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Particulate Organic Matter Export from Three Headwater Streams: Discrete versus Continuous Measurements

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Particulate organic matter (POM) export from three small headwater streams of the southern Appalachian Mountains was estimated using continuous and discrete (grab) measurement methods for 2 yr. Total annual POM export estimated from continuous measurements was always greater (28–68 kg ash-free dry mass (AFDM)) than estimates (8–44 kg AFDM) made from discrete measurements (i.e. POM concentration × total discharge). Continuous export samples were collected using a weir and gaging flume connected to a Coshocton proportional sampler designed to deliver 0.6% of discharge into a series of three settling barrels. The settling barrels removed a consistent proportion of POM (85–87%). The proportion of stream flow sampled by the Coshocton samplers was constant for each of the samplers (range 0.53–0.6%). The constant extraction efficiencies and proportional sampling of discharge allowed for the calculation of total export independent of discharge measurements (i.e. total export = amount in barrels ÷ extraction efficiency ÷ Coshocton percentage). The inability of the discrete method to adequately sample storm and bedload transport accounts for the underestimates of total annual export. This underestimation has important implications for studies which use discrete measurements to estimate POM export.

La quantité de matières organiques particulaires (MOP) rejetées par trois petits cours d'eau d'amont de la partie sud des Appalaches a été estimée pendant deux ans à l'aide de méthodes de mesures continues et discrètes (aléatoires). La quantité annuelle totale de MOP éliminées estimée par mesure continue était toujours plus grande (28–68 kg de matière sèche sans cendre (MSSC)) que celle estimée (8–44 kg (MSSC)) par les mesures discrètes (c.-à-d. concentration de MOP × débit total). Les échantillons de mesure en continu ont été prélevés à l'aide d'un déversoir et d'un canal de jaugeage relié à un échantillonneur proportionnel Coshocton conçu pour diriger 0,6 % de l'écoulement dans une série de trois barils de décantation. Ces barils retenaient une proportion constante des MOP (85–87 %). La proportion de l'écoulement prélevé par les échantillonneurs Coshocton était constante pour chacun des échantillonneurs (gamme : 0,53–0,6 %). L'efficacité d'extraction constante et le prélèvement proportionnel du débit ont permis de calculer les rejets totaux indépendamment des mesures de débit (c.-à-d. rejets totaux = quantité dans les barils + efficacité d'extraction + % de Coschocton). L'incapacité de la méthode discrète à échantillonner adéquatement les transports de crues et de fond explique la sous-estimation de la quantité annuelle totale. Cette sous-estimation a d'importantes incidences sur les études où l'on fait appel à des mesures discrètes pour estimer les MOP éliminées.

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Unidirectional downstream transport is an important element in conceptualizing streams as longitudinally linked systems (Vannote et al. 1980; Minshall et al. 1985) or as net importers or exporters (Cummins 1974) of energy, nutrients, or organic matter. Therefore, considerable attention has been placed on measuring and characterizing export, concentration, and composition of stream seston. The majority of export measurements have been made in streams draining cool temperate forests of North America and Europe and have utilized noncontinuous measurements of export (i.e. discrete grab samples) weighted on the basis of discharge (Fisher and Likens 1973; Hobbie and Likens 1973; Bormann et al. 1969) or time (Brinson 1976; Naiman 1976). Malmqvist et al. (1978) is one of the few studies whch have made continuous measurements over an extended period of time, although their estimates are still dependent on discharge measurements.

The errors associated with export measurements have been considered as problems associated with laboratory methods (i.e. filter weights, ashing techniques, and carbon determinations) or with replicability of the grab seston estimate (Baker et al. 1974; Perry and Rose 1984; Hickel 1984) rather than as problems associated with the type of sample collected. The objectives of this study were to compare discontinuous measurements weighted for discharge with continuous measurements of export and to examine the factors which are responsible for differences between the two methods.

