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COMPUTATION OF FLUVIAL SUSPENDED SEDIMENT DISCHARGE

by

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SOCIETE CENTRALE
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INTRODUCTION

Given a gauging station in a stream, let us assume that at a given time both the mean concentration, c, and the water discharge, Q , are available, then the suspended sediment discharge, in weight of material per unit time denoted Q_{si}, is determined by multiplying these two quantities, so we have:

$$Q_{si} = k\,c\,Q \qquad (1)$$

where k is a factor depending on the units employed and the index i indicates that the instantaneous sediment discharge is calculated.

To calculate the sediment load over a given period of time, T , we have to integrate over this period, so we have :

$$Q_s = \int_o^T k\,c\,Q\,dt \qquad (2)$$

Usually Q_{si} is in tons per day (tons/day), C in milligrams per liter (mg/l) and Q in cubic meters per second (m^3/s) and consequently k is equal to 0.0864.

In fact, in most cases no continuous records of concentration are available and one has to deal with individual values of concentration. Obviously to define adequately the changes in concentration with time a sufficient number of samples should have been obtained which is the only way to integrate the many variables which intervene in the highly involved process of erosion and movement of sediment in streams. The following quotation from COLBY shows the complexity of the phenomenums.

> "Relationships of sediment discharge to characteristics of sediment, drainage basin, and streamflow are complex because of the large number of variables involved, the problems of expressing some variables simply, and the complicated relationships among the variables. At a cross section of a stream, the sediment discharge may be considered to depend: on depth, width, velocity, energy gradient, temperature, and turbulence of the flowing water; on size, density, shape, and cohesiveness of particles in the banks and bed at the cross section

> and in upstream channels; and on the geology, meterology, topography, soils, subsoils and vegetal cover of the drainage area. Obviously, simple and satisfactory mathematical expressions for such factors as turbulence, size and shape of the sediment particles in the streambed, topography of the drainage basin, and rate, amount, and distribution of precipitation are very difficult, if not impossible, to obtain."

Prior to any computation basic data should be collected, as pointed out by the U.N. Sediment Specialist, "compilation of data for daily records takes a long time to complete so the water discharge record for these stations should be given a high priority and supplied to the Hydrochemistry Branch at an early date and so should be the following items":

- Copy of the water level strip chart for the entire year
- Listing of all discharge measurements
- Copy of all rating tables (or/and curves) used during the year
- Description of the cross-section (station analysis)
- Copy of daily water discharge and water level.

An efficient way to evaluate the adequacy of sampling is to plot the concentrations values on the gauge-height record as soon as possible after the data are available.

Note : In the following paragraphs we draw heavily on George Poterfield's "Computation of Fluvial Sediment Discharge" - Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book C3 Chapter C3.

1. RELATION BETWEEN SINGLE-VERTICAL AND CROSS-SECTIONAL CONCENTRATIONS

If sediment samples are obtained routinely at a single vertical in a cross section, the relation of the concentration of the single-vertical sample to the mean concentration in the cross section must be determined prior to computation of sediment discharge. This relation, in the form of a coefficient, is determined by comparison of the results of cross-section samplings carried out by teams of the Hydrochemistry Branch with concentrations of samples taken at the same time by the observer.

The so-called cross-section coefficient defined as the ratio of the real mean concentration to the concentration at a single vertical may vary with the season and/or the gauge height. In figure 1, cross section coefficient is plotted versus discharge and time of the year, it can readily be seen that the correlation with discharge is poor; however the correlation with season indicates a possible trend.

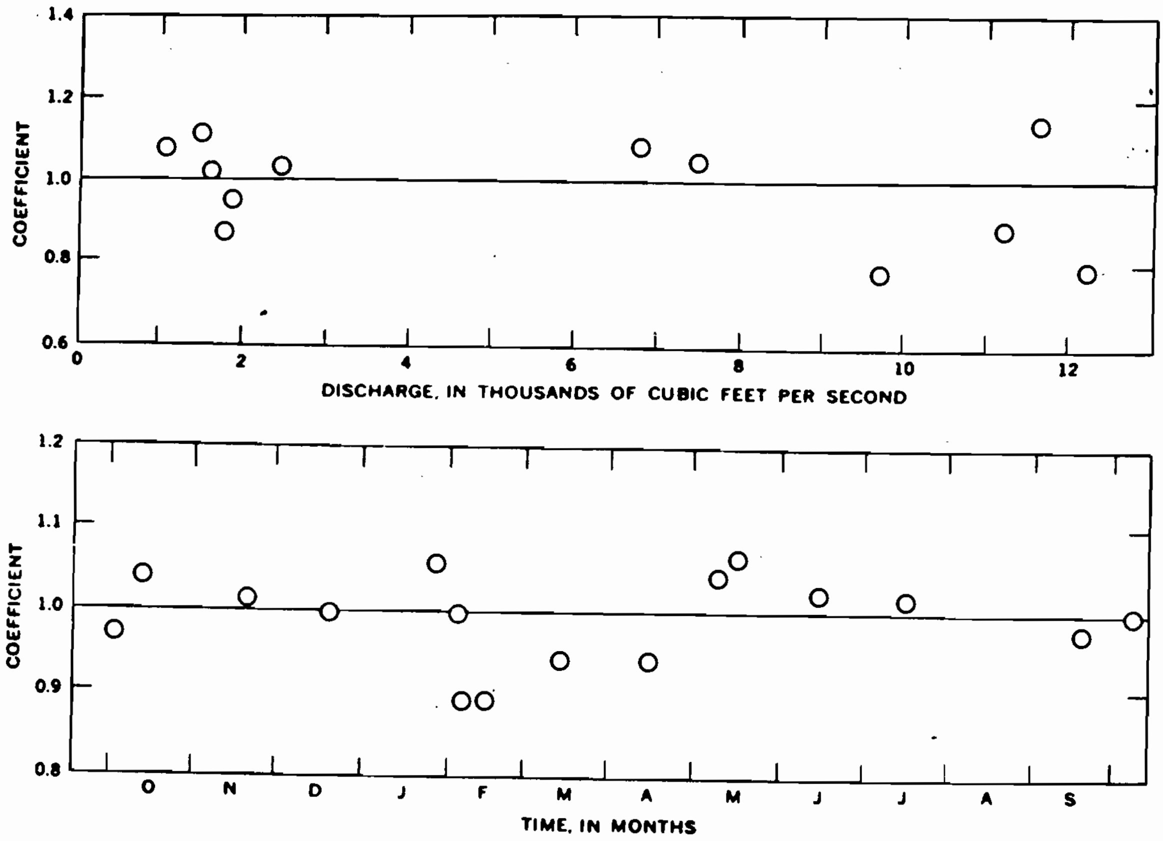
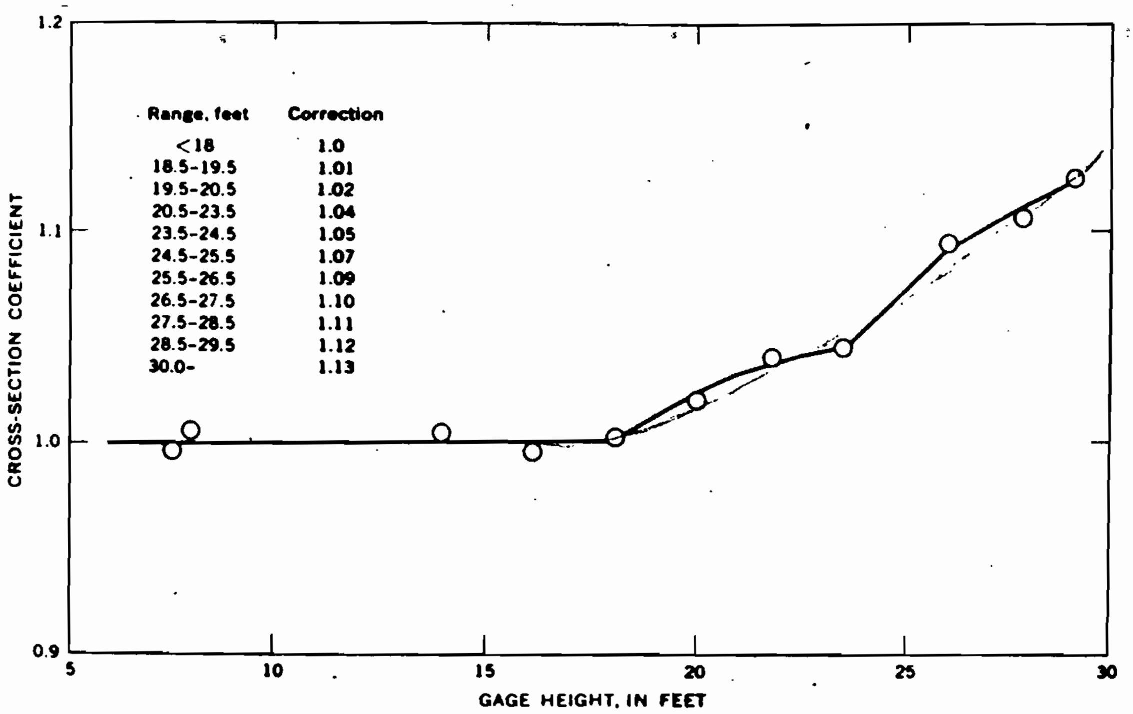


Figure 1.—Relation of cross-section coefficient to discharge and season for San Joaquin River near Vernalis, Calif.

In figure 2 a reasonable correlation with stage is indicated and thus the values may be used to correct concentration obtained at a single vertical.



Range, feet	Correction
<18	1.0
18.5-19.5	1.01
19.5-20.5	1.02
20.5-23.5	1.04
23.5-24.5	1.05
24.5-25.5	1.07
25.5-26.5	1.09
26.5-27.5	1.10
27.5-28.5	1.11
28.5-29.5	1.12
30.0-	1.13

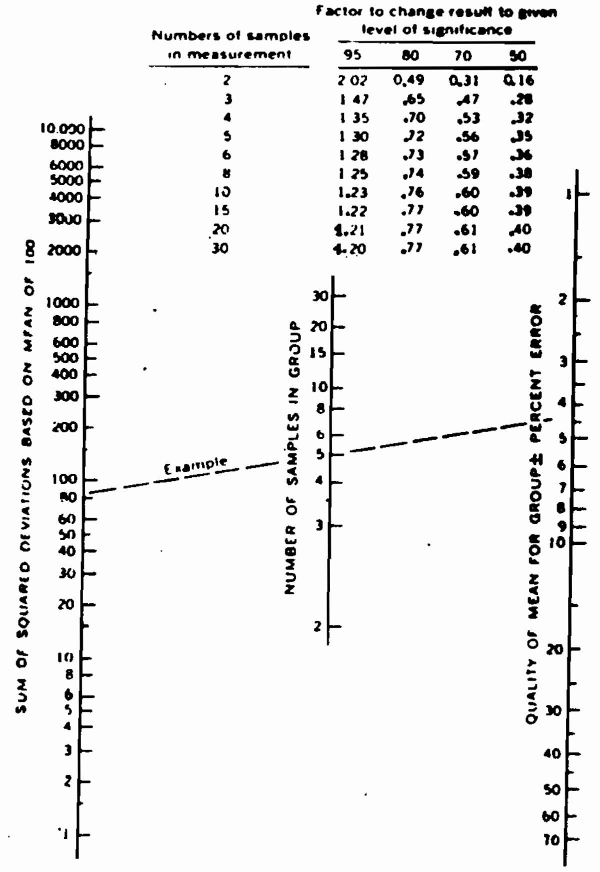
Figure 2 —Relation of cross-section coefficient to gage height.

To evaluate the quality of a cross-section coefficient the following procedure developped by GUY may be used. Two groups of data are involved for adjusting the concentration of single-vertical sample, namely, a list of the concentrations of the single-vertical samples and a list of the concentration of the cross-section samples.

An example is presented in table 1 with the purpose of testing the quality of the mean of a single group, first the data are converted to a base of 100 (the percentage each observation is of the mean), i.e. $104 = \frac{643 \times 100}{618}$ then the sum of the squared deviations from the base 100, i.e. $16 = (104-102)^2$, is determined, and these data are entered on the alinement chart given in figure 3.

Table 1

	Measured observations	Base of 100	
		Observations	Squared deviations
	643	104	16
	618	100	0
	593	96	16
	649	105	25
	587	95	25
Sum	3090		82
Mean	618		



Numbers of samples in measurement	Factor to change result to given level of significance			
	95	80	70	50
2	2.02	0.49	0.31	0.16
3	1.47	.65	.47	.28
4	1.35	.70	.53	.32
5	1.30	.72	.56	.35
6	1.28	.73	.57	.36
8	1.25	.74	.59	.38
10	1.23	.76	.60	.39
15	1.22	.77	.60	.39
20	1.21	.77	.61	.40
30	1.20	.77	.61	.40

Figure 3 .—Alinement chart to determine the quality of the mean for a group of samples given the sum of squared deviations at the 90-percent level of significance. The quality of the mean for other levels is obtained by use of the factors shown. After Guy (1968, p. B166).

