Assessing the Accuracy of Suspended Sediment Rating Curves for a Small Basin

D. E. WALLING

Department of Geography, University of Exeter, Exeter, Devon, England

Sediment rating curves are often used to estimate suspended sediment loads where the sampling program is insufficient to define the continuous record of sediment concentration. Use of this technique will involve errors in the values of sediment load produced, and comparison with measured daily values has been employed by several workers to assess the magnitude of these errors. Comparisons are more difficult for small- and medium-sized catchments because of the general lack of direct measurements of loads. Recording turbidity meters could be employed to provide a continuous record of sediment concentration which can be used to calculate sediment loads. Results are presented for the river Creedy in which the values of sediment load calculated from the continuous concentration record have been compared with estimates derived from rating curves. The rating-curve data have been grouped according to season and stage tendency to provide various rating relationships. Values of annual sediment load estimated by using a rating curve could involve errors of up to +280%, whereas the errors for monthly loads could range between +900% and −90%. Careful consideration should be given to possible error terms before rating-curve estimates of sediment load are used in statistical and other analyses.

A knowledge of the suspended sediment loads of rivers has become increasingly important and necessary in recent years. Reasons for this interest include evaluation of sediment transport to the oceans, geomorphological studies of denudation and rates of erosion, assessment of soil erosion and soil loss, reservoir sedimentation, environmental impact assessment, water treatment, and problems of sediment-associated nutrients and pollutants. Methods of data collection are now well documented [*Guy and Norman*, 1970; *Federal Inter-Agency Sedimentation Project*, 1963], and in the absence of specialized installations for continuous collection of a representative aliquot of water and sediment [*Brown et al.*, 1970; *Barnes and Frevert*, 1954], resort must be made to collection of water samples and analysis of their suspended sediment concentration. A record of streamflow discharge is necessary in order to compute sediment loads from concentration data, and in the ideal case the sediment sampling program should be organized to allow direct interpolation of a continuous trace of suspended sediment concentration [*Porterfield*, 1972]. In many cases, daily or even less frequent samples would be sufficient during periods of stable discharge, but intensive sampling activity could be necessary during flood events. Sampling programs of this nature can be successfully undertaken on large rivers, where flood events last several days and sediment concentrations change relatively slowly, but problems can arise with smaller catchments, where floods are short lived and the associated storm period concentrations fluctuate very rapidly (see, for example, Figure 3). In these circumstances an automatic pump sampling apparatus [*Walling and Teed*, 1971; *Yorke*, 1976] could be used to collect frequent storm period samples, the sampling apparatus initiated by the rising stage and the subsequent sampling interval controlled by stage, discharge, or time increments. Rising- and falling-stage samplers or single-stage samplers could also prove useful [*Federal Inter-Agency Sediment Project*, 1961; *Schick*, 1967; *Knedlhans*, 1971].

In the absence of manpower or automatic apparatus for frequent sampling, and laboratory facilities for analysis of numerous samples, many workers have utilized the rating-curve technique to estimate suspended sediment loads. A rating curve consists of a graph or equation, relating sediment discharge or concentration to discharge, which can be used to estimate sediment loads from the streamflow record. A study by *Campbell and Bauder* [1940] on the Red River in Texas provides an early documented example of the use of sediment rating curves in the United States. They developed a 'silt rating curve' by plotting daily suspended load against daily river flow on logarithmic coordinates. A subsequent report by *Miller* [1951] described analysis of sediment loads from the San Juan River and provided a more detailed evaluation of the technique, including discussion of the need to construct seasonal rating curves and the use of streamflow duration curves to calculate sediment loads. Whereas *Campbell and Bauder* [1940] were primarily interested in using rating curves as an alternative for a daily sampling program in calculating loads, *Miller* [1951] was concerned with the possibility of applying a rating derived from a short period of sediment measurements to a long streamflow record in order to estimate long-term suspended sediment loads. The rating curve technique has since been widely applied in estimating sediment loads both for large catchments [*Temple and Sundborg*, 1972; *Livesey*, 1975] and for small- and medium-sized catchments [*Douglas*, 1973; *Piest*, 1963], where the difficulties of adequately defining the rapidly fluctuating record of sediment concentration by direct sampling make its use more necessary.

ACCURACY OF SEDIMENT LOAD DATA

Because of the many important potential uses of sediment load information, it is essential that the reliability and accuracy of the data are known. In the case of values of measured daily load obtained from a sampling program designed to define average daily concentration, *Colby* [1956] states that errors might range from 5% for a large stream in which flows are comparatively constant, the sediment load dominantly fine, and the concentrations high enough to be sampled accurately to almost unlimited magnitude for flashy streams with low-quality discharge records and for which sediment samples are only collected once or twice a day. Some of the inaccuracies in measured daily sediment loads will inevitably cancel each other out when the values are summed over longer periods, but *Colby* [1956] has again suggested that some published measured annual sediment discharges may in certain circumstances be as low as one half or as high as double the true suspended sediment load for the year. Errors in sediment load estimation can result from sample collection techniques

Paper number 7W0083.

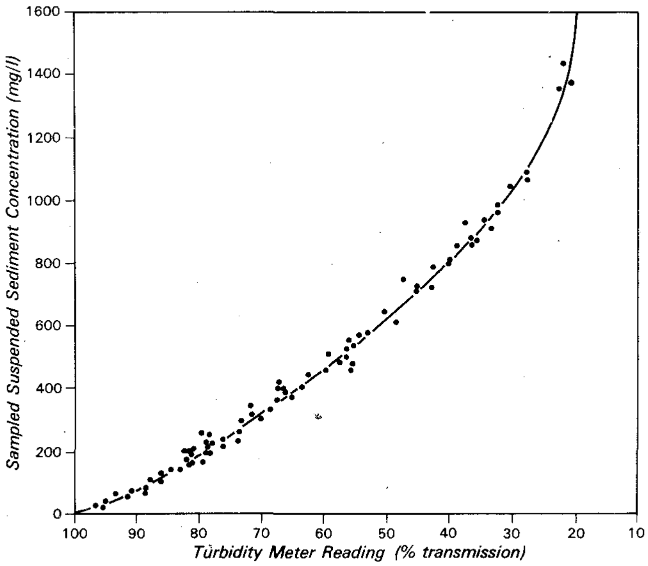

Fig. 1. A calibration curve of turbidity meter readings against suspended sediment concentration for the river Creedy.

and laboratory procedures [*Loughran,* 1971; *Douglas,* 1971] and from use of unreliable river flow data, but it is to be expected that the greatest errors will result from the inadequacy of a sampling program in defining the detailed temporal record of suspended sediment concentration. More information is required on the error term associated with values of sediment load. Unlike runoff data there is no simple water balance-type check that can be applied to assess the possible reliability of the figures, and material presented in printed form can appear deceptively accurate.