Study Sites

Three small headwater streams, located at the U.S. Forest Service Coweeta Hydrologic Laboratory (CHL), Macon

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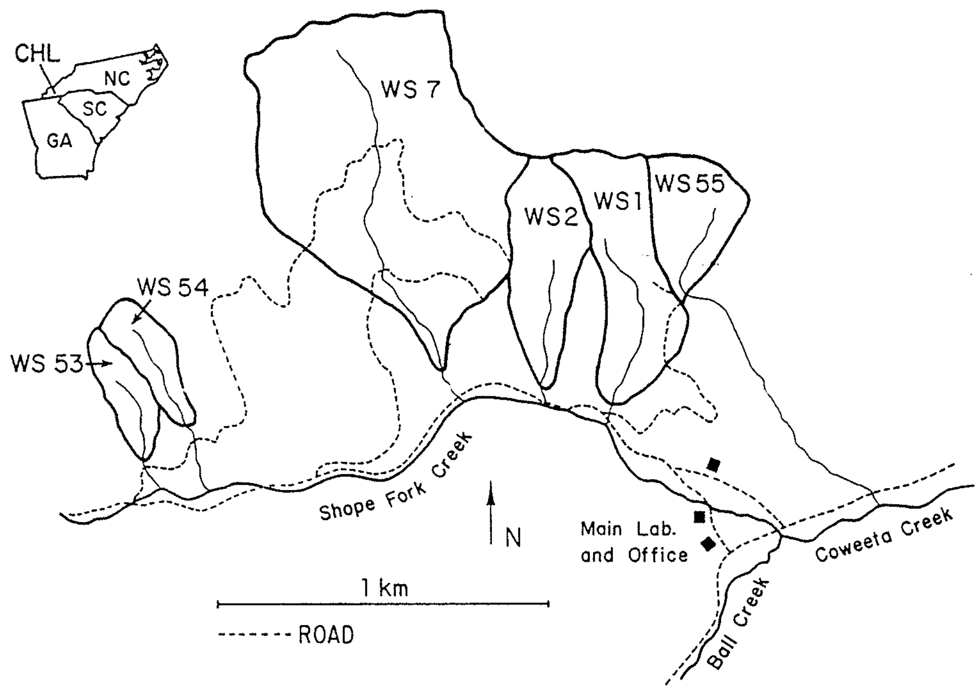

FIG. 1. Location of the Coweeta Hydrologic Laboratory (CHL), the three study streams draining catchments 53, 54, and 55, and the stream (WS 2) used to estimate winter discharges.

TABLE 1. Characteristics of study streams. Elevations were measured at the gaging flumes. Discharges are for the period January 1985 – March 1987.

	WS 53	WS 54	WS 55
Catchment			
Area (ha)	5.2	5.5	7.5
Elevation (m asl)	829	841	810
Channel			
Length (m)	135	260	170
Bankfull area (m^2)	365	406	314
Gradient ($cm \cdot m^{-1}$)	27	33	20
Discharge ($L \cdot s^{-1}$)			
Average	0.53	0.81	0.93
Maximum	22.87	22.76	24.07
Minimum	0.06	0.05	<0.01
Temperature (°C)			
Average	12.9	12.4	12.7
Maximum	19.5	19.5	19.4
Minimum	1.5	3.3	1.6
Annual degree-days	4696	4541	4626

County, North Carolina, USA (Fig. 1), were chosen for study. These streams are located in the Blue Ridge Province of the southern Appalachian Mountains. All three streams are first order, have southern aspects, and are heavily shaded by mixed hardwood forests and riparian rhododendrons. They are high-gradient streams with similar elevations, stream areas, thermal regimes, and discharge patterns (Table 1). Stream substrates consist of either rock outcrops (15–30% of channel area) or areas of cobble and boulders intermixed with sand and gravel. These streams are similar to other streams at CHL in being characterized by low ion concentrations ($<1\ mg \cdot L^{-1}$) and pH of 6.6–6.8 (Swank and Douglass 1975). There have been few disturbances in the study watersheds since the 1930's. WS 53 was experimentally treated with methoxychlor in 1980 (Cuffney et al. 1984; Wallace et al. 1982b). In 1961–62 the entire Coweeta basin was sprayed with DDT to control the elm spanworm (*Ennomos subsignarius* (Hubner)) (Grzenda et al. 1964). Additional site descriptions for WS 53 and WS 54 can be found in Wallace et al. (1982b, 1986a, 1986b) and Cuffney et al. (1984).

