Response of a Laboratory Alluvial Channel to Changes of Hydraulic and Sediment-Transport Variables

GEOLOGICAL SURVEY PROFESSIONAL PAPER 562-D

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By R. E. RATHBUN, H. P. GUY, *and* E. V. RICHARDSON

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

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A comparison of the feed and recirculation systems of flume operation for laboratory studies of sediment transport and resistance to flow

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SYMBOLS

Symbol	
a	Constant in the relation between V and qS.
b	"Least squares" slope of V versus qS relation.
B_f	Bed configuration.
C_f	Concentration of fine material, in milligrams per liter.
C_t	Concentration of sediment in the flow, in milligrams per liter.
D	Mean depth of flow, in centimeters.
d	Representative particle size in terms of fall diameter, in millimeters.
d_{50}	Median particle size of the sediment, in millimeters.
d_{16}	Particle size for which 16 percent of the sediment by weight is finer, in millimeters.
d_{84}	Particle size for which 84 percent of the sediment by weight is finer, in millimeters.
e	Base of the natural logarithm, 2.718.
$\mathbf{F}$	Froude number, equals $V/\sqrt{gD}$.
f	Darcy-Weisbach resistance coefficient, equals $8gDS/V^2$.
g	Acceleration of gravity, equals 980 centimeters per second per second.
K	Constant.
$\log_e$	Logarithm to the base e, or the natural logarithm.
Q	Discharge of water-sediment mixture, in liters per second.
Q_s	Sediment-transport rate, in grams per second.
q	Unit discharge of water-sediment mixture, in liters per second per meter.
q_s	Unit sediment-transport rate, in grams per second per meter.
S	Slope of the energy grade line, equal to the water-surface slope at equilibrium, in meters per meter.
S_c	Shape factor for the cross-section.
S_p	Shape factor for the sediment particles.
T	Time, in seconds.
V	Mean velocity, based on continuity principle, in centimeters per second.
ω	Fall velocity of median particle size of the sediment, in centimeters per second.
W	Width of flume, in centimeters.
γ	Specific weight of water, in grams per cubic centimeter.
ρ	Mass density of the water, in grams per cubic centimeter.
ρ_s	Mass density of the sediment, in grams per cubic centimeter.
σ	A measure of the gradation of the sand, equals $\frac{1}{2}\left(\frac{d_{50}}{d_{16}}+\frac{d_{84}}{d_{50}}\right)$.
ϕ	Function of.
ν	Kinematic viscosity of the water, in square centimeters per second.

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

RESPONSE OF A LABORATORY ALLUVIAL CHANNEL TO CHANGES OF HYDRAULIC AND SEDIMENT-TRANSPORT VARIABLES

By R. E. Rathbun, H. P. Guy, and E. V. Richardson

ABSTRACT

The feed and recirculation systems of flume operation were compared in a series of experiments conducted in a tilting plastic flume 10 meters long, 20 centimeters deep, and 20 centimeters wide. No significant differences were observed in the mean values of the sediment-transport rate, water-surface slope, depth of flow, and mean velocity for the two systems in the equilibrium steady state.

The responses of the laboratory alluvial channel with a constant water discharge to changes of sand-bed slope, tail-water depth, and sediment-transport rate were determined. The results observed were: (1) For the feed system, changes of the sediment-feed rate resulted in new equilibrium values of the water-surface slope, depth of flow, and sediment-transport rate; (2) for the feed system, changes of the sand-bed slope and to the tail-water depth resulted in the flume system returning to the equilibrium values of the water-surface slope, depth of flow, and sediment-transport rate that existed before the change; (3) for the recirculation system, changes of the sand-bed slope and tail-water depth resulted in new equilibrium values of the water-surface slope, depth of flow, and sediment-transport rate; and (4) for the recirculation system, changes of the sediment-transport rate resulted in continually changing nonequilibrium conditions, and equilibrium conditions were established only when the external feeding or extracting of sediment was terminated. The second and third results do not indicate a true difference between the feed and recirculation systems because in the feed system both the water discharge and the sediment-transport rate were controlled, whereas only the water discharge was controlled in the recirculation system.

The recirculation system has the advantage of ease and economy of operation, and the feed system has the advantage of direct quantitative control of the sediment-transport rate.

INTRODUCTION

For many years man has attempted to understand the phenomena of sediment transport and resistance to flow in alluvial channels. In an effort to understand these phenomena, numerous laboratory experiments have been conducted in open-channel flumes with a sand bed. These experiments attempted to simulate a natural alluvial channel under laboratory conditions where the different variables could be controlled or varied as desired. One of the first and most extensive of these investigations was by Gilbert (1914), who studied the transport rates of a number of sands under a variety of flow conditions.

One of the problems that confronts investigators in flume studies is the replacement of the sediment removed from the flume by the flowing water. Two general procedures have been developed for providing a supply of sediment at the inlet of the flume. These are the sand-feed system, or feed system, and the recirculation system. In the feed system, the general operating procedure is to catch the water-sediment mixture leaving the downstream end of the flume, remove the sediment, and recirculate the water to the upstream end of the flume, where sediment is fed into the flow at the desired rate. In the recirculation system, the water-sediment mixture leaving the downstream end of the flume is recirculated to the upstream end of the flume. Figure 1 shows schematic diagrams of the general arrangement of the feed and recirculation systems of flume operation.

Early investigators were forced to use the feed system in their flume studies because they lacked equipment to pump water-sediment mixtures. All the studies completed through about 1940, the results of which were compiled by Johnson (1943), used the feed system. After the development of pumps which could pump water-sediment mixtures, later investigators almost exclusively used the recirculation system in laboratory studies of sediment transport and resistance to flow. These studies included the works of Einstein (1950) and Barton and Lin (1955), the extensive series of experiments completed by Simons and Richardson and summarized by Guy, Simons, and Richardson (1966), and the work of Brooks (1958), Laursen (1958), Kennedy (1961), Kennedy and Brooks (1965), Raudkivi (1967), and Vanoni and Hwang (1967). Williams (1967) used the feed system.

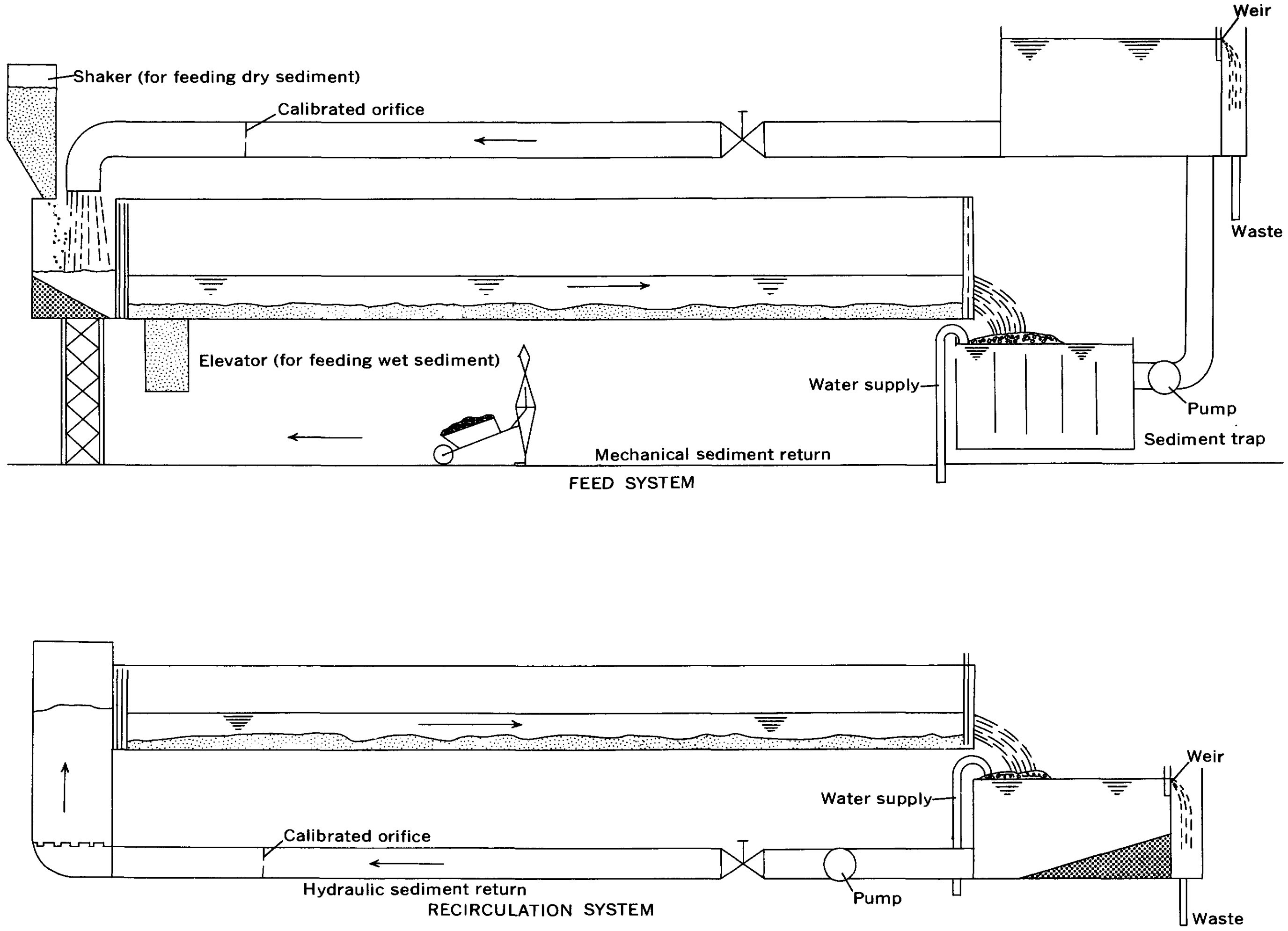

FIGURE 1.—Schematic diagrams of the recirculation and feed systems of flume operation for alluvial channel experiments. For the feed system, both the wet and the dry methods are shown.

The use of the two types of flume systems has raised the question of the comparability of results obtained from the feed system with results obtained from the recirculation system. Are the equilibrium conditions established by the two systems the same and are the relations among the variables at equilibrium the same? It is important also to consider how the feed and recirculation systems respond to a change of a given controlled variable such as depth of flow, slope, water discharge, or sediment-transport rate and the time interval required to reach equilibrium conditions after a change has been imposed on the system.

The purpose of this report is to describe the results of a study in which the equilibrium values of the sediment-transport rate, water-surface slope, depth of flow, and mean velocity were compared for the feed and recirculation systems, and the responses of several dependent variables to a change in a specific independent variable were determined for the feed and recirculation systems of flume operation for alluvial channel flume experiments.

This report is divided into seven sections. The first section gives the general procedures for flume experiments and the various combinations of independent and dependent variables that have been used. The second section describes the experimental apparatus and procedures. The third section compares the feed and recirculation systems under equilibrium conditions. The fourth section describes the responses of the laboratory alluvial channel to a change in one of the independent variables. The fifth section discusses the advantages and disadvantages of the feed and recirculation systems of flume operation. The sixth section is a summary of the results and conclusions. The seventh section discusses the limitations of the present study and recommendations for future studies.

GENERAL PROCEDURES FOR LABORATORY ALLUVIAL CHANNEL EXPERIMENTS

The extent and usefulness of laboratory studies of sediment transport and resistance to flow may be limited by (1) the ranges of variable values for a given flume system (2) the large number of variables and the dependencies and interdependencies among them, (3) the ability or inability to control or eliminate the effects of certain variables, and (4) the order and importance of the questions to be answered. These limitations are applicable to both the feed and the recirculation systems of flume operation.

The variables to be considered in flume experiments include those that describe the characteristics of the flow, the fluid, the sediment, the geometry of the system, and the variations in these quantities with time. The important variables are as follows:

$$\phi[T, Q, Q_s, S, D, V, C, C_t, W, B_f, d, \omega, \sigma, g, \gamma, C_f, S_c\ S_p, \rho, \rho_s]=0. \qquad (1)$$

Simons and Richardson (1966) have discussed in detail the effect that many of these variables have on resistance to flow in alluvial channels.

Under controlled laboratory conditions many of these variables can be maintained at constant values. Thus, for a study in a given flume that uses a specific liquid (water) at a constant temperature and a specific sediment, the variables describing the sediment (d, ω, σ, S_p, ρ_s), the fluid (γ, ρ), and the flume (W, S_c) have constant values. The shape factor for the cross section, S_c, is constant because the average shape of the cross-sectional area of the flow is rectangular. At a specific location, one dimension of the rectangle changes with time, and this variation is accounted for by the depth of flow. The acceleration of gravity, g, has a constant value, and the concentration of fine sediment, C_f, is generally zero. The fine-sediment concentration is important because Simons, Richardson, and Haushild (1963) found that the fine-sediment concentration significantly affected the coarse-sediment-transport rate and resistance to flow.

Experimenters have usually studied the equilibrium condition where the mean values of the variables are independent of time. Equilibrium flow in a laboratory flume is defined as the condition where the time-average water-surface slope is approximately constant and is equal to the time-average sand-bed-surface slope, and where the sediment-transport rate is approximately independent of time. The word "approximately" was used in this definition because investigators have noted (Simons and others, 1963; Rathbun and Guy, 1967) that the observed values of water-surface slope, depth of flow, and sediment-transport rate vary considerably about the means of the observed values for a given equilibrium condition, especially when the bed forms are dunes or antidunes.

Under the restrictions of a specific flume, a specific liquid, and a specific sediment and when mean values of the variables are obtained for equilibrium-condition experiments so that time is eliminated as a variable, the list of variables is reduced to

$$\phi[Q, Q_s, S, D, V, C_t, B_f]=0. \qquad (2)$$

If certain fundamental relations that exist among the variables are used, the list of variables can be reduced further. The mean velocity is given by the law of continuity, or

$$V=\frac{Q}{DW}. \qquad (3)$$

The mean sediment concentration is given by

$$C_t=K\frac{Q_s}{Q}, \qquad (4)$$

where K is a constant whose value depends on the system of units used. The resistance to flow is often represented by the Darcy-Weisbach resistance coefficient, f. Simons and Richardson (1966) stated that

$$f=\phi[S, D, d, \omega, \sigma, g, \rho] \qquad (5)$$

and that the bed configuration may be substituted for the resistance coefficient to give

$$B_f=\phi[S, D, d, \omega, \sigma, g, \rho] \qquad (6)$$

Equation 6 does not say that the bed configuration is a unique or single-valued function of these variables but only that the bed configuration is some unknown function of these variables.

By using equations 3, 4, and 6, the list of variables can be reduced to

$$\phi[Q, S, D, Q_s]=0. \qquad (7)$$

The experimenter usually selects from these four variables the variables to be independent and the variables to be dependent for his particular study. An independent variable is defined as a condition imposed on the system, whereas the dependent variable is defined as the condition that results when equilibrium is established.

In the feed system, the water discharge and the sediment-transport rate are usually controlled independent or imposed variables, and the depth of flow and water-surface slope are the dependent variables. This system was employed by Gilbert (1914), and the terms "sand-feed" or "feed" have been associated generally with experiments in which the sediment-transport rate is an independent variable. In the studies of the U.S. War Department, Army Corps of Engineers, however, (1935), water discharge and water-surface slope were independent variables and sediment-transport rate and depth of flow were the dependent variables, even though the feed system was used, because sediment was fed into the upper end of the flume at a rate just sufficient to balance the sediment-transport rate.

Williams (1967) used a feed system in which the sediment-transport rate and the depth of flow were the independent variables and water discharge and water-surface slope were the dependent variables. The water depth was controlled at the desired value by adjustment of the water discharge, and equilibrium occurred through changes of the water-surface slope and bed roughness.

In recirculation systems, the water discharge is usually an independent variable and the sediment-transport rate is a dependent variable. Either the depth of flow or the water-surface slope can be selected as the second independent variable. Simons and Richardson (Simons and others, 1961) preselected the water-surface slope only approximately; thus, slope was an independent variable within limits, and the depth of flow was a dependent variable. The water-surface slope was set at the beginning of the run by adjusting the tailgate, and equilibrium conditions occurred through adjustments in the depth of flow, sediment-transport rate, bed roughness, and, to some extent, slope. For the water-surface slope to have been a truly independent variable, the tailgate adjustments to maintain the preselected slope would have had to be continued until equilibrium had been established. Simons and Richardson (Guy and others, 1966) also used other combinations of the independent and dependent variables.

Most of the other investigators using the recirculation system, such as Brooks (1958), Laursen (1958), and Stein (1965), have used the water discharge and the depth of flow as the independent variables and the water-surface slope and the sediment-transport rate as the dependent variables. These investigators found it more convenient to use depth of flow as an independent variable than water-surface slope because their recirculation systems were closed with respect to the quantity of water in the system. Therefore, the depth of flow was determined by the amount of water in the system at the start of the experiment. Simons and Richardson (Simons and others, 1961) added or wasted water to maintain a constant head in an open tailbox.

Another method of flume operation, which in theory would be possible but in reality may not be practical, is the operation of a recirculation system with the sediment-transport rate as an independent variable. Water discharge and sediment-transport rate would be the independent variables, and the depth of flow would be adjusted by the investigator to give a predetermined sediment-transport rate, and equilibrium would occur through the adjustments of the depth of flow, water-surface slope, and bed roughness. Although the depth of flow is adjusted by the operator of the flume, it is in theory a dependent variable because the final or equilibrium value of the depth is inconsequential.

Other combinations of the independent and dependent variables are possible because the four fundamental variables Q, S, D, and Q_s when used as two independent and two dependent variables, yield a total of six different combinations. Not all these combinations have been used in practice.

There are complications in the planning of flume experiments and in the interpretation of the results. Measurements of sediment-transport rates and resistance to flow in alluvial channel flumes by Brooks (1958) and Simons and Richardson (1966) have revealed certain nonunique relations among the variables. The word "unique" implies that there is only one value for the dependent variable corresponding to a given value of the independent variable. Brooks (1958) reported "that neither the velocity nor the sediment discharge concentration could be expressed as a single-valued function of the bed shear stress, or any combination of depth and slope, or bed hydraulic radius and slope." Although the relations among the variables are nonunique when the broad spectrum of bed forms is considered, there is, as pointed out by Simons and Richardson (1966), a unique relation among the variables for a given bed configuration.

