Erosion and Sediment Transport Measurement (Proceedings of the Florence Symposium, June 1981). IAHS Publ. no. 133.

A study of the variability of suspended sediment measurements

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ABSTRACT A study was made of the variability of suspended sediment concentration data collected using paired equal-transit-rate samples, paired single-vertical and equal-transit-rate samples, and paired automatic pumping-type and equal-transit-rate samples. Data were selected from two gauging locations in the US Southern Plains. Equal-transit-rate sample concentrations collected by experienced operators showed better agreement than did those collected by less experienced operators. Agreement was less at the more difficult to sample location that had a large channel, a truss bridge, and a large sand load. The long term sediment load for this location was computed with the higher of each of the paired concentrations obtained by less experienced operators. This load was 30% higher than the truer load derived with the lower concentrations. Data obtained with the single-vertical sampling method and automatic pumping-type samplers can be used to determine the entire suspended sediment load, if long term sediment yield errors up to about 10% can be tolerated.

Etude de la variabilité des résultats de mesures de sédiments en suspension

RESUME Une étude a été éffectuée sur la variabilité des données recueillies par un couple d'appareils à prélever les échantillons "equal transit rate", un couple d'appareils: l'un "equal transit rate" et l'autre opérant sur une seule verticale, et un couple d'appareil du type à pompage automatique avec un appareil "equal transit rate". Les données ont été choisies à deux stations de jaugeage des plaines du Sud des Etats Unis. Les échantillons pris avec les appareils de type "equal transit rate" par des techniciens expérimentés montrent un meilleur accord entre les résultats que dans le cas de techniciens moins expérimentés. Les différences sont les plus prononcées pour un site pour lequel il est le plus difficile de prélever un échantillon: large chenal, pont metallique à poutre en treillis et une forte charge en sable. La valeur à long terme de la charge en sédiments pour ce site a été calculée avec les valeurs les plus élevées des couples de concentration obtenus avec les techniciens les moins expérimentés. Cette charge était de 30% plus élevée que la valeur exacte determinée à partir de concentrations plus faibles. Les données obtenues avec la méthode d'échantillonnage sur une seule verticale et avec l'échantillonneur à pompage automatique peuvent être utilisés pour l'ensemble des relevés de transport de sédiments, si on peut tolérer sur la masse totale de sédiments transportés calculée sur une longue période une erreur d'environs 10%.

INTRODUCTION

The recent and generally worldwide emphasis on controlling environmental pollution is focussing attention on the accuracy and adequacy of sediment transport and sediment deposition data collected both in the past and at present. This emphasis is due in part to the awareness that many water pollutants such as phosphorus, organic nitrogen, pesticides, and heavy metals are mainly transported by attachment to sediment particles.

This paper investigates the variability of suspended sediment measurements using data collected from streams in the Southern Plains of the USA. Although the suspended sediment samplers currently used in the US have been studied for sampling accuracy under controlled conditions in the laboratory (Interagency Committee, 1952; Coleman, 1962), virtually no reports of field accuracy studies have been published. In this study we could not ascertain the amount of error inherent to depth integrating suspended sediment samplers themselves, nor to the equal-transit-rate (ETR) sampling method which was used as a basis of comparison. However, this study does show variability attributable to operator groups, the single-vertical (SV) sampling method, and automatic pumping-type samplers (PS), for several flow ranges for two streams.

DATA SELECTION AND METHOD OF STUDY

The suspended sediment concentration data for this study were selected from data collected by the US Department of Agriculture to determine the downstream hydrological effects of upstream floodwater detention reservoirs and other basin treatments. Figure 1 shows the streamgauging locations for the original study. Throughout the study period, most runoff events at these locations were sampled with depth integrating suspended sediment samplers. US D-49 samplers (Interagency Committee, 1963) were used during higher flows, and US DH-48 (Interagency Committee, 1963) samplers were employed during lower flows. The ETR sampling procedure (Interagency Committee, 1963), which involves collection of a composite sample by depth integration at several equally spaced intervals across a stream, was used in conjunction with these samplers. Because of inherent sampling problems in natural streams, such as debris in the flow and dunes on the stream bed, all samples were collected in duplicate to increase data reliability.