Estimates of sediment yield based on rating-curve calculations will in most cases involve greater errors than those obtained from direct measurements, and this can be ascribed primarily to the scatter associated with the rating relationship. Several workers [*Colby,* 1956; *Guy,* 1964; *Walling and Teed,* 1971; *Porterfield,* 1972] have analyzed such scatter in detail and have described controls associated with season, water temperature, hysteretic effects related to rising and falling stage, relative timing of water and sediment hydrographs, exhaustion effects, and varying patterns of tributary inflow. The technique used to construct the rating curve and the adequacy of the number of data points have also been shown to be significant controls on the accuracy of resultant calculations of sediment load in a valuable study by *Bennett and Sabol* [1973].

In view of these potential errors, several workers have attempted to assess the accuracy of rating-curve-derived load estimates by comparing them with direct measurements. The early investigation by *Campbell and Bauder* [1940] studied 60 months of record for the Red River, and a reasonably close agreement was found between rating-curve load estimates and measured values for seven subperiods. The errors for the individual periods varied between −25% and +14.8%, while for the total period the error was reduced to +1.5%. *Miller* [1951] carried out similar calculations for the San Juan River near Bluff, Utah, and found an error for the total 19-year period of +4%. However, if rating curves derived from sediment measurements taken during a single year were applied to the 19-year flow record, the errors varied between −26% and +236%. An assessment of the accuracy of the rating-curve technique for five rivers in Alberta and West Saskatchewan, Canada, carried out by *Kellerhals et al.* [1974], demonstrated average errors in estimation of the summer period sediment load of 21%, the dominant tendency being for underestimation.

Other investigations have employed more sophisticated procedures to derive and apply rating relationships. In a very detailed study, *Colby* [1956] made allowance for the particle size characteristics of the sediment, season, and other factors and introduced rating 'shift' in order to adjust the rating curve to periodic measured values. Resultant estimates of monthly sediment load for the Colorado River near Grand Canyon were between 50% and 170% of the measured sediment discharges, although use of ratings without shift gave values between 20% and 700% of those measured. On the same basis the annual sediment discharges for an 8-year period for the river indicated average errors of 6% and 18%, respectively. *Abraham* [1969] used multivariate rating relationships, including time since preceding peak flow and an index of antecedent floods as well as discharge, on four rivers in California. The average error obtained when annual suspended loads computed by the rating relationships were compared with measured loads was 24%. Several alternative rating relationships including zero intercept quadratics were employed by *Bennet and Sabol* [1973] in their study of the accuracy of sediment transport curves. They used data from the Iowa River and the Rio Grande to assess the optimum form. Using a 6-year measured sediment record, the first three to construct the transport curve and the remaining three to test the rating estimates, they found errors in estimation of the 3-year mean of 7% and 18% for the two rivers, respectively.

It is difficult to reach any general conclusion from these studies concerning the likely errors involved in using rating-curve techniques to estimate sediment loads, since the magnitude of the error will depend on many factors, including the nature of the catchment, the time interval of the load being calculated, and the procedure used to derive and apply the

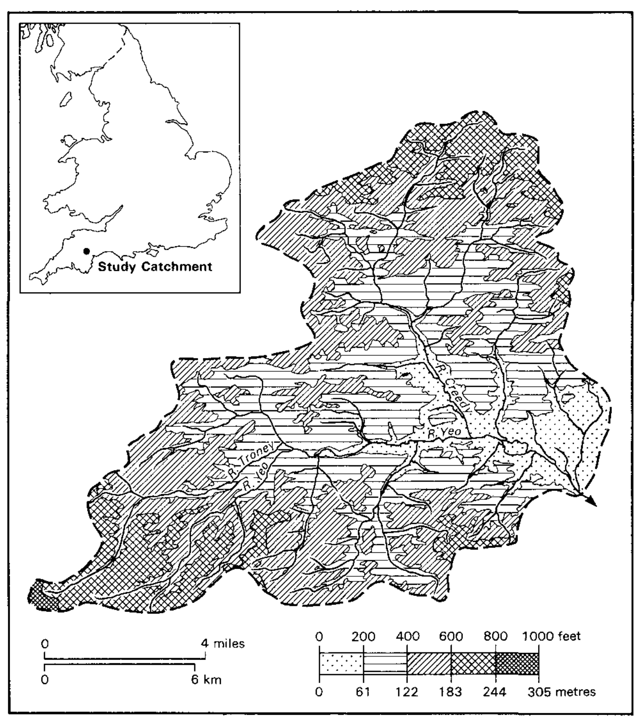

Fig. 2. The catchment of the river Creedy.