Materials and Methods

Continuous Export Estimates

A 2-ft-diameter (0.6m) Coshocton wheel proportional runoff sampler (Parsons 1954) mounted below a portable weir (Fig. 2) was used to deliver 0.6% of stream flow into three covered 125-L settling barrels. Water entered near the bottom of each barrel and exited just below the surface. This arrangement maximized settling and minimized the loss of floating particles. A hardware cloth trap (mesh = 4 × 4 mm) placed upstream of the weir excluded large particulate organic matter (POM) and prevented clogging of the flume or Coshocton wheel sampler. The collection apparatus was sampled at weekly (10 December 1984 – 14 May 1985) or biweekly (14 May 19 85 – 7 December 1986) intervals over a 2-yr period. Export data from WS 54 after December 1985 are not reported here because this stream was used in an experimental manipulation.

Export barrels were sampled by first flushing out the pipe leading from the Coshocton sampler to barrel 1 by holding the opening of the Coshocton sampler in the outflow of the weir for 15–30 s. Average water depth in each barrel was estimated from four measurements evenly spaced around the circumference of the barrel. Water volume in the barrel was then calculated from a regression relating water depth (centimetres) and volume (litres) (i.e. volume = 1.6663 ×

depth − 3.0829; r^2 = 0.999). Concentrations of particles in each barrel were measured by vigorously stirring the water and then collecting three replicate aliquots at about middepth near the middle of the barrel. Each aliquot was filtered through a preweighed and ashed glass fiber filter (Gelman type A/E). The amount of water filtered was varied with the amount of suspended material in each barrel. The amount (grams ash-free dry mass (AFDM)) of POM in each barrel (B) was calculated as

$$B = C \times [V_b \div V_f]$$

where C is the POM concentration (grams AFDM per litre) and V_b and V_f are the volume (litres) of water in the barrel and the aliquot filtered. Total amount in the barrels (B_t) is the sum of the averages of the replicates for the three barrels.

Total export (Expt) in each collection interval was calculated as

$$\text{Expt} = B_t \div E_f \div C_s$$

where E_f is the export barrel extraction efficiency, B_t is the amount (grams AFDM) recovered from the three barrels, and C_s is the proportion of discharge sampled by the Coshocton subsampler. Export barrel extraction efficiencies (i.e. [inlet concentration − outlet concentration] ÷ inlet concentration) and proportion of total flow sampled by the Coshocton sampler (i.e. inlet discharge ÷ flume discharge) were measured during the period of weekly samplings.

The H-flumes acted as sediment traps and required periodic cleaning to maintain accurate stage measurements. Cleanings were done approximately once a month after all barrels had been sampled and emptied. Flumes were cleaned by slowly resuspending the material in the flume while the Coshocton subsampler was filling barrel 1. Flume cleanings lasted 5–30 min depending on the amount of material in the flume. After the flume was cleaned, barrel 1 was sampled as described above. Organic matter contained in the flume was calculated as amount in barrel 1 ÷ Coshocton percentage. The amount of POM recovered from the flume was usually apportioned over two sampling periods in relation to the amount of POM exported in each sampling period (i.e. amount in flume × amount in export collection period 1 ÷ total export in periods 1 and 2).

Grab Export Estimates

Grab export samples were taken immediately prior to collecting barrel samples. Grab samples were collected at the mouth of the gaging flume after the Coshocton subsampler was stopped. Extreme care was taken to avoid disturbing the flume or stream while collecting grab samples. Sample volumes were determined by the amount of material in export and ranged from 2 to 8 L. Six grab samples were taken from each stream on each sample date and filtered through preweighed and ashed glass fiber filters (Gelman type A/E). Export was calculated as average concentration × total discharge during the sampling interval. Average concentration was the mean of the POM concentrations measured at the beginning and end of the sampling interval. Filters from grab, barrel, and flume cleanings were dried (60°C for 5 d), weighed, ashed (500°C for 1–2 h), rewetted, dried (2 d), and reweighed to determine ash content and AFDM.