Fig. 1 Streamgauging locations in the River Washita basin.

Early in the original study the duplicate sample data indicated that most sample pairs agreed well for gauging locations where the stream was small and the sediment in transport was largely silt and clay. Conversely, paired sample concentrations for those locations where the stream was large and the sediment contained a sizeable percentage of sand, agreed less. If a large stream had a truss-type bridge, requiring the operator to completely reel in the sampler repeatedly to avoid bridge members, variation between paired samples was further increased.

For this study, data were selected from two locations to reflect the two extremes in sampling conditions. A site on Creek East Bitter with a drainage area of 91 km^2 (Fig. 1) was chosen to represent an easily sampled location. Here at bankfull flows the stream was about 18 m wide, 3 m deep, and the sediment was predominantly silt and clay. The stream was stable and had a concrete weir to facilitate discharge data collection. In 1966 a concrete slab was constructed across the stream bed, including part of the banks, to prevent development of scour holes at higher flows.

The River Washita at Alex, Oklahoma (Fig. 1), draining an area of 12 410 km^2, was chosen to represent a site with difficult conditions for sampling. Here at bankfull flows the width was 55 m and the maximum flow depth was about 5 m. Sampling was undertaken almost exclusively from a truss bridge, and the sediment load at this station contained considerable sand, calculated as possibly between 25 and 30% of the long term total load.

In 1966 an effort was made to lessen the strenuous field sampling work. For some samplings the second ETR sample was replaced by a single-vertical (SV) sample, i.e. a depth integrated sample taken at only one point near mid stream. The specific SV sampling point was marked on the bridge railing for gauging locations with a bridge, or on the cable for locations with a cableway.

In 1966, automatic pumping-type suspended sediment samplers (PS) became available and these were installed at all but one of the gauging locations. Sampler models included the US PS-66A and US PS-67 that have been superseded by the very similar US PS-69 (Interagency Committee, 1980) and a smaller, lower cost sampler, developed for small streams (Allen *et al.*, 1976). Although these samplers greatly increased the number of laboratory analyses, they substantially decreased the man-hours required for manual sampling, especially during hours of darkness. The quality of the sediment records was also improved by a more complete sampling coverage of each and every runoff event.

Selection of paired concentration data for analysis has been restricted to samples collected during flow recessions in order to minimize the change in sediment concentration during a duplicate measurement period (Fig. 2). ETR data were not selected if the time interval between duplicate samples was greater than about 30 min at the River Washita, or about 15 min at the Creek East Bitter. Similar considerations governed the selection of paired concentration data for SV *vs.* ETR samples (Fig. 2) and PS *vs.* ETR samples (Fig. 3). In the analysis for the River Washita, 562 pairs of ETR *vs.* ETR data, 114 pairs of ETR *vs.* SV data, and 211 pairs of ETR *vs.* PS data were used, whereas for the Creek East Bitter 212 pairs of ETR *vs.* ETR data, 43 pairs of ETR *vs.* SV data, and 45 pairs of ETR *vs.* PS data were employed.

ANALYSES AND FINDINGS

Duplicate ETR sample concentrations

The first year's experience of constructing continuous sediment concentration graphs from sample data strongly indicated that when ETR duplicate samples differed appreciably in sediment concentration, the low values invariably are more reliable because of better fits with the data taken immediately before and after the data (Fig. 2). This deduction was strengthened by the PS data, which permitted a more complete definition of concentration trends (Fig. 3). Nine types of incidents in field sampling and laboratory analysis of suspended sediment have been identified as the possible causes of abnormally high, low, and randomly high or low concentration measurements. However, two problems appear to overshadow all others, and both produce higher than normal concentrations. One involves dipping the sampler nozzle into the bed, which may arise either because the sampler contacted the bed in the trough between two dunes, the sampler sank into the bed when the bed was soft and the sampler transit speed was excessive, or from "ploughing" into the bed when travel reversal involves movement of the sampler in an upstream direction. The other problem occurs when an operator is late in reversing the sampler's travel and permits the sampler to linger in the high concentration zone near the bed. For any one ETR measurement the operator must make contact between the sampler and the bed several times, and therefore increases the possibility