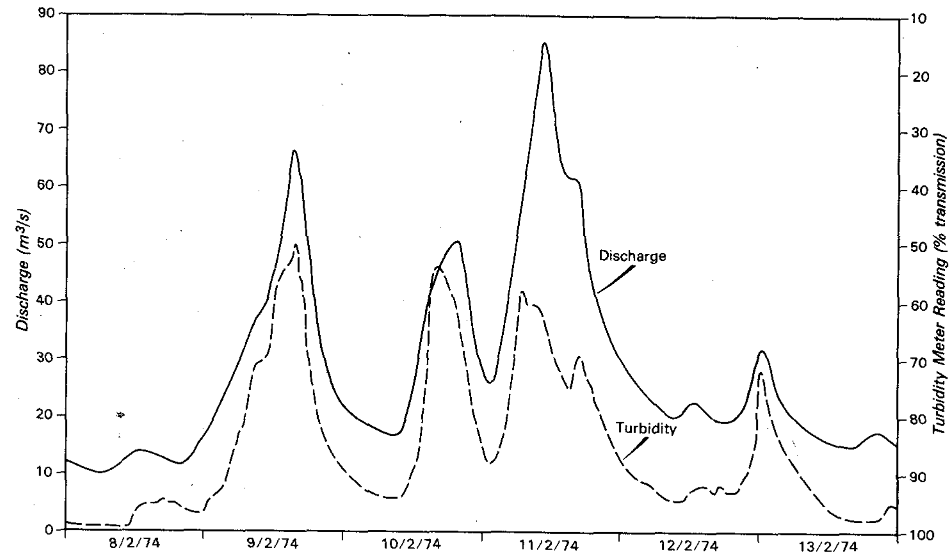

Fig. 3. An example of the detailed fluctuations in turbidity occurring during a series of storm hydrographs on the river Creedy.

rating relationship. Nevertheless, it should be recognized that rating-curve-derived estimates involve a large error term and may be as much as 50% or more in error. Where a least squares logarithmic regression procedure is used to derive the rating-curve, it might be expected that the resulting loads would be underestimated because of the bias given to the values below the fitted line by the regression technique. However, both positive and negative errors are to be found in most of the above studies.

RIVER CREEDY STUDY

Most of the studies on the accuracy of sediment loads estimated by using rating curves outlined above were carried out on large catchments where measured daily loads were available for evaluation purposes. Small catchments present a problem in this context because it is difficult to obtain detailed measured values for comparative purposes, and yet it is in these catchments that rating curves often have to be used to estimate sediment loads owing to the problems of defining the sediment concentration record by direct sampling. The author's own work on the sediment dynamics of rivers in Devon, England [*Walling,* 1971; *Troake and Walling,* 1973], has made extensive use of rating curves for calculating sediment yields, and this promoted a desire to assess their accuracy.

With this purpose in mind, trials of the use of photoelectric turbidity meters for recording sediment concentrations have been carried out since 1967. Many criticisms have been leveled at the use of recording turbidity meters for assessing fluctuations in suspended sediment concentration [e.g., *Burz,* 1970], but in the author's experience, good results can be obtained if an instrument is field calibrated for a particular site and is used on a small- or medium-sized catchment with relatively homogeneous rock type and a predominantly silt- and clay-sized load. Simple turbidity sensors utilizing an extinction effect and consisting of a single light source and photocell [*Jackson,* 1964] or two photocells mounted at unequal distances from a single light source [*Fleming,* 1969] have been employed. The sensors have been mounted directly in the stream channel, and they have been cleaned regularly to avoid the problems associated with algal growth. Calibration has been against the average depth-integrated suspended sediment concentration for the channel section obtained by using US DH 48 and US DH 59 samplers and the equal transit rate sampling procedure [*Federal Inter-Agency Sedimentation Project,* 1963]. A typical calibration plot is shown in Figure 1. The plot is nonlinear owing to the electronic circuitry of this particular instrument, but in other cases, essentially linear calibration relationships have been obtained.

The use of recording turbidity meters can provide detailed information on the fluctuation in suspended sediment transport in a river section. Because of the good relation obtained between sediment concentration and turbidity (Figure 1) at the river Creedy site, it was decided to use the continuous turbidity records and the associated calibration plot to provide continuous records of suspended sediment concentration. The concentration record could in turn be combined with a continuous record of water discharge to provide values of sediment load which could be used as a means of assessing the accuracy of rating-curve-derived load estimates. In order to facilitate comparison of the load values, the rating curves were constructed by using values abstracted from the continuous concentration record rather than those obtained by direct sampling. Even if the concentration record derived from the turbidity trace does not completely reproduce the true record, it is thought to provide a very close approximation to a possible concentration record for the associated discharge record.

Some results from analysis of 2 years of suspended sediment concentration record from the river Creedy can usefully be presented. This river drains a catchment of 258 km² (Figure 2) which is developed on Permian marls and sandstones and Carboniferous culm measures or shales and which experiences a mean annual precipitation of approximately 930 mm. The gaging station is operated by the South West Water Authority, England, and consists of a rated section. Two years of turbidity records for the water years 1972–1973 and 1973–1974 have been analyzed by using the calibration curve presented in Figure 1, and an example of the detail provided for individual storm events is given in Figure 3.

Tests on the continuous discharge and concentration records indicated that instantaneous values of flow and turbidity

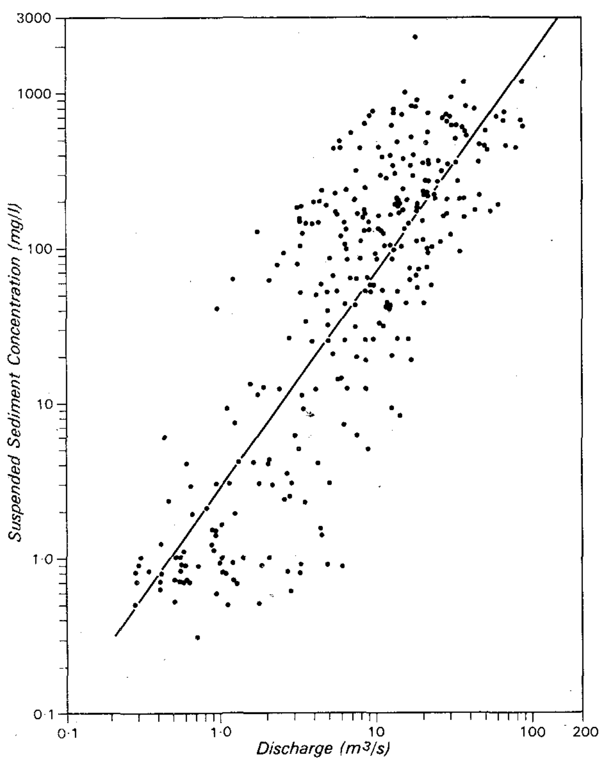

Fig. 4. The rating curve defined by the total data set.