Discharge

Stream flow at the base of each watershed (Fig. 1) was channeled into a 1.5-m-long plywood trough with a 1-ft (0.3 m) H-

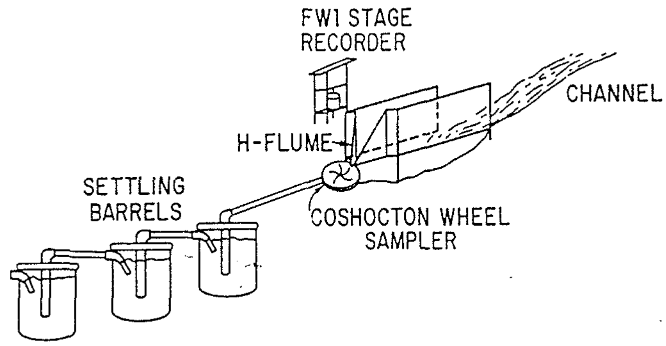

FIG. 2. Sampling apparatus used to collect continuous data on seston export. The Coshocton wheel proportional sampler transfers ~0.6% of the stream flow into the three covered 100-L settling barrels. Water enters each barrel at a point ~45 cm below the water surface (~15 cm above the bottom of the barrel). Water exiting the barrels is removed at ~10 cm below the water surface. The H-flume and FW1 stage recorder provide continuous discharge records during nonfreezing months (April–November).

TABLE 2. Seston barrel extraction efficiencies and percentage of stream flow sampled by Coshocton proportional samplers. Extraction efficiencies are calculated as (inlet concentration − outlet concentration) ÷ inlet concentration. Discharge range is the range of discharges over which extraction efficiencies were calculated.

	WS 53	WS 54	WS 55
	Seston barrel extraction efficiencies		
Mean	0.8452	0.8704	0.8584
SE	0.0131	0.0120	0.0167
N	13	16	15
	Coshocton flow subsample		
Mean	0.5988	0.6190	0.5339
SE	0.0091	0.0088	0.0073
N	20	20	21
Discharge range ($L \cdot s^{-1}$)	0.3–4.2	0.5–4.9	0.4–9.0

flume (Agricultural Research Service 1962) attached to the downstream end (Fig. 2). Stage heights were continuously measured during nonfreezing months (i.e. April – November) using a strip chart recorder at a stilling well connected to the H-flume (Fig. 2). Discharge rating curves (i.e. stage in centimetres versus discharge in litres per second) were derived for each watershed from field measurements and used to calculate instantaneous and total daily discharges from stage data. WS 2 (Fig. 1) discharge (i.e. daily average, maximum, and minimum) was used to estimate study stream discharge during ungaged months (December – March). These discharge estimates were based on regression equations developed during gaged months.

Results

Characteristics of Continuous Export Samplers

Field measurements indicated that the Coshocton proportional subsamplers sampled a very constant proportion of stream flow over a wide range of velocities (Table 2). However, the proportion of stream flow sampled differed

TABLE 3. Discharge ($L \cdot s^{-1}$) and residence time (h) in seston barrels during the two study years. Sample collection began on 10 December 1984 (i.e. year 1: 1984–85) and ended on 7 December 1986 (i.e. year 2: 1985–86). Percentiles (50th and 95th) refer to discharges below which 50 and 95% of the observations lie. Average, 50, and 95 percentile discharges are determined from data on mean daily discharges. Maximum and minimum discharges are determined from instantaneous discharges. WS 54 was experimentally manipulated during year 2 and data from that year are not included here.

	WS 53		WS 54	WS 55	
	Year 1	Year 2	Year 1	Year 1	Year 2
Discharge characteristics					
Average	0.58	0.33	0.91	0.94	0.50
50th	0.50	0.29	0.75	0.74	0.47
95th	1.25	0.63	1.94	2.29	1.06
Max.	13.91	22.87	12.95	13.97	24.07
Min.	0.16	0.14	0.25	0.15	0.05
Seston barrel residence times					
Average	23.9	42.1	15.3	14.8	27.8
50th	27.8	47.9	18.5	18.8	29.6
95th	11.1	22.1	7.2	6.1	13.1
Min.	1.0	0.6	1.1	1.0	0.6
Max.	86.8	99.2	55.6	92.6	277.8

significantly among the three Coshocton subsamplers. The Coshocton on WS 55 sampled significantly less flow than did those on WS 53 and WS 54 ($P < 0.05$, ANOVA, Student–Newman–Keuls test; Zar 1974). In addition, Coshocton samplers on WS 54 and WS 55 differed significantly from the expected (Parsons 1954) value of 0.6% (*t*-test; Zar 1974). These differences arise from variability in the construction, installation, and settling of the samplers.