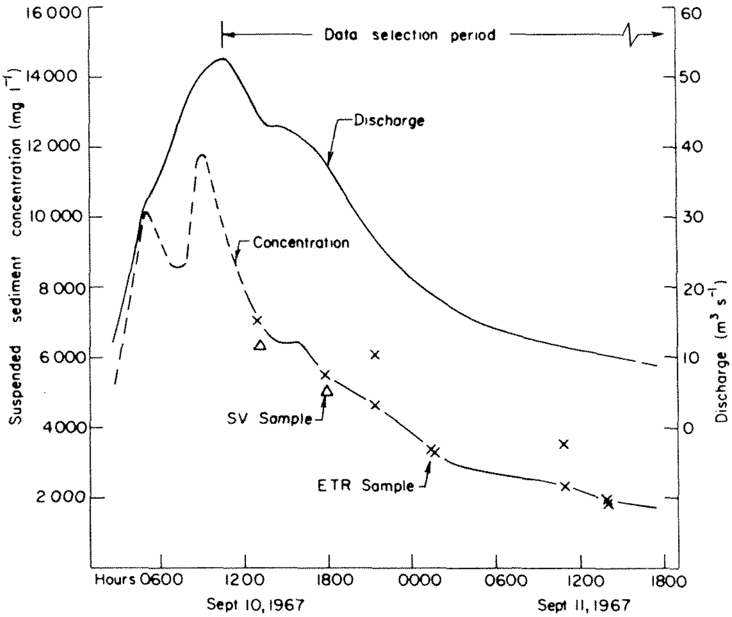

Fig. 2 A typical sediment graph and hydrograph for the River Washita showing ETR and SV sample concentrations.

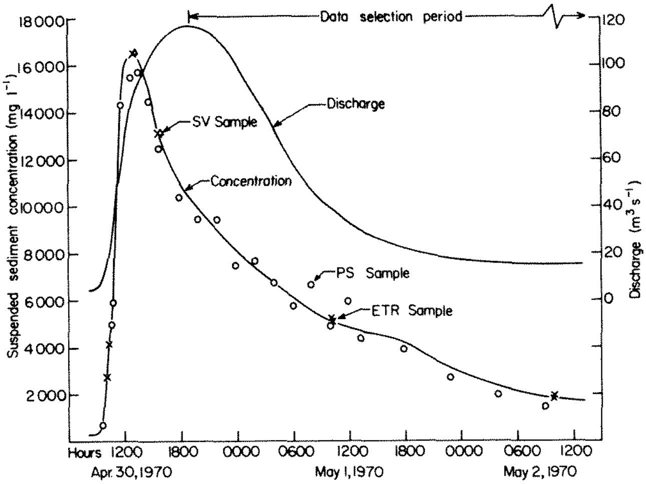

Fig. 3 A typical sediment graph and hydrograph for the River Washita showing PS, ETR, and SV sample concentrations.

of both types of error. These findings further strongly suggest that the lower concentration measurements in the paired sets of ETR measurements should be taken as a base from which to make comparisons.

Nineteen operators collected the samples compiled in these data sets. Because the data were partitioned by location, flow rate, and variability range, several operators had few or no data in certain categories. Therefore, the operators were divided into two groups, regular and occasional operators. Regular operators were those who had been assigned routine streamgauging duties for 2 or more years. These operators sampled the baseflow of streams weekly and helped sample virtually all stormflow events. Most of these operators collected better quality samples than the occasional operators. Occasional operators rarely sampled the baseflow but helped sample most intermediate and large-size stormflow events. Sometimes occasional operators would experience a period of six months without taking any samples. Although occasional operators were less experienced, a few seemed to collect samples as well as did most regular operators.