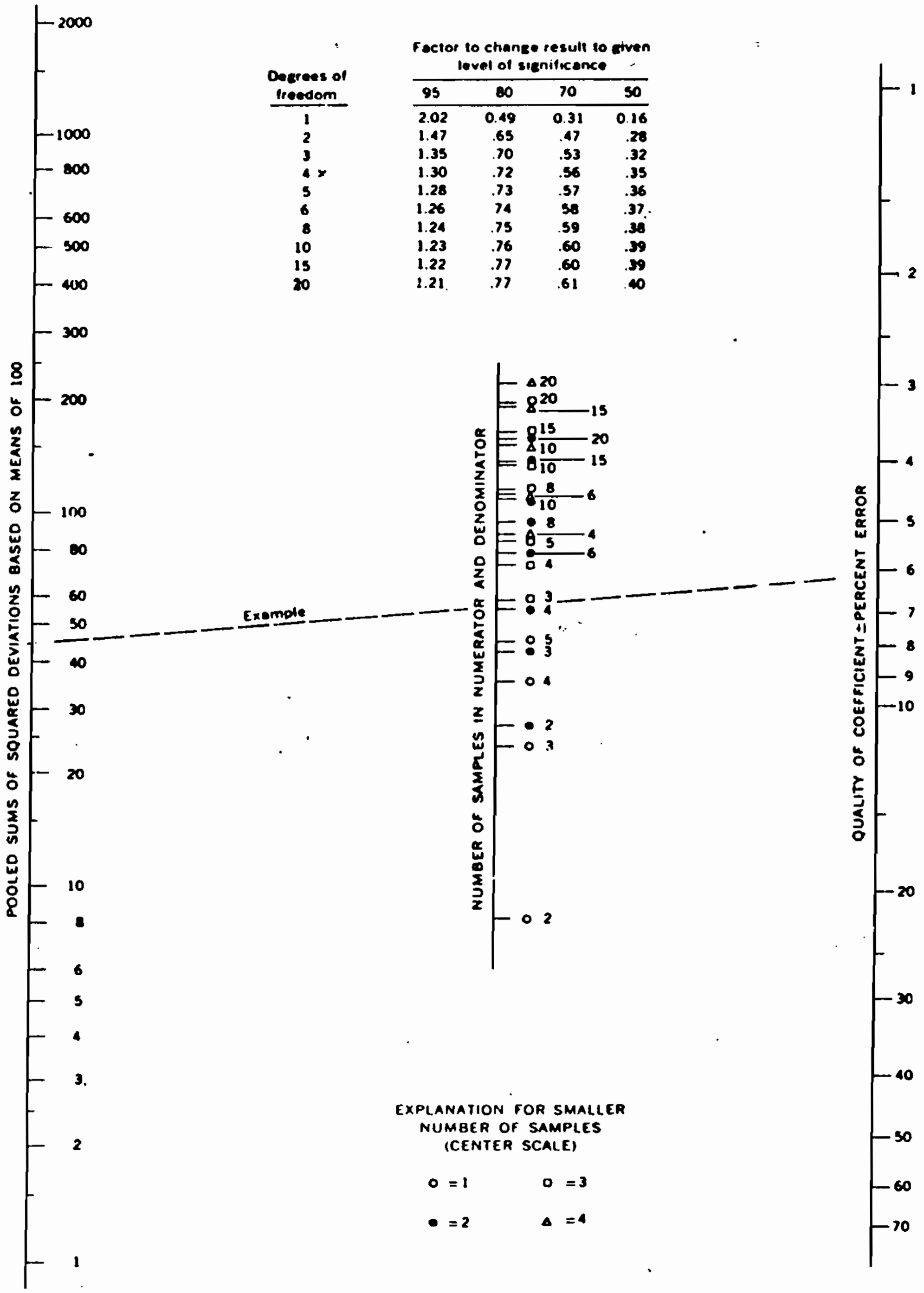
In the example the number of samples if 5 the sum of the square deviations is 82 and the resulting quality of the mean for the group, that is, 618, expressed in percent error is ± 4.5% at the 90 percent level of significance. For the 95 percent level of significance we should multiply the result by 1.30 and for the 80 percent level by 0.72 obtaining ± 6.0% and 3.0% respectively.

In table 2 an example is presented to test the quality of the cross-section coefficient. Two cross-section concentrations and four single-vertical concentrations are used, the same procedure as for testing the mean of a group is followed for each group, for instance $99 = \frac{715}{720} \times 100$ and $1 = (100-99)^2$ likewise $104 = \frac{600}{624} \times 100$ and $16 = (104 - 100)^2$; however, it is the sum of the square deviations for the two groups which is calculated and entered on the alinement chart given in fig. 4.

Sample groups	Measured concentrations (mg/l)	Mean	Base of 100	
			Concentrations	Sum of squared deviations
Cross section	715	720	99	1
	725		101	1
Single vertical	624	600	104	16
	606		101	1
	600		100	0
	570		95	25
				44 (total)

Table 2

In the example the number of samples are 2 and 4 and are represented in the center scale by, .4 , (the dot stands for the number 2) the sum of the square deviations is 44 and the resulting quality of the cross-section coefficient expressed in percent error is ± 6% at the 90 percent level of significance. For a different level of significance the terms "degrees of freedom" is defined as two less than the total number of samples in both groups, in the foregoing example the total number of samples is 6 so the degrees of freedom is 4 (6 - 2) and the corresponding result for the 95 percent level of significance will be ± 6 x 1.30 = ± 7.8 percent likewise for the 80 percent level of significance one obtains ± 6 x 0.72 = ± 4%.



Degrees of freedom	Factor to change result to given level of significance			
	95	80	70	50
1	2.02	0.49	0.31	0.16
2	1.47	.65	.47	.28
3	1.35	.70	.53	.32
4	1.30	.72	.56	.35
5	1.28	.73	.57	.36
6	1.26	74	58	.37
8	1.24	.75	.59	.38
10	1.23	.76	.60	.39
15	1.22	.77	.60	.39
20	1.21	.77	.61	.40

EXPLANATION FOR SMALLER
NUMBER OF SAMPLES
(CENTER SCALE)

○ =1 □ =3

● =2 △ =4

Figure 4—Alinement chart to define the quality of a coefficient for a given sampling design and pooled sums of squared deviations at the 90-percent level of significance. The quality for other levels is obtained by use of the factors shown. The explanation used on the center scale indicates the smaller number of the two groups of samples used.

2. TEMPORAL CONCENTRATION GRAPH

The drawing of a temporal concentration curve from individual values of concentration is the first step in the computation of sediment discharge. It is not only useful to study the variations of concentration with time but to estimate concentration graphs for missing periods or for inadequately sampled periods. For a given watershed, though the absolute values of concentration may vary considerably from event to event, the shape of the concentration graph presents characteristics which are likely to be the same for runoff events of the same order. Each station should be sampled in detail during sufficient runoff events to provide a catalog of the shape and magnitude of the sediment curves pertinent to the station.

The following is drawn from Porterfield:

> Development of a temporal concentration graph may be difficult if too few samples were obtained. Preparation of the concentration graph will require application of theoretical and practical principals of sedimentation. Inadequate sampling results in a less accurate graph, and much more time is required to prepare the graph. Because of the extra time, in addition to loss in accuracy, it is usually less expensive to collect additional samples than to estimate the concentration graph.
>
> A sampling program for each station should be designed to obtain optimum results when the desired accuracy of record is balanced against the many physical and economic conditions. A few samples properly spaced with time may adequately define the concentration of a flood event at certain stations, providing that the personnel computing sediment discharge have detailed knowledge of seasonal sediment trends for the complete range of flow conditions experienced. Lack of knowledge of these trends, such as at a new station or a station with a large number of variable conditions affecting sediment erosion and transport, requires an intensive sampling program. Successful station operation requires continuous modification of the sampling program to obtain the best accuracy possible with a reasonable expenditure of time and effort.
>
> Concentration data should be interpreted and the graph drawn by personnel with a knowledge of the sampling program, the physical and cultural environments affecting the stream regimen and sediment sources, and the fundamentals of sediment transport. After the graph is drawn, it should be reviewed and modified as required prior to computation of daily mean concentration values and sediment discharges. Changes in the graph are made easily at this point and may eliminate possible future recomputation.

Difficulties may be encountered while drawing the continuous graph because of paucity of samples, unusual storm events, or periods of missing records. Valuable guidance may be available from past records of sediment discharge at the site and at nearby sites. A study of these records before plotting the data and drawing the graph should be a required part of the computation procedure. Some of the factors that should be considered prior to drawing the concentration graph and examples of concentration graphs are included in the following section.

Concentration values are plotted on a gage-height chart or a copy of the chart. If an analog record of stream stage is not available because of the use of digital recorders, a plot of gage height or discharges from the digital record must be made for the important periods of changing stage and concentration, such as during storm runoff.

If possible a scale should be chosen so that concentration values can be plotted to three significant figures.

Study of past records

A study of the variation and range of suspended-sediment concentration with time at a given point, or sampling station, reveals many similarities among different flood events. A plot of concentration values with time and with flood stage will define graphs that can be used to estimate concentration graphs for missing periods or for inadequately sampled periods. The absolute values and duration of these values may vary considerably from event to event; however, the shape of the temporal graph may be similar among the several events. Thus, the first step in drawing the concentration graph is to study the plotted points for trends, sketch in the parts of the graph well defined previously - for the entire historical record if necessary.

A file of historical concentration graphs that are characteristic of the variation and range of suspended-sediment concentration should be assembled to facilitate the use of these graphs during development of the temporal concentration graph and to reduce the number of past records stored in current files. Characteristic graphs may be different for different basins, and many characteristic graphs may exist for each station.

Estimates for periods of missing data

The shape and magnitude of the temporal concentration graph for individual rises have characteristics based on the principles previously discussed. A knowledge of the typical patterns from past records is helpful when interpreting the concentration data and constructing the concentration graph for periods of inadequate concentration data.

Concentration data are considered inadequate when a significant part of a record cannot be defined within probable limits of 5 or 10 percent. The efficient and reasonably accurate development of a continuous concentration graph or determination of sediment discharge during the period of missing data requires careful study, in which experience and ability to make sound estimates based on concentration data collected during other periods are most helpful. The length of the inadequately defined period may range from 20 minutes to several days. The short period usually occurs on streams having rapid changes of water discharge and concentration and very frequently occurs at the beginning of a rise resulting from intense rainfall. This situation is particularly critical on streams with small drainage areas. Long periods of missing data may occur because the sampling site is inaccessable during floods or because of loss of equipment or samples.

<u>An estimated concentration graph is preferable to direct estimates of sediment discharge</u>. During short periods of missing data, a continuous concentration graph may be estimated accurately and used to compute daily mean concentration and sediment discharge. During long periods of missing data, an accurate estimate of concentration may not be possible, and daily values of sediment discharge must be estimated directly from the historical relation between water and sediment discharge by interstation correlation or by comparison with records obtained at an upstream or downstream station. A complete record of daily values facilitates interpretation or statistical evaluation of the data by computer techniques; therefore, if possible, estimates of both sediment concentration and discharge should be made. During periods that sediment discharge was estimated directly, daily concentration values must be estimated independently of sediment discharge if the period includes rapid or large changes in concentration or water discharge. An independent estimate of daily mean concentration is necessary because published values of concentration are time weighted, and daily time-weighted values of concentration cannot be computed from daily values of water and sediment discharge that represent periods of changing streamflow and concentration. If an acceptable estimate of concentration is impossible, no daily concentration will be published, and a leader (..) will be placed in the concentration column.

The methods or combination of methods used to estimate missing data may vary from station to station and seasonally for the same station. Each period of missing data, therefore, must be studied, and the best estimate made on the basis of existing data and circumstances; regardless of the method chosen the estimate should be verified by a second method.

3. EXAMPLES OF THE SEDIMENT-CONCENTRATION GRAPH

The preceding sections discuss many reasons for the variation of sediment concentration with time and discharge. This section presents examples of (1) the relation between concentration and discharge (or gage height) for basins of various size, climatic conditions, geology, and land use and (2) variations of this relation that may occur in a large basin.

Figure 5 is an example of the typical, sharp discharge peak and concentration graph produced when high-intensity rainfall of short duration occurs over a small basin and the stream channel is dry or has only low flow prior to the storm. The typical concentration graph will rise rapidly and peak at or slightly before the discharge peak, after which it decreases rapidly, generally at a faster rate than the recession in water discharge. The shape of the recession curve usually is parabolic. At the discharge peak, the concentration may fluctuate rapidly for a short period before starting to recede. The duration of the concentration peak is seldom greater than that of the water-discharge peak. Note that the concentration did not start to increase prior to the increase in water discharge.

An example of a concentration graph of a stream in a small basin, Corey Creek near Mainesburg, Pa., (31.6 km^2) when the runoff increased at a slower rate is shown in figure 6. This basin generally has better vegetal cover, less intense precipitation, a more humid climate, and a higher base flow than the basin illustrated in figure 5.

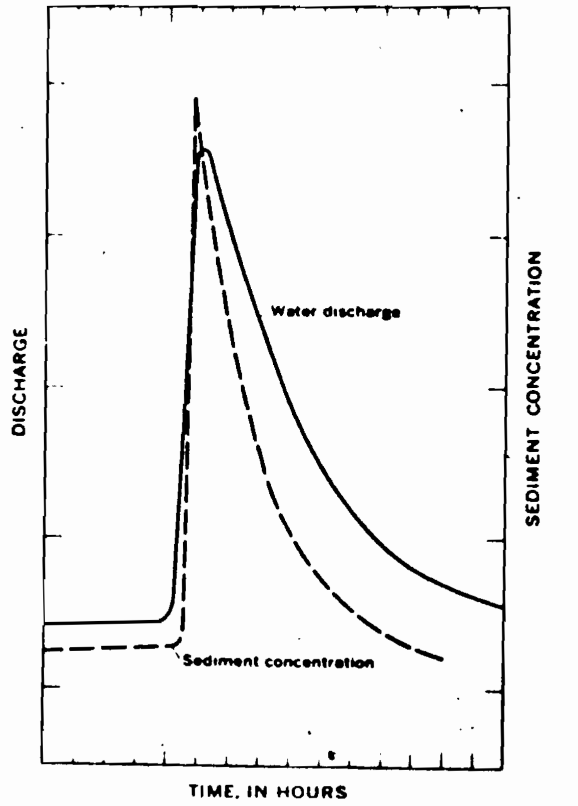


Figure 5—Typical effect of high-intensity short-duration rainfall on discharge and concentration for a small-drainage-basin stream having a very small amount of base flow or none.

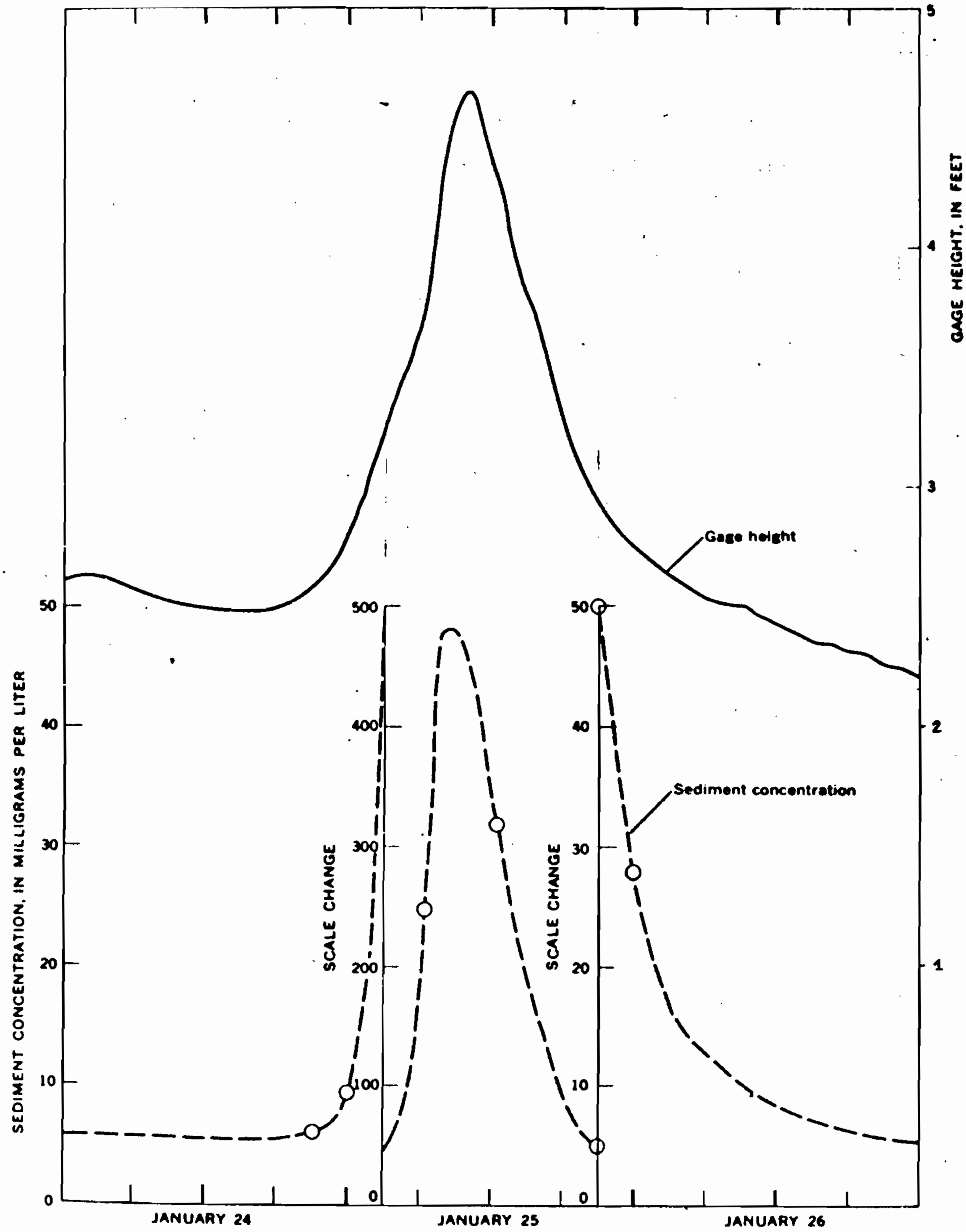


Figure 6 —Gage height and sediment concentration, Corey Creek near Mainesburg, Pa.