Seston barrel extraction efficiencies were constant over the range of velocities reported in Table 2 and did not differ significantly among the three streams ($P < 0.05$, ANOVA; Zar 1974). The three seston barrels removed an average of 85.8% of the organic particles in transport. However, barrel extraction efficiencies were not measured during storms or at discharges $>9\ L \cdot s^{-1}$; consequently the particle retention in the barrels at extreme discharges is not known empirically.

The design of the barrels limits the loss of floating particles but the deposition of nonfloating particles is a function of particle size and residence time. High discharges could reduce barrel extraction efficiencies by decreasing residence times, resulting in underestimates of export. Alternatively, efficiencies might increase if median particle size increases during storms (Wallace et al. 1982a), resulting in overestimates of export. Nevertheless, residence time in the barrels was seldom (i.e. <5% of the time) <6 h (Table 3), and even during maximum recorded discharge ($23\ L \cdot s^{-1}$), residence time was 36 min and current velocities were sufficiently low ($<0.14\ cm \cdot s^{-1}$) that extraction efficiencies of 78–86% would be expected (i.e. settling of particles >19 μm in diameter; T. F. Cuffney, unpubl. data; Morisawa 1968). In addition, most of the total organic matter retained by the export barrels (i.e. 82–92%, CV = 9%) settled out in the first barrel (Table 4). The amount recovered from barrel 3 was always <17%. Based on these calculations, the seston barrel efficiencies would not radically change over the entire range of discharge encountered.

Comparison of Grab and Continuous Export

The discrete (grab) method underestimated annual POM export obtained using the continuous method (Table 5) for all three streams and in both years. For the discrete method, underestimates developed immediately, continued to acrue through time (Fig. 3A), and were greatest for WS 53 (55–73%) and least for WS 55 (27–53%). Underestimates were greater during year 2 (10 December 85 – 10 December 86) than year 1. The amount of POM export that originated from H-flume cleanings was <10% of that collected by the seston barrels.

The differences between grab and continuous export estimates are primarily due to the inclusion of storms in the continuous estimates of export (Fig. 3B). These storms were rarely encountered during the collection of grab seston. During the first year, 23.5% (WS 53) to 41.1% (WS 55) of the sample collection intervals were influenced by storms (i.e. maximum − minimum discharge equals or exceeds $2\ L \cdot s^{-1}$ in a 24-h period). However, these intervals represented 50–66% of annual export as estimated by continuous methods (Table 5). The second year of study was influenced by a severe drought and major storms were less frequent than during year 1. However, the influence of these storms on export increased during year 2, with 71–79% of annual export occurring in collection intervals which included storms.

Export concentrations derived from continuous (barrel) and discrete (grab) methods also show the influence of storms (Table 6). The concentrations derived from barrel samplers (i.e. export ÷ total discharge) are always higher than those measured by discrete methods because barrel estimates include storms. Mean annual concentrations derived from barrels were higher for the drought year than for year 1 whereas grab estimates for year 2 were less than year 1. Maximum concentrations derived from continuous samplers were 3–7 times maximum grab concentrations. These values do not fully reflect the increase in POM concentrations which accompany a storm, since estimates from barrels are averages over the collection interval rather than over short-duration storms. POM concentrations in these streams can reach 10–100 times baseflow con-

TABLE 4. Summary of the proportion of total POM export recovered from each of the export collection barrels 1, 2, and 3 during year 1.

