of the depth was sampled. Whenever it was possible, samples were taken on the crests of bed forms. Four samples, each containing about 6.5 pounds of water-sediment mixture, were collected by the equal-transit rate method[1] for each run.

In one run having antidunes (run no. 17), the suspended-sediment concentration was slightly higher than the total sediment concentration. This may have been a result of the sampling technique or of sampling too close to the bed; but, probably merely indicates that for this flow condition the total sediment concentration and the suspended-sediment concentration are equal. Concentrations of suspended sediment ranged from 0 to 29,900 ppm.

Bed Material

Bed material was sampled during each run with a one-inch diameter plastic tube by collecting full-depth cores at 5-ft intervals along the flume. For analysis, all the cores for each run were composited.

Particle-Size Distributions

Particle-size distributions of the total sediment discharge, suspended-sediment discharge, and bed material were determined by the visual accumulation tube method (Federal Inter-Agency

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1. The sampling technique corresponded to the ETR method; however, because water-sediment mixture was not collected everywhere at stream velocity the ETR method was not adhered to strictly. Probably, the measured concentrations are only slightly different than those that would have been measured if the ETR method had been used.

River Basin Committee, 1957B). Graphs of the size distributions were plotted on logarithmic probability paper for each run in order to establish the median standard fall diameter and the gradation coefficient. The median standard fall diameter is the size for which 50 per cent, by weight, of the sediment is finer or coarser. The gradation coefficient is defined as:

$$\sigma = 1/2 \left(\frac{d}{d_{16}} + \frac{d_{84}}{d}\right)$$

where d_{16} and d_{84} are the sizes for which 16 and 84 percent, respectively, of the material is finer.

ω Fall Velocity

Values of/an estimate of the fall velocity of the bed material at the temperature of each run, were computed by applying a corrective velocity to the standard fall velocity of the median fall diameter. For the computations, a shape factor of 0.7 was used and fall velocities of the median fall diameters and corrective velocities were determined from Tables 2 and 4, respectively, of Report No. 12, "Some Fundamentals of Particle Size Analysis" (Federal Inter-Agency River Basin Commission, 1957A). The range of fall velocities of bed material was from 0.12 to 0.17 fps. The average fall velocity of bed material for the low-temperature runs was 0.13 fps, and that of the high-temperature runs was 0.16 fps.

EFFECT OF TEMPERATURE ON THE SEDIMENTATION FLUID AND PARTICLE CHARACTERISTICS

Changes in temperature affect both the density and viscosity of flow. In a natural stream densities vary, because of temperature changes, a maximum of about 1 percent; however, viscosities can vary as much as about 150 percent. In this study the average water temperatures for the low- and high-temperature runs were 11.6 and 29.0°C, respectively, for which the kinematic viscosities are 1.35×10^{-5} and 0.89×10^{-5} square feet per second--a variation of about 52 percent. Viscosity among other things, affects the fall velocity of the sediment particles. Thus, whenever the temperature changes, the viscosity changes and in turn, the fall velocity of the sediment is altered. Figure 3 shows the degree that the fall velocity of different sizes of natural sand particles varies with temperature.

Figure 3 - Variation of fall velocity with temperature for different nominal diameters (naturally worn quartz particles having a shape factor of 0.7).

Because the variation of viscosity with temperature is different for different fluids, the variation of fall velocity with temperature also is different for different fluids. D. B. Simons, E. V. Richardson, and W. L. Haushild (written communication, 1961) measured changes in viscosity with temperature for various percentage dispersions of bentonite and kaolin in water. The dispersions behaved as non-Newtonian fluids, that is, there was no constant proportionality factor (viscosity) between the rate of deformation and the shear stress. They also computed fall velocities for particles having shape factors of 0.7 by using the measured apparent viscosity for each dispersion with the drag coefficient-Reynolds number relation (Federal Inter-Agency River Basin Commission, 1957). The computed fall velocities for each dispersion were close to those measured in a visual accumulation tube in which the settling medium was the dispersion. The agreement between the computed and measured fall velocities indicates that the apparent viscosity curves they presented can be used with the drag coefficient-Reynolds number relation to compute fall velocities in like dispersions at various temperatures. Figure 4, which is based on such computations, shows that for a sample of Elkhorn River sand whose median fall diameter is about 0.26 mm, the absolute rate of change of fall velocity with temperature is less with the water-clay dispersions than, with distilled water, at least, throughout the range from 10 to 40°C. Figure 5, which is derived from the