Kennedy and Brooks (1965) considered the question of which combinations of the independent and dependent variables yield unique functional relations among the variables and which combinations yield multiple-valued relations for certain ranges of the variables. A brief summary of their conclusions and the investigators who have used the various combinations of variables is:

Variables			
Independent	*Dependent*	*Unique*	*Investigator*
Q,Q_s	S,D	Yes	Gilbert (1914).
Q,S	Q_s,D	No	U.S. War Dept. (1935), Simons, Richardson, and Albertson (1961).
D,S	Q,Q_s	No	Simons and Richardson (1966).
Q,D	Q_s,S	Yes	Brooks (1958); Laursen (1958); Kennedy and Brooks (1965); Stein (1965).
Q_s,D	Q,S	Yes	Williams (1967).

It is assumed in this summary that the properties of the fluid and the sediment, the acceleration of gravity, and the flume width are constant. The mean velocity and the resistance to flow as represented by the Darcy-Weisbach resistance coefficient are not included in the list of dependent variables because they are functions of the four fundamental variables. The combination of independent and dependent variables used by Williams (1967) has been added to the results of Kennedy and Brooks (1965). The other possible combination is with Q_s and S as the independent variables. It is expected that this combination would yield multiple-valued results. The method of designing flume experiments should not be confused with the analysis of the data. In data analysis, only one dependent variable is allowable, and it can be any of the variables given in equation 7.

The flume capabilities also can impose limitations on the dependent and independent variables. For example, in the data of Simons and Richardson (in Guy and others, 1966), the maximum depth of flow that would occur on the steep slopes was limited by the maximum water discharge capacity of the pump.

The existence of nonunique relations among the variables for certain combinations of the independent and dependent hydraulic and sediment-transport variables in flume studies is important because nonunique relations among the variables also occur in natural sand-channel streams. Dawdy (1961) has shown that the relation between stage and discharge is discontinuous for many sand-channel streams. Furthermore, Kennedy and Brooks (1965) believed that "rivers naturally fall into the range of variables (slope, depth, velocity) where relationships are multiple-valued due to changes in bed forms."

Because of the two types of flume systems and because of the freedom which the experimenter has in selecting the independent variables, questions have arisen as to the comparability of results obtained with the feed system and results obtained with the recirculation system. It is well known that differences exist among the flume data of the various investigators. Some of these differences may be the result of differences in the characteristics of the flumes and sediments used. Other differences may result from variations in operational procedures including the obtainment of data before equilibrium was attained. Blench (1962) has stated that the recirculation system is suitable for qualitative work but that he has reverted to the feed system for quantitative studies. As justification he cited difficulties with steady pumping of the water-sediment mixture and the tendency for long term oscillations in the amount of sediment transported or discharged by the flume. He did, however, note that the recirculation system "produces very realistic river behavior even with steady discharge."

Maddock (1968) has suggested that when water discharge and sediment-transport rate are independent variables, as in the feed system, then

$$V \propto (qS)^{0.5} \qquad (8)$$

where q is the unit discharge, or Q/W. When water discharge and slope are the independent variables, as in the recirculation system, he proposed

$$V \propto (qS)^{0.4} \qquad (9)$$

Equations 8 and 9 suggest that the relations among the variables q, V, and S are different for the feed and recirculation systems of flume operation.

The discussion of the feed and recirculation systems of flume operation has thus far been limited to a consideration of the equilibrium characteristics of the systems. It is important to consider also how these two systems of flume operation respond when nonequilibrium conditions are imposed upon the systems in equilibrium. A general qualitative expression relating the variables for alluvial channel flow has been proposed by Lane (1955). This expression has the form

$$Q_s d \propto QS. \qquad (10)$$

In addition to being an equilibrium expression, equation 10 indicates qualitatively the responses of the variables to nonequilibrium conditions. For example, if a recirculation system is used with a given sediment and a constant water discharge, then equation 10 predicts that the water-surface slope varies directly as the sediment-transport rate. If the sediment-transport rate is also constant, as is possible in the feed system, then equation 10 predicts that the water-surface slope is uniquely determined and the water-surface slope at equilibrium will be the one corresponding to the specific Q and Q_s, regardless of what other changes are imposed on the system. This result predicted by equation 10 is in agreement with the result of Kennedy and Brooks (1965) that for a given flume with a given sediment, D and S are uniquely determined when Q and Q_s are the independent variables.

EXPERIMENTAL APPARATUS AND PROCEDURE

APPARATUS

The experimental runs for this study were made in a tilting plastic flume 10 meters long, 20 cm (centimeters) wide, and 20 cm deep. The flume could be operated either as a recirculation system in which both the water and sediment were recirculated from the downstream end of the flume to the upstream end or as a feed system in which only the water was recirculated. In the feed system, the sediment transported from the end of the flume was removed with a screened trap, dried, and returned to the flow at a constant rate by a vibrating sediment feeder. Though the sediment was fed in the dry condition, it was assumed to be thoroughly wetted upon entrance to the flume at the headbox. Figure 2 shows a diagram of the flume and associated equipment.

The slope of the flume could be varied from 0 to 0.085 meters per meter, and the discharge range was from 0 to approximately 100 liters per second per meter of width. The water depth and the backwater curve at the downstream end of the flume were controlled either with a tailgate or by the water level in the tailbox. Longitudinal locations in the flume were referenced to stations at 1-meter intervals along the flume; station 1 was 50 cm downstream from the flume entrance.

Water discharges were determined by means of a calibrated orifice meter equipped with a water-air manometer. The orifice was in the return pipe of the flume. Water temperatures were measured with a mercury thermometer. In the first several runs, the water temperature was approximately that of the laboratory-air temperature. In later runs, a water heater and an electronic temperature controller were used to maintain a constant water temperature of 24.0°C. In the summer, the laboratory-air temperature sometimes exceeded 24°C and it was necessary to add cold water periodically to keep the water temperature at about 24°C.

The water-surface slope was determined from the readings of a series of 11 piezometers with taps positioned at 1-meter intervals along the centerline of the flume bottom. The initial 2-meter section of the flume was affected by entrance conditions and was not considered in the determination of the water-surface slope. The taps were connected with plastic hoses of equal lengths to the piezometer tubes at a central location. To prevent the sediment from entering the hoses, the tap openings were covered with small squares of stainless steel screen with openings of about 0.2 mm. The water levels in the piezometer tubes were an accurate reproduction of the water-surface elevations along the flume and quickly changed when the water level in the flume changed. Water-surface slopes were determined from the elevations of the water columns in the piezometers by plotting the elevation against the longitudinal location and drawing a straight line of "best fit". Comparable results were obtained by applying a simple "least squares" procedure to the readings.

The slope of the flume bottom (not necessarily the same as the slope of the surface of the sand bed) was determined from two stilling wells attached to the outside of the flume 9 meters apart at stations 1 and 10. The heights of these wells were adjustable so that the water level in each well could be positioned at exactly the same elevation as the bottom of the flume. These wells were connected by plastic hoses to tubes on the piezometer board. The difference in water level of these two tubes divided by the distance between the stilling wells was the flume-bed slope.

The depth of flow was determined by measuring the difference in elevation between the water surface and the sand-bed surface with a point gage. The mean depth of flow was the average of measurements at several locations; the number of measurements depended upon the bed form.

Total sediment-transport rates were determined by sampling with a trap at the tailbox of the flume. This trap had rigid plastic sides and a bottom and a back of stainless steel screen which had openings small enough

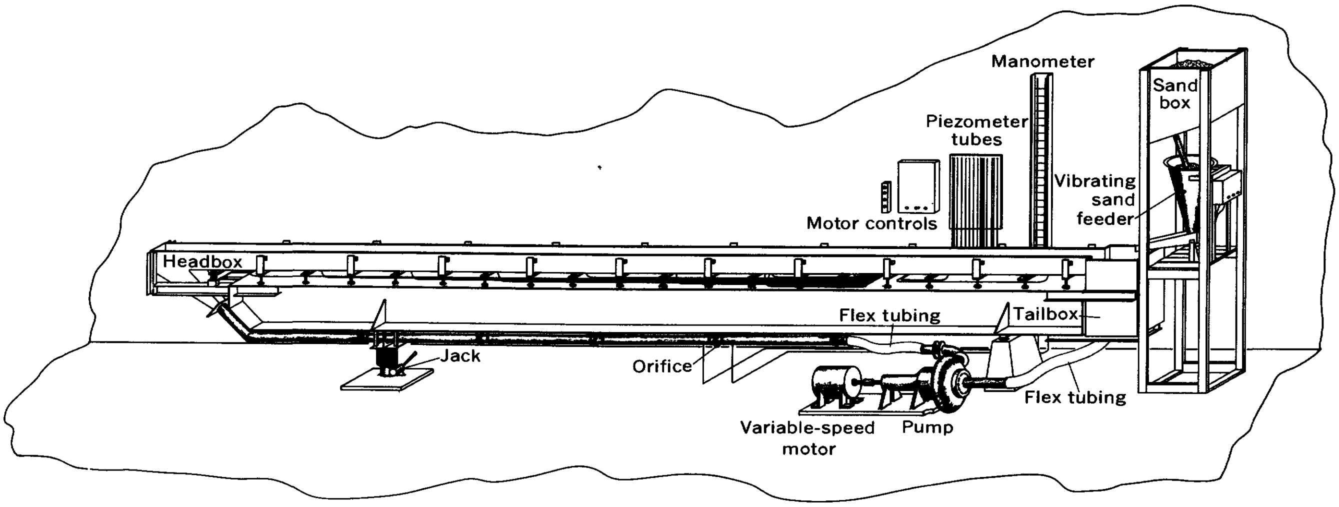

FIGURE 2.—Schematic diagram of the experimental flume and associated equipment used in this study.

to trap the sediment. The trap fit in the tailbox of the flume so that all the water-sediment mixture leaving the flume passed into the trap. The amount of sediment transported from the end of the flume in a given time, and hence the sediment-transport rate, was thus determined. When the recirculation system was used, the vibrating sediment feeder was used to replace an amount of sediment equal to the sediment trapped so as to maintain a constant amount of sediment in the system. For the first sample of a recirculation system run, it was necessary to estimate the feed rate for the sediment feeder. Thereafter, when a sample of the sediment in transport was taken, the feed rate was set at the sediment-transport rate determined from the previous sample; thus, the flume was operating with either a small deficiency or a small excess of sediment from one sample period to the next. The amount of sediment in any given sample, however, was insignificant when compared with the amount of sediment in the flume.

The volume of sediment collected in the trap was measured in a graduated cylinder. The relation between the volume of wet sediment and the dry weight of the sediment was determined by calibration. The wet sediment had a mean bulk density of 1.677 grams per cubic centimeter. Use of this procedure permitted a rapid determination of the sediment-transport rate.

When the feed system was used, the trap was left in the tailbox and all the sediment leaving the end of the flume was trapped. The sediment was siphoned from the trap into measuring containers placed in a small tank. The water removed by the siphon was returned from the small tank to the tailbox of the flume by means of a small pump; the discharge of the pump was adjusted to keep a constant water depth in the tailbox and, consequently, a constant head on the flume pump.

Sediment was fed at a constant rate with the vibrating sediment feeder. The feed rate was checked periodically by measuring the volume of dry sediment fed over a given time interval. Volume of sediment was converted to the weight of sediment using the bulk density of the dry sediment, which was found to be 1.563 grams per cubic centimeter. The sediment-feed and sediment-transport rates were rapidly determined by the volumetric measurement procedure, and a rapid comparison of the two rates was therefore possible. One obvious criterion for equilibrium in the feed system is that the sediment-transport rate equals the sediment-feed rate.

BED MATERIAL

The sediment used in this study consisted of well-rounded quartz particles having a median fall diameter, d_{50}, of 0.30 mm and a median fall velocity of 4.4 cm per sec (centimeters per second). The gradation of the sediment, σ, was 1.26.

PROCEDURE

The first part of this study consisted of the comparison of the feed and recirculation systems of flume operation under equilibrium conditions. The general procedure consisted of selecting the water discharge and the water-surface slope. The initial depth of flow was fixed approximately by the amount of water in the flume system in the early experiments when the water level in the tailbox served as the downstream control of the depth. As equilibrium conditions were approached and the water depth in the flume increased or decreased, the amount of water in the tailbox was increased or decreased so that the water level in the tailbox remained constant. In later runs, an adjustable tailgate was used to obtain the desired depths. Again the water level in the tailbox was maintained at a constant level. Equilibrium conditions were established using the recirculation system because the hydraulic sediment return of the recirculation system was much simpler to use than the mechanical return of the feed system and the supply of dry sediment for the feed system was limited. Equilibrium was considered established when the depth of flow was approximately uniform along the flume (excluding the section affected by the entrance conditions) and when the water-surface slope and sediment-transport rate were approximately independent of time. The determination of the establishment of equilibrium was somewhat arbitrary because the flume system asymptotically approached equilibrium conditions. As Laursen (1958) has noted, the final decision as to whether equilibrium has been established depends considerably on the judgment of the flume operator.

After equilibrium was established, a number of measurements of the water discharge, depth of flow, water-surface slope, sediment-transport rate, and water temperature were made. The number of measurements depended roughly on the magnitude of the variation with time of the variables. Figure 3 shows how the values of the variables varied with time for run 6. For water discharge, depth of flow, and water-surface slope, the deviations of the measured values from the mean values are shown in the lower part of the figure, and the measured sediment-transport rates are shown in the upper part. It is apparent that the values of observed slope show the greatest deviations from the mean and that the values of the water discharge deviate the least from the mean. The sediment-transport rate apparently was more uniform for the feed system than for the recirculation system. However, the sampling times were longer for the feed system than for the recircula-

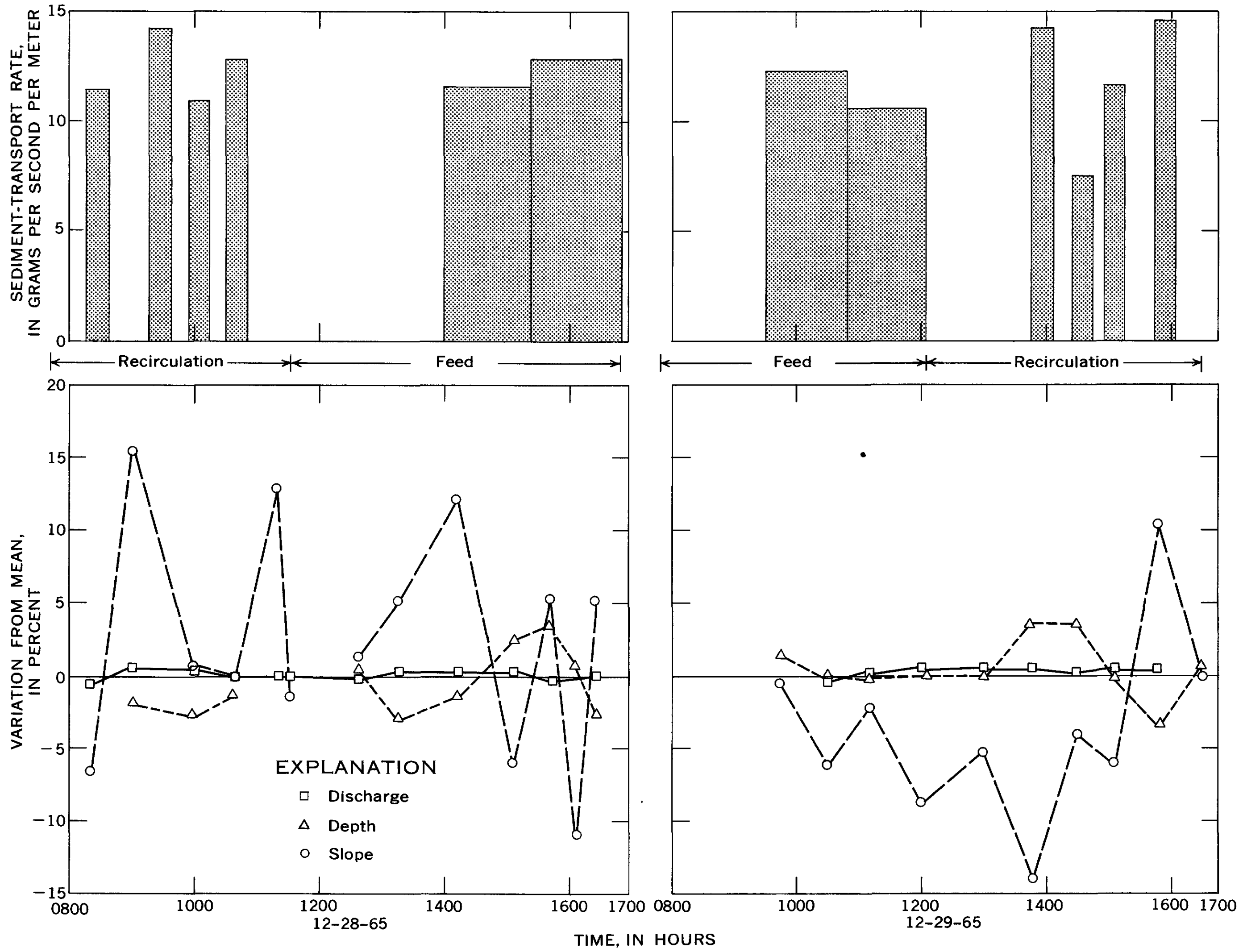

Figure 3.—Variation with time of sediment-transport rate, water-surface slope, mean depth of flow, and water discharge in run 6.

tion system, and there was a greater tendency for the oscillations in the sediment-transport rate to be averaged for the feed system.

After the collection of sufficient data to define the equilibrium conditions for the recirculation system, the change to the feed system was made. The water discharge and sediment-feed rate were set equal to the mean equilibrium values of the water discharge and sediment-transport rate for the recirculation system. Measurements of the water discharge, depth of flow, water-surface slope, sediment-transport rate, water temperature, and sediment-feed rate were continued until sufficient data were obtained to define the equilibrium conditions for the feed system. These measurements were begun as soon as the change to the feed system was completed so that measurements would be obtained during the transition to the new equilibrium conditions if the change to the feed system resulted in new hydraulic and sediment-transport conditions.