	WS 53			WS 54			WS 55		
	1	2	3	1	2	3	1	2	3
Mean	0.920	0.051	0.029	0.889	0.072	0.039	0.822	0.130	0.047
SE	0.009	0.006	0.003	0.010	0.007	0.004	0.011	0.008	0.005
Max.	0.978	0.172	0.073	0.966	0.198	0.127	0.933	0.246	0.164
Min.	0.759	0.011	0.010	0.727	0.022	0.012	0.643	0.049	0.005
N	34	34	34	34	34	34	33	33	33

TABLE 5. Comparison of total annual export (kg AFDM·yr⁻¹) estimates obtained using continuous (barrel) and discrete (grab) methods. Percent reduction is the percent of annual export obtained by grab estimates to that of barrel estimates [(barrel − grab estimate) ÷ (barrel estimate) × 100]. Storm export is the amount (kg) of barrel export obtained during sampling intervals which included a storm. A storm is defined to have occurred when maximum and minimum discharges differ by 2 or more $L \cdot s^{-1}$ in a 24-h period. Percent due to storms is the percent of annual export which is attributable to collection intervals with storms. *N* is the number of collection intervals which contained at least one storm. There are 34 collection intervals in year 1 and 26 in year 2.

	WS 53		WS 54	WS 55	
	Year 1	Year 2	Year 1	Year 1	Year 2
Annual export					
Barrel	35.40	27.83	67.63	55.86	47.07
Grab	15.80	8.08	44.22	39.35	24.78
% reduction	55.4	71.0	34.6	29.5	47.3
Storm export					
Total	15.58	19.67	36.79	35.33	37.01
% due to storms	49.8	70.7	56.1	65.7	78.6
N	8	9	11	14	11

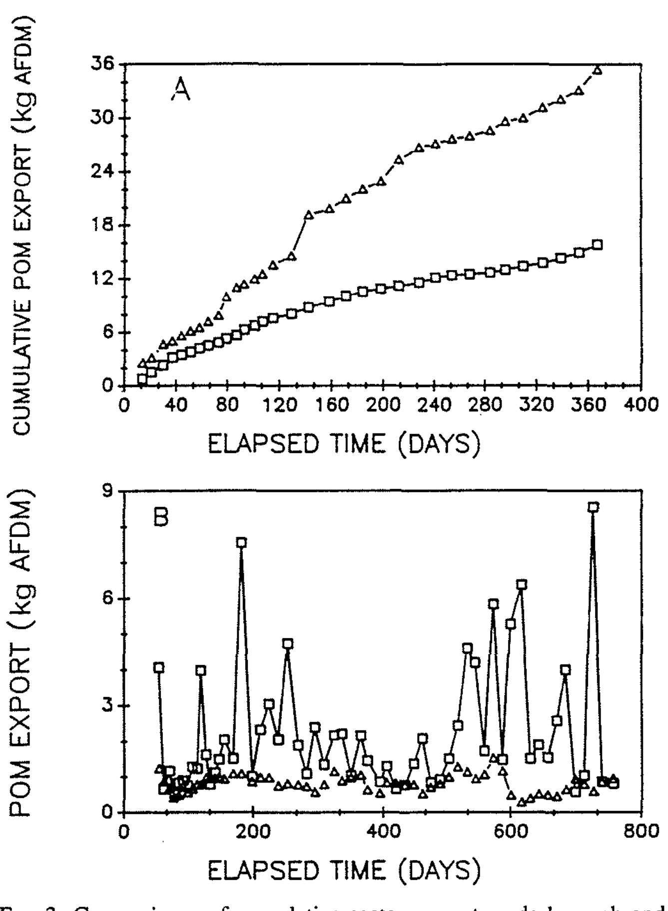

FIG. 3. Comparisons of cumulative seston export made by grab and barrel techniques for WS 53. (A) Cumulative effect of the two methods in estimating annual export during year 1 using discrete (□) and continuous (▲) methods. (B) Differences between estimates of POM export obtained from grab (□) and continuous (▲) methods for each collection interval over the 2-yr study period. Results are similar for WS 54 and WS 55.

centrations on the rising limb of the storm hydrograph (Cuffney et al. 1984), which indicates the importance of storms in producing the differences in seston concentrations between the two methods. Much more similar concentrations are produced by the two methods during periods when discharges are stable and there are no storms (see minima in Table 6).