Figure 4 - Variation in fall velocity of median particle size of Elkhorn River, Nebraska sand with fluid temperature in distilled water and in 5 percent, by weight, dispersions of kaolin and bentonite.

Figure 5 - Relative variation of fall velocity of median particle size of Elkhorn River, Nebraska sand with fluid temperature in distilled water and in 5 percent, by weight, dispersions of kaolin and bentonite.

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curves of Figure 4, shows that relative rates of change of fall velocity with temperature also are less with the water-clay dispersions than with distilled water. This graph may also be interpreted to indicate that with water-clay dispersions, when the fall velocity of the particles is decreased by a change in the dispersion, the relative rate of change of fall velocity with temperature decreases. Thus, even though the addition of fine sediment may cause the viscosity of a dispersion to vary with temperature to a greater extent than the viscosity of distilled water, the net effect may be that the variation of fall velocity with temperature is reduced.

EXPERIMENTAL RESULTS

The water temperatures and total sediment concentrations associated with the pairs of low- and high-temperature runs are shown in Figure 6. In the figure straight lines join the runs of each pair. In the lower flow regime, the data indicate that when the bed form was ripples an increase in temperature caused an increase in the total sediment concentration; when the bed form was dunes with ripples superposed a temperature increase caused the total sediment concentration to decrease; and when the bed form was dunes a temperature increase caused either an increase or a decrease in the total sediment concentration. In the transition between the lower and upper regimes of flow an increase in temperature caused an increase in the total sediment concentration. In the upper flow regime, when the bed form was plane or mild antidunes an increase in temperature caused either an increase or a decrease in the total sediment concentration; however, when the bed form was antidunes a temperature increase caused a decrease in the total sediment concentration.

Figure 6 - Temperatures and total sediment concentrations for each pair of runs.

The changes in the flow resistance that resulted from the temperature changes are shown in Figure 7. In the figure lines

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Figure 7 - Temperatures and resistance coefficients for each pair of runs.

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join the runs of each pair. In the lower flow regime the resistance to flow generally decreased when the temperature was increased. In the upper flow regime temperature increases, likewise, were associated with decreases in flow resistance. However, in the transition between lower and upper regimes of flow, the flow resistance increased when the temperature was increased.

In several pairs of runs the bed form was changed as a result of the temperature change (see figures 6 and 7). Actually, the most dramatic changes in bed form occurred in the three pairs of runs classified as transition, particularly in runs 7 and 8. However, because of the range of conditions covered by the term "transition", the change in bed form has not been indicated in the figures. In the three pairs, the low-temperature runs were associated with relatively flat beds (see Figure 8); whereas, the high temperature runs were

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Figure 8 - Bed form in low-temperature transition runs:

A. Run ; B. Run ; C. Run .

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associated with beds having slightly washed out dunes. (see Figure 9). Also, in the low-temperature transition runs both

Figure 9 - Bed form in high-temperature transition runs:
A. Run ; B. Run ; C. Run .

the flow resistances and the total sediment concentrations were low, and in the high-temperature transition runs both the flow resistances and the total sediment concentrations were high.