After the completion of the feed system part of the experiment, the usual procedure was to revert to the recirculation system and to continue the hydraulic and sediment-transport measurements. The purpose of this procedure was to permit a comparison of the sediment-transport rate under conditions where the sediment-transport rate was an independent or controlled variable before the change and a dependent variable after the change. The measurements were begun as soon as the change in the method of operation was completed, and the measurements were continued until sufficient data were obtained to define the equilibrium conditions for the recirculation system.

The second part of this study was to determine the responses of the laboratory flume systems to changes that caused nonequilibrium conditions, with the water discharge maintained at a constant value. The runs consisted in general of three parts: (1) establishment of equilibrium conditions; (2) imposition of a change, resulting in nonequilibrium conditions; and (3) reestablishment of equilibrium. The change imposed upon the system consisted of either increasing or decreasing the sand-bed slope by raising or lowering the upper end of the flume, either increasing or decreasing the tail-water depth at the downstream end of the flume by adjusting the tailgate, or increasing or decreasing the amount of sediment transported by changing the sediment-feed rate for the feed system and by adding sediment to the recirculating system or extracting a portion of the recirculating sediment. These changes were imposed upon both the feed and recirculation systems in a total of 12 experimental runs. The runs were completed in a sequence such that a run that resulted in increased values of the water-surface slope and sediment-transport rate was followed by a run that was expected to yield decreased values of the water-surface slope and sediment-transport rate. The equilibrium conditions established at the conclusion of one run served as the initial equilibrium conditions for the next run.

Numerous measurements of the water discharge, water-surface slope, depth of flow, sediment-transport rate, and water temperature were made for both the nonequilibrium conditions and the equilibrium conditions. The sediment-feed rate was also checked periodically in the feed system runs. During the initial stages of each run when the nonequilibrium conditions prevailed, measurements of the variables were completed as rapidly as possible. It required about 1 minute to read and record the readings of the 11 piezometers used to determine the water-surface slope, the reading of the manometer used to determine the water discharge, and the reading of the thermometer used to determine the water temperature. The depth of flow was determined from 18 measurements of the water-surface elevation and 18 measurements of the sand-bed elevation at 0.5-meter intervals along the flume centerline. The initial 2-meter section of the flume was affected by entrance conditions and was not considered in the determination of the depth of flow. The measurement of the depth of flow required about 9 minutes. For feed-system runs, the determination of the sediment-feed rate required about 2 minutes. Thus, a complete set of measurements of the variables could be obtained in about 10 minutes for recirculation-system runs and in about 12 minutes for the feed-system runs. The sediment-transport rate determinations in the recirculation-system runs were made concurrently with the other measurements. In the feed-system runs, all the sediment transported from the end of the flume was collected continuously (divided into discrete increments of time), and the sediment volumes and the corresponding sediment-transport rates were determined after the completion of a run.

The magnitudes of the changes imposed upon the systems during these experimental runs and the durations of the runs were such that significant changes occurred in the sediment-transport rate, the water-surface slope, and the depth of flow. Significant changes generally did not occur in the resistance to flow as represented by the Darcy-Weisbach resistance coefficient. The water-discharge used in runs 12 and 13 was about 10 percent larger than the approximately constant water discharge used in runs 14–23.

COMPARISON OF THE FEED AND RECIRCULATION SYSTEMS

In the first part of this study, the feed and recirculation systems were compared under equilibrium conditions in 11 experimental runs that covered a wide range of flow conditions with bed forms ranging from ripples to antidunes. The mean values of the measured variables at equilibrium flow conditions and the parameters computed from the measured variables are given in table 1. The variations of the variables about their mean values were essentially the same for the two systems. Comparison of the measured variables and the calculated parameters is as follows.

SEDIMENT-TRANSPORT RATE

The sediment-transport rate should be one of the more sensitive indicators of any possible differences between the feed and recirculation systems. In the procedure employed in runs 1–11, the mean equilibrium sediment-transport rate for the recirculation system was used as the sediment-feed rate when the change from the recirculation system to the feed system was made. If differences between the two systems had existed, the equilibrium conditions established in the recirculation part of the run would have been disturbed, and different values of the water-surface slope, depth of flow, and bed roughness would have resulted. Because the sediment-feed rate was fixed, and, hence, the sediment-transport rate, a new permanent equilibrium condition could not be established. Differences between the two flume systems would have been reflected in changing conditions and an inability to establish equilibrium. Changing conditions were not observed in any of the 11 runs, and the equilibrium conditions of the recirculation system did not change within the limits of experimental variation or error when the change to the feed system was made. Figure 4 is a comparison of the unit sediment-transport

TABLE 1.—*Summary of experimental data for runs 1–11*

Run number	Operational system	Discharge (l/sec/m)	Mean depth (cm)	Mean velocity (cm/sec)	Water-surface slope × 10^3 (m/m)	Temperature (° C)	Sediment transport	
							Rate (g/sec/m)	Concentration (mg/l)
1	Recirculation	30.4	5.97	50.9	4.13	19.8	26.9	885
	Feed	30.2	6.10	49.6	3.90	21.1	24.2	798
2	Recirculation	37.5	7.42	50.5	3.22	20.4	20.6	550
	Feed	37.4	7.71	48.6	3.50	20.8	16.7	446
3	Recirculation	22.4	4.50	50.0	5.28	20.7	19.8	875
	Feed	22.7	4.70	48.4	4.67	20.5	28.8	1,270
	Recirculation	22.2	4.42	50.2	4.87	21.0	20.6	925
4	Recirculation	32.8	5.32	61.4	6.08	20.4	55.0	1,680
	Feed	32.6	5.50	59.4	5.51	21.1	50.0	1,540
	Recirculation	32.5	5.14	63.2	5.90	21.5	52.9	1,630
5	Recirculation	24.6	5.63	43.8	3.06	24.3	13.0	529
	Feed	24.7	5.72	43.2	3.30	24.7	15.7	637
	Recirculation	24.6	5.83	42.2	2.92	25.0	11.7	474
6	Recirculation	37.0	8.41	44.2	2.40	25.2	12.4	335
	Feed	37.0	8.59	43.1	2.31	25.1	11.8	318
	Recirculation	37.2	8.63	43.0	2.25	25.4	11.9	320
7	Recirculation	19.7	6.05	32.6	2.12	24.6	2.74	139
	Feed	19.7	6.12	32.1	2.06	23.9	2.73	139
8	Recirculation	14.9	4.70	31.7	2.74	24.2	2.71	182
	Feed	14.9	4.74	31.5	2.74	23.9	3.28	220
	Recirculation	15.0	4.84	31.0	2.83	24.1	3.08	234
9	Recirculation	25.2	3.99	62.8	7.83	21.0	69.0	2,750
	Feed	24.9	4.14	60.4	7.78	21.2	84.2	3,380
	Recirculation	24.9	4.00	62.4	7.82	21.0	65.2	2,610
10	Recirculation	17.5	4.59	38.2	3.24	24.0	8.59	490
	Feed	17.6	4.59	38.4	3.19	24.0	8.59	488
	Recirculation	17.5	4.60	38.1	3.20	24.0	9.00	514
11	Recirculation	29.4	3.87	76.1	8.96	24.0	146	4,960
	Feed	28.6	3.80	75.4	8.78	24.0	140	4,890
	Recirculation	27.8	3.70	75.2	9.40	24.0	145	5,210

rate for the recirculation system with the unit sediment-transport rate for the feed system when a change is made from the recirculation system to the feed system. The mean sediment-transport rates for each run fall on both sides of, but near, the line of perfect agreement. The size of the rectangle about each point represents the confidence limits at the 95 percent level of significance of the mean values used to establish the point.

In eight of the 11 runs (runs 1, 2, and 7 are the exceptions), a change was made from the feed system to the recirculation system with only the water discharge held constant. Under these conditions, the sediment-transport rate changed from an independent variable to a dependent variable, and the water-surface slope, depth of flow, bed roughness, and sediment-transport rate were free to change if differences existed between the feed and recirculation systems. Figure 5 is a comparison of the unit sediment-transport rate for the recirculation system with the unit sediment-transport rate for the feed system when a change is made from the feed system to the recirculation system. The mean sediment-transport rates for each run fall on both sides of, but near, the line of perfect agreement. It can be concluded on the basis of the results presented in figure 5 that no significant differences at the 95 percent level of significance exist between the sediment-transport rate for the recirculation system and the sediment-transport rate for the feed system.

WATER-SURFACE SLOPE

The results of the comparison of the mean values of the water-surface slope for the recirculation and feed systems are shown in figure 6. Values of the water-surface slope for runs 1, 3, 4, and 11 were slightly larger for the recirculation system than for the feed system and values of the water-surface slope for runs 2 and 5 were smaller for the recirculation system than for the feed system. The differences in water-surface slopes were not significant at the 95 percent level of significance.

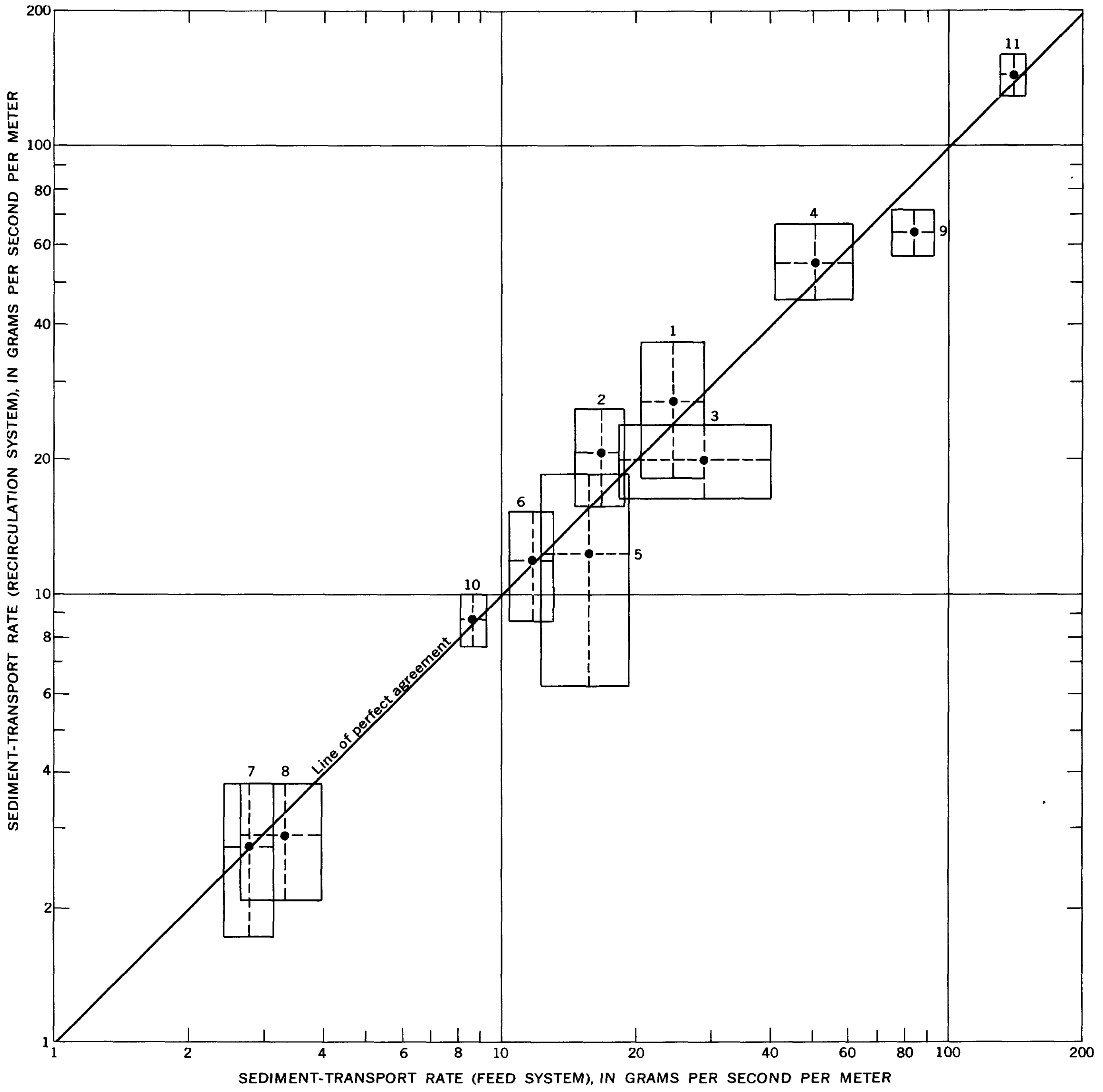

FIGURE 4.—Comparison of the unit sediment-transport rate when a change is made from the recirculation system to the feed system, runs 1–11.

DEPTH OF FLOW

The results of the comparison of the mean values of the depth of flow for the recirculation and feed systems are shown in figure 7. Mean depth of flow values were in general slightly smaller for the recirculation system than for the feed system. The differences in depths of flow were not significant at the 95 percent level of significance.

VELOCITY

The mean velocity was computed from the equation of continuity, equation 3. Because the water discharge was controlled within very narrow limits, the flume width was constant, and the depths of flow were, in general, slightly smaller for the recirculation system than for the feed system, the mean velocities were slightly larger for the recirculation system than for the feed

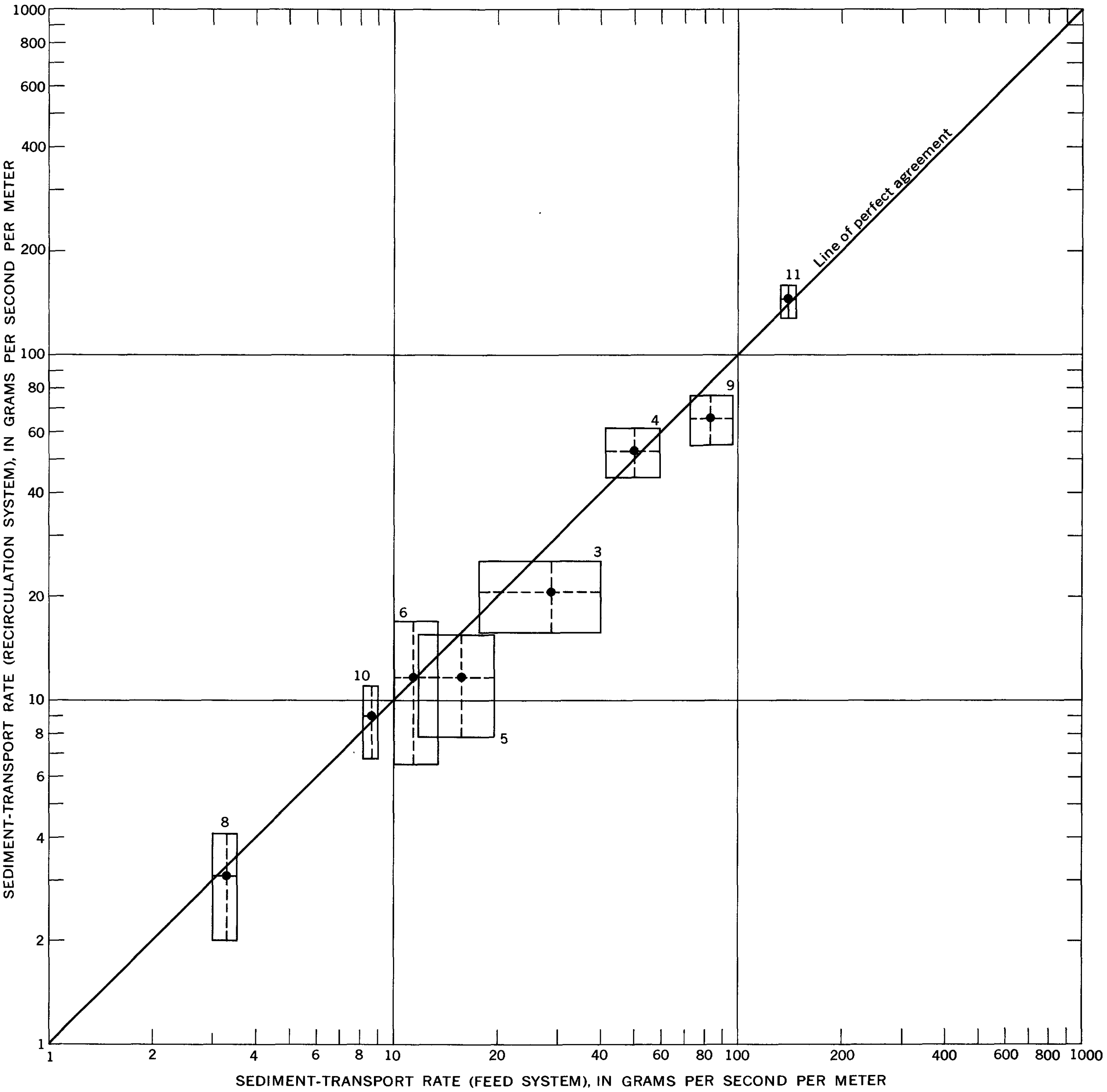

FIGURE 5.—Comparison of the unit sediment-transport rate when a change is made from the feed system to the recirculation system, runs 3–6 and 8–11.

system, as figure 8 shows. The differences in mean velocities were not significant at the 95 percent level of significance.

Agreement between derived parameters, such as the Darcy-Weisbach friction factor, as defined by equation 5, and the stream power (γDSV) was found for the two systems. Agreement was expected because of the agreement between water-surface slope, depth of flow, and mean velocity values for the two systems. On the basis of these results and the results shown in figures 5–8, we conclude that no significant differences at the 95 percent level of significance exist between the equilibrium values of the sediment-transport rate, water-surface slope, depth of flow, mean velocity, Darcy-Weisbach resistance coefficient, and stream power for the recirculation system and for the feed system.