Figure 7 shows the effect on sediment concentration in the Rio Grande near Bernalillo, N. Mex., of two separate releases of water from a tributary reservoir over 160 km. upstream. In both instances, the release is at the same rate of discharge; the major difference is in the quantity of water in the stream at the time of release (the initial flow). The shape of the hydrograph is similar in both cases, but there is a marked difference in the sediment-concentration graph owing to the initial flow conditions. Figure 7A illustrates low initial flow conditions. The released water erodes sediment from the bed and the banks of the stream and causes an initial sediment peak, followed by the usual recession, similar to that illustrated in figure 5 After the initial recession another rise in concentration occurs which represents the suspended material contained in, or picked up by, the released water. Figure 7B illustrates the effect of initial channel storage on concentration. Because of high initial flow, the change in stage and velocity is less, and there is little or no additional erosion of sediment from the bed and banks of the stream by the initial increase in flow. The concentration pattern for the released water, however, is the same as that for figure 7A .. The interface between the water initially in the river and the released water is defined not only by the changes in suspended sediment but also by a change in temperature and conductivity. In other words, the water represented by the hydrograph peak preceding the sediment-concentration graph is water that was in the channel prior to the release and moved downstream ahead of the release.

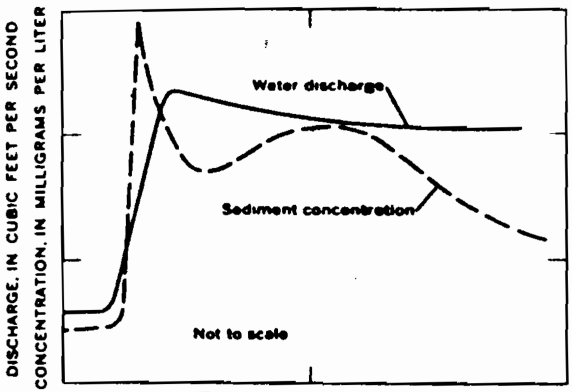


Fig.7A. LOW INITIAL FLOW

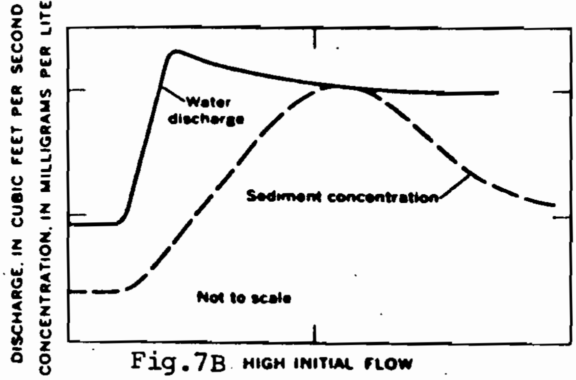


Fig.7B HIGH INITIAL FLOW

Figure 7 —Effect of two different flow conditions on discharge and concentration for the Rio Grande near Bernalillo, N. Mex.

The examples shown in figures 8–11 illustrate for the Colorado River near San Saba, Tex., the range of concentration peaks and the variation of concentration with time which can occur in a river that drains a large basin of diverse geologic, topographic, climatic, and land-use characteristics.

The graphs for the period May 1-6, 1952 (fig. 8), illustrate a typical water-discharge peak and sediment-concentration graph for a large stream when the flow was caused by thunderstorm activity in a small area of the basin. The graphs differ from those shown for a small basin (fig. 5) in that (1) the increase in discharge from 0400 and 1700 hours May 1 is water previously in the channel and (2) the rate of increase of discharge was attenuated by the distance from the source to the station. These two differences cause the significant rise in concentration to be delayed.

Several general conclusions regarding the sediment characteristics of this station can be inferred from figure 8 and illustrate the type of analysis that should be applied to each station record. First, the concentration from 0400 to 1700 hours on May 1 is only slightly larger than the concentration on the preceding day and illustrates a general rule that the concentration graph seldom will show a large increase before the actual storm

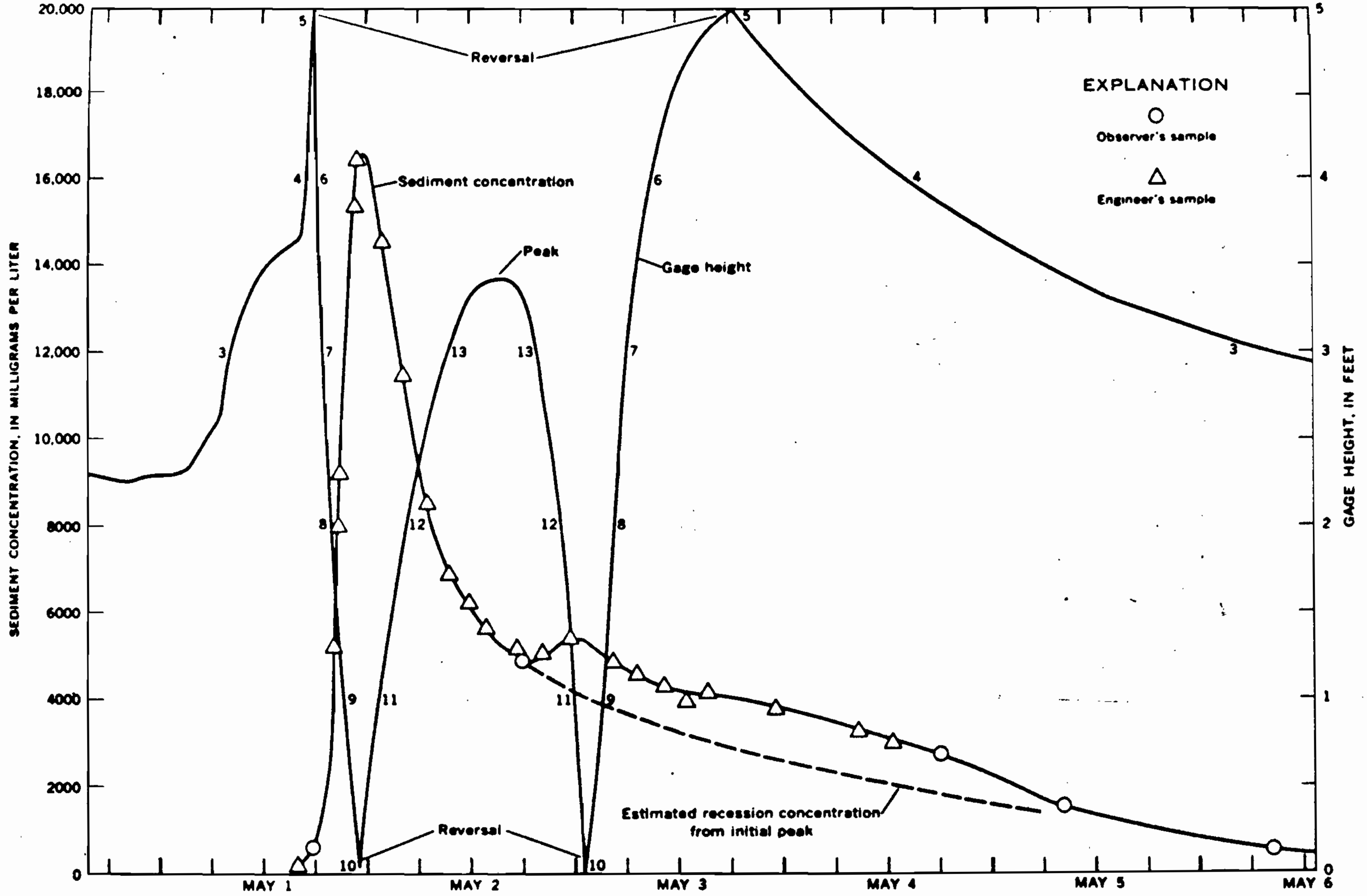


Figure 8 -Gage height and sediment concentration, Colorado River near San Saba, Tex., May 1-6, 1952.

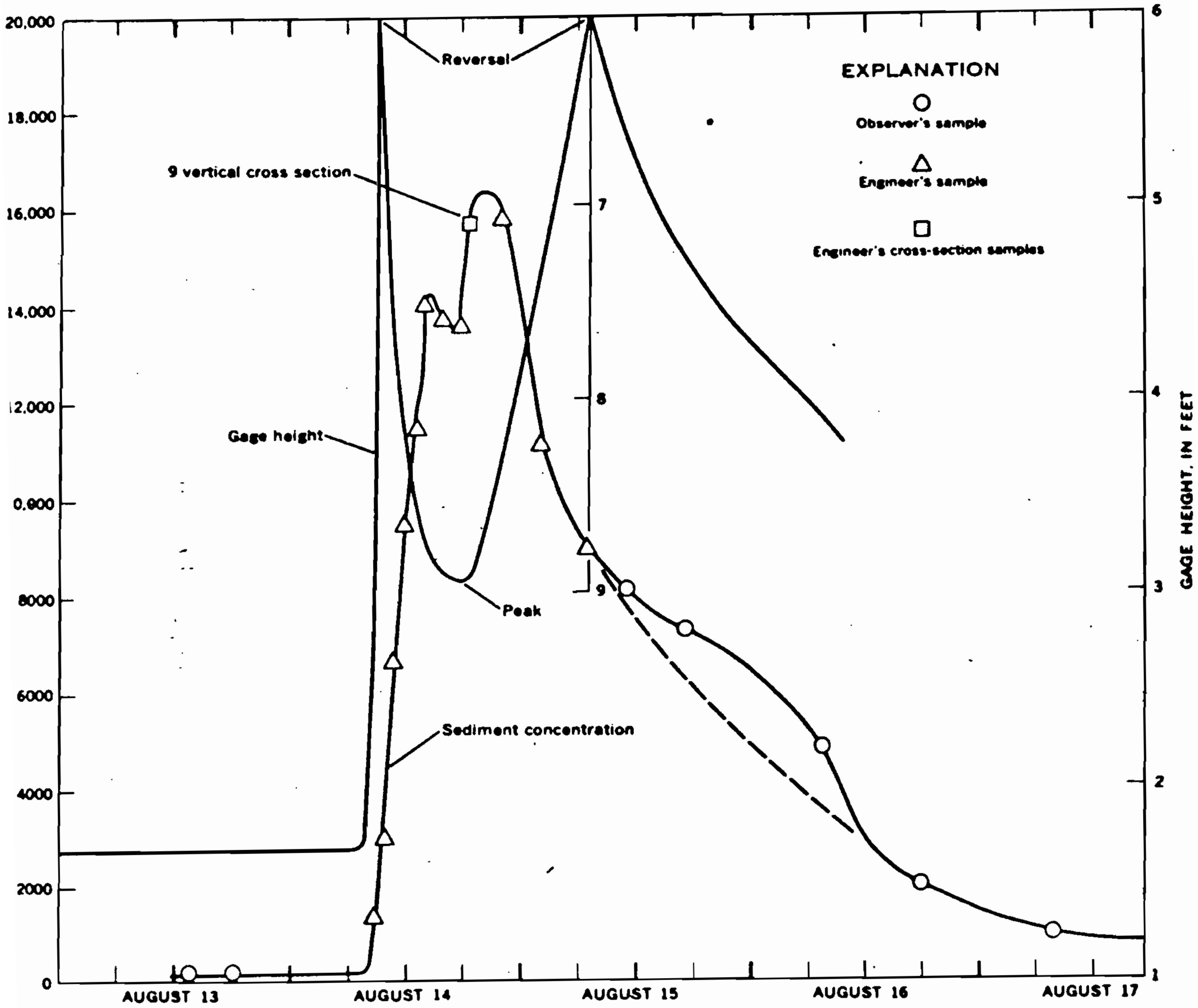


Figure 9 —Gage height and sediment concentration, Colorado River near San Saba, Tex., August 13-17, 1951.