Comparisons of variability between paired ETR samples from the River Washita and the Creek East Bitter are shown in Table 1. Comparisons were made with variation ratios, defined as the higher concentration minus the lower concentration divided by the lower concentration for any one data set. For the two lower streamflow ranges at the Creek East Bitter (Table 1), data collected by regular operators varied less between paired sample concentrations than did data collected by occasional operators. For example, in the 2.3-15 m^3 s^{-1} range, 79% of all measurements collected by regular operators had variability ratios less than 0.05, whereas only 60% of those collected by occasional operators were in this range. For the flow range >15 m^3 s^{-1}, this trend was reversed, with the occasional operators data having less variability than those of the regular operators, an anomaly that we cannot explain.

For the River Washita, data collected by regular operators consistently varied less than those collected by the occasional group. In general, however, data collected by both groups of operators varied more than they did at Creek East Bitter. Presumably this was caused by a greater percentage of sand in transport and by the locations being more difficult to sample because of the truss bridge and the larger channel. At the River Washita, occasional operators had a disapportionate amount of data that varied greatly. For flows >50 m^3 s^{-1}, 13% of all data collected by occasional operators had variability ratios greater than 0.40, whereas only 1% of the data from regular operators were in this category. For any category when the difference between the regular and occasional operator data is 6% or greater, the data are statistically significant.

The analyses of concentrations in Table 1 do not indicate the differences in estimates of long term sediment transport which result from use in load computations of data collected by regular *vs.* occasional operators. However, Table 2 reveals that if the higher of paired concentrations were used to construct sediment graphs, the computed transport at the Creek East Bitter would have been 10% higher for the occasional operators and 3.5% higher for the regular operators. Equivalent increases for the River Washita would have been 30% using data from the occasional operators and 6% using data from the regular operators. If we had used mean sediment concentration data throughout our analyses, these percentages would have been half as large.

ETR vs. SV sample concentrations

Because fewer of these data were available, the analyses are less detailed than for the paired ETR measurements. Table 3 shows mean concentrations for the data grouped by discharge ranges for each stream. At the Creek East Bitter the mean concentrations consistently increased with increasing discharge, which is the

Table 1 Percent of ETR measurements within variability ranges for regular and occasional operators

Flow rate range ($m^3 s^{-1}$)	Operator group	Variability range (ratio)					
		<0.05	0.05–0.10	0.10–0.20	0.20–0.30	0.30–0.40	>0.40
Creek East Bitter							
<2.3	Regular	79	9	5	6	0	1
	Occasional	70	13	6	2	2	7
2.3-15	Regular	79	13	4	0	0	4
	Occasional	60	17	8	2	5	8
>15	Regular	44	22	11	0	0	22
	Occasional	50	25	13	0	0	12
River Washita							
<10	Regular	63	15	9	6	1	6
	Occasional	51	23	8	7	1	10
10-50	Regular	64	15	11	2	3	5
	Occasional	60	11	10	6	2	11
>50	Regular	69	20	7	1	2	1
	Occasional	27	33	13	7	7	13

Table 2 Percent variations in sediment transport calculated from measurements by regular and occasional operators

Flow range ($m^3 s^{-1}$)	Proportion of total sediment transport	Mean variation ratios of operators		Weighted variation ratios of operators	
		Regular	Occasional	Regular	Occasional
Creek East Bitter					
0-2.3*	0.044	0.05	0.06	0.0022	0.0026
2.3-15	0.219	0.05	0.08	0.0110	0.0175
15-30	0.202	0.03	0.06	0.0061	0.0121
>30	0.536	0.03	0.13	0.0161	0.0697
Σ Weights				0.035	0.102
River Washita					
0-10*	0.042	0.12	0.18	0.0050	0.0076
10-50	0.308	0.10	0.23	0.03008	0.0708
50-100	0.310	0.06	0.10	0.0186	0.0310
100-150	0.215	0.02	0.84	0.0043	0.1806
>150	0.125	0.04	0.11	0.0050	0.0138
Σ Weights				0.064	0.304

*Approximate wading range.