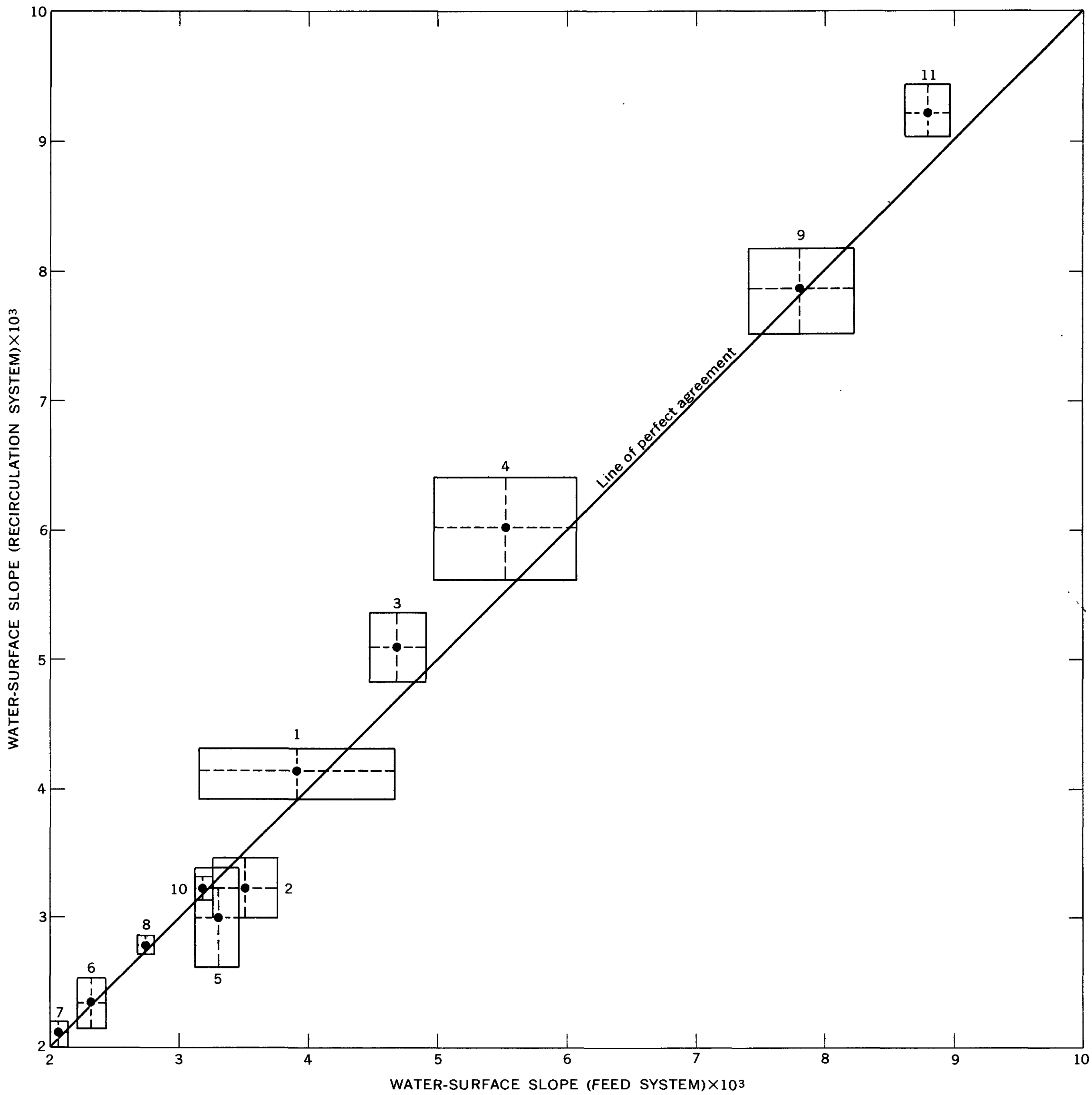

FIGURE 6.—Comparison of the water-surface slope for the recirculation and feed systems, runs 1–11.

RESPONSES OF THE FLUME TO CHANGES OF THE HYDRAULIC AND SEDIMENT-TRANSPORT VARIABLES

The second part of this study consisted of determining the responses of the feed and recirculation systems of flume operation to three types of changes that caused nonequilibrium hydraulic and sediment-transport conditions in the flume. A series of 12 experimental runs (runs 12–23) was completed, and the qualitative results of these runs are given in table 2. A summary of the equilibrium values of the variables for each run is given in table 3. The bed forms for these runs were transition (Task Committee on Bed Forms in Alluvial Channels, 1966), and the Froude number ($\mathbf{F}=V/(gD)^{0.5}$) ranged from 0.58 to 0.86. The unit sediment-transport rate q_s,

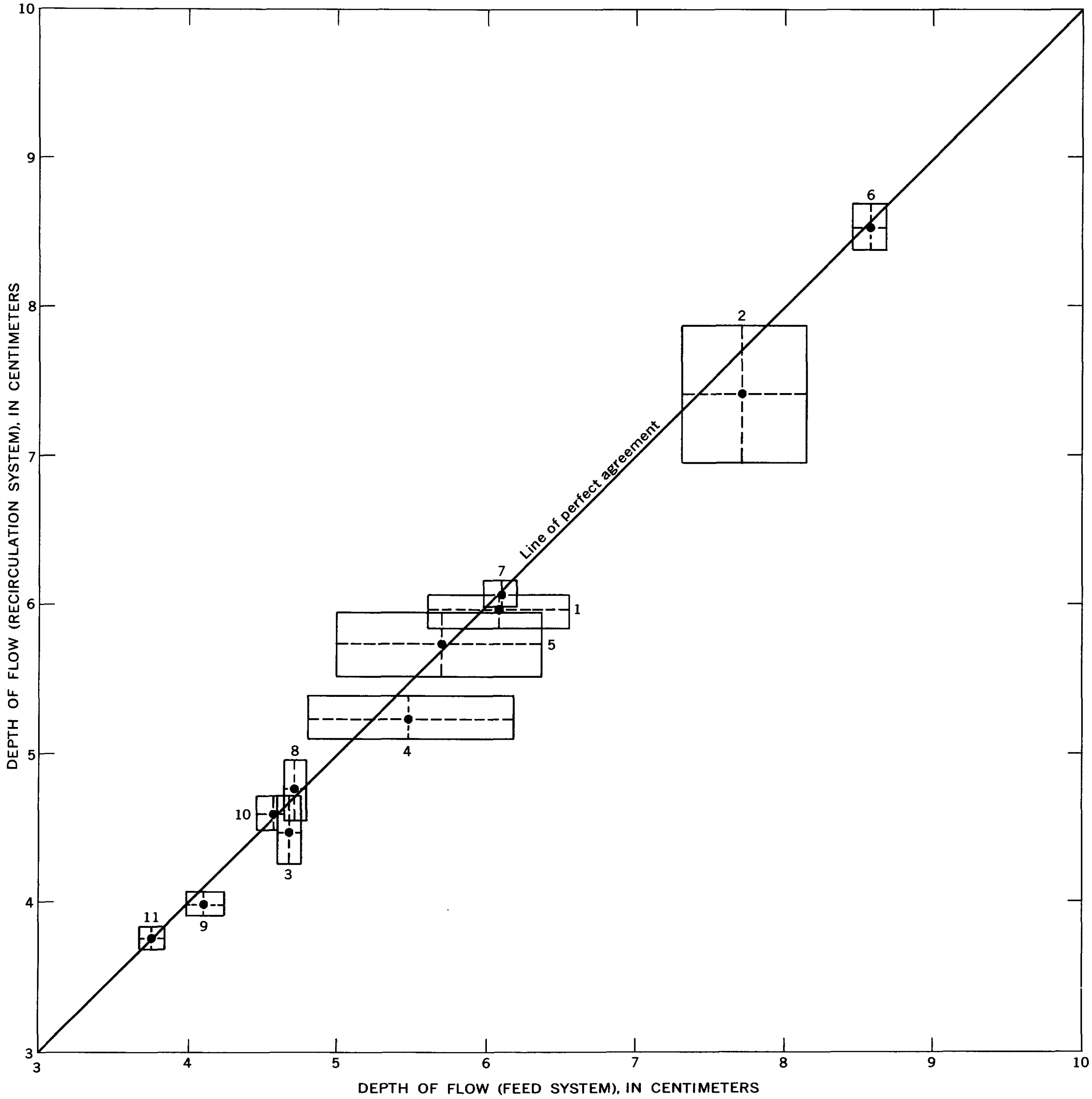

FIGURE 7.—Comparison of the mean depth of flow for the recirculation and feed systems, runs 1–11.

ranged from 13.2 to 53.7 grams per second per meter and were in the middle of the range of unit sediment-transport rates for runs 1–11.

Numerous measurements of the different variables were obtained during the periods of nonequilibrium conditions as well as during the periods of equilibrium conditions. Results from these experiments are shown in a figure for each run (figs. 9–20 for runs 12–23, respectively). The following comments are applicable to these figures:

1. The rate of sediment transport from the end of the flume is represented by the use of block diagrams.

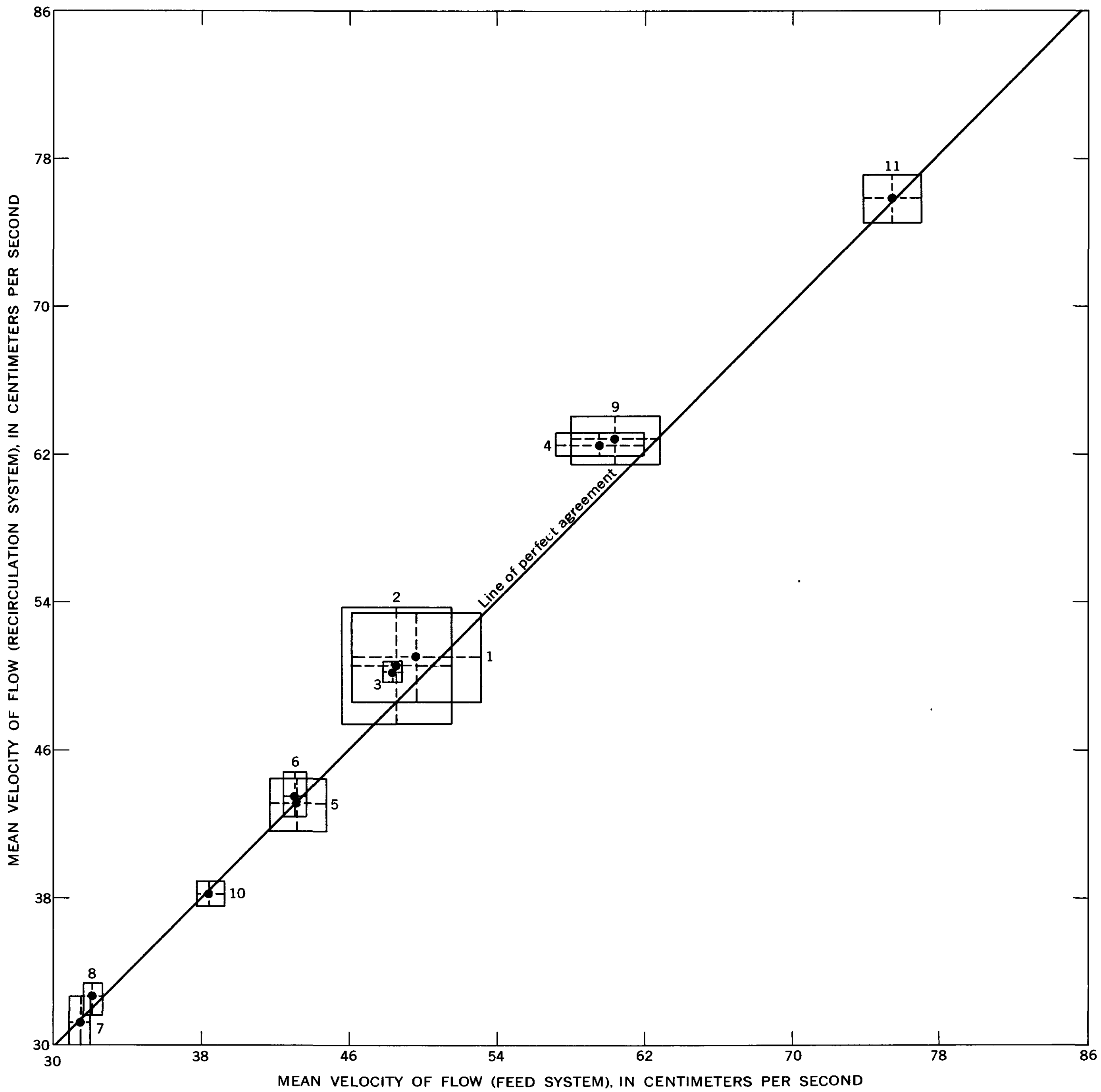

FIGURE 8.—Comparison of the mean velocity of flow for the recirculation and feed systems, runs 1–11.

With the feed system, a continuous record (divided into discrete increments) of the sediment-transport rate was obtained.

2. The triangles represent measurements of the sediment-feed rate for the feed system.
3. The horizontal lines and the numbers near the ordinate scale represent the variable values for the equilibrium that existed prior to the change imposed upon the system.
4. During nonequilibrium and equilibrium conditions, the depth of flow values are the average of 18 observations at 0.5-meter intervals over the section of the flume from station 2.5 to station 11. During nonequilibrium conditions, local depth differences

TABLE 2.—*Comparison of the responses of the feed and recirculation systems to changes of sand-bed slope, tail-water depth, and sediment-transport rate when water discharge is constant*

Method of operation and run	Variable changed	Response				
		Water-surface slope	Depth of flow	Sediment-transport rate	Rate of approach to equilibrium conditions	Equilibrium conditions
Recirculation, run 18.	Slope increased by raising upstream end of flume.	Increased	Decreased	Increased	Rapid	New.
Recirculation, run 15.	Slope decreased by lowering upstream end of flume.	Decreased	Increased	Decreased	do	Do.
Feed, run 12b	Slope increased by raising upstream end of flume.	Slope was initially steeper and then returned to value existing before flume was raised.	Depth was initially shallower and then returned to value existing before flume was raised.	Sediment-transport was initially larger and then returned to value existing before flume was raised.	Slow	Original.
Feed, run 13	Slope decreased by lowering upstream end of flume.	Slope was initially flatter and then returned to value existing before flume was lowered.	Depth was initially deeper and then returned to value existing before flume was lowered.	Sediment-transport rate was initially smaller and then returned to value existing before flume was lowered.	do	Do.
Recirculation, run 17b	Sediment-transport rate increased by adding sand with feeder to recirculating system.	Slope increased as long as sediment was added.	Depth decreased as long as sediment was added.	Sediment-transport rate increased as long as sediment was added.	Slow	Changing.
Recirculation, run 19.	Sediment-transport rate decreased by extracting a portion of the recirculating sediment.	Slope decreased as long as sediment was extracted.	Depth increased as long as sediment was extracted.	Extracted part of sediment-transport rate decreased, total sediment-transport rate decreased as long as sediment was extracted.	do	Do.
Feed, run 14b	Sediment-transport rate increased by increasing sediment-feed rate.	Slope increased until sediment-transport rate equaled sediment-feed rate.	Depth decreased until sediment-transport rate equaled sediment-feed rate.	Sediment-transport rate increased until it equaled sediment-feed rate.	do	New.
Feed, run 16	Sediment-transport rate decreased by decreasing sediment-feed rate.	Slope decreased until sediment-transport rate equaled sediment-feed rate.	Depth increased until sediment-transport rate equaled sediment-feed rate.	Sediment-transport rate decreased until it equaled sediment-feed rate.	do	Do.
Recirculation, run 22.	Tail-water depth increased by adjusting tailgate.	Decreased	Increased	Decreased	Rapid	New.
Recirculation, run 21.	Tail-water depth decreased by adjusting tailgate.	Increased	Decreased	Increased	do	Do.
Feed, run 20	Tail-water depth increased by adjusting tailgate.	Slope was initially flatter and then returned to value existing before depth was changed.	Depth was initially deeper and then returned to value existing before depth was increased.	Sediment-transport rate was initially smaller and then increased until it equaled sediment-feed rate.	Slow	Original.
Feed, run 23	Tail-water depth decreased by adjusting tailgate.	Slope was initially steeper and then returned to value existing before depth was decreased.	Depth was initially shallower and then returned to value existing before depth was increased.	Sediment-transport rate was initially larger and then decreased until it equaled sediment-feed rate.	do	Do.

TABLE 3.—*Summary of experimental data for runs 12–23*

Run	Change imposed on system	Operational system	Discharge (l/sec/m)	Mean depth (cm)	Water-surface slope × 10^3 (m/m)	Flume-bed slope × 10^3 (m/m)	Temperature (° C)	Sediment transport	
								Rate (g/sec/m)	Concentration (mg/l)
12a		Recirculation	24.5	5.64	3.10	3.09	24.0	13.2	539
12b	Increase flume slope	Feed	24.7	5.40	3.15	4.72	23.8	13.4	544
13	Decrease flume slope	do	24.5	5.56	3.16	3.12	24.9	13.2	539
14a		Recirculation	22.4	4.55	4.62	4.76	24.0	28.0	1,250
14b	Increase feed rate	Feed	22.2	4.31	5.91	4.76	24.0	39.5	1,780
15	Decrease flume slope	Recirculation	22.4	4.62	4.84	3.53	24.4	29.1	1,300
16	Decrease feed rate	Feed	22.3	5.00	3.67	3.53	24.6	15.2	681
17a		Recirculation	22.4	5.01	3.64	3.73	24.7	17.0	760
17b	Add sediment	do	22.3	4.60	4.95	3.73	25.2	32.1	1,440
18	Increase flume slope	do	22.2	4.28	5.97	4.72	24.5	44.2	2,000
19	Extract sediment	do	22.3	4.62	4.67	4.72	24.6	27.1	1,210
20	Increase depth	Feed	22.2	4.50	4.84	4.72	25.6	28.1	1,260
21	Decrease depth	Recirculation	22.2	4.06	6.64	4.72	24.2	53.7	2,420
22	Increase depth	do	22.4	4.58	4.78	4.72	24.1	29.0	1,300
23	Decrease depth	Feed	22.3	4.45	4.85	4.72	24.0	28.6	1,280

(in the upstream or downstream flume section most affected by the change) were greater than differences shown by the data in the figures.