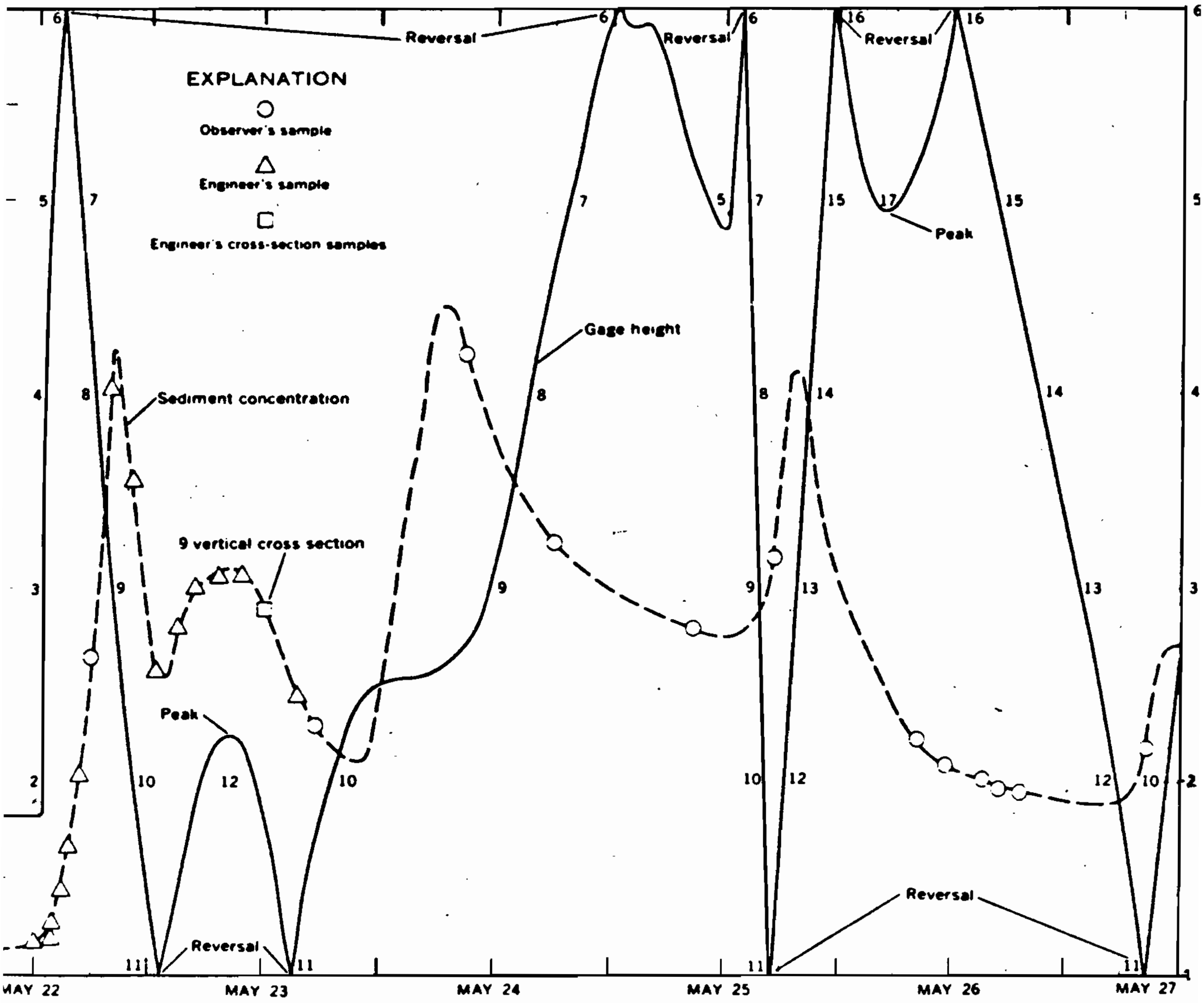


Figure 10—Gage height and sediment concentration, Colorado River near San Saba, Tex., May 22-27, 1951.

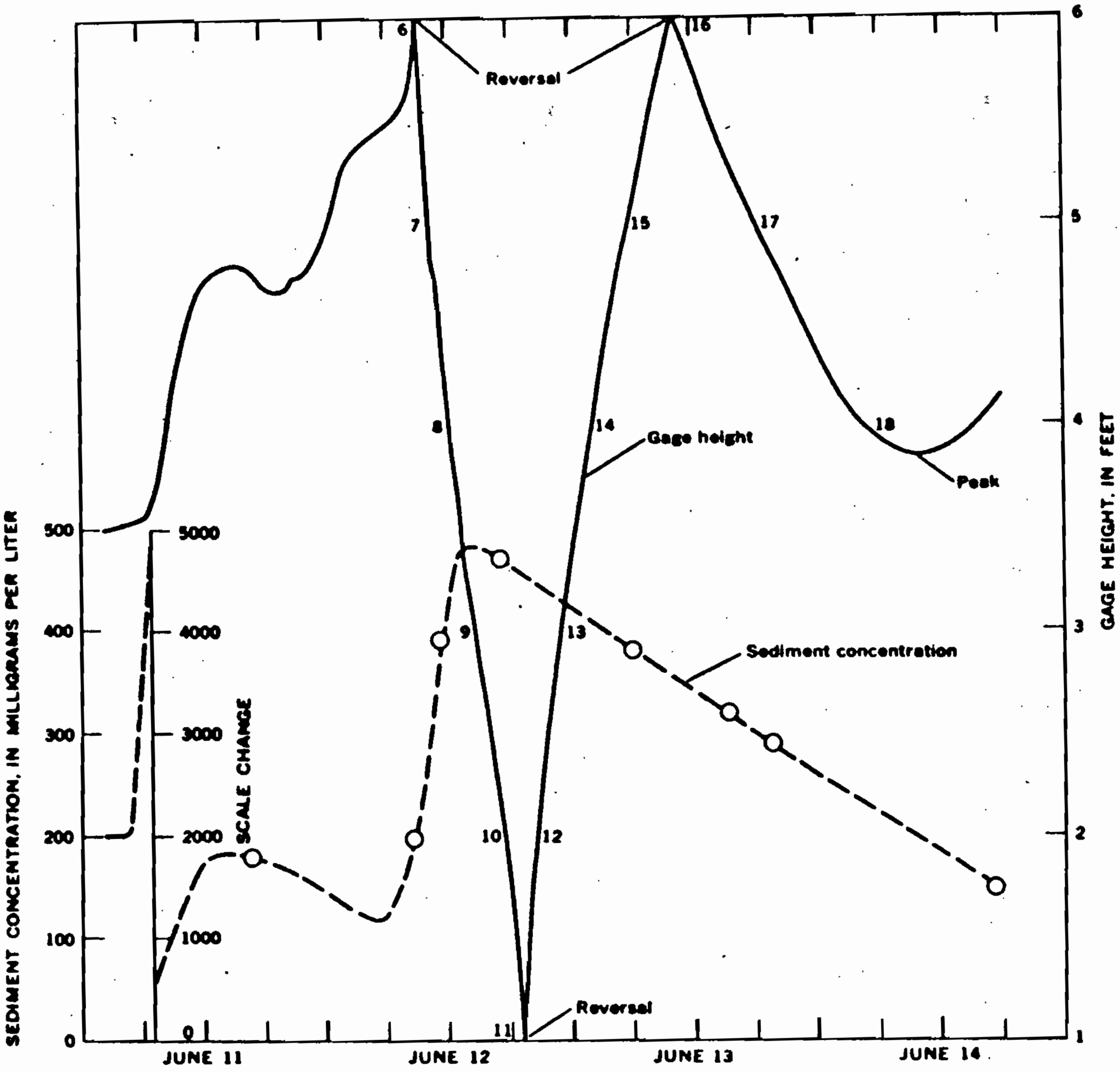


Figure 11—Gage height and sediment concentration, Colorado River near San Saba, Tex., June 11-14, 1951.

water reaches the station—in this instance, at about 1630 hours. Second, the water peak occurred about 24 hours after the first storm water reached the station, although the concentration peak occurred about 7 hours after the first storm water reached the station.

These graphs illustrate that, for this station, the concentration peak usually precedes the water peak and indicate that, by a comparison of the initial peaks in figures 8-11, the longer the time period between the first arrival of storm water and the storm peak, the longer the time interval between the concentration peak and water peak. Or, conversely, the concentration peak occurred about 7 hours after the initial storm water reached the station, even though the time interval between the initial storm water reaching the station and the water peak increases. Although this time interval (7 hours) should not be considered a firm rule at this station, it could be used in conjunction with the general shape of the concentration curve shown in figure 19 to describe adequately the curves in figures 8-11 even though only two samples had been collected each day.

The May 1-6 rise (fig. 8) has a near

classic hydrograph recession; however, the concentration graph fails to follow the classic pattern. The sediment recession seems normal until 1800 hours May 2, after which the concentration increases and is somewhat above the normal recession curve until about 1200 hours May 5. For purposes of illustration, a normal concentration recession line was estimated for May 2-5 and is represented by a dashed line. The sediment represented by the difference in the estimated graph and the graph based on samples probably was introduced into the main stem by inflow from a small storm on one or more tributaries in the lower part of the basin. The tributary flow contained a higher concentration of suspended sediment than the river, but the water discharge was insufficient to be noticed on the stage record. The effect of various sediment sources superimposed on one hydrograph is more pronounced in the examples to follow.

The period August 13-17, 1951 (fig. 9), has a hydrograph similar to that previously discussed (fig. 8), and runoff apparently came from one source. Correspondingly, the sediment-concentration graph would be expected to have a single rise and characteristic recession. The sediment samples indicate, however, that possibly three major sources of water and suspended material combined to form the single water peak. The initial concentration peak occurred about 4 hours prior to the water peak. Then a tributary flow of higher concentration combined with the initial flow and caused a secondary, and higher, concentration peak. Evidence of a third source of material is indicated by the change in recession rate of concentration about 0300-0800 hours August 16. Finally, on August 16 the sediment concentration dropped abruptly to a level that may have occurred August 15 had the flood peak contained water and sediment from only one source.

The graphs for May 22-27, 1951 (fig.10), indicate the effect of several peaks produced from several rainstorms or from drainage of several subbasins, or from both. The first increase in discharge was rapid, and the initial concentration peak was conventional, although the peak concentration was not as high as that previously experienced (fig. 9). The difference between this graph and those in the previous examples may be the result of different antecedent conditions in the basin or sediment from a different subbasin. The second concentration peak superimposed on the original sediment recession could not be predicted from the gage-height trace. The third concentration peak may be anticipated because of the abrupt decrease in rate of recession about 2200 hours May 23. The fourth concentration peak, that of May 25, apparently follows the characteristic pattern. The fifth peak (May 27) could not be anticipated from study of the hydrograph and may have been caused by small downstream tributary flow or more likely by bank sloughing which followed the extensive period of high flow.

The period June 11-14 (fig.11) has a higher water discharge than the preceding examples and a longer delay time between arrival of the first floodwater and the peak discharge, as usually characterized by long periods of general low-intensity rainfall. The sediment concentrations are lower than in the preceding examples. The low concentration may be attributed to antecedent conditions caused by the May storms or, more likely, to the less intense rainfall but longer duration of the June storms.

The examples discussed previously demonstrate some of the variations in concentration graphs that may be expected in a large basin when the runoff events are produced in upstream tributaries of diverse characteristics by isolated rainfall of short duration and high intensity. Figure 12 illustrates a storm event on a large stream, Susquehanna River at Harrisburg, Pa. (drainage area, 62,400 square km), that drains a basin consisting of three major physiographic provinces with generally good vegetal cover. The March 3-14 flood was caused by intermittent rainfall that occurred March 2-10 throughout the State. The sediment concentration started to increase with the increase in water discharge, unlike the example in

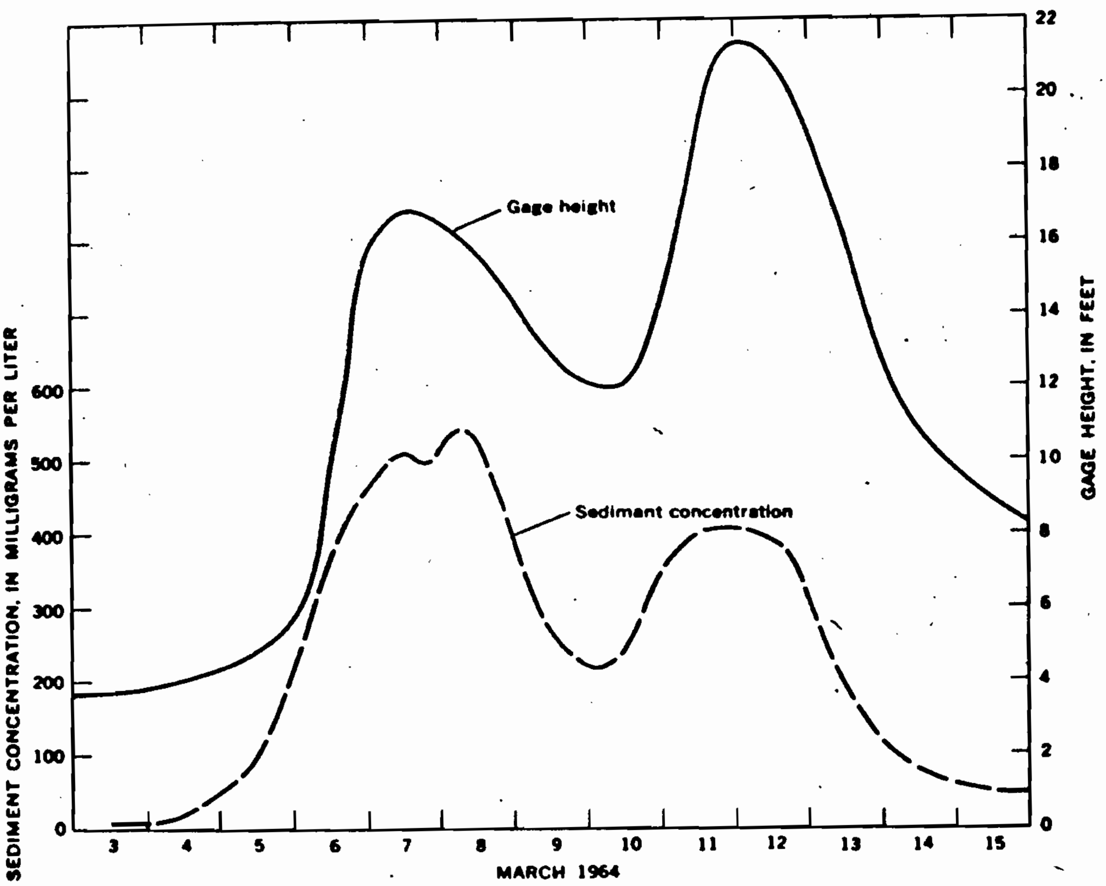


Figure 12—Gage height and sediment concentration, Susquehanna River at Harrisburg, Pa.

figure 8 , because the source area of the water and sediment was local as well as upstream and the concentration continued to increase until the discharge started to decrease. Even so, there was a small secondary concentration peak March 8. The second water-discharge peak on March 11-12, although higher than the first peak, had a lower concentration because less soil was readily available for erosion after the first few days of rain.

The hydrograph of the discharge and suspended-sediment concentrations of the Willamette River at Portland, Ore., during the recordbreaking floods of December 1964 (fig. 13) is a good example of the relation between discharge and concentration for a large flood on a large river. The discharge continued to increase for 4 days until it reached a peak. Sediment concentration, however, reached the maximum value the second day following the beginning of the rise and decreased over 50 percent by the time the water discharge reached a maximum value. Several common characteristic trends may be noted here: (1) The large increase in discharge at the outset caused a minor increase in concentration, (2) the discharge increased slowly for several days to reach a maximum value whereas the concentration increased rapidly and reached a maximum value, in less time, and (3) the water discharge receded slowly, being sustained by additional rainfall and contributions from bank and channel storage, whereas the concentration receded rapidly after reaching the maximum value.

Figure 14 presents both the hydrograph and the concentration graph concerning the Ciujung river at Rangkasbitung for the 20th, 21st and 22nd of December 1978. Though no data are available about concentrations during the rising stage on the 20th it can readily be seen that for the same range of water levels, concentrations can be completely different. The second water discharge peak on December 22 is in fact partly dependent on the first peak which occured on the 21st so concentrations are lower for the same range of water discharges, the same can be said about the peak on the 23rd. So the shape of the concentration graph for complex flood is completely different from the single peak flood concentration graph.