The apparent contradictory nature of the data on both flow resistance and sediment concentration corresponds with the findings of other studies. Lane and others (1949) reported that for comparable mean daily discharges in the Colorado River, daily suspended-bed-material discharges are two to three times greater in the winter than they are in the summer. Straub (1954) found similar increases in the Missouri River. Hubbell and others (1956) reported that in the Middle Loup River at Dunning, Nebraska both the suspended-bed-material concentration and the total bed-material concentration increased when the temperature decreased. They also reported that the flow resistance decreased when the temperature decreased. On the other hand, Ho (1939) observed that sediment concentrations increased when the water temperature was increased. Likewise, M. G. Mostafa (written communication, 1949), on the basis of his studies with fluids having vastly different viscosities, concluded that a fluid having a high viscosity would in most cases transport a lower total bed-material discharge than a fluid having a low viscosity; in other words, an increase in water temperature should usually increase the total bed-material discharge. Other experimenters (J. S. McHown, written communication, 1942; and Barton and Albertson, 1953) similarly have indicated that an increase in temperature increases the sediment transport. Data collected by D. B. Simons, E. V. Richardson, and W. L. Haushild (written communication, 1961) in the same flume as was used in this study indicate that when the viscosity is increased by the addition of fine sediment (comparable to an increase in viscosity by a reduction in temperature), the flow resistance and bed-material concentration may either increase or decrease; the change depends on the conditions of flow.

The most striking facts from the data are that both the total sediment concentration and flow resistance (and shear) change when the temperature changes, and that the observed changes correspond in one way or another with those observed by most other investigators. These facts seem particularly significant because they indicate that the effects of temperature changes, like the effects of some other variables, are not always direct and in the same direction.

ANALYSIS OF THE DATA

It has been found by many investigators that the size of bed material has a considerable effect on the amount of sediment transported in alluvial channels. Simons and Richardson (1961) found by comparing the data collected for different bed materials that the size of bed material, as characterized by the median standard fall diameter, has an important effect on the forms of bed roughness which, in turn, affect the rate of sediment transportation. Because the fall diameter is determined from fall velocity, the variation in bed form and other flow phenomena that occur with different fall diameters actually reflect the effects of the fall velocity of the bed material. Thus, whenever the viscosity of the sedimentary fluid changes because of a temperature change, the fall velocity changes and the influence of the bed material on the rate of sediment transport and the flow resistance is altered.

The shear on the bed, τ_o , has beenplotted against the total bed-material concentration with the form of bed roughness as a third variable in Figure 10. The data used for the graph

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Figure 10 - Relation between bed shear and total bed-material concentration in an 8-ft. wide flume for relatively constant water temperature and depth.

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were collected in an 8-ft flume and were for a relatively constant water temperature and depth (Simons and Richardson, 1961; Simons, Richardson, and Albertson, 1961). A similar graph with data from this study also has been prepared (see Figure 11).

Figure 11 - Relation between bed shear and total sediment concentration for the low- and high-temperature runs.

In both figures there are two relations. Figure 10 shows distinct relations for the 0.28 mm sand and the 0.45 mm sand, and figure 11 gives separate relations for the low- and high-temperature runs. Each curve in these figures shows that in the lower flow regime the total sediment concentration increases as the shear on the bed increases; in the transition, the concentration remains about constant, but the shear suddenly decreases; and in the upper flow regime the concentration increases as the shear on the bed increases. Also the rate of change of concentration with shear, $dC / d\tau$, is the greatest in the lower flow regime just before the sudden decrease in the shear. If representative fall velocities are substituted for the sizes and temperatures indicated in figures 10 and 11 respectively, is apparent that there is a different shear-concentration relation for each fall velocity.

The relative positions of the curves in the two figures are somewhat different. Possibly, the differences between the relations exist because the two sands given in figure 10 have different size gradations; whereas, in figure 11, the size gradation was constant, except as it was modified by temperature. However, the differences could also reflect the effect of different sized flumes. In any case, the figures indicate that for a given channel shape and depth, there is a reasonably well-defined relation between the shear on the bed and the total bed-material concentration for every different distribution of fall velocities of the bed material.