Table 3 Comparison of SV and ETR sample mean sediment concentrations

Creek East Bitter				
Discharge range ($m^3 s^{-1}$)	<2.3	2.3-15	15-30	>30
Number of samples	6	27	6	4
Mean ETR conc. ($mg\ l^{-1}$)	2 869	7 634	15 168	36 112
Mean SV conc. ($mg\ l^{-1}$)	2 838	8 647	15 664	37 824
River Washita				
Discharge range ($m^3 s^{-1}$)	<10	10-50	100-150	>150
Number of samples	7	35	31	19
Mean ETR conc. ($mg\ l^{-1}$)	5 108	4 713	9 180	8 150
Mean SV conc. ($mg\ l^{-1}$)	5 143	4 850	8 895	8 134

generally expected trend. In the case of the River Washita, however, mean sediment concentration values for the lowest discharge group were higher than those of the next higher discharge range, which possibly results from chance because of the limited number of samples. Sediment concentrations in the highest discharge range (>150 $m^3 s^{-1}$) were less than those in the next two lower discharge ranges. This possibly resulted because in a stream of this size the peak sediment concentration generally occurred well before the peak discharge for each flow event and was decreasing when the discharge reached a maximum.

Mean concentrations for the ETR and SV data agreed well for all flow ranges at both locations (Table 3), and there is no statistical difference between the data. This indicates that ETR sampling could be replaced with the easier and simpler SV sampling method. In the case of Creek East Bitter, where suspended sediment contains little sand, SV sampling appears a logical and appropriate method. However, two detailed suspended sediment distribution studies for the River Washita (Allen & Welch, 1967) have revealed great vertical and lateral variations in sand concentration in the stream, despite a uniform distribution of silt and clay sized material. Selection of the SV sampling location at this site, therefore, may have been fortuitous, and this technique should not be used as the principal method of sampling for similar streams until its appropriateness has been further investigated.

ETR vs. PS sample concentrations

Table 4 shows that ETR and PS concentrations agree well for flows in Creek East Bitter below 15 $m^3 s^{-1}$. At higher flows, only one paired observation was available, the PS concentration being about 8% higher than the ETR concentration. Plotting trends (not included) of all other ETR and PS data during higher flows support this single observation. The PS intake point was probably responsible for the higher concentration, being located near mid stream and about 0.2 m above the stream bed. Although this intake point was roughly near mid depth for lower flows, it was in the bottom 10% of depth for the highest flows and therefore in the high sand concentration zone. Since 75% of the sediment transport at this location occurs at flow >15 $m^3 s^{-1}$, the probable error from using PS data alone could still be close to 8%.

Table 4 Comparison of PS and ETR sample mean sediment concentrations

Creek East Bitter					
Discharge range ($m^3 s^{-1}$)	<2.3	2.3-15	>15		
Number of samples	26	18	1		
Mean ETR conc. ($mg l^{-1}$)	1 947	5 430	21 466		
Mean PS conc. ($mg l^{-1}$)	1 921	5 431	23 281		
River Washita					
Discharge range ($m^3 s^{-1}$)	<10	10-50	50-100	100-150	>150
Number of samples	38	122	37	10	4
Mean ETR conc. ($mg l^{-1}$)	1 366	3 429	6 731	9 249	5 936
Mean PS conc. ($mg l^{-1}$)	1 290	3 114	6 266	8 721	6 086

At the River Washita location, PS concentrations were generally low (Table 4). The PS intake point was probably responsible since it was fixed on a bridge pier near the stream bed near the toe of the left bank. If an approximate error of 6 or 7% could be tolerated in the sediment transport data, the entire field data at this location could be obtained with only a pumping type sampler.

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