taken from the charts at one hourly intervals were adequate to define the detail of the two records. These values were transferred to a computer file for ease of subsequent data processing. The values of turbidity were converted to equivalent concentrations with a computer routine employing a segmented polynomial to describe the calibration curve depicted in Figure 1. Initially, a hypothetical sampling scheme with a weekly periodicity was used to abstract data from the concentration record for use in constructing instantaneous sediment concentration/discharge rating curves. However, these data were found inadequate for establishing clearly defined relationships owing to the lack of values associated with periods of high flow, and a scheme of aperiodic sampling during storm events was added to remedy this deficiency. In total, 309 observations of sediment concentration C and discharge Q were available from the 2-year period for construction of rating relationships. No attempt has been made in this discussion to assesss the variation in sediment load estimates that could arise from the use of rating curves based on varying numbers of data points and sampling schemes. Rather, it has been assumed that the data set used for rating-curve construction reflects a very detailed sampling program and that the resulting evaluation of errors in sediment load estimation should provide an indication of the minimum errors involved.

Rating relationships have been constructed by using linear least squares regression of the logarithmic transformed data. This conforms to the approach adopted by many previous workers and can also be justified on statistical grounds in terms of data normality, linearity of the relationship, and considerations of homoscedasticity. An attempt has also been made to subdivide the data set to make allowance for two major influences on rating curve scatter, namely, seasonal effects and hysteresis related to rising and falling stage. The rating relationship developed from the total set of observations is illustrated in Figure 4, and in Figure 5 the data have been grouped according to season to give two rating lines. Insufficient observations were available to develop rating equations for individual months, but inspection of the data suggested that use of broadly defined winter (October through March) and summer (April through September) periods was worthwhile. In Figure 6 the data set has been subdivided according to considerations of rising and falling stage. A rising stage was distinguished by the discharge at a particular point in time being 0.5 m³/s or more greater than the discharge for the preceding hour (i.e., $Q_{i+1} \geq Q_i + 0.5$). The threshold condition of 0.5 m³/s was employed to ignore very small changes in stage not reflected in the concentration record and small bumps on the recession curves of larger events. All remaining observations were classed as falling-stage values, although use of the terms falling stage and steady stage might be more appropriate. Finally, the observations were grouped according to both season and stage, and the resulting four relationships are presented in Figure 7. Details concerning the form of the individual equations and their goodness of fit are provided in Table 1. Levels of explanation of the individual equations are not particularly high and range from 49% to 70% of the variance of the concentration data. These would improve if sediment discharge rather than sediment concentration was used as the dependent variable, but the effect would be largely spurious because water discharge would be common to both the dependent and independent variables. The major constraint on the degree of explanation provided by the equations is the scatter about the associated rating curve, and it does not seem that nonlinear functions would provide any marked improvement, although the use of multivariate relationships may prove worthwhile.

The various rating relationships were applied to the hourly flow data by using a computer routine, and the resulting

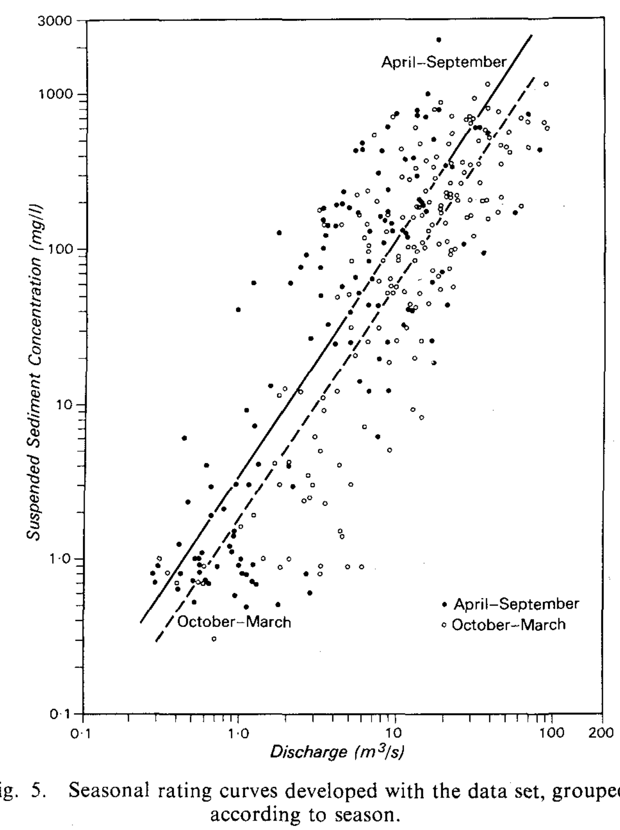

Fig. 5. Seasonal rating curves developed with the data set, grouped according to season.

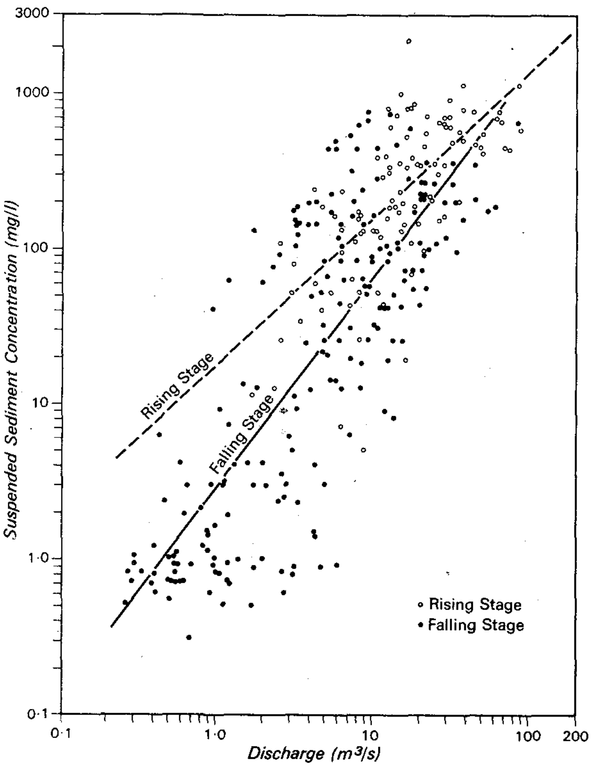

Fig. 6. Stage-differentiated rating curves.