GENERAL EXPLANATION FOR TEMPERATURE EFFECTS

Three fundamental relationships provide the basis for a general qualitative explanation of the effect of temperature changes on sediment transport and flow resistance in alluvial channels. These relationships are: (1) For every different bed material size gradation, fluid medium, depth, and basic channel shape, there appears to be a general discontinuous relation (such as those in figures 10 and 11) between the shear on the bed and the total bed-material concentration; (2) The influence of the bed material changes whenever its fall velocities change; and (3) The fall velocities of the bed material change whenever the properties of the settling medium change.

The implication of these relationships is that for a given depth and basic channel shape, the fall velocities of the bed material determine the relation between the shear and the total bed-material concentration for a particular fluid medium, and that if the properties of the fluid medium change, the fall velocities change and a new relation between the shear and the total bed-material concentration is established. Because any particularly bed material has many possible fall velocities, many different relations between the shear and the total bed-material concentration/are possible even for a constant depth and basic channel shape.

When the temperature changes, the fall velocities of the bed material change. These changes cause the shear on the bed, the total bed-material concentration, the flow resistance, and sometimes the form of bed roughness to change. These factors adjust until a state of equilibrium is reached in which their mutual association satisfies the specific relation between the shear and the total bed-material concentration for the new depth and the new fall velocities of the bed material. The mutual changes and their direction depend on the relative relation between the original and new shear-concentration relations.

In general, there appear to be three areas of flow in which temperature changes have the most effect. The first area is indicated in figures 10 and 11 by the segments of the curves that were defined for the lower-flow regime when the form of bed roughness was mostly ripples. In this part, the curves are almost parallel to each other. Thus, if the shear changes only slightly when the temperature changes, the total bed-material concentration might change appreciably. The second area is indicated by the segments of the curves where the sudden decrease in shears occurred; these segments reflect the transition between the upper and lower regimes of flow when the form of bed roughness changed from dunes to plane bed. In this area, if the shear changes only slightly, the total bed-material concentration could change drastically. The third area is indicated by the segments of the curves that were defined for the upper-flow regime. In this area, the curves are roughly parallel and have flat slopes. Consequently, a temperature change might also cause a relatively large change in the total bed-material concentration.

CONCLUSIONS

In this study, average water temperatures for the low- and high-temperature runs were 11.6 and 29.0°C, respectively, for which the kinematic viscosities are 1.35×10^{-5} and 0.89×10^{-5} square feet per second. Particles having shape factors of 0.7 and standard fall velocities equal to the median standard fall velocity of the bed material have computed fall velocities for these viscosities that average 0.13 and 0.16 feet per second, respectively.

Even though the apparent viscosity of a water-fine sediment dispersion may vary with temperature to a greater extent than the viscosity of distilled water, the variation of the fall velocities of sand particles with temperature may be less in the water-fine sediment dispersion than in distilled water.

Changes in water temperature cause changes in the sediment concentration, flow resistance, shear, and, sometimes, the bed form. The magnitude and direction of the changes are not the same for all flows.

The most dramatic bed form changes in this study were observed when the flow was in the transition between the upper- and lower-flow regimes and the bed changed from slightly washed out dunes to nearly a plane bed.

The observed changes in flow resistance and sediment transport correspond in one way or another with the changes observed by other investigators.

Graphs based on data from an 8-ft wide flume and from this study show that with a basic channel shape and relatively constant depth, the relation between bed shear and total bed-material concentration is well defined for every different fall velocity of the bed material, regardless of whether the fall velocity is different because the bed material is different or because the viscosity of the settling medium is different.

When the temperature changes, the fall velocity of the bed material changes. This change causes the shear on the bed, the total bed-material concentration, and the flow resistance to adjust until a state of equilibrium is reached in which the mutual association of these variables satisfies the specific shear-concentration relation for the new depth and the new fall velocity of the bed material.

In general, there seems to be three conditions of flow when temperature changes cause the greatest changes, percentagewise, in the total bed-material concentration. These conditions are when the bed form is ripples, when the bed form is antidunes, and when the flow is in the transition range.

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