5. During nonequilibrium conditions, an abrupt change or break in the water-surface slope sometimes occurred during the initial stages of a run. This break occurred either in the upstream or downstream section of the flume, the location depending on the type of change imposed on the system. When a break was observed, the water-surface slope calculation was based on the longer of the two sections. The shorter section was usually 2–3 meters

in length. Initial slope differences, therefore, were greater than the differences shown by the data in figures 9–20.

6. For equilibrium conditions, water-surface-slope values were determined from the water-surface elevations measured by the 10 piezometer taps between stations 2–11.
7. The determination of when equilibrium had been established was based on the manner in which the depth of flow, water-surface slope, and sediment-transport rate varied with time. In the feed system, the agreement of the sediment-transport rate with the sediment-feed rate was also a necessary criterion for equilibrium.

Runs 12–23 are discussed in detail in the following paragraphs. The water discharge was a constant or independent variable and the water-surface slope, depth of flow, and the bed roughness were dependent variables in all the runs. The sediment-transport rate was an independent variable in the feed system runs and in two of the recirculation system runs (17b and 19) and was a dependent variable in the other four recirculation system runs.

Run 12 (*increase slope, feed system*).—In run 12b, after establishment of equilibrium conditions with the recirculation system in run 12a, the sand-bed slope was increased about 50 percent by raising the upper end of the flume, and the feed system was used with a sediment-feed rate equal to the mean equilibrium value of the sediment-transport rate for run 12a. Figure 9 shows graphically the variation with time of the several variables during run 12b. The increase in sand-bed slope caused degradation of the sand bed in the upstream section of the flume; the degradation resulted in a flattening slope and a gradual approach to the final equilibrium value of the water-surface slope. The initial sediment-transport rate was larger and the initial mean depth of flow was shallower than the final equilibrium values of these variables. The final equilibrium values of the water-surface slope, depth of flow, and sediment-transport rate, however, were within 4.3 percent of the equilibrium values of these variables that existed before the change in sand-bed slope. The maximum difference between initial and final equilibrium values was for the depth of flow. About 6 hours was required to achieve equilibrium after the change in slope.

Run 13 (*decrease slope, feed system*).—In run 13 the sand-bed slope was decreased about 50 percent by lowering the upper end of the flume, and the feed system was used with the same water discharge and the same sediment-feed rate as in run 12b. Figure 10 shows graphically the variation with time of the several variables during run 13. The decrease in sand-bed slope resulted in aggradation in the upstream section of the flume, and the sediment-transport rate was less than the sediment-feed rate. The initial depth of flow was deeper than the final equilibrium value. As the sand bed aggraded in the upstream section of the flume, the water-surface slope increased, the depth of flow decreased, and the sediment-transport rate increased until equilibrium conditions were established. The final equilibrium values of the water-surface slope, depth of flow, and sediment-transport rate were within 3.0 percent of the equilibrium values of these variables that existed before the change in sand-bed slope. About 8.2 hours was required to achieve equilibrium after the change in slope.

Run 14 (*increase sediment-feed rate, feed system*).—In run 14b, after establishment of equilibrium conditions with the recirculation system in run 14a, the sediment-feed rate was set at a value 1.35 times the mean equilibrum value of the sediment-transport rate for run 14a. Figure 11 shows graphically the results of run 14b. The increased sediment-feed rate caused aggradation in the upstream section of the flume; the aggradation caused the slope to increase gradually, the mean depth of flow to decrease, and the sediment-transport rate to increase. The process of increasing slope, decreasing depth, and increasing sediment-transport rate contin-

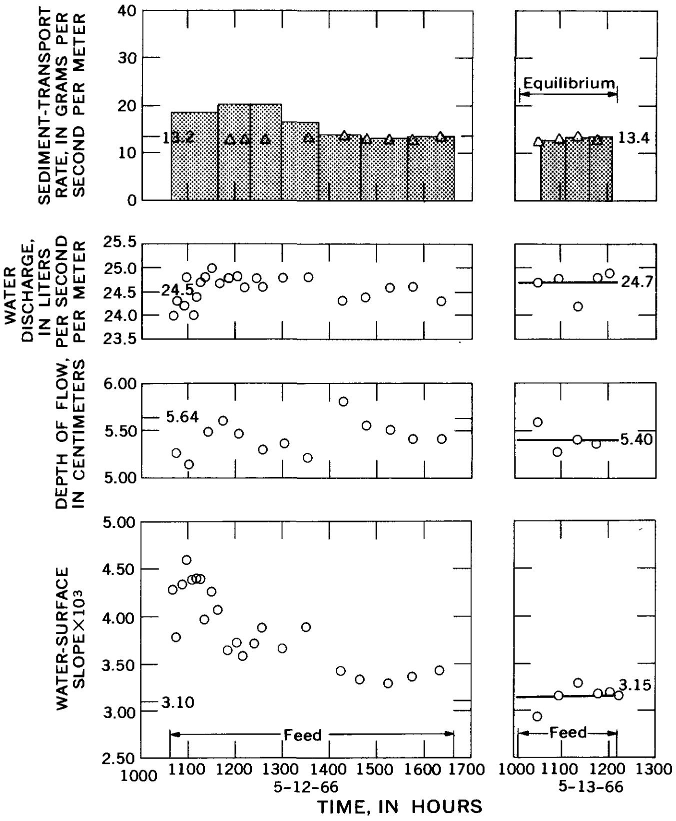

FIGURE 9.—Response of the feed system to an increase in sand-bed slope, run 12b.

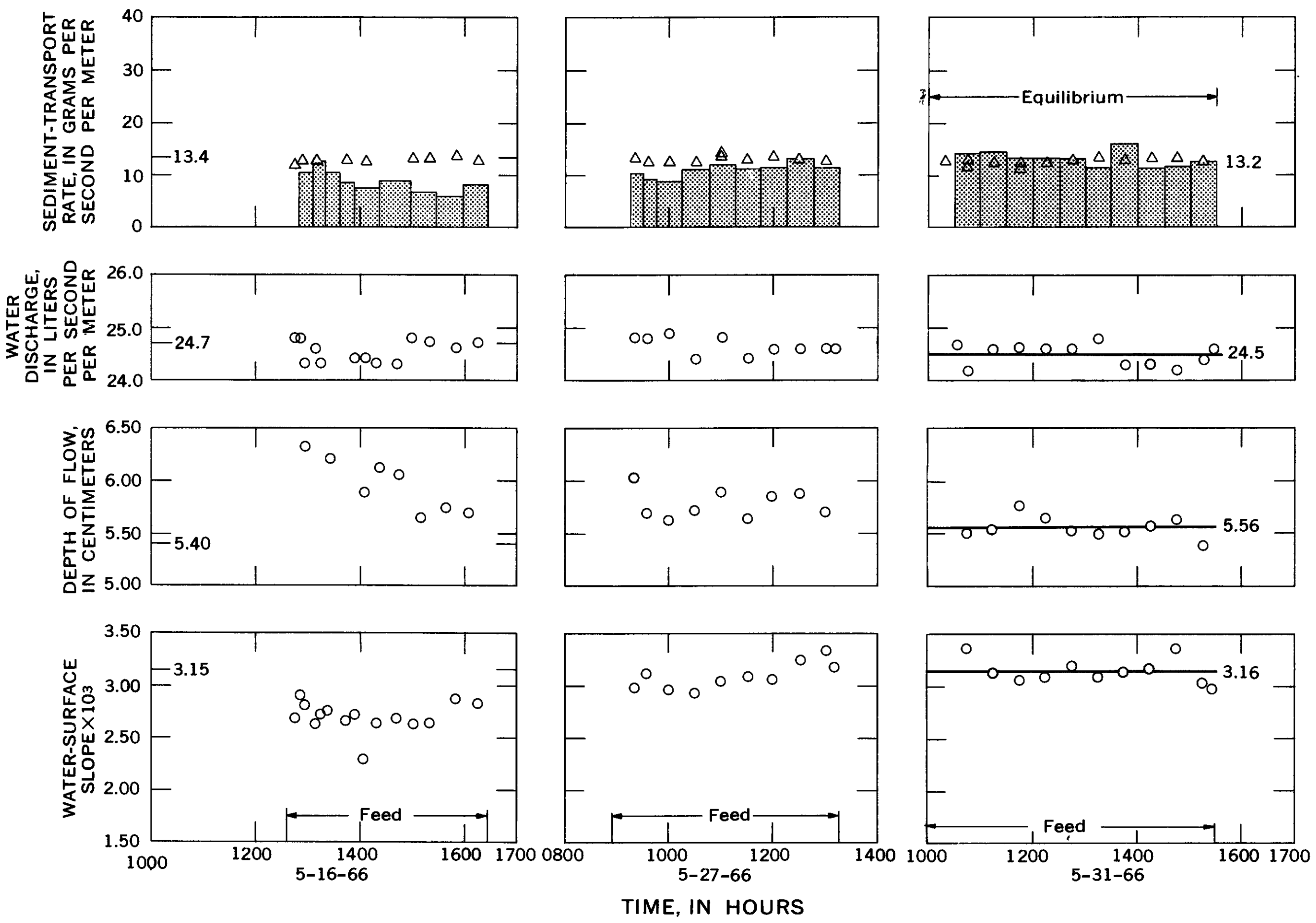

Figure 10.—Response of the feed system to a decrease in sand-bed slope, run 18.

ued until the sediment-transport rate approximately equaled the sediment-feed rate at which time the slope and depth had also attained approximately constant values. The fluctuations of the variable values about the mean equilibrium values, which are indicated by the solid lines and the numbers near the right ordinate in figure 11, should be noted. Equilibrium was reached in about 7.5 hours after the increase in sediment-feed rate. The water-surface slope was 28 percent larger, the depth of flow was 5.3 percent less, and the mean bed-surface elevation was 0.42 cm higher than the equilibrium values of these variables that existed before the increase in sediment-feed rate.

Run 15 (decrease slope, recirculation system).—In run 15 the sand-bed slope was reduced about 26 percent (from 0.00476 to 0.00353 m per m) by lowering the upper end of the flume. The recirculation system was used, and new equilibrium conditions were established almost immediately. The rapid response of the recirculation system to the decrease in flume slope is shown by the data presented in figure 12. The water-surface slope was 18 percent less, the depth of flow was 7.2 percent larger, and the sediment-transport rate was 26 percent less than the equilibrium values of these variables that existed before the decrease in sand-bed slope.

Run 16 (decrease sediment-feed rate, feed system).—In run 16 the sediment-feed rate was reduced to about 48 percent of the mean sediment-transport rate for the equilibrium conditions at the end of run 15. Because the sediment-transport capacity of the flume system was larger than the sediment-feed rate, degradation occurred in the upstream section of the flume. The degradation caused the water-surface slope to decrease and the depth of flow to increase. The slope continued to decrease, and the depth increased until the sediment-transport rate had decreased to a rate equal to the sediment-feed rate. The mean sand-bed surface elevation decreased 0.75 cm during the run. The variation with time of the several variables during run 16 is shown in figure 13. Equilibrium was obtained about 9.2 hours after the decrease in sediment-feed rate. The water-surface slope was 24 percent less and the depth of

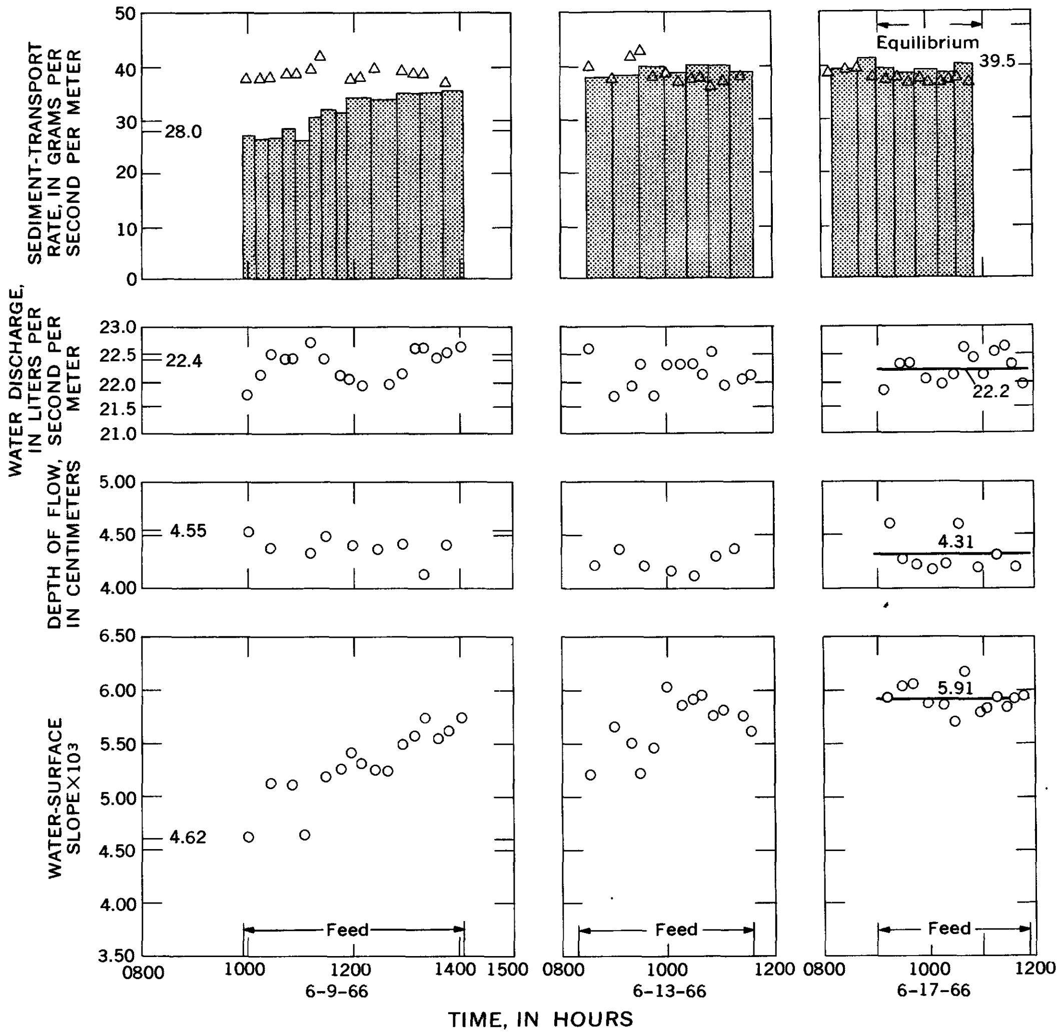

Figure 11.—Response of the feed system to an increase in sediment-feed rate, run 14b.

flow was 7.6 percent larger than the equilibrium values of these variables that existed before the decrease in sediment-feed rate.

Run 17 (increase sediment-transport rate, recirculation system).—Run 17b was made after equilibrium conditions were determined using the recirculation system in run 17a. In run 17b sediment at a rate equal to about 65 percent of the equilibrium sediment-transport rate of run 17a was added continuously to the recirculating system by feeding sediment into the tailbox with the sediment feeder. Because the amount of sediment transported from the downstream end of the flume is usually the input to the upstream end of the flume in a recirculation system, the sediment added to the system resulted in a larger input of sediment at the flume inlet. This sediment input exceeded the sediment-transport capacity of the flume for the given hydraulic conditions and aggradation occurred. The aggradation caused the slope to steepen, the depth of flow to decrease, and the sediment-transport rate to increase. As the sediment-transport rate increased, the sediment input at the flume inlet increased, and the cycle of adjustment of the water-surface slope and depth of flow in response to the increasing sediment-transport rate continued. The result was a flume system of changing hydraulic and sediment-transport conditions, and it was impossible to achieve equilibrium conditions as long as sediment was being added to the system.

The addition of sediment was terminated after 4.25 hours of operation. During the period of adding sediment, the water-surface slope increased 36 percent and the sediment-transport rate increased 89 percent, whereas the depth of flow decreased 8.0 percent with respect to the equilibrium values of these variables that existed at the start of run 17b. Equilibrium conditions were assumed established about 1.7 hours after the ces-

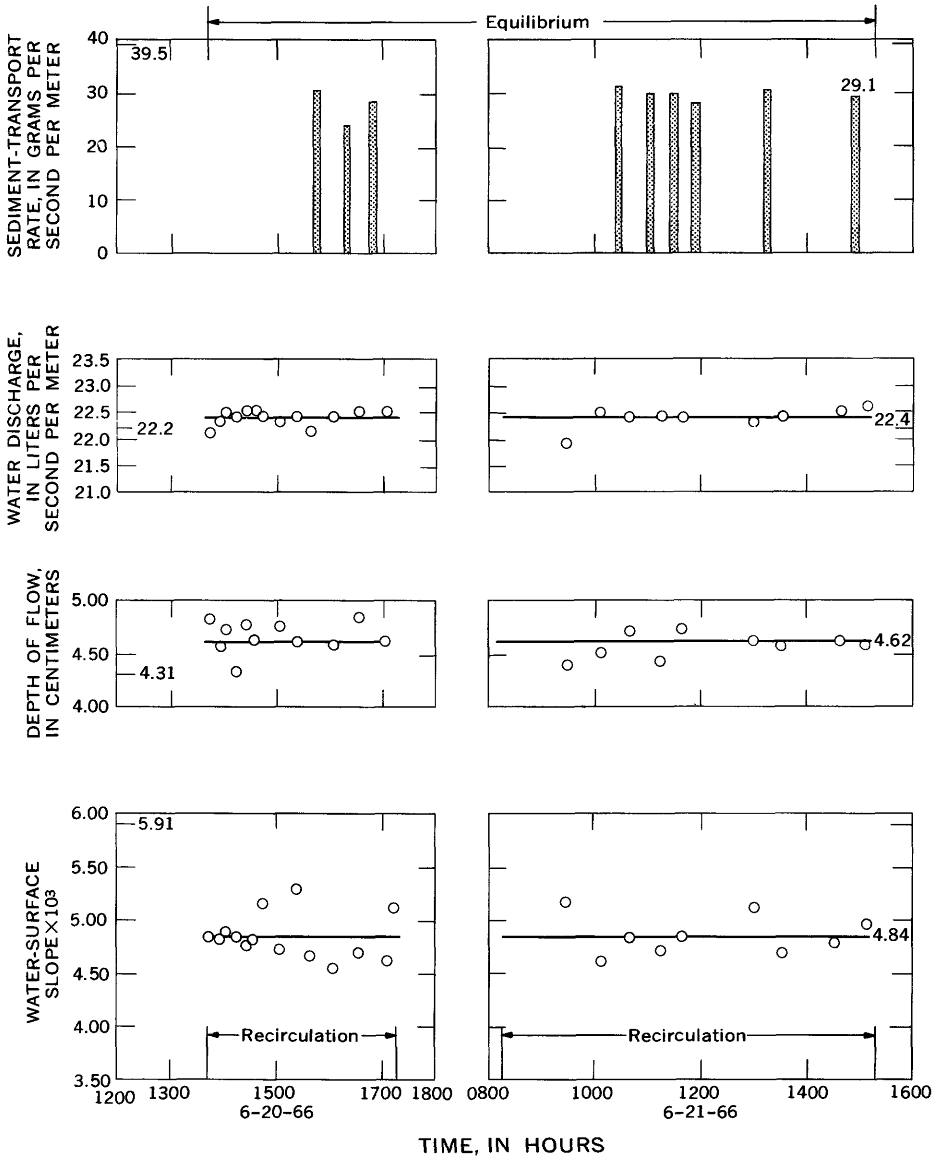

FIGURE 12.—Response of the recirculation system to a decrease in sand-bed slope, run 15.

sation of the addition of the sediment; however, the data indicated that equilibrium was established almost immediately after the addition of sediment was stopped. The variation with time of the several variables in run 17b is shown graphically in figure 14. The mean bed-surface elevation increased 0.81 cm during the run.