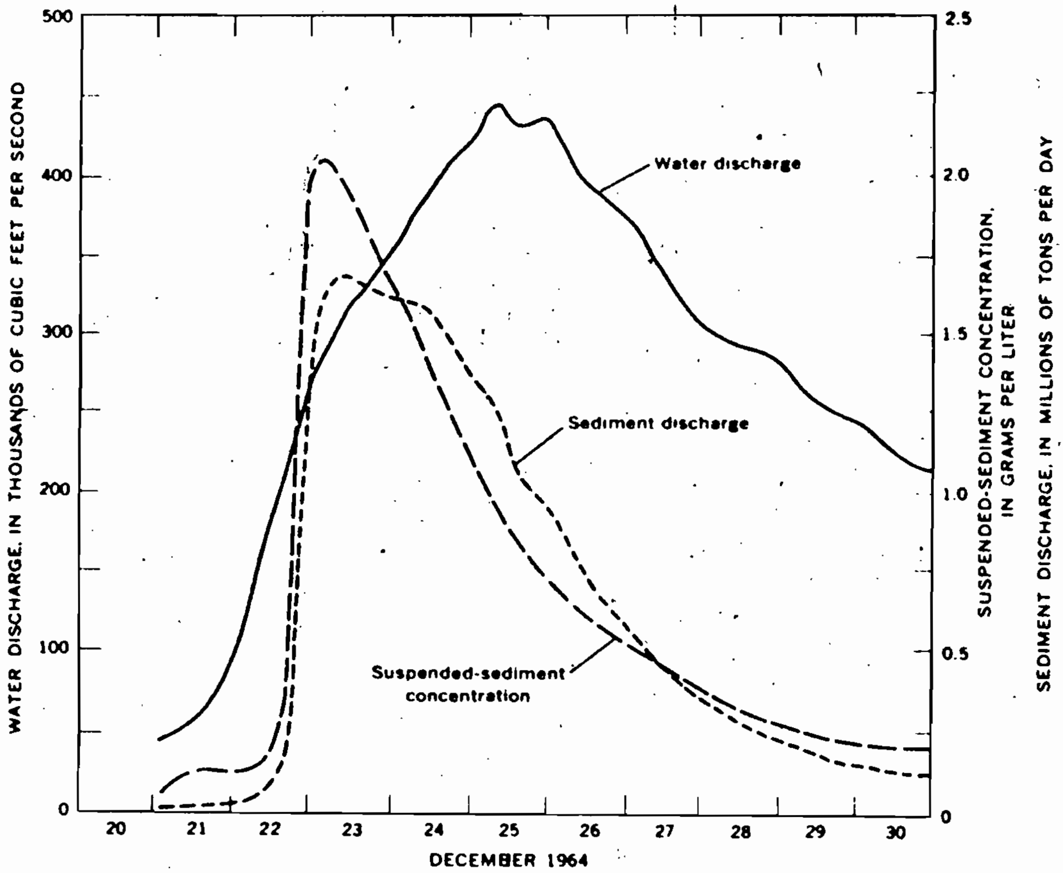


Figure 13 –Suspended-sediment concentration, sediment discharge, and water-discharge, Willamette River at Portland, Oreg., December 21-30, 1964. (After Waananen and others, 1971, p. 116.)

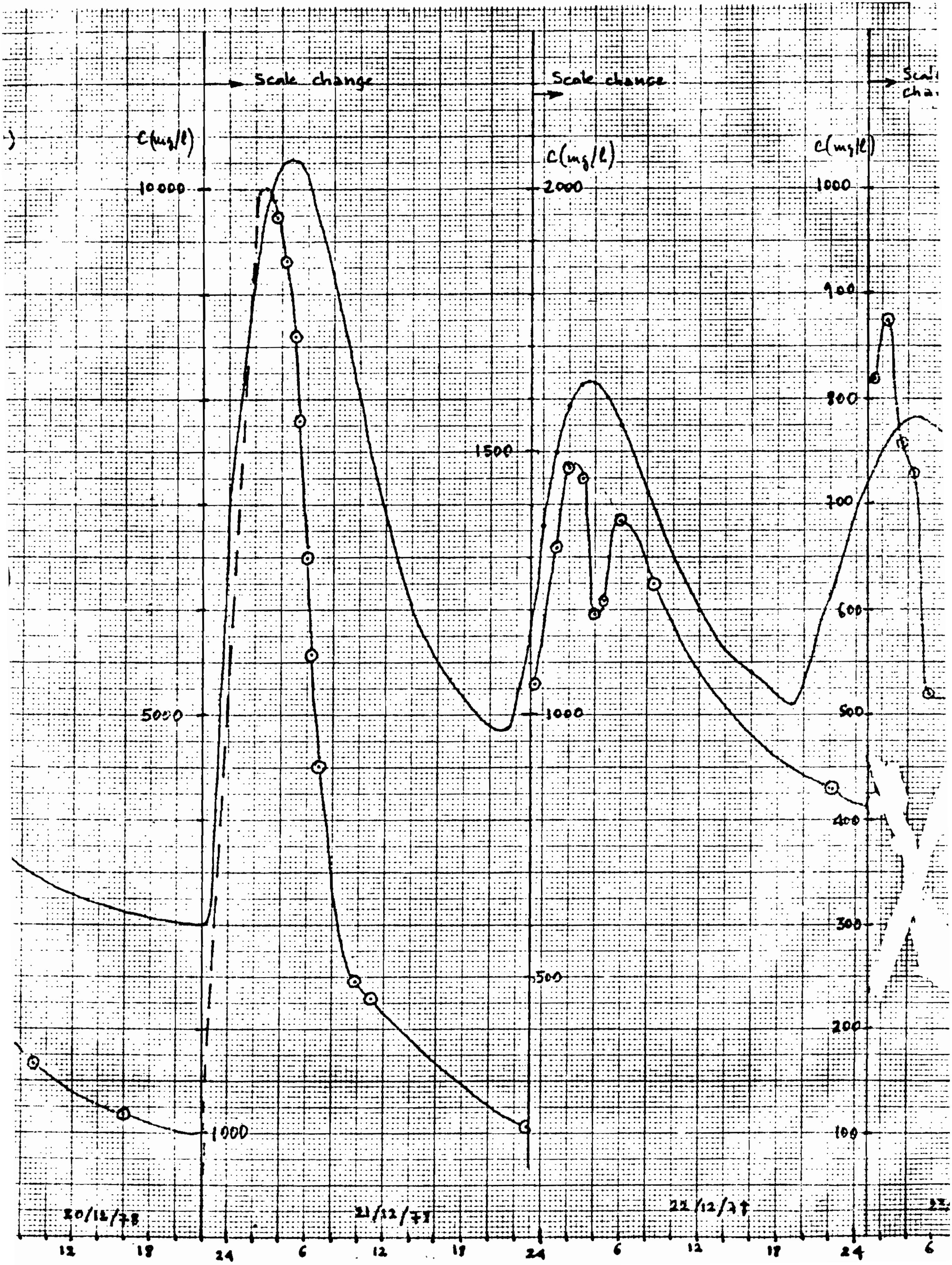
CIUJUNG (RANGKASBITUNG) FIG. 14

Hydrograph and concentration graph - From 20/12/78 to 23/12/78

———— Gauge Height versus time

—●—●— Concentration versus time

Scale changes to the concentration graph so as to enable to read the graph with sufficient accuracy (at least 2 significant figures)



4. COMPUTATION OF DAILY SEDIMENT DISCHARGE

At a given time the instantaneous sediment discharge is defined as the product of the concentration and the water discharge, namely,

$$Q_{si} = k\,c\,Q \qquad (1)$$

as mentioned previously when concentrations are expressed in milligrams per liter (mg/l) and water discharges in cubic meters per second (m^3/s) the conversion factor, k , is equal to 0.0864 and sediment discharges are reported in metric tons per day (ton/day).

Let us assume that for a given time interval denoted, Δt_i, the mean concentration and mean water discharge are known, let us denote them c_i and Q_i respectively, during that time interval, for instance, expressed in hours, the suspended load in tons is equal to :

$$Q_s = \frac{0.0864\ c_i\ Q_i}{24}\ \Delta t_i \qquad (3)$$

Let us go further and assume that a given day is subdivided in time intervals denoted, Δ_1 , Δ_2, . . ., Δ_i, ... Δ_n and such that :

$$\sum_1^n \Delta t_i = 24 \quad \text{(hours)}$$

then the suspended load for the whole day will be the sum of the loads for each time interval and so we get :

$$Q_s = \sum_1^n \frac{0.0864\ c_i\ Q_i}{24}\ \Delta t_i \qquad (4)$$

Computation of daily sediment discharges requires subdivision of the day when both water discharges and concentrations are changing. A common source of error consists in multiplying the daily mean concentration and the aily mean water discharge to obtain the daily sediment discharge, this procedure is not correct since the average of the products of two variable quantities is not the same as the product of the averages of the quantities. Subdivision is not required if either discharge or concentration is constant during the day.

The daily mean water discharge is expressed in the form of a finite sum by :

$$\bar{Q} = \frac{1}{24} \sum_{1}^{n} Q_i \Delta t_i \qquad (5)$$

and the daily mean concentration by :

$$\bar{c} = \frac{1}{24} \sum_{1}^{n} c_i \Delta t_i \qquad (6)$$

where Δt_i is in hours

and it is obvious that if both Q_i and c_i are not constant

$$Q_s = \sum_{1}^{n} \frac{0.0864 \; c_i \; Q_i}{24} \Delta t_i$$

is not equal to $0.0864 \times \bar{Q} \times \bar{c}$.

When subdividing a day, variations of both water discharge and concentration should be taken into account. Quite often a subdivision adequate for water discharge may not be so for sediment discharge.

Let us illustrate the foregoing with an example. On the 21st of December 1978 at Rangkasbitung (see fig. 14) changes in concentration and water discharges are described in the following table 1. See Annex at the end for the stage-discharge rating curve.

Table 1

Ciujung at Rangkasbitung

Clock Time (t)	Time Interval (Δ t)	Gauge Height (H)	Water Discharge (Q)	Sediment Concentration (C)	Q x C x Δ t
0	0.5	280	219	(5200)	569 400
1	1.0	326	285	(7500)	2 137 500
2	1.0	366	349	(9500)	3 315 500
3	1.0	392	393	(10000)	3 930 000
4	1.0	409	423	9600	4 060 800
5	1.0	411	427	8500	3 629 500
6	1.5	402	411	6500	4 007 250
8	2.0	368	352	3300	2 323 200
10	2.0	320	276	2450	1 352 400
12	2.0	278	216	2150	928 800
14	2.0	242	170	1900	646 000
16	3.0	220	144	1700	734 400
20	2.5	197	118	1250	368 750
21	1.0	196	117	1150	134 550
22	1.0	205	127	1000	127 000
23	1.0	232	158	1050	165 900
24	0.5	272	208	1150	119 600
Total 24					28 550 550

We use to compute the sediment discharge the so-called midinterval thod which assumes the values of the water discharge and sediment concen- ation for a specific time represent the average values for the time inter- l that extends ahead and behind halfway to the preceding and following clock mes. This amounts to using the "trapezoidal rule" also called "midsection thod" when computing water discharges.

So we obtain for the daily sediment discharge

$$Q_s = \frac{0.0864}{24} \sum_{1}^{17} Q_i \; C_i \; \Delta t_i$$

after rounding off to 3 significant figures

$$Q_s = 103\ 000 \text{ tons}$$

for the daily mean water discharge we obtain :

$$\bar{Q} = \frac{1}{24} \sum_{1}^{17} Q_i \Delta t_i$$

$$\bar{Q} = 244 \text{ m}^3/\text{s}$$

and for the daily mean concentration :

$$\bar{C} = \frac{1}{24} \sum_{1}^{17} C_i \Delta t_i$$

$$\bar{C} = 3710 \text{ mg/l}$$

If subdivision is not used, then daily sediment discharge would be

$$Q_s = 0.0864 \times \bar{Q} \times \bar{C} = 78200 \text{ tons}$$

o the error caused by not subdividing is 24800 tons, that is, -24 percent.

In the following table the same day is subdivided in equal time interals of 6 hours.

Clock Time (t)	Time Interval (Δ t)	Gauge Height (H)	Water Discharge (Q)	Sediment Concentration (C)	Q x C x Δt
3	4	392	393	(10000)	3 930 000
9	4	344	313	2750	860 750
15	4	230	155	1800	279 000
21	4	196	117	1150	134 550
Total		1162	978	15700	5 204 300

Since time intervals are constant we obtain for the daily sediment ischarge

$$Q_s = \frac{0.0864}{4} \sum_1^4 c_i Q_i = 112\ 000 \text{ tons}$$

or the daily mean water discharge

$$\bar{Q} = \frac{1}{4} \sum_1^4 Q_i = 245 \text{ m}^3/\text{s}$$

or the daily mean concentration

$$\bar{C} = \frac{1}{4} \sum_1^4 c_i = 3930 \text{ mg/l}$$

Though the foregoing subdivision is quite adequate for the computation f the daily mean water discharge it gives rise to a 9 per cent.error in the omputation of the daily sediment discharge.

The matter of units is sometimes confusing, for instance, to express nstantaneous sediment discharges in tons per day, however this is only a atter of habit.

When a day is subdivided, the cross-section coefficient should be ap- lied, if need be, prior to computing concentration values from the concentra- ion graph,in particular when the coefficient may change with stage.

In fig. 15 the concentration graph is adjusted graphically by using he coefficient values determined in the plot in fig. 2 . For instance, for gauge height of 29 feet the cross-section coefficient is 1.12 so the cor- esponding concentration, that is, 360 mg/l is multiplied by 1.12 and the esulting concentration is 403 mg/l rounded off to 400 mg/l, the same is done or several points and a new adjusted sediment concentration graph is drawn. bviously when the cross-section coefficient is constant there is no need to orrect individual value of concentrations but the coefficient may be applied irectly to the sediment discharge.