estimates of annual sediment load are compared with the loads calculated from the continuous record of sediment concentration in Table 2. Four rating-curve estimates are listed corresponding to use of, first, a single rating for all flow data (Figure 4); second, two ratings distinguished according to season (Figure 5); third, two ratings defined according to stage tendency (Figure 6); and fourth, four ratings differentiated according to season and stage tendency (Figure 7). Errors can be calculated in different ways, and in this analysis they are expressed as a percentage of the value calculated from the continuous concentration data, i.e.,

$$\text{Error (\%)} = \left(\frac{\text{Rating-Curve Estimate}}{\text{Continuous Record Load}} - 1 \right) \times 100$$

The errors listed in Table 2 demonstrate that annual sediment loads calculated by using a single rating curve may involve overestimation by up to 60%. The use of seasonally distinguished ratings does little to improve the load estimates, but the application of separate rating equations for rising and falling stages results in a significant improvement in the estimate. Nevertheless, even the use of stage-differentiated equations can give rise to errors in annual load estimates as high as +30%.

The patterns of errors involved in estimation of monthly sediment loads are illustrated in Figure 8. At this level, both marked positive and negative errors are evident, and these can vary between in excess of +900% and as low as −90% of the values calculated from the continuous record. The use of stage-differentiated ratings again provided improved estimates, but the errors involved are still of such magnitude to suggest that the rating-curve technique is of little value in estimating monthly sediment loads in this catchment.

The values of sediment load estimated from rating-curve calculations and presented above result from the application of instantaneous rating relationships to hourly flow data. It may be that use of rating curves developed from daily mean sediment concentrations and used in association with a record of daily mean flows could provide more accurate estimates of

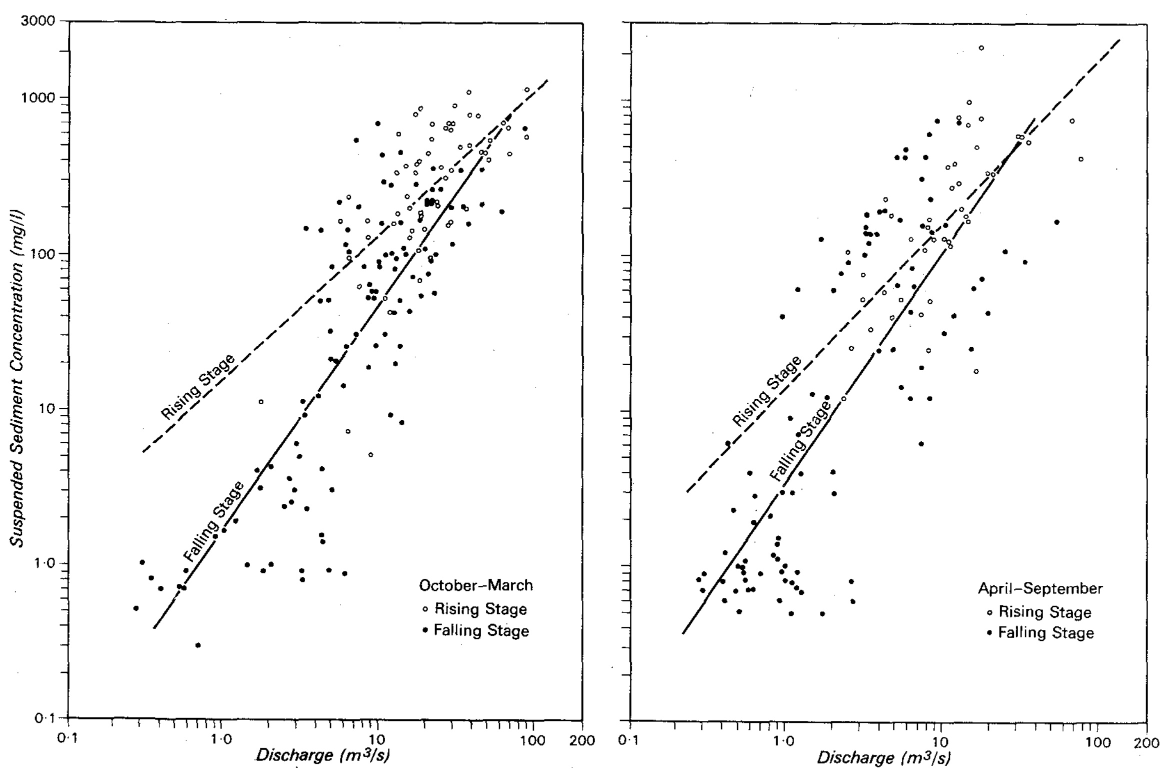

Fig. 7. Rating curves developed with the data set, grouped according to season and stage tendency.

TABLE 1. Values of a and b in the Equation $C = aQ^b$ and Goodness of Fit for the Various Sediment Rating Relationships

Data Group	a	b	n	r
All	3.087	1.408	309	0.83
Summer	3.749	1.501	138	0.83
Winter	1.950	1.498	171	0.84
Rising stage	16.278	0.944	103	0.70
Falling stage	2.742	1.348	206	0.80
Summer rising stage	13.521	1.067	42	0.70
Summer falling stage	3.451	1.462	96	0.78
Winter rising stage	15.885	0.930	61	0.70
Winter falling stage	1.675	1.457	110	0.83

monthly and annual loads. In turn, annual sediment discharge/streamflow relationships such as those employed by *Nordin and Sabol* [1973] and *Frenette et al.* [1974] could be used to estimate annual loads if a greater length of record were available for establishing the rating equations. However, daily and annual rating curves can be viewed as tending toward statistical abstraction when they are compared to the in-

TABLE 2. Comparison of Rating-Curve Estimates of Annual Sediment Load With Loads Calculated From the Continuous Concentration Record

Basis of Sediment Load Estimate	Annual Load for Water Year, tonnes		Error,* %	
	1972–1973	1973–1974	1972–1973	1973–1974
Continuous concentration record	7412.7	20577.4		
Single rating (Figure 4)	9429.7	33648.2	+27.2	+63.5
Seasonal ratings (Figure 5)	8533.9	33138.5	+15.1	+61.0
Stage distinguished ratings (Figure 6)	7708.6	26898.6	+4.0	+30.7
Ratings distinguished by season and stage (Figure 7)	7100.7	26895.4	−4.2	+30.7

* Error is the error involved in the use of the rating curve.