It is interesting to speculate on the final condition of the system if the addition of the sediment had been continued. The final condition probably would have been one of large sediment-transport rate with flow in the upper regime; the final condition would have depended on the water discharge.

Run 18 (increase slope, recirculation system).—In run 18 the flume slope was increased about 26 percent (from 0.00373 to 0.00472 m per m) by raising the upper end of the flume. The change for run 18 was the converse of the change for run 15, and, as in run 15, equilibrium conditions were established immediately. The increase in flume slope caused a 21 percent increase in water-surface slope, a 38 percent increase in sediment-transport rate, and a 7 percent decrease in depth of flow with respect to the equilibrium values of these variables that existed before the increase in flume slope. The data from run 18 are shown in figure 15.

Run 19 (decrease sediment-transport rate, recirculation system).—The change for run 19 was the converse

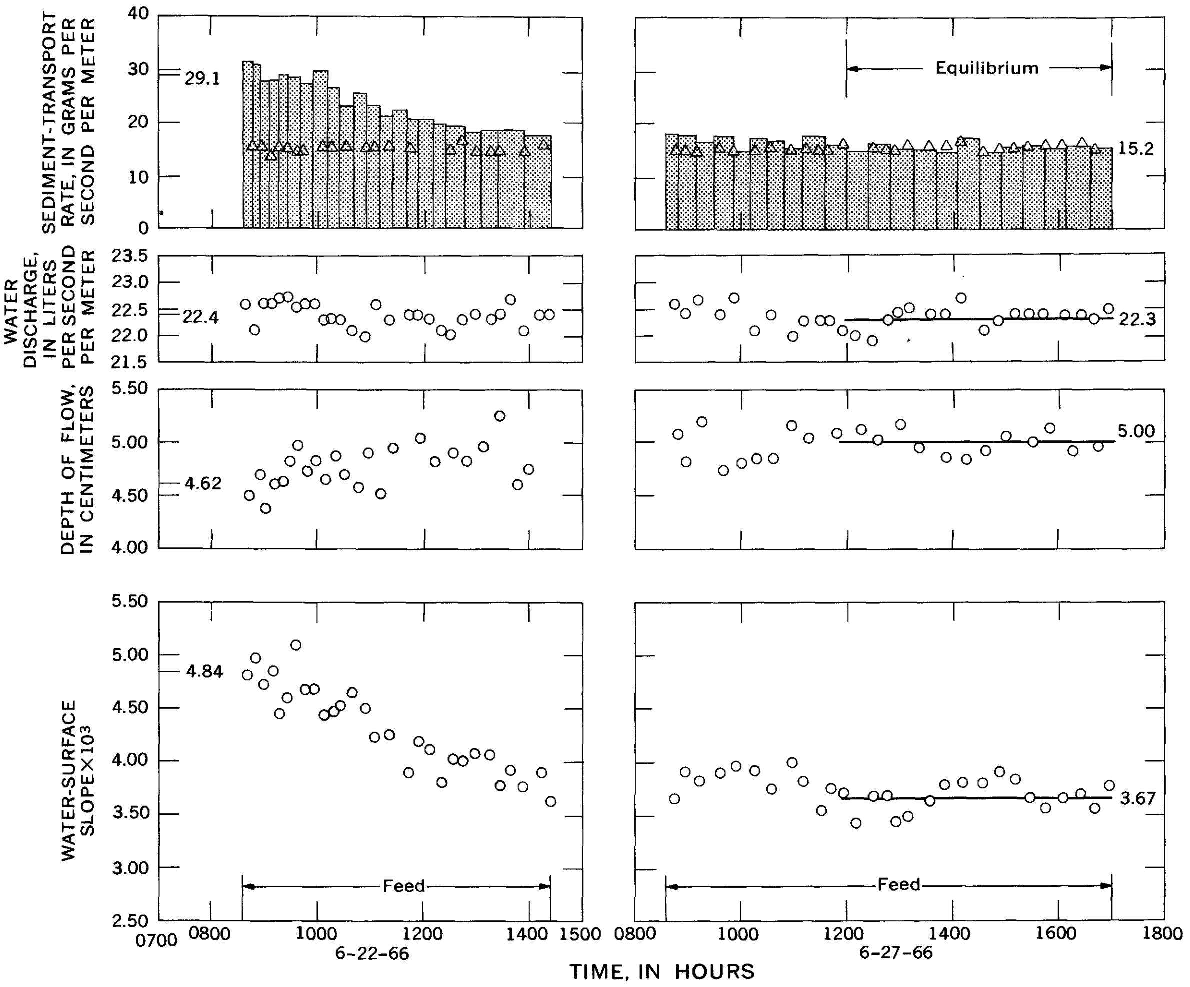

FIGURE 13.—Response of the feed system to a decrease in sediment-feed rate, run 16.

of the change for run 17b. A proportional sediment trap was placed in the tailbox of the flume so that about one-third of the sediment transported from the end of the flume was trapped and removed from the system. Thus the amount of sediment returned to the upstream end of the flume was decreased. Degradation occurred because the sediment input to the flume was less than the sediment-transport capacity of the flume for the given conditions. The degradation caused a decreasing slope, an increasing depth of flow, and a reduced amount of sediment transported. Because about one-third of the sediment transported was removed continuously from the flume system, the input to the flume was reduced continuously also, and the cycle of change and adjustment in the variables was repeated. As in run 17b, equilibrium conditions could not be established. However, when the extraction of sediment was discontinued after 3.7 hours of operation, equilibrium was established almost immediately. The variation with time of the several variables in run 19 is shown graphically in figure 16. The data shown for the sediment-transport rate during nonequilibrium conditions of the system are the rates of extracting sediment, whereas the data shown for the equilibrium conditions of the system are the total sediment-transport rates. During the period of extracting sediment, the water-surface slope decreased 22 percent, the sediment-transport rate decreased 39 percent, and the depth of flow increased 7.9 percent with respect to the equilibrium values of these variables that existed at the time the extraction of sediment was begun. The mean sand-bed elevation decreased 0.79 cm during run 19.

It is interesting to speculate on the final condition of the system if the extraction of sediment had been continued. Rathbun and Guy (1967) found that the mean velocity for cessation of motion on a ripple bed for the sediment used in this study was about 10.4 cm per sec. For the water discharge used in run 19 (22.3 l per sec

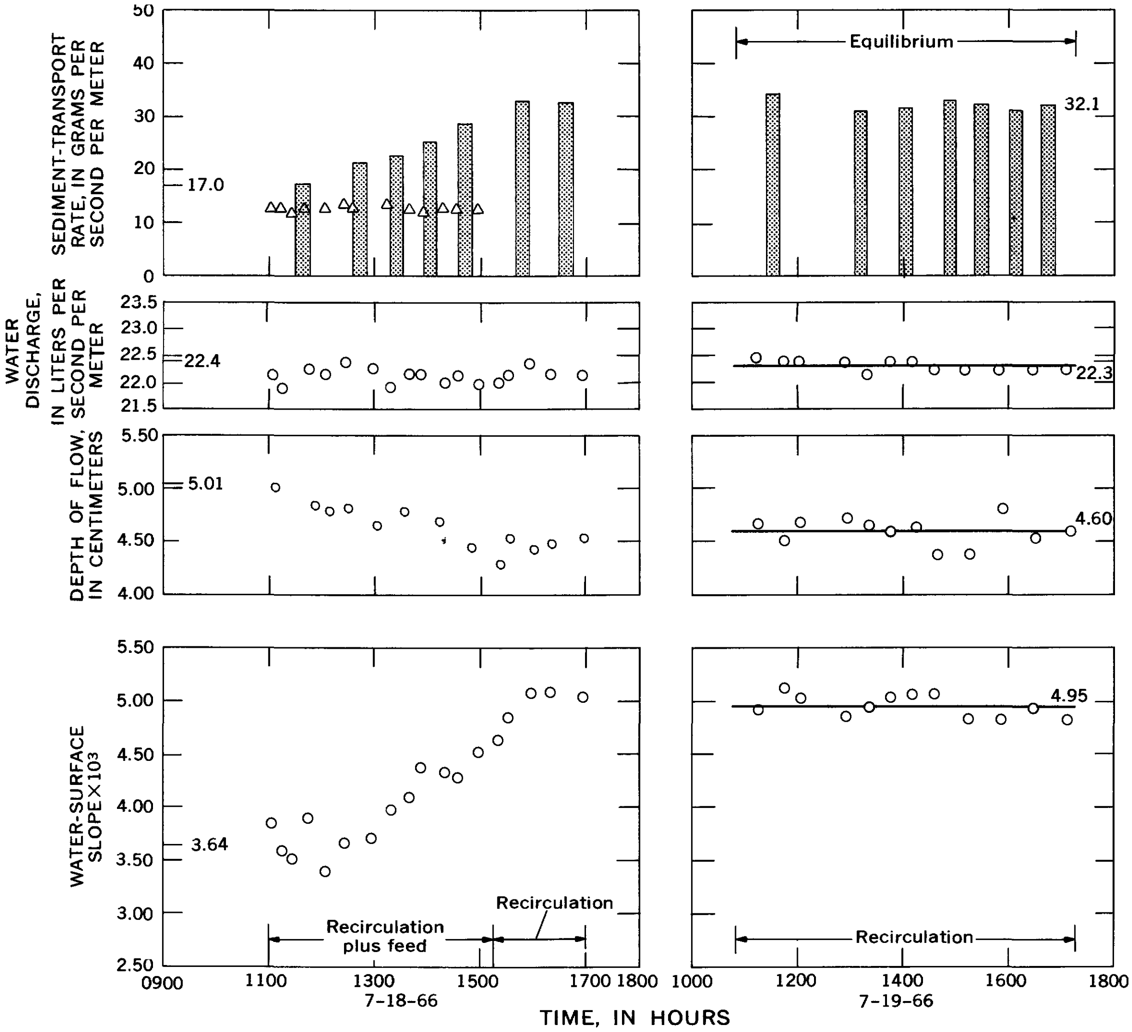

FIGURE 14.—Response of the recirculation system to an increasing sediment-transport rate, run 17b.

per m), this velocity would require a depth of flow of about 21 cm, which is more than the depth capacity of the flume. Thus the final conditions would have been a low sediment-transport rate, a deep depth of flow, and a flat slope. It is assumed that the sediment bed in the flume is thick enough that the bottom of the flume would not be exposed as degradation of the sediment bed occurs. Exposure of the flume bottom would be the more likely limiting condition.

Run 20 (*increase depth, feed system*). In run 20 the tailgate was adjusted to increase the tail-water depth, and the feed system was used. The data are shown in figure 17. As with changes in flume slope for the feed system, the feed system was expected to return to the equilibrium conditions that existed before the change in tail-water depth. The final equilibrium values of the variables were within 3.7 percent of the values of the variables that existed before the change in tail-water depth. The maximum difference was for the sediment-transport rate. About 11.5 hours of operation after the increase in tail-water depth was necessary for the establishment of equilibrium.

Run 21 (*decrease depth, recirculation system*).—In run 21 the tailgate was adjusted to decrease the tail-water depth, and the recirculation system was used. Equilibrium was established in about 0.5 hour. The decrease in tail-water depth caused a 37 percent increase in water-surface slope, a 9.8 percent decrease in depth of flow, and an 85 percent increase in the sediment-transport rate with respect to the equilibrium values that existed before the decrease in tail-water depth. The data for run 21 are shown in figure 18.

Run 22 (*increase depth, recirculation system*).—Run 22 was the converse of run 21. As expected, new equilibrium conditions were developed. Because it was desired to return to approximately the same equilibrium

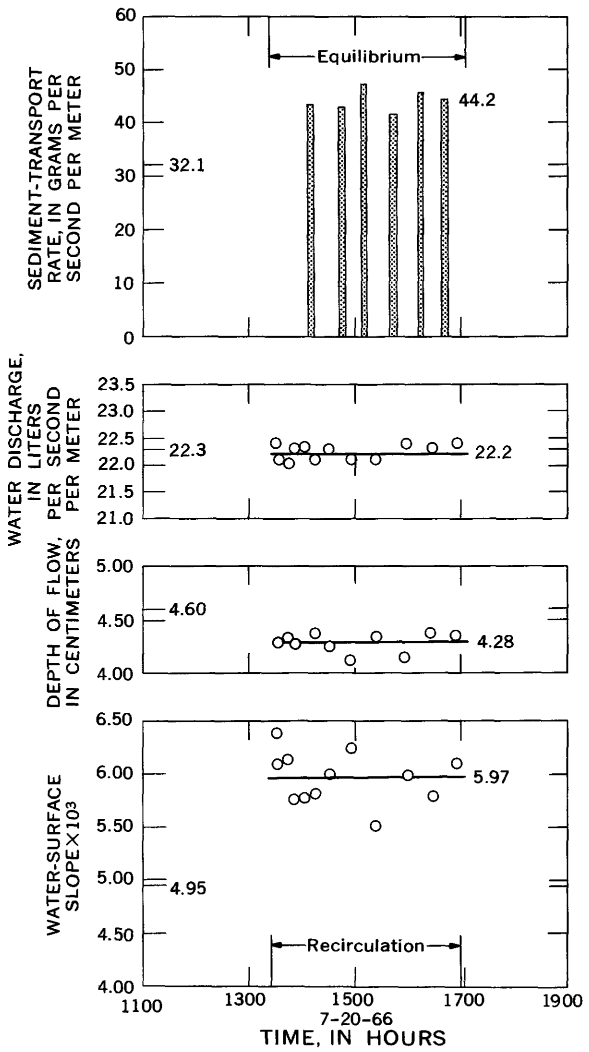

FIGURE 15.—Response of the recirculation system to an increase in sand-bed slope, run 18.

conditions that existed at the start of run 21, one large tailgate adjustment was made initially, and two smaller adjustments were made later. Equilibrium was established after the large adjustment in about 0.75 hour, and equilibrium was established almost immediately after the two smaller adjustments. The data for run 22 are shown in figure 19. The first small adjustment of the tailgate was at 1528 hours on the first day, and the second was at 0806 hours on the second day. The fact that these tailgate adjustments were made are evident from the changes in the sediment-transport rate and in the water-surface slope. The adjustments to the tailgate caused a 28 percent decrease in the water-surface slope, a 12.8 percent increase in the depth of flow, and a 46 percent decrease in the sediment-transport rate with respect to the equilibrium conditions that existed prior to the increase in the tail-water depth.

Run 23 (decrease depth, feed system).—Run 23 is the converse of run 20. The tailgate was adjusted to decrease the tail-water depth, and the feed system was used. This adjustment resulted initially in the rapid degratation in the downstream section of the flume and a very large sediment-transport rate. Figure 20 shows the increased sediment-transport rate, the increased water-surface slope, and the decreased depth of flow that existed in the initial stages of the run. Because the sediment-feed rate was considerably less than the sediment-transport capacity for the conditions in the flume, the initial rapid degradation in the downstream section of the flume changed to degradation in the upstream section of the flume and aggradation in the downstream section. This degradation and aggradation resulted in a decreasing slope, a decreasing sediment-transport rate, and an increasing depth. These variables continued to change until conditions were reached at which the sediment-transport rate equaled the sediment-feed rate. The variation with time of the several variables in run 23 is shown graphically in figure 20. The final equilibrium values of the variables were within 2.8 percent (maximum difference was for the depth of flow) of the equilibrium values of the variables that existed before the adjustment of the tailgate. Because of the degradation during the initial period of the run, the mean bed-surface elevation decreased 0.98 cm.

The results of runs 12–23 are summarized as follows:

1. For the feed system, changes of the sediment-feed rate resulted in new equilibrium values of the water-surface slope, depth of flow, and sediment-transport rate (runs 14b, 16).
2. For the feed system, changes of the sand-bed slope and tail-water depth resulted in the flume system returning to the equilibrium values of the water-surface slope, depth of flow, and sediment-transport rate that existed before the change (runs 12b, 13, 20, 23).
3. For the recirculation system, changes of the sand-bed slope and tail-water depth resulted in new equilibrium values of the water-surface slope, depth of flow, and sediment-transport rate (runs 15, 18, 21, 22).
4. For the recirculation system, changes of the sediment-transport rate resulted in continually changing nonequilibrium conditions. Equilibrium conditions were established only when the external feeding or extracting of sediment was terminated. When the feeding or extracting of sediment was stopped, new equilibrium values of the water-surface slope, depth of flow, and sediment-transport rate were obtained (runs 17, 19).