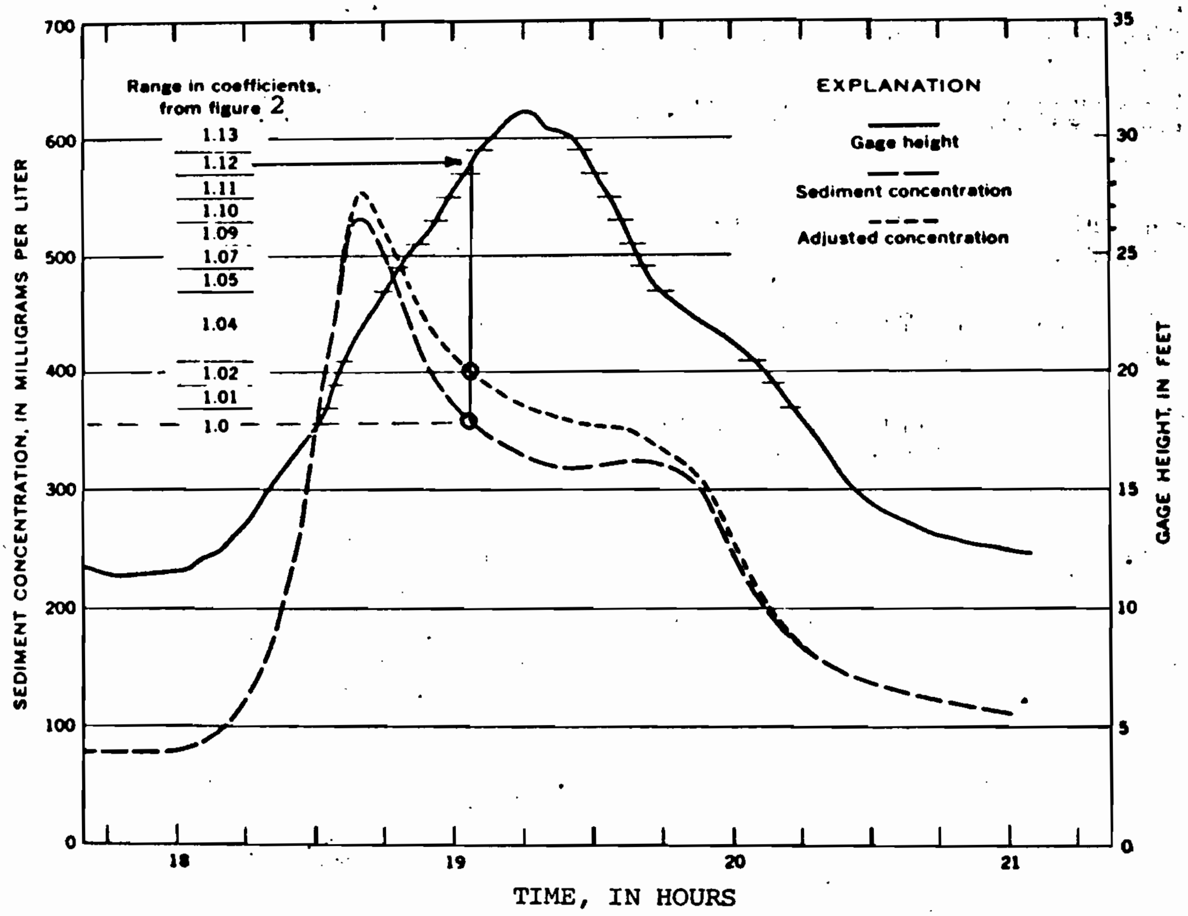


Figure 15—Graphical adjustment of concentration.

5. RATING CURVE TECHNIQUE

In the absence of financial and/or labour resources sufficient to maintain an intensive sampling programme, or where the rapidly fluctuating response of a basin would make such a programme impractical, resort is often made to the use of sediment rating curves.

A suspended sediment rating curve is usually presented in one of two basic forms, either as a suspended sediment concentration versus water discharge or a suspended sediment discharge versus water discharge relationship. In both cases a logarithmic plot is commonly used with a least-squares regression employed to fit one or several straight lines through the scatter of points assuming a relation such as :

$$Q_{si} = a\,Q^{n} \qquad (7)$$

Figure 16 clearly demonstrates, what was to be expected, that there apparently does not exist a simple relationship between suspended sediment and discharge

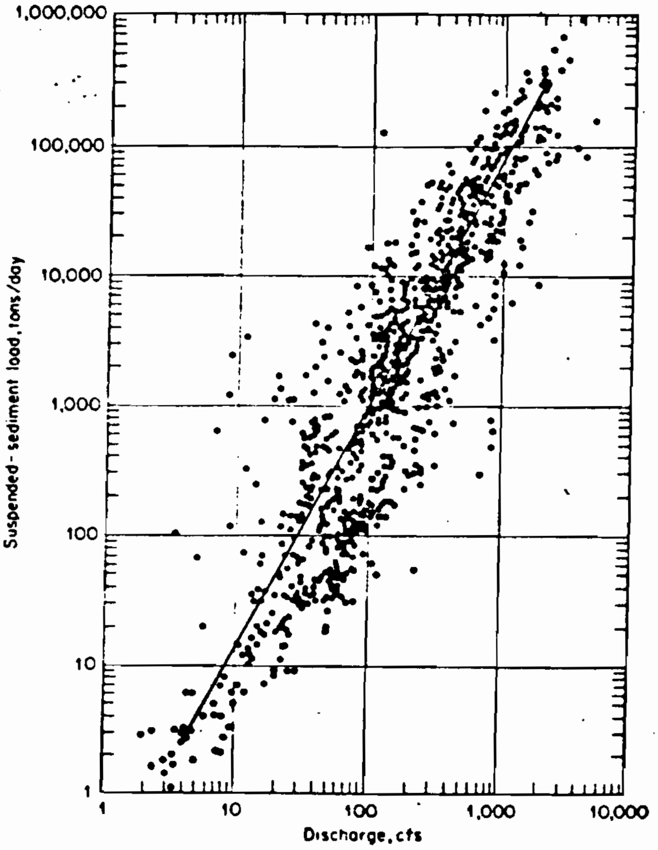


Fig. 16 Suspended-material-rating curve for the Powder River. [*After* LEOPOLD *et al.* (*1953*).]

and that for a given level of discharge the suspended sediment loads range up to two orders of magnitude. The rating plot being a univariate expression it cannot be expected to describe a complex multivariate system and that accounts for the scatter of points.

An obvious explanation is that a given flow rate may be a result of different hydrologic events which in turn could bring about different suspended-sediment loads.

Although apparently simple in concept, critical evaluation of the data, careful application of the technique and appreciation of its limitations are required if the approach is to be used effectively.

A serious source of error is the use of daily mean discharges to calculate sediment loads. We quote Colby (1956):

> "an instantaneous sediment rating curve is theoretically not applicable to the direct computation of daily sediment discharges from daily water discharges except for days on which the rate of water discharges is about constant throughout the day"

Studies carried out by Walling (1979) show that underestimation errors of up to 50 per cent may be involved by using of daily mean discharges instead of using instantaneous discharges.

From a mathematical point of view the foregoing is obvious. If we assume that formula (7) holds true the daily mean sediment discharge is defined as :

$$\bar{Q}_{s\ day} = \frac{1}{T}\int_0^T A\, Q^n dt \qquad \text{T expressed in the proper unit} \quad (8)$$

and the mean daily water discharge as :

$$\bar{Q} \doteq \frac{1}{T}\int_0^T Q\ dt$$

and unless Q is constant throughout the day we have the inequality

$$Q_s = \frac{1}{T} \int_0^T A Q^n \, dt \neq A \left[\frac{1}{T} \int_0^T Q \, dt \right]^n$$

Let us resume the example of the Ciujung River at Rangkasbitung on the 21st and 22nd of December 1978. Though the number of data is far too small and the range of runoff events taken into account is not by far large enough it is interesting to compare the results obtained through the rating curve technique with those found previously when using the concentration graph.

So that not to underestimate the suspended load during high flows two formulae are adopted as illustrated in fig. 17 :

for $H \leqslant 3.10$ m or $Q \leqslant 260 \text{ m}^3/\text{s}$ $\quad c = 0.191\, Q^{1.58}$

for $H \geqslant 3.10$ m or $Q > 260 \text{ m}^3/\text{s}$ $\quad c = 32 \left(\frac{Q}{100}\right)^{3.81}$ (Q in m^3/s) (c in mg/l)

So we obtain for Q_s in tons/day :

$H \leqslant 3.10$ $\quad Q_s = 0.0165\, Q^{2.58}$

$H > 3.10$ $\quad Q_s = 276 \left(\frac{Q}{100}\right)^{4.81}$

and taking into account the functional adjustment of the stage-discharge relationship (see Annex at the end), that is :

$0.40 < H \leqslant 1.02$ $\quad Q = 35.2\, H^{2.19}$

$1.02 < H \leqslant 4.60$ $\quad Q = 36.3\, H^{1.74}$

We can express, Q_s , in the following form as a function of H :

$1.02 < H \leqslant 3.10$ $\quad Q_s = 175\, H^{4.50}$

$3.10 < H \leqslant 4.60$ $\quad Q_s = 2.11\, H^{8.37}$

So on December the 21st if the day is subdivided in 6 intervals of 4 hours each we obtain :

Clock - time	Gauge height	Q_{si}
2	3.66	109804
6	4.02	240799
10	3.20	35677
14	2.42	9337
18	2.07	4623
22	2.05	4425
	Σ	404665

$$Q_s = \frac{\Sigma Q_{si}}{6} = 67000 \text{ tons}$$

Assuming that 103000 tons in the real sediment discharge the error is in the region of - 35 per cent, however if the sediment rating curve is applied directly to the mean water discharge for this day we have :

$$Q_s = 0.0165\ (244)^{2.58} = 24000 \text{ tons}$$

that is, an error of nearly -80 per cent

Likewise on December the 22nd we have :

Clock - time	Gauge-height	Q_{si}
3	3.25	40621
9	2.72	9154
15	2.20	6080
21	2.30	7427
	Σ	63282

$$Q_s = \frac{\Sigma Q_{si}}{4} = 16000 \text{ tons}$$

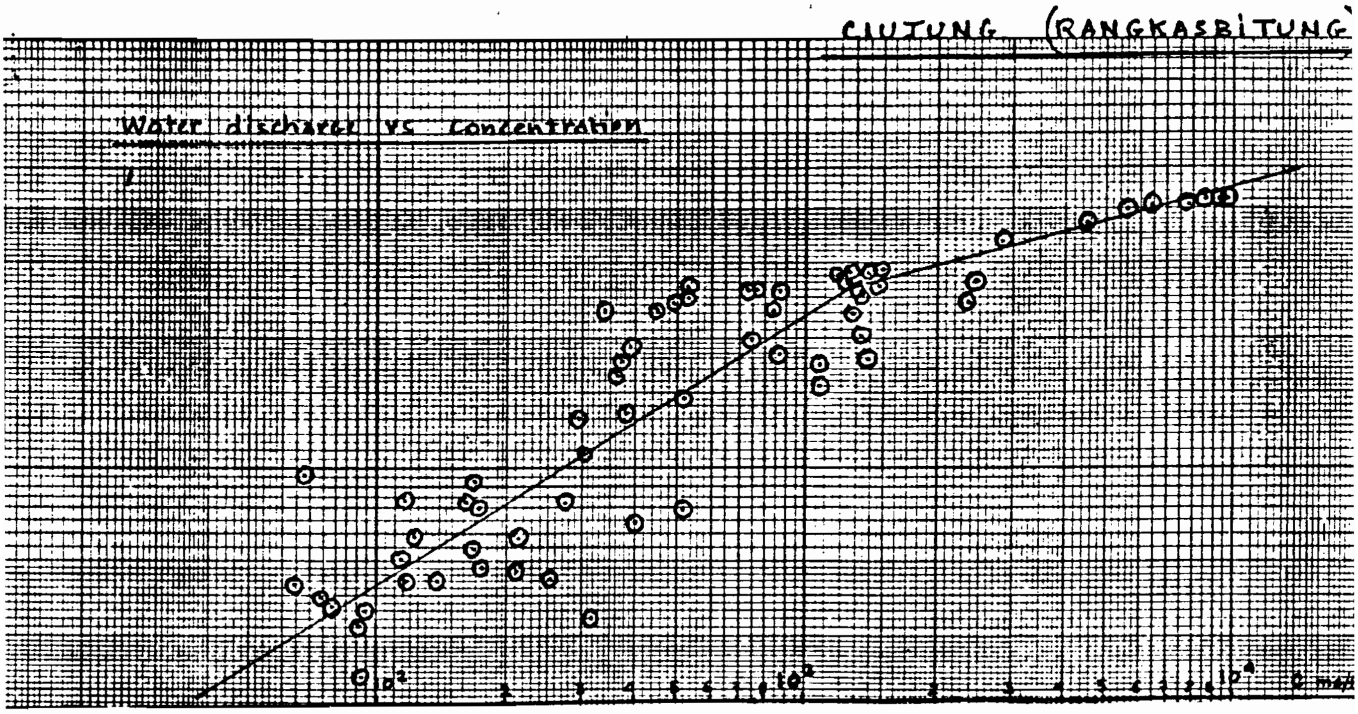
The resultant error is -18 per cent and by using the daily mean water ischarge we have :

$$Q_s = 13000 \text{ tons}$$

hat is, a -33 per cent error.

The errors are less serious on the 22nd of December since the variaions of water discharges are smaller than on the 21st.

FIG 17



ote : Although the break in slope is somewhat arbitrary in fig.17 the formula for $Q > 260$ m³/s is on the conservative side since the samples were taken during the falling stage of the flood.

To make the rating curve scatter less serious the data may be subdided, for example according to season and rising or falling stage which are ite often major causes of the scatter. In some cases correlations may be eatly improved by subtracting the base flow from the water discharge.

Sometimes a storm-by-storm analysis may be carried out, that is, sediment rating curves are drawn for individual storms.

Flow-duration curves have been widely used with sediment rating curves to compute the sediment load. The basis of this method is to obtain the average runoff rates for a series of duration increments and to apply these to the rating curve to determine the associated sediment concentration or load. In order not to underestimate the loads, small discharge intervals should be used particularly at high discharges where small inaccuracies could lead to significant errors, however larger increments can be employed where the duration curve is near horizontal. Two standard tables of duration increments are presented in table 2 . The use of flow-duration curves shortens the computation time but is less accurate that to subdivide the day and compute intantaneous sediment discharges.

In conclusion, we may say with Porterfield that whatever the way of applying the sediment rating curve technique "Data must be available for a number of adequately defined hydrographs representing a range of flow and seasons to insure reasonable success with these methods", in particular that was not the case with the example of the Ciujung River at Rangkasbitung In any case the sediment rating curve can only be expected to yield approximate annual sediment loads, however estimation of monthly loads are not significant, let alone daily loads.