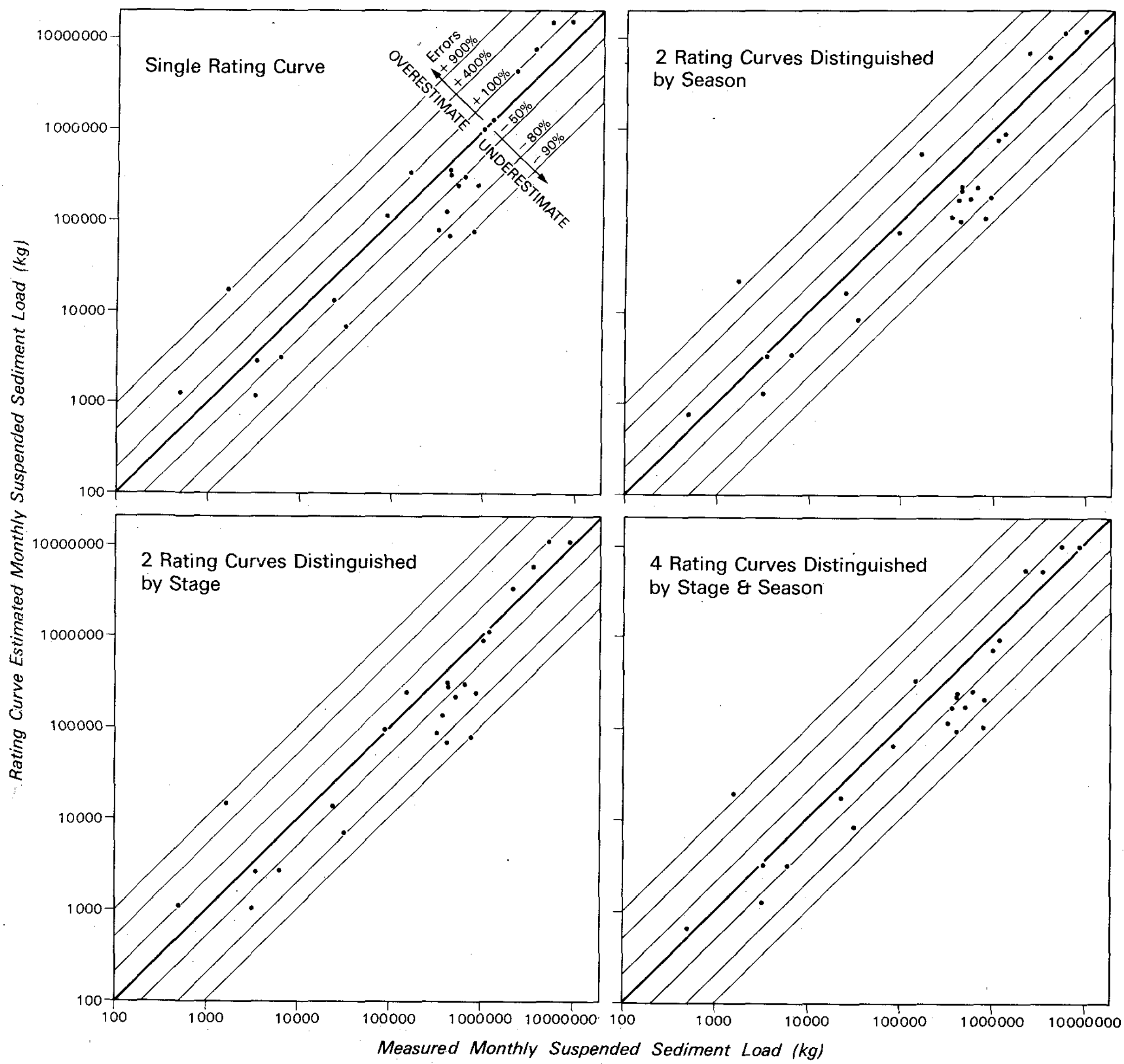

Fig. 8. Comparison of monthly suspended sediment loads calculated by using the continuous turbidity record with those estimated by using the four major groups of rating relationships.