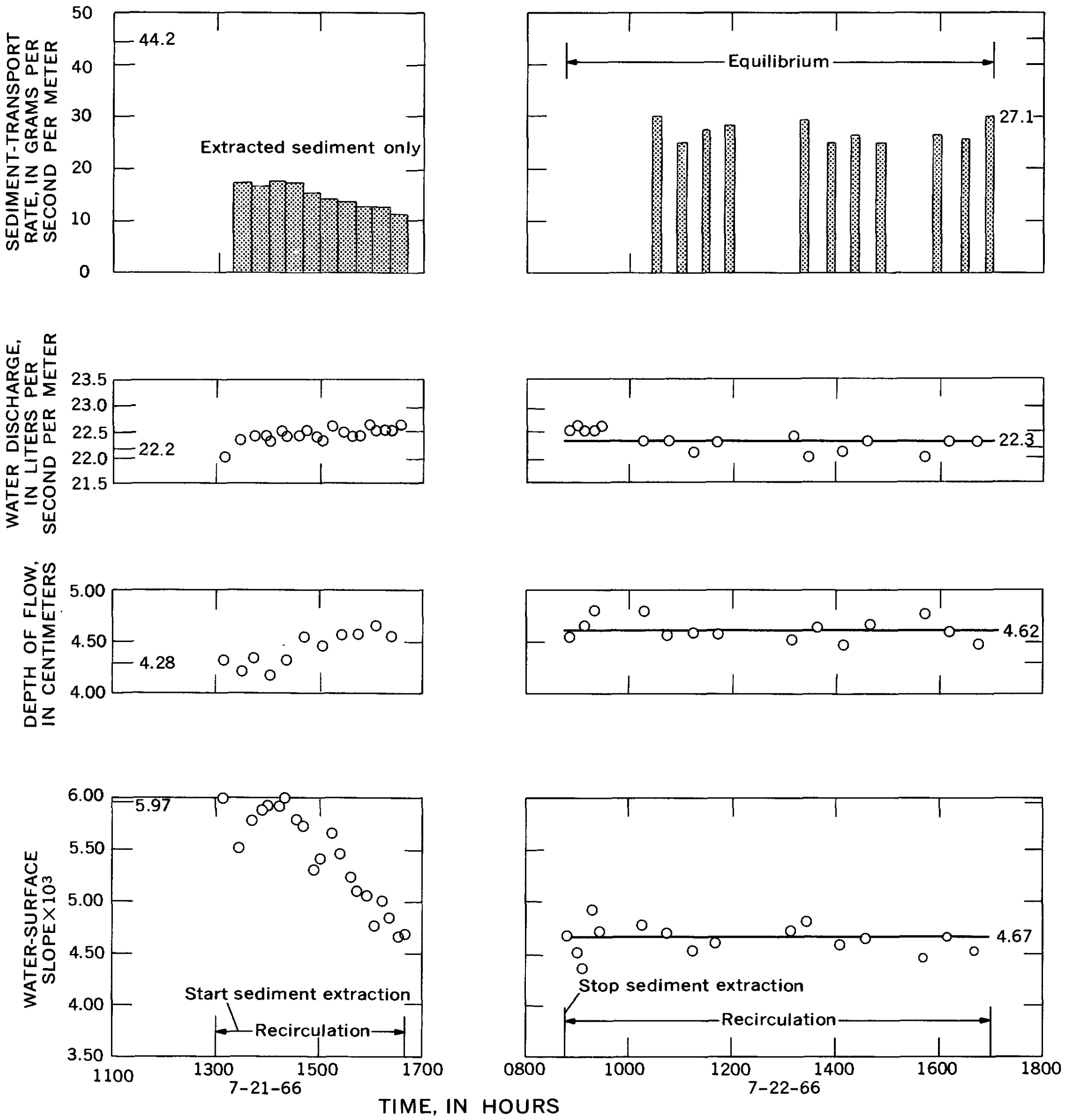

FIGURE 16.—Response of the recirculation system to a decreasing sediment-transport rate, run 19.

The feed and recirculation systems apparently responded differently to changes in sand-bed slope and tail-water depth. This apparent difference is not a true difference when the interrelations among the variables are considered. In the feed system, both the water discharge and the sediment-feed rate were fixed or independent variables. When Q and Q_s are the independent variables, the variables are uniquely related (Kennedy and Brooks, 1965), and S, D, and bed roughness can have only single values for the fixed values of Q and Q_s. In the recirculation system, Q and S were usually the independent or controlled variables as equilibrium was established to begin a run. When the sand-bed slope or tail-water elevation was changed, only the water discharge was controlled, and all other variables were free to adjust to new values. If the depth of flow had been controlled in addition to the water discharge when the sand-bed slope was changed, then the variables would be uniquely related (Kennedy and Brooks, 1965) and could not permanently change in value. If slope had been fixed in addition to water discharge when the tail-water depth was changed, unique relations would not exist among the variables (Kennedy and Brooks, 1965), and permanent changes in value may or may not occur.

The responses of the feed and recirculation systems to changes of sand-bed slope, tail-water depth, and sediment-transport rate were predicted qualitatively by the proportionality among the variables Q, Q_s, d, and S proposed by Lane (1955). In the present study, the water discharge was constant, and d was constant be-

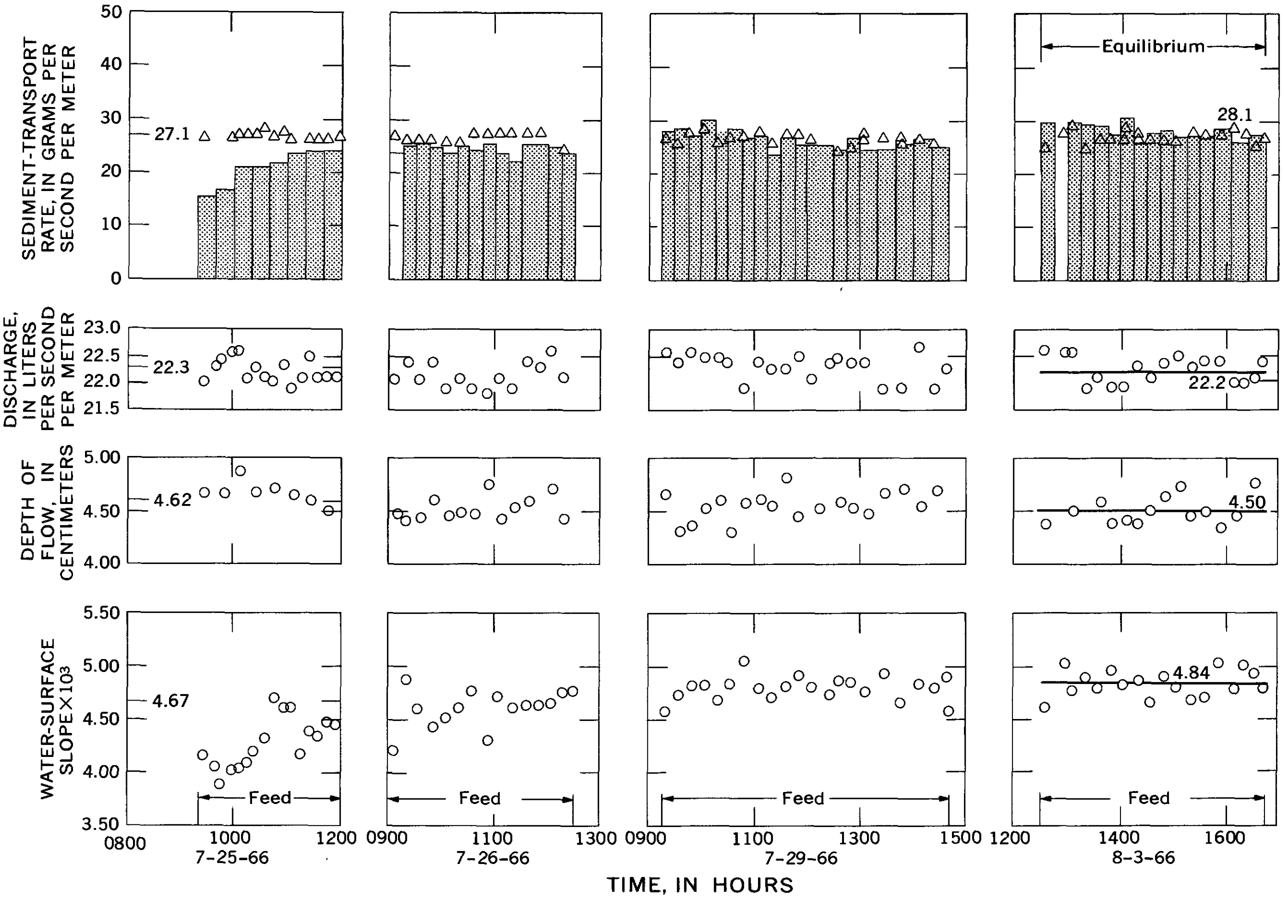

FIGURE 17.—Response of the feed system to an increase in the tail-water depth, run 20.

cause a uniform sediment was used. When d and Q are constant, the proportionality of Lane (1955) predicts that the sediment-transport rate and the water-surface slope are directly related. A comparison of the direct proportionality of Q_s and S with the results of runs 12–23 is:

1. In run 14b, S increased when Q_s was increased by increasing the sediment-feed rate; and in run 16, S decreased when Q_s was decreased by decreasing the sediment-feed rate.
2. In runs 12b, 13, 20, and 23, Q_s was constant, and the flume slope or tail-water depth was changed to cause nonequilibrium hydraulic and sediment-transport conditions. S initially deviated from its equilibrium value but returned after the reestablishment of equilibrium conditions to its equilibrium value that existed prior to the change.
3. In runs 15 and 22, Q_s was decreased by changes to the sand-bed slope and tail-water depth, and S decreased in both runs. In runs 18 and 21, Q_s was increased by changes to the sand-bed slope, and tail-water depth and S increased in both runs.
4. In run 17b, Q_s and S increased continuously as sediment was added to the recirculation system. In run 19, Q_s and S decreased continuously as sediment was extracted from the recirculation system.

In the operation of both feed and recirculation systems, the depth of flow and the water-surface slope can be changed by adjustments of the flume slope, or the tailgate at the downstream end of the flume, or of both. These adjustments, however, do not exclude changes in the depth of flow and the water-surface slope resulting from changing hydraulic and sediment-transport conditions in the flume. Runs 12–23 showed that changes in the depth of flow and the water-surface slope can occur with no adjustment to the tailgate (runs 14b, 15, 16, 17b, 18, 19) and with no adjustment to the tailgate or the flume slope (runs 14b, 16, 17b, 19). Depth adjustments can occur only in flume systems that operate with a constant-head tailbox. If the flume system is closed with respect to the quantity of water, then depth adjustments cannot occur.

The experimental data were used to determine if, as suggested by Maddock (1968), the relation between

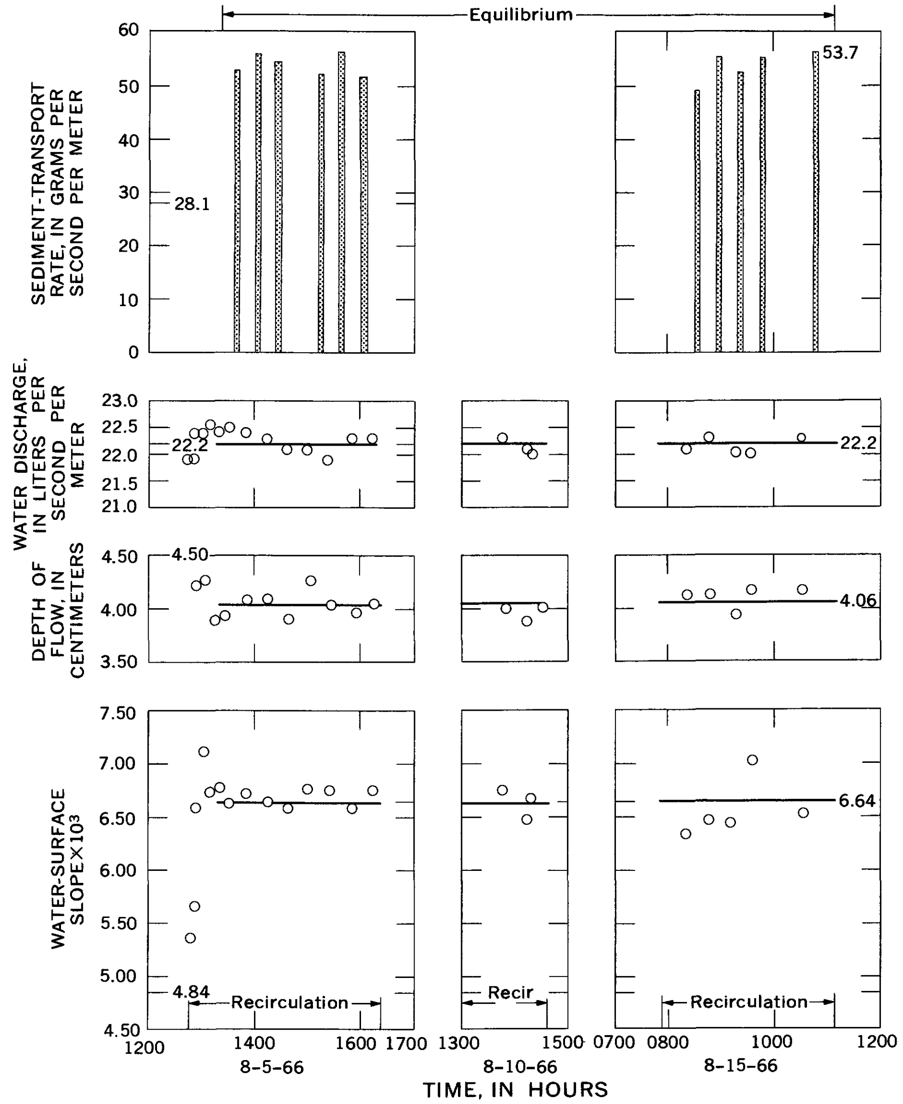

FIGURE. 18.—Response of the recirculation system to a decrease in the tail-water depth, run 21.

mean velocity V, and the unit water discharge-slope product, qS, for the feed system significantly differs from this relation for the recirculation system. Recall equations 8 and 9 (p. D5). Because $q=VD$, the qS product differs from stream power, γVDS, only by the presence of the constant γ in the stream power relation. Equations 8 and 9 were put in the general form

$$V=a\ (qS)^b. \qquad (11)$$

If logarithms are taken, the result is

$$\log_e V=\log_e a+b \log_e (qS). \qquad (12)$$

Least squares procedures were used in applying the experimental data to equation 12 to determine the values of the constants b and $\log_e a$. Six different combinations of the data were used and the results are summarized in table 4. The first three entries are the results of using the experimental data from runs 1–11, in which the equilibrium conditions for the feed and recirculation systems were compared. The first entry is for the overall mean values of V and qS for runs 1–11, in which the mean values of these variables for each part of the run (recirculation, feed, and recirculation) were weighted in accordance with the number of observations of each variable in each part. For the recirculation runs (entry 2), the mean values were weighted in proportion to the number of observations made for each of the two recirculation parts of the run. In the last three entries, the mean values of V and qS for the equilibrium conditions obtained in runs 12–23 were included with the

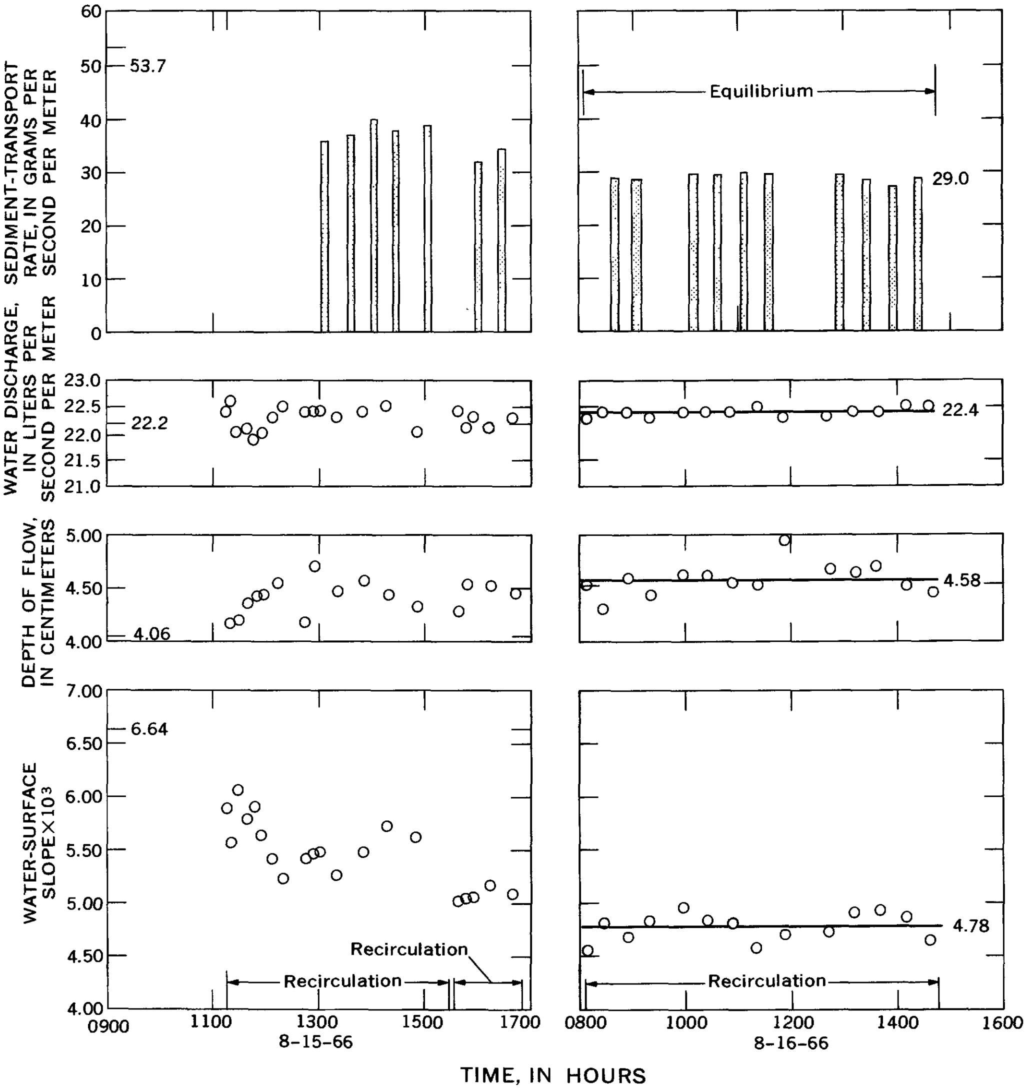

Figure 19.—Response of the recirculation system to an increase in the tail-water depth, run 22.

mean values from runs 1–11. For the "overall" entry (entry 4), the mean equilibrium values for each of the runs 1–23 were used, regardless of whether the method of operation was feed or recirculation. Only data for feed-system runs were used in entry 6 and only data for recirculation-system runs were used in entry 5.