TABLE 2 Duration curve intervals utilized by Miller (1951) and Piest (1964) for calculating sediment loads

Miller % limits		Piest % limits	
100 - 99.98	*cont:*	100 - 96.0	*cont:*
99.98 - 99.90	1.5 - 0.5	96.0 - 91.0	4.0 - 3.0
99.9 - 99.5	0.5 - 0.1	91.0 - 85.0	3.0 - 2.0
99.5 - 98.5	0.1 - 0.02	85.0 - 75.0	2.0 - 1.4
98.5 - 95.0	0.02 - 0.00	75.0 - 65.0	1.4 - 1.0
95.0 - 85.0		65.0 - 55.0	1.0 - 0.8
85.0 - 75.0		55.0 - 45.0	0.8 - 0.6
75.0 - 65.0		45.0 - 35.0	0.6 - 0.4
65.0 - 55.0		35.0 - 25.0	0.4 - 0.2
55.0 - 45.0		25.0 - 19.0	0.2 - 0.1
45.0 - 35.0		19.0 - 13.0	0.1 - 0.08
35.0 - 25.0		13.0 - 9.0	0.08 - 0.06
25.0 - 15.0		9.0 - 7.0	0.06 - 0.04
15.0 - 5.0		7.0 - 5.0	0.04 - 0.02
5.0 - 1.5		5.0 - 4.0	0.02 - 0.00
contd.		*contd.*	

A word of caution about the least-squares method (and the use of the calculator)

It is a common pratice when using the least-squares method to give all the measurements an equal statistical weight in spite of the fact that most of the measurements available for defining the relation will always be located at the low and medium stages. Thus an extrapolation of the formula to the higher stages, where at best very few and usually no data are available, will be biased by the greater number of "low-lying" data points. It follows that the least-squares method should be done carefully and checked against other methods.

In particular, one has to plot the points prior to computing the coefficients in order to decide "by eye" if one or several straight lines have to be adjusted. Results given by a calculator must always be checked especially when working with a "program", especially if the line "computed" differs significantly from the line which would have been drawn by eye.

NNEX

rawing and Extension of the RANGKASBITUNG Rating Curve

The sediment unit may have to deal with a suspended sediment problem n a location without a gaging station. In that case, the staff will have to arry out not only sampling operations but water discharges measurements as ell and furthermore to establish the rating curve. An example is presented ere (fig. 18 to 22).

We employed the Stage-Velocity-Area method which consists in dealing eparately with cross-section area and mean velocity as functions of gage eight. To justify the method it is supposed on hydraulical grounds that he relation between mean velocity and gage height is simpler than the stage/ ischarge one and therefore the drawing and extension of a line through and eyond the scatter of points will be easier (Fig.20) with the stage/velocity rve than with the stage/discharge rating curve.

It is a common practice "to smooth" the rating curve by adjusting dis- arge differences for equal gage height increments so as to obtain increasing constant differences for increasing gage heights (mathematically this ounts to assuming that the first derivative of the stage discharge function an increasing or constant function of the gage height and in most cases it logical to think so). (Fig. 21)

The procedure can be summarized as follow :

1. Plot the discharge measurements versus gage heights on ordinary graph paper and fit a curve to the data points by visual estimation (Fig.18A, 18B)
2. With the drawing of the cross section (fig.19) compute the cross section area for different gage heights and draw the cross section area versus gage height curve
   A = fct (H)
3. Divide each discharge measurement by the corresponding cross section area which is taken on the curve drawn in step 2, so as to get the mean velocity. Plot

the velocity versus gage height points (ordinary paper) and fit a curve through the points (fig.20): $\bar{U}$ = fct (H)

4. Compute the discharge for a sufficient number of gage heights (with equal gage height increments) by multiplying the corresponding cross-section area (step 2) and the mean velocity taken on the curve drawn in step 3 (fig.18A, B) $Q = A\bar{U}$

5. For equal gage height increments calculate the differences between the discharges calculated in step 4 for successive gage heights (see Table in fig.18A, B). Plot these differences versus gage height and fit a curve through the points (fig. 21)

6. "Arrange" the discharges values so that differences for equal gage height increments fit the curve drawn in step 5

7. Plot the values found in step 6 and draw the corresponding curve on the same sheet of paper used for step 1 in order to compare with the curve drawn in step 1 and to make sure that no gross error was made while performing the steps 2 to 6

More detailed procedures are described in many books.

c.f. "Drawing and Extension of the Rating Curves in Different Condition of Stream Flow" by A. Muzet, DPMA Bandung.

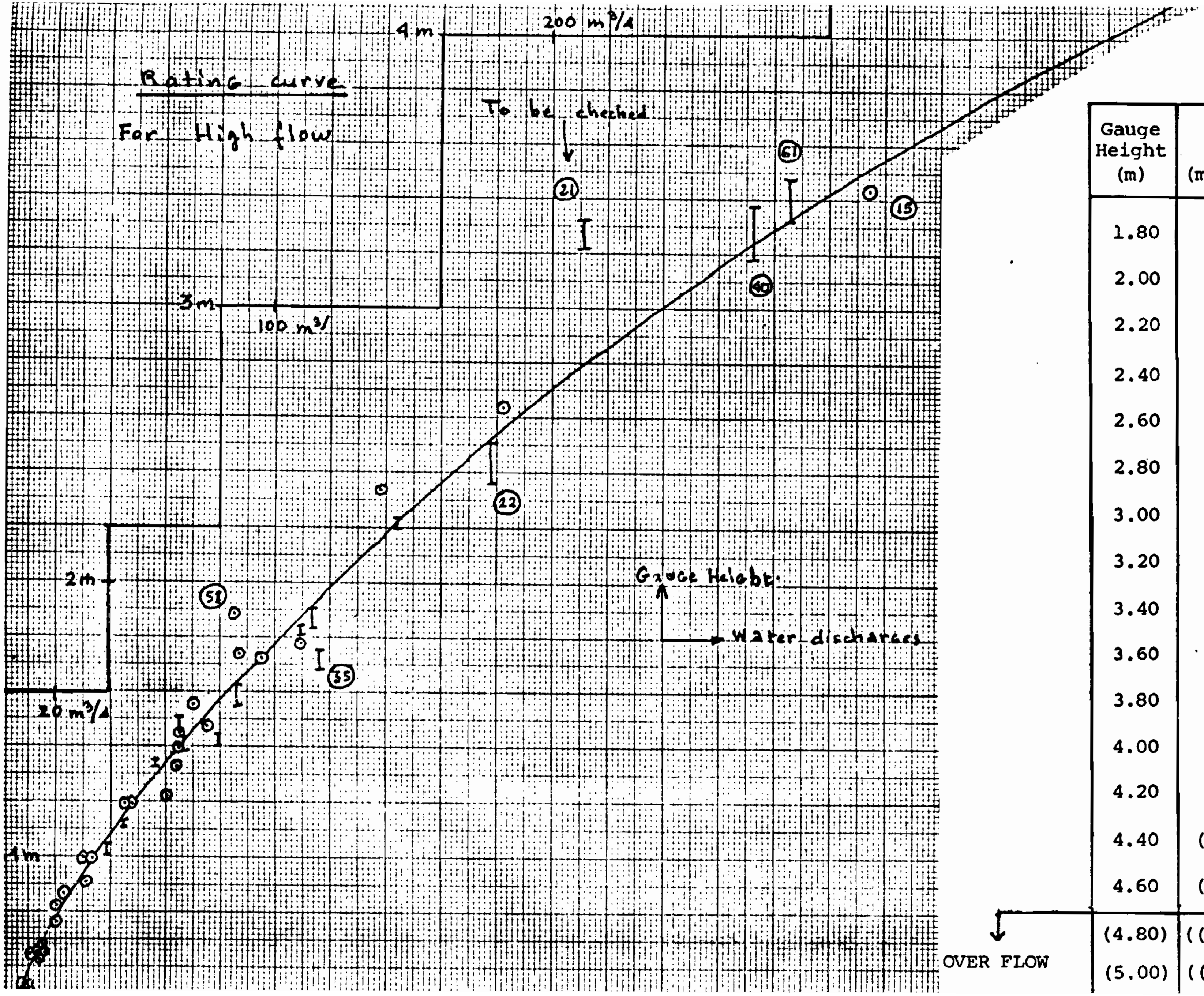
"Stage-Discharge Relations at Stream Gaging Stations" by Osten A. TILREM - Copy of this book is available at the Hydrometry Unit.

emark : Through plotting on a log-log paper it was found that the rating curve may be adequately defined by the following relationship, see fig. 22:

$0.40 < H \leq 1.02$ $Q = 35.2\ H^{2.19}$ H in meters

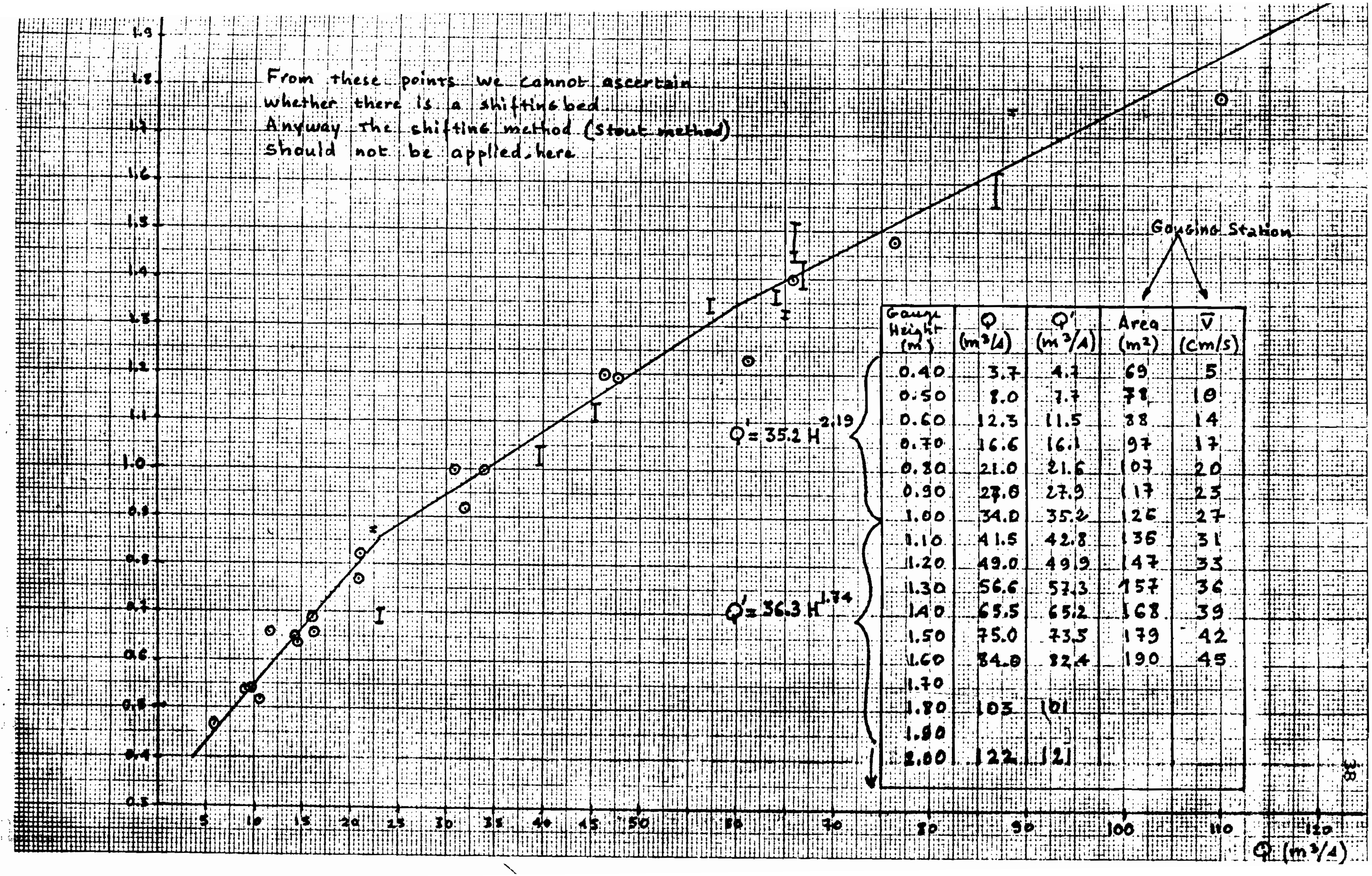
$1.02 < H < 4.60$ $Q = 36.3\ H^{1.74}$ Q in cubic meters per second

Using the foregoing formulae give rise to errors which are in any cases less than 3 percent for gauge heights beyond 1 meter. See tables in fig. 18A and 18B.



			Gauging Station		
Gauge Height (m)	Q – (m^3/s)	Q = $36.3H^{1.74}$	Area (m^2)	$\bar{V}$ (cm/4)	Δ ($m^3/$
1.80	103	101	211	49	
					19
2.00	122	121	232	53	
					20
2.20	142	143	254	56	
					22
2.40	164	167	276	59	
					23
2.60	187	191	297	63	
					25
2.80	212	218	319	66	
					27
3.00	239	246	341	70	
					28
3.20	267	275	363	74	
					30
3.40	297	305	386	77	
					32
3.60	329	337	408	81	
					34
3.80	363	370	431	84	
					36
4.00	399	405	453	88	
					37
4.20	436	441	476	92	
					39
4.40	(475)	478	500	95	
					41
4.60	(516)	517	523	99	
					42
(4.80)	((558))	556	(546)	(102)	
					45
(5.00)	((603))	597			

OVER FLOW



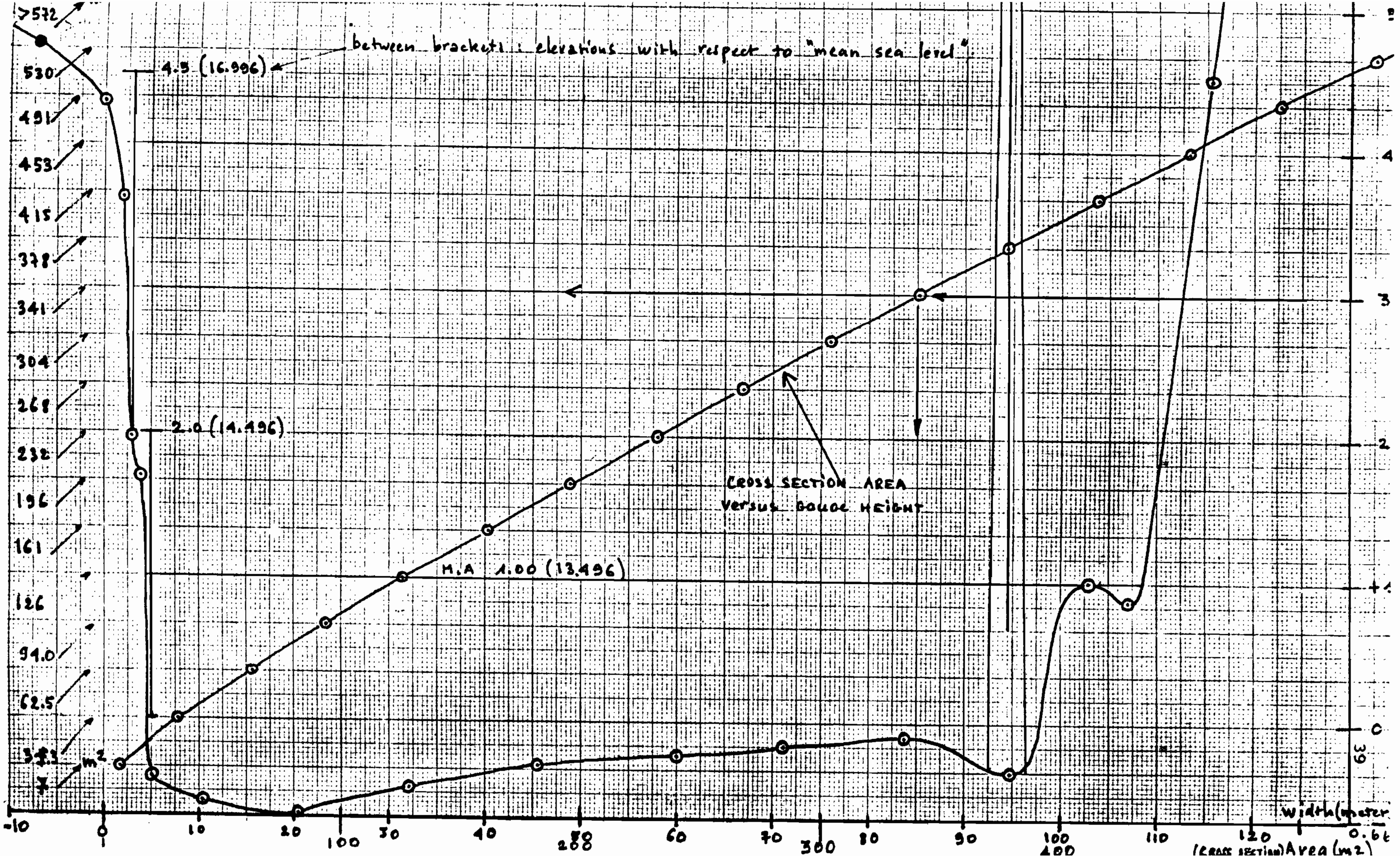
From these points we cannot ascertain
whether there is a shifting bed
Anyway the shifting method (Stout method)
Should not be applied here