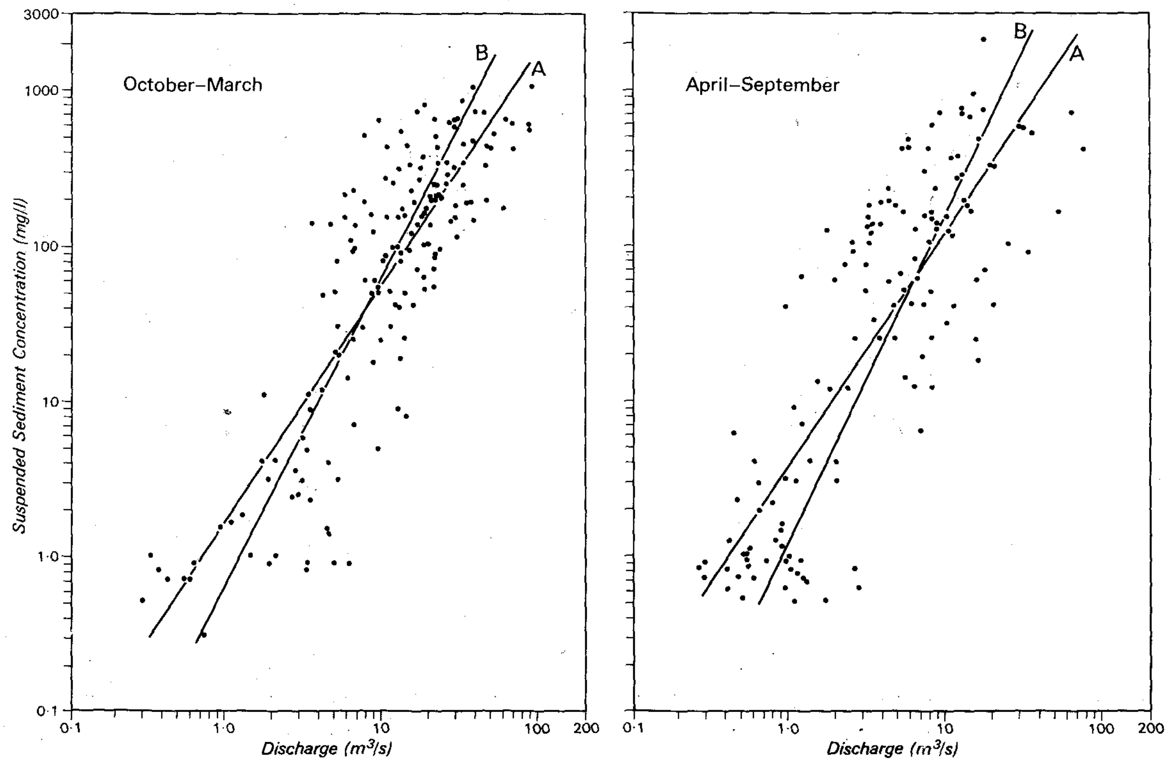

Fig. 9. Comparison of least squares, line A, and eye-fitted, line B, seasonal rating lines.

stantaneous rating relationships used here to reconstruct the continuous trace of sediment concentration. Furthermore, the errors cited above refer to sediment loads calculated for the same period as that used for derivation of the rating relationships. Additional inaccuracies could arise when a rating curve based on a short period of measurement is employed to estimate loads for a longer period for which discharge data are available. The split record approach could be used to assess the accuracy of rating relationships derived from one part of the record in estimating the loads for the remaining period, but this is beyond the scope of the present analysis.

It was stated earlier that logarithmic rating relationships fitted by least squares regression could underestimate sediment loads because of the bias afforded to the lower values of concentration or sediment discharge by the logarithmic transformation. The results of this study do not clearly demonstrate this tendency, and the values of annual load calculated from the various rating plots are in nearly all cases overestimates (Table 2). Plots of the concentration streamflow relationship

TABLE 3. Comparison of Annual Sediment Loads Estimated by Least Squares and Eye-Fitted Seasonal Rating Relationships

Basis of Sediment Load Estimate	Annual Load for Water Year, tonnes		Error,* %	
	1972–1973	1973–1974	1972–1973	1973–1974
Continuous concentration record	7412.7	20577.4		
Least squares–fitted seasonal ratings	8533.9	33138.5	+15.1	+61.0
Eye-fitted seasonal ratings	17376.1	78113.4	+134.4	+279.6

*Error is error involved in the use of the rating curve.

for individual storm runoff events on this river demonstrate a marked hysteretic effect, concentrations for a given discharge being considerably higher on the rising stage than on the falling stage. This characteristic will tend to balance the bias introduced by the least squares procedure, because the rising limb of a hydrograph is generally of a much shorter duration than that of the falling limb. More emphasis should therefore be given to concentrations associated with falling stage, and these are primarily the lower concentrations for a given discharge. Use of stage-related rating plots removes this feature of the lumped rating and provides one explanation for the resulting reduced overestimation of annual loads. There are many alternatives to the least squares–fitted straight line on the logarithmic rating plot, and several workers, including the writer, have favored subjectively fitted straight lines. Eye fitting allows increased weight to be given to the upper portions of the plot, and a more meaningful line, in terms of characterizing the sediment dynamics of a catchment, can often result. This is demonstrated by Figure 9, in which both least squares and eye-fitted straight lines have been superimposed on the seasonally differentiated data plots. In both cases the eye-fitted line gives a lower intercept and an increased slope or exponent in comparison to the least squares line. It is impossible to demonstrate any objectivity for the eye-fitted line, but in order to compare the errors in estimating sediment loads associated with the two lines, loads were also calculated by using the subjectively fitted seasonal rating relationships. The results are shown in Table 3. Greatly increased overestimation results from the use of the eye-fitted lines, errors rising to as much as +279%, and this suggests that the least squares–fitted lines do introduce a bias toward underestimation. Although it could be argued that an eye-fitted line provides a more meaningful representation of the sediment transport characteristics of a catchment, the least squares regression line should probably be used for estimation of sediment loads if severe overestimation is to be avoided.

CONCLUSIONS

Because of the problems of adequately defining fluctuations in sediment concentration by direct sampling, sediment rating curves are often used to estimate suspended sediment loads from small- and medium-sized catchments. However, little work has been carried out on assessing the possible magnitude of the errors involved because of the difficulty of obtaining values of measured load. *Guy* [1965] has suggested that a means of continuously recording sediment concentrations should be employed in such catchments if accurate information on sediment loads is required. The author has found that recording turbidity meters can provide worthwhile information on fluctuation in suspended sediment concentration providing that the instruments are field calibrated for a particular site and they are used on small- or medium-sized catchments with relatively homogeneous rock type and a predominantly silt- and clay-sized load. Comparison of sediment load values for the river Creedy calculated from a continuous record of sediment concentration, provided by a recording turbidity meter, with those obtained by using rating curves, suggests that considerable errors could be associated with rating-curve estimates.

Even when rating relationships differentiated by season and stage are used, annual loads could be overestimated by as much as 30%, and errors in estimation of monthly loads could vary between +900% and −80%. The results presented here, concerning errors involved in the use of sediment rating curve procedures, refer specifically to instantaneous rating curves used in combination with hourly flow data. Different findings could result from the use of daily or even annual rating curves. Nevertheless, it is felt that in the future, more careful consideration should be given to the use of sediment load values calculated by using rating curves, particularly from small- and medium-sized catchments. In many applications these error terms can have important implications. For example, there is no guarantee that the error term will be constant from one catchment to another, and statistical analysis of the influence of such controls as climate and land use on sediment yields could be rendered of little value. It is an important assumption of some statistical tests that variables are measured without error [e.g., *Poole and O'Farrell,* 1971]; this may be far from the case when rating-curve estimates of sediment load are involved.