Table 4.—*Summary of the least squares values of* $\log_e$ a *and* b

Entry	Runs included	$\log_e a$	b
1	Overall, 1–11[1]	1.852±0.171	0.43±0.04
2	Recirculation, 1–11	1.841±0.154	.44±0.03
3	Feed, 1–11	1.860±0.210	.43±0.05
4	Overall, 1–23[1]	1.942±0.145	.42±0.03
5	Recirculation, 1–23	1.885±0.120	.43±0.03
6	Feed, 1–23	1.915±0.192	.42±0.04

Runs 1–11 and 12–23 were considered separately as well as together because runs 12–23 covered only a part of the range of hydraulic and sediment-transport conditions covered by runs 1–11. The possibility existed that the combination of all the experimental data might be biased toward the range of conditions covered by runs 12–23 because of the large number of runs in this range. The results presented in table 4, however, show no significant differences between the V versus qS relation for runs 1–11 and for runs 12–23.

The limits shown in table 4 for the b and $\log_e a$ values are based on the 95 percent confidence level of significance. The b or slope values range from 0.42 to 0.44, and no significant differences exist among the six values of b. The b values are not significantly different from 0.40, except the value for entry 2 (runs 1–11). This b value is

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[1] Overall implies mean values based on all runs, regardless of whether the system of operation was feed or recirculation.

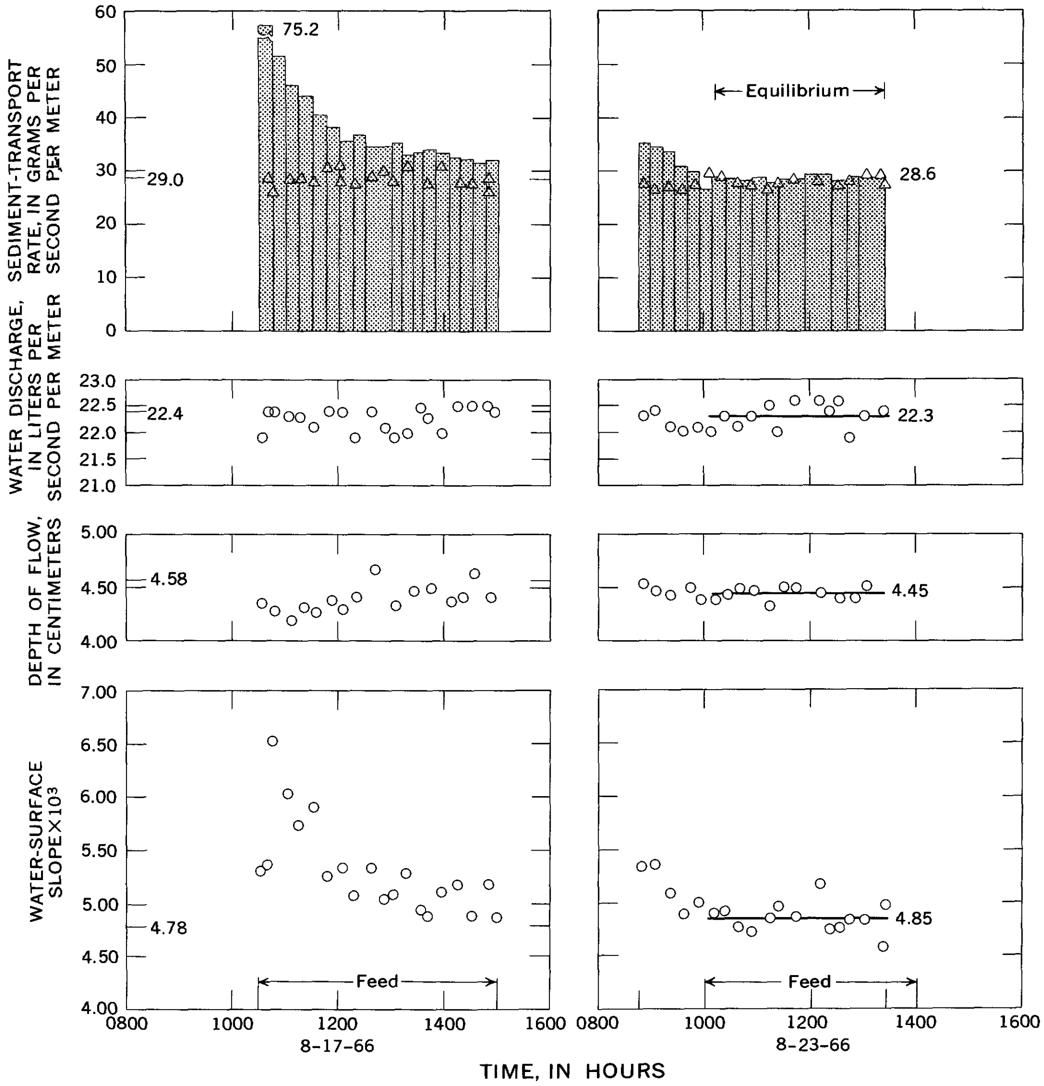

FIGURE 20.—Response of the feed system to a decrease in the tail-water depth, run 23.

just significantly different from 0.40 at the 95 percent confidence level but is not significantly different from 0.40 at the 97.5 percent level. The differences between the feed and recirculation systems suggested by equations 8 and 9 are not substantiated by the experimental data of this study. The $\log_e a$ values also do not differ significantly from each other.

Figure 21 shows the V versus qS relations for the experimental data of this study. The circles are the data using the overall mean values of V and qS for all the runs. The solid line represents the least squares line for the data from overall mean (runs 1–23) values; these data had the maximum $\log_e a$ value and the minimum b value. The dashed line represents the least squares line for the data using the recirculation (runs 1–11) values; these data had the maximum b value and the minimum $\log_e a$ value. All the other least squares lines that represent the relations for other combinations of the data lie between these two. It may be concluded that the data of this study show that the relation between the mean velocity and the unit discharge–slope product for the feed system does not differ significantly from this relation for the recirculation system.

ADVANTAGES AND DISADVANTAGES OF THE FEED AND RECIRCULATION SYSTEMS

From the experience gained in this study, in which both the feed and recirculation systems were used, it is possible to compare the two systems with respect to the advantages and disadvantages of each. As indicated in the preceding pages, the main difference between the two systems is the procedure by which the sediment is

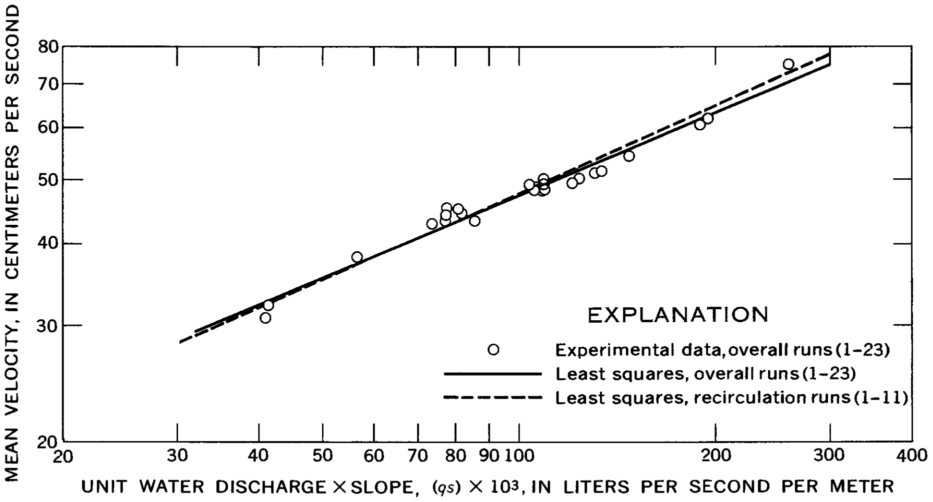

Figure 21.—Mean velocity versus unit water discharge-slope product relations for the feed and recirculation systems of flume operation.

transported from the downstream end of the flume to the upstream end. This transport is accomplished hydraulically in the recirculation system, whereas some mechanical means of sediment return must be used in the feed system (fig. 1). The flume used in the present study was small, and the amount of sediment for operating the flume as a feed system was not excessive. Operation of a feed system for a large flume may not be practical, however. For example, the sediment-transport rate for upper regime flow conditions in an 8-foot-wide flume may be as much as 5.9 pounds per second per foot of width, or 2,035 tons per day for an 8-foot width.

An additional disadvantage of the feed system is that the sediment must be fed into the flume at a reasonably constant rate. Gilbert (1914) experienced considerable difficulty with his sand-feeding devices. He stated (p. 23): "The hopper feeding was at best not sufficiently uniform to be used in measuring the load carried by the experimental stream." At large sediment-transport rates, Gilbert had to feed the sediment by hand. He filled a small box of known sediment capacity and emptied it at regular intervals. This procedure of hand-feeding had the disadvantage of discontinuous sediment feeding but had the advantage of permitting a reasonably accurate determination of the sediment-feed rate. Gilbert (1914) summarized his experiences with sand feeding as follows (p. 241): "None of the devices we employed to feed debris to the current achieved uniformity. Those which depended on the flow of wet debris through an aperture failed because the proportion of water could not be kept constant. The others depended on handwork and experienced the irregularity usual to handwork."

In addition to the hopper-type sand feeder used by Gilbert (1914) and feeding sediment by hand, a third general type of sediment feeding procedure has been used. This third type is the elevator infeed system, and the procedure consists of placing wet sediment in a receptacle and then gradually raising the receptacle into the flow so that the sediment is removed by the water flowing over it. The elevator infeed system has the advantages that the sediment does not have to be dried and that little attention to the sediment feeder is necessary during a run. The elevator infeed system has the disadvantages that the length of time the feed system can be run without interruption is limited by the size of the infeed receptacle, and that there is no way of checking the sediment-feed rate during the run. Also voltage fluctuations and the decreasing load on the electrical drive system for the infeed receptacle may cause unknown variations in the sediment-feed rate.

In this study, a vibrating sediment feeder was used, and a reasonably constant sediment-feed rate could be obtained if certain precautions were observed. The sediment had to be completely dry, because even small amounts of moist sediment caused variations in the sediment-feed rate. Also the depth of sediment in the hopper had to be constant. The sediment depth in the hopper of the sediment-feeder was kept constant by using a large secondary storage bin which fed sediment directly into the hopper (fig. 2). The sediment had to be kept free of debris, which would also cause variations in the sediment-feed rate. Fluctuations in the voltage supply caused variations in the sediment-feed rate. The vibrating sediment feeder has the advantage that the sediment-feed rate can be checked easily at any time during the run. Even with modern equipment, however, obtaining a constant sediment-feed rate is difficult. Johnson (1942) recognized the limitations of feed systems and pointed out that the usefulness of the bed-load data in the summary of flume experiments that he compiled (1943) is limited by the effects of the various types of equipment and procedures used in feeding the sediment.

Difficulties with sediment feeding in the feed system can be eliminated by using the recirculation system in which the transported sediment is returned hydraulically to the upstream end of the flume. There is some variation in the rate of return of the sediment to the upstream end of the flume because the rate at which the sediment is transported from the downstream end of the flume varies with time. This variation in the rate of return is an advantage because sediment-transport rates of natural alluvial channels also vary with time. Therefore, it should be possible to operate a recirculation system with a shorter flume than that necessary for a feed system because the naturally varying sediment-transport conditions are established almost immediately in the upstream section of the recirculation flume. In the feed system, however, some length of the upstream section of the flume is necessary for dampening of the manmade oscillations in the sediment-feed rate and for establishing the natural oscillations of sediment transport.

The feed system has the advantage that the sediment-transport rate in the flume can be controlled directly. A specific sediment-transport rate can be obtained in the recirculation system only by trial and error.

No specific cost analysis of the two systems of flume operation was made during this study, but the following observations were made. First, the feed system required a larger supply of sediment than the recirculation system for continuous operation because dry sediment was necessary for the sediment feeder. Because the supply of sediment was limited, the length of time the feed system could be run without interruption was limited. An example is run 14b, the results of which are presented in figure 11. A total of 9 days was required to complete run 14b, in which the feed system was used. Operation of the flume was limited to 3 days with two 3-day periods of no operation that were necessary for drying the sediment. Second, the feed system required constant attention with respect to removal of the trapped sediment, replacement of the water, and checks of the sediment-feed rate; the recirculation system required no attention other than that required to obtain the necessary measurements. Third, the recirculation system responded much more quickly to changes in the sand-bed slope, tail-water depth, and sediment-transport rate than the feed system; therefore equilibrium could be established much more rapidly for a recirculation system than for a feed system as the hydraulic and sediment-transport parameters were varied in a series of experiments.

In summary, the recirculation system has the advantage of ease and economy of operation, whereas the feed system has the advantage of direct control of the sediment-transport rate.

SUMMARY

The feed and recirculation systems of flume operation for laboratory alluvial channel experiments were compared under a variety of hydraulic and sediment-transport conditions, and the responses of the laboratory flume systems to changes of the hydraulic and sediment-transport variables were determined. The experiments for this study were conducted in a tilting plastic flume 10 meters long, 20 cm wide, and 20 cm deep. This flume could be operated either as a feed system or as a recirculation system. The sediment had a median fall diameter d_{50}, of 0.30 mm and a gradation σ, of 1.26.

The equilibrium conditions for the feed and recirculation systems were compared in a series of 11 runs that covered a wide range of flow conditions and a variety of bed forms from ripples to antidunes. The mean equilibrium values of the water-surface slope, depth of flow, velocity, and sediment-transport rate for the recirculation system were not significantly different at the 95-percent level of significance from the mean equilibrium values of these variables for the feed system.

The responses of the feed and recirculation systems of the laboratory flume to changes of sand-bed slope, tail-water depth, and sediment-transport rate were determined with the water discharge constant. Data from 12 experimental runs showed that:

1. For the feed system, changes of the sediment-feed rate resulted in new equilibrium values for the water-surface slope, depth of flow, and sediment-transport rate.
2. For the feed system, changes of the sand-bed slope and the tail-water depth resulted in the return of the water-surface slope, depth of flow, and sediment-transport rate to the equilibrium values that existed before the change.
3. For the recirculation system, changes of the sand-bed slope and tail-water depth resulted in new equilibrium values for the water-surface slope, depth of flow, and sediment-transport rate.
4. For the recirculation system, changes of the sediment-transport rate (by addition of sediment to the recirculating sediment or extraction of sedi-

ment from the recirculating sediment) resulted in continually changing nonequilibrium conditions. Equilibrium conditions were established only when the external feeding or extracting of sediment was terminated. New equilibrium values for the water-surface slope, depth of flow, and sediment-transport rate were obtained when the feeding or extracting of sediment was stopped.

The results of the 12 runs suggest that the feed and recirculation systems responded differently to changes in sand-bed slope and tail-water depth. However, this difference is not a true difference when the interrelations among the variables Q, Q_s, S, and D are considered. If the sediment-feed rate, Q_s, and the water discharge, Q, are constant, then the variables are uniquely related (Kennedy and Brooks, 1965), and S, D, and bed roughness can only have single values for the fixed Q and Q_s. Thus, when the sand-bed slope or tail-water depth was changed, S and D had to return to the previous equilibrium values determined by the fixed Q and Q_s. In the recirculation system, only the water discharge was maintained constant, and S, D, and Q_s were free to adjust to new values when the sand-bed slope or tail-water depth was changed.

The recirculation system has the advantages of ease and economy of operation because the sediment is returned hydraulically to the upstream end of the flume. Hydraulic return of the sediment requires no attention or effort on the part of the flume operator. For the feed system, the sediment must be separated from the flow, prepared for feeding, transported to the upstream end of the flume, and introduced continuously at a reasonably constant rate. The operator must attend the sediment-feeding mechanism throughout the duration of the experimental run. If dry sediment is required for the sediment-feeder, as it was in the present study, the length of time the flume can be operated depends upon the available supply of dry sediment. Also, the time between runs must be sufficiently long to permit the sediment to dry. Drying the sediment also requires additional handling of the sediment. The feed system has the advantage that the sediment-transport rate can be set directly, whereas in the recirculation system, a specific sediment-transport rate can be obtained only by trial and error. The recirculation system responded much more rapidly to changes in sand-bed slope, tail-water depth, and sediment-transport rate than did the feed system.

The responses of the feed and recirculation systems of the laboratory flume to changes of sand-bed slope, tail-water depth, and sediment-transport rate were predicted qualitatively by the proportionality of Lane (1955).

LIMITATIONS AND RECOMMENDATIONS

One limitation of this study is that the experiments were conducted in a single flume and one sediment was used. The second limitation is that the determination of the responses of the feed and recirculation systems of flume operation to changes of variables was limited to a single water discharge. Similar results would be expected for other discharges, and perhaps the rate at which equilibrium was established would be faster or slower, depending upon whether the water discharge was larger or smaller than the water discharge used in this study.

The two limitations of the present study suggest the following subjects for further study: Similar experiments with a graded sediment; similar experiments with different water discharges; similar experiments with the imposition of large changes of the variables so that significant changes in the bed roughness occur; and experiments to test the response of a feed system with a constant sediment-feed rate to changes in water discharge.

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