$Q' = 35.2\,H^{2.19}$

$Q' = 36.3\,H^{1.74}$

Gauging Station

Gauge Height (m)	Q (m³/s)	Q' (m³/s)	Area (m²)	$\bar{V}$ (cm/s)
0.40	3.7	4.7	69	5
0.50	8.0	7.7	78	10
0.60	12.3	11.5	88	14
0.70	16.6	16.1	97	17
0.80	21.0	21.6	107	20
0.90	27.0	27.9	117	23
1.00	34.0	35.2	126	27
1.10	41.5	42.8	136	31
1.20	49.0	49.9	147	33
1.30	56.6	57.3	157	36
1.40	65.5	65.2	168	39
1.50	75.0	73.5	179	42
1.60	84.0	82.4	190	45
1.70				
1.80	103	101		
1.90				
2.00	122	121		


>572
530
491
453
415
378
341
304
268
232
196
161
126
94.0
62.5
33.3
7
m²
between brackets : elevations with respect to "mean sea level".
4.5 (16.996)
2.0 (14.496)
M.A 1.00 (13.496)
CROSS SECTION AREA versus GOUGE HEIGHT
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
100
200
300
400
width (meter
(cross section) Area (m2)
0.6t
39
0
1
2
3
4
5

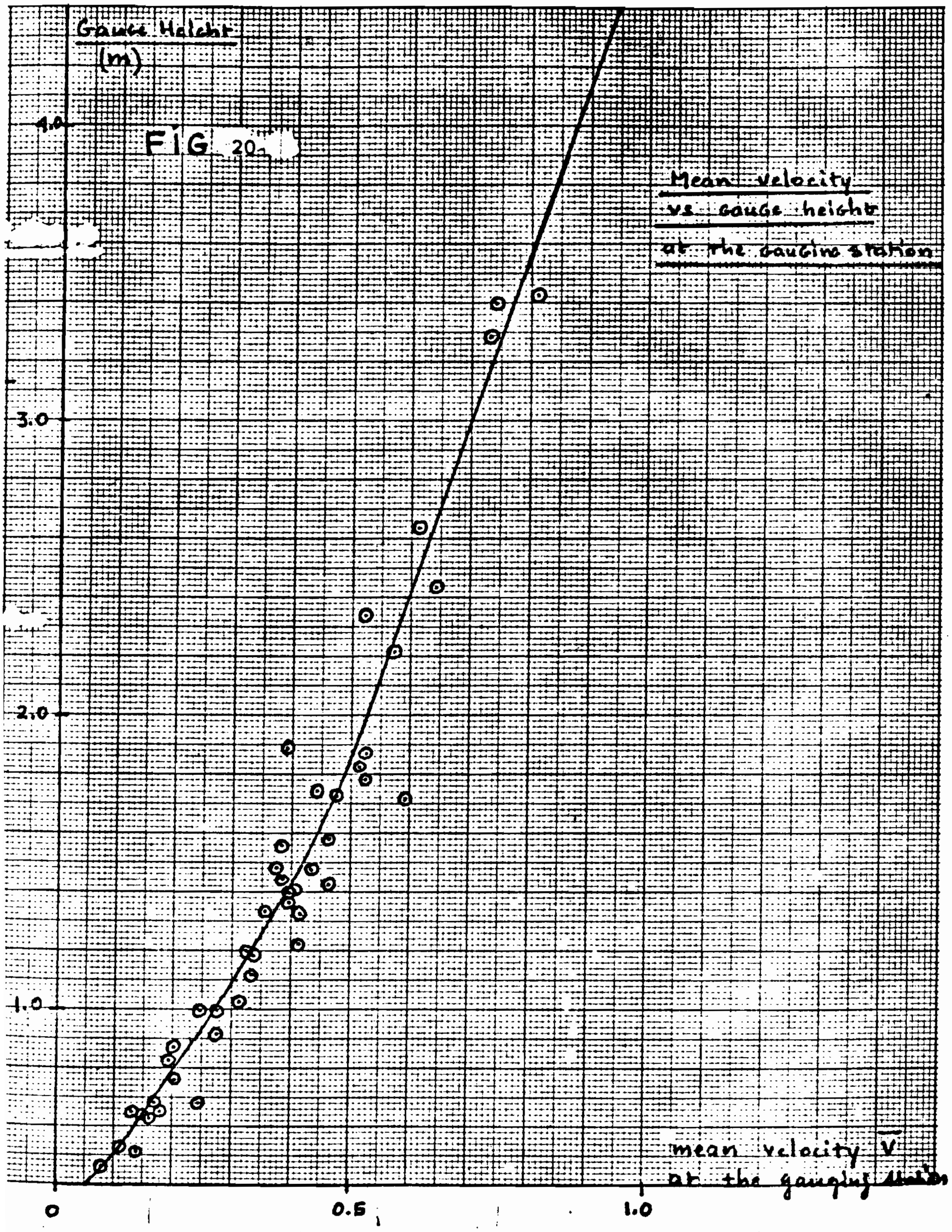


FIG 20

Mean velocity vs gauge height at the gauging station

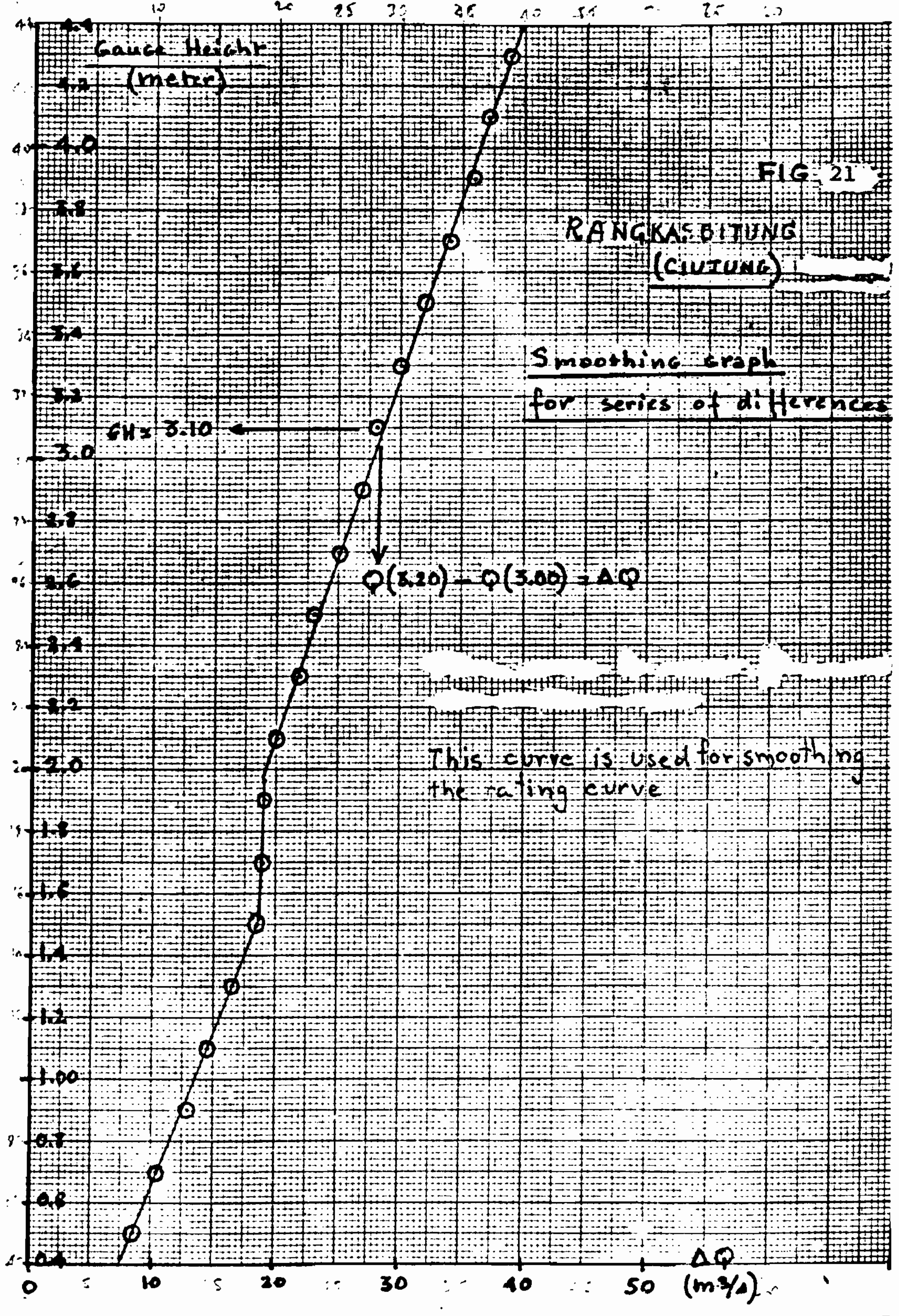
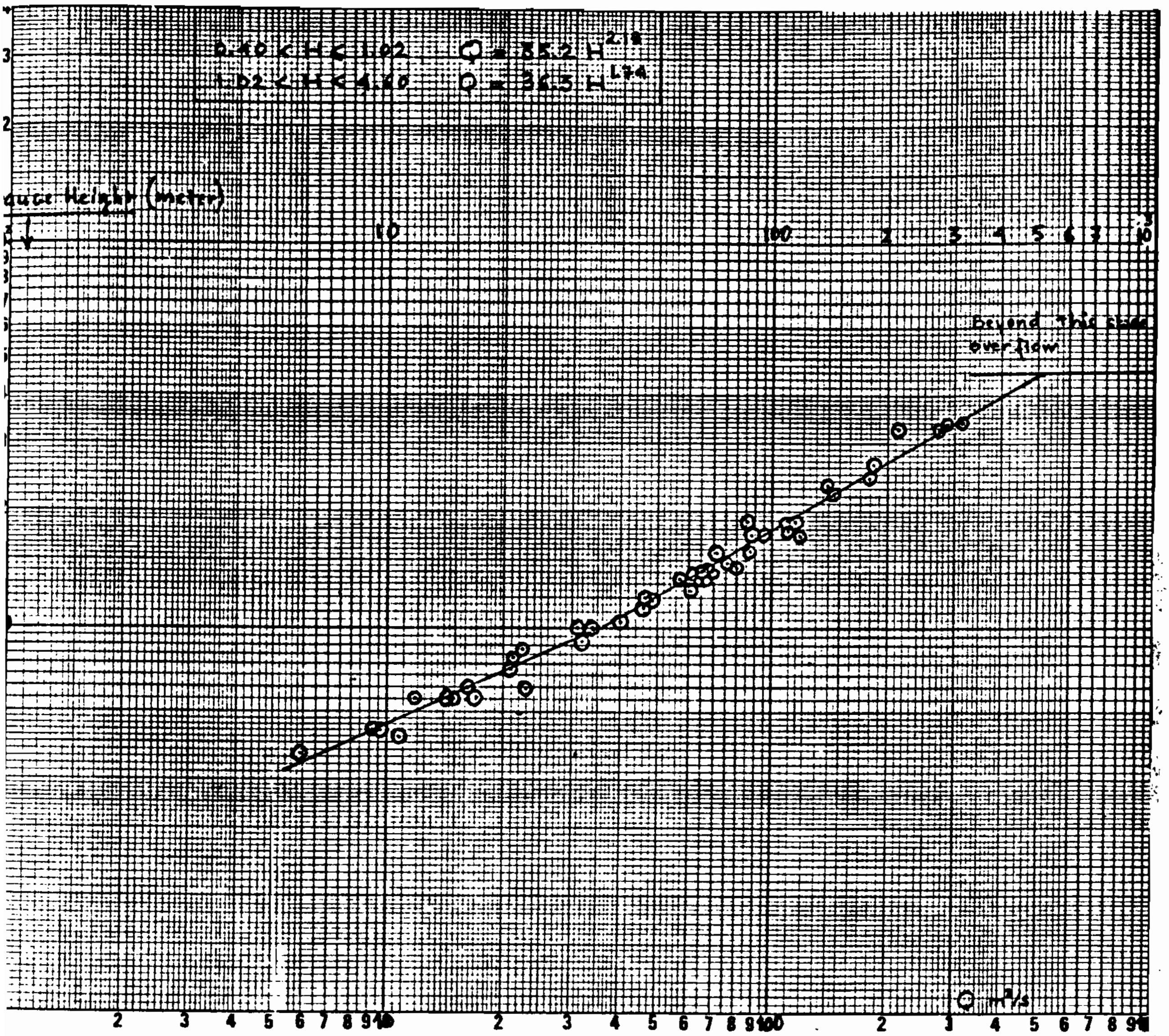


FIG. 21

Gauge Height
(metre)
RANGKASBITUNG
(CIUJUNG)
Smoothing graph
for series of differences
GH = 3.10
Q(3.20) – Q(3.00) = ΔQ
This curve is used for smoothing
the rating curve
ΔQ
(m³/s)
0.4
0.6
0.8
1.00
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
0
10
20
30
40
50



. Fig.22 Rangkasbitung (Ciujung). Rating curve on log-log paper.