Acknowledgments. The author is indebted to the Natural Environment Research Council of England, who provided financial support for work on sediment dynamics in the Department of Geography, University of Exeter. The assistance with computer analysis given by G. Skinner of the Faculty Data Processing Unit and the cooperation of the South West Water Authority are very gratefully acknowledged.

REFERENCES

Abraham, C. E., Suspended sediment discharges in streams, *Tech. Pap. 19,* 10 pp., Hydrol. Eng. Center, U.S. Army Corps of Eng., Davis, Calif., April 1969.

Barnes, K. K., and R. K. Frevert, A runoff sampler for large watersheds, *Agr. Eng., 35,* 84–90, 1954.

Bennett, J. P., and G. V. Sabol, Investigation of sediment transport curves constructed using periodic and aperiodic samples, *Symposium on River Mechanics,* vol. 2, pp. 49–60, International Association of Hydraulic Research, Delft, Netherlands, 1973.

Brown, H. E., E. A. Hansen, and N. E. Champagne, Jr., A system for measuring total sediment yield from small watersheds, *Water Resour. Res., 6,* 818–826, 1970.

Burz, J., Experiences with photometric turbidity measurements, *Int. Ass. Hydrol. Sci. Publ., 99*(2), 519–530, 1970.

Campbell, F. B., and H. A. Bauder, A rating-curve method for determining silt discharge of streams, *Eos Trans. AGU, 21,* 603–607, 1940.

Colby, B. R., Relationship of sediment discharge to streamflow, open file report, 170 pp., U.S. Geol. Surv., Reston, Va., 1956.

Douglas, I., Comments on the determination of fluvial sediment discharge, *Aust. Geogr. Stud., 9,* 172–176, 1971.

Douglas, I., Rates of denudation in selected small catchments in Eastern Australia, *Univ. Hull Occas. Pap. Geogr., 21,* 1–127, 1973.

Federal Inter-Agency Sedimentation Project, The single stage sampler for suspended sediment, *Rep. 13,* Minneapolis, Minn., 1961.

Federal Inter-Agency Sedimentation Project, Investigation of a pumping sampler with alternate suspended sediment handling systems, *Rep. Q,* Minneapolis, Minn., 1962.

Federal Inter-Agency Sedimentation Project, Determination of fluvial sediment discharge, *Rep. 14,* Minneapolis, Minn., 1963.

Fleming, G., Suspended solids monitoring: A comparison between three instruments, *Water Water Eng., 73,* 377–382, 1969.

Frenette, M., J. Lamas, and M. Larinier, Modèle de simulation du transport solide en suspension des Rivières Chateauguay et Chaudière, *Rapp. Sci. CRE 74/05,* 34 pp., Centre de Rech. sur l'Eau, Univ. Laval, 1974.

Guy, H. P., An analysis of some storm-period variables affecting stream sediment transport, *U.S. Geol. Surv. Prof. Pap., 462E,* 1964.

Guy, H. P., Fluvial sediment measurement based on transport principles and network requirements, *Int. Ass. Hydrol. Publ., 67,* 395–409, 1965.

Guy, H. P., and V. W. Norman, Field methods for measurement of fluvial sediment, *Tech. Water-Resour. Invest. U.S. Geol. Surv., C2*(3), 1970.

Jackson, W. H., An investigation into silt in suspension in the River Humber, *Dock and Harbour Auth., 45,* 526, 1964.

Kellerhals, R., A. D. Abrahams, and H. von Gaza, Possibilities for using suspended rating curves in the Canadian Sediment Survey Program, *Rep. REH/74/1,* 86 pp., Dep. Civil Eng., Univ. of Alberta, Edmonton, Alberta, Canada, 1974.

Knedlhans, S., Mechanical sampler for determining the water quality of ephemeral streams, *Water Resour. Res., 7,* 728–730, 1971.

Livesey, R. H., Corps of Engineers methods for predicting sediment yields, Present and Prospective Technology for Predicting Sediment Yields and Sources, *ARS-S-40,* pp. 16–32, U.S. Dep. of Agr., Washington, D. C., 1975.

Loughran, R. J., Some observations on the determination of fluvial sediment discharge, *Aust. Geogr. Stud., 9,* 54–60, 1971.

Miller, C. R., Analysis of flow duration sediment rating curve method of computing sediment yield, report, 55 pp., U.S. Bur. of Reclam., Washington, D. C., 1951.

Nordin, C. F., and G. V. Sabol, Estimating average sediment yields from annual streamflow and sediment records, *Symposium on River Mechanics,* vol. 1, pp. 93–104, International Association of Hydraulic Research, Delft, Netherlands, 1973.

Piest, R. F., Long term sediment yields from small watersheds, *Int. Ass. Hydrol. Sci. Publ., 65,* 121–140, 1963.

Poole, M. A., and P. N. O'Farrell, The assumptions of the linear regression model, *Trans. Inst. Brit. Geogr., 52,* 145–158, 1971.

Porterfield, G., Computation of fluvial-sediment discharge, *Tech. Water-Resour. Invest. U.S. Geol. Surv., C2*(3), 1972.

Schick, A. P., Suspended sampler, *Rev. Geomorph. Dyn., 17,* 181–182, 1967.

Troake, R. P., and D. E. Walling, The hydrology of the Slapton Wood Stream, A preliminary report, *Field Stud., 3,* 719–740, 1973.

Temple, P. H., and A. Sundborg, The Rufiji River, Tanzania, hydrology and sediment transport, *Geogr. Ann. Ser. A, 54,* 345–368, 1972.

Walling, D. E., Sediment dynamics of small instrumented catchments in south-east Devon, *Trans. Devonshire Ass., 103,* 147–165, 1971.

Walling, D. E., and A. Teed, A simple pumping sampler for research into suspended sediment transport in small catchments, *J. Hydrol., 13,* 325–337, 1971.

Yorke, T., Ten years of experience with automatic pumping-sediment samplers, *Proceedings of the Third Federal Inter-Agency Sedimentation Conference,* 7.54–7.64, Water Resources Council, Washington, D. C., 1976.

(Received August 31, 1976;
revised December 23, 1976;
accepted January 3, 1977.)