Discussion

Influence of Storms

The present work is the first to estimate potential errors resulting from grab methods and shows that grab methods underestimate export because they underrepresent storms. Numerous investigators have noted that seston concentrations increase dramatically on the raising limb of the hydrograph and often before measurable increases in discharge occur (Fisher and Likens 1973; Bilby and Likens 1979; Gurtz et al. 1980; Fisher and Grimm 1985; Farr and Clarke 1984). This hysteresis has been attributed to the direct erosive effects of falling rain, increased subsurface flows during the falling limb of the hydrograph (Gregory and Walling 1973), and rapid suspension, during the rising hydrograph, of light materials in areas of streambed located adjacent to the stream margins at low flow (Bilby and Likens 1979). These peaks in concentration are brief and unpredictable. Consequently, even intensive sampling will underrepresent the impact of storms and underestimate export.

Significance for Other Rivers

The applicability of CHL stream data to larger rivers or to rivers in different geographical areas depends on how discharge (i.e. storm flow) and bedload characteristics relate to those of the study streams. The suitability of systematic grab sampling for estimating annual export can be related to the predictability of storms within geographic areas. Accurate results would be expected in areas, such as the arid intermountain region (e.g. Salmon River, Cummins et al. 1983), which have very predictable flows (i.e. an early summer peak corresponding to snowmelt). Results obtained in streams of the arid southwest, which have highly unpredictable flows dominated by sudden summer storms and intense floods (Busch and Fisher 1981; Fisher and Grimm 1985), would be highly inaccurate. In wetter climates (e.g. Pacific Northwest, Midwest, East, and Southeast) which have less seasonality in rainfall, there would still be a high probability of missing major storms and underestimating export. Therefore, there are only a few areas within North America where systematic grab sampling will not result in underestimates of export due to the unpredictability of storms.

The influence of storms on larger rivers is not well documented. Larger rivers have less quickflow, and peak discharge is delayed and attenuated compared with upstream reaches (Richards 1982). However, Naiman (1982) found that POM export from large rivers of boreal forest regions is significantly affected by infrequent and unpredictable storms. Richey et al. (1986) reported that concentrations of suspended sediments in the Amazon River are generally greatest on the ascending limb of the hydrograph and that peak concentrations are reached prior to peak discharge. The pattern observed for suspended sediments in the Amazon River is similar to the pattern that is typically seen in small streams (Fisher and Likens 1973; Gurtz et al. 1980; Fisher and Grimm 1985; Farr and Clarke 1984). However, in small streams the difference between peak concentra-

TABLE 6. Annual average seston concentrations (mg AFDM·L^{-1}) derived from continuous (barrel) and discrete (grab) methods. WS 54 was experimentally manipulated during year 2 and data from that year are not included here.

	WS 53		WS 54		WS 55	
	Barrel	Grab	Barrel	Grab	Barrel	Grab
Year 1						
Mean	1.945	0.839	2.319	1.613	2.068	1.546
SE	0.263	0.036	0.395	0.012	0.324	0.131
Max.	7.546	1.230	13.000	3.220	9.089	3.335
Min.	0.519	0.405	0.663	0.553	0.500	0.459
N	31	31	31	31	31	31
Year 2						
Mean	2.358	0.773			3.673	1.262
SE	0.519	0.060			1.029	0.138
Max.	6.365	1.523			21.382	3.410
Min.	0.571	0.283			0.313	0.311
N	25	25			25	25

tion and peak discharge is a matter of hours or minutes compared with months on the Amazon River.

Problems associated with measurements of bedload and the distribution of POM in the water column may rival those associated with the distribution and predictability of storms in estimating POM export. The proportion of transport moving as bedload is thought to decrease as stream size increases (Richards 1982) so that bedload is a more important problem in small high-gradient streams than in larger low-gradient rivers. Gibbs (1967) has estimated that bedload accounts for <10% of sediment transport in the Amazon River because of the overriding influence of the water column. Nonuniform distribution of POM is a more important problem in larger rivers. Curtis et al. (1979) have shown that sediment concentrations in the Amazon River are not uniformly distributed and typically increase with depth so that specialized sampling techniques are required even for grab estimates of export (Hedge et al. 1986; Richey et al. 1986). Most estimates of export in large rivers are made using grab samples collected in the water column, and bedload is often missed entirely. Our export estimates, both continuous and grab, for CHL streams were made at a flume and therefore include bedload and are not affected by nonuniform physical distributions of POM, although grab samples are affected by nonuniform temporal distributions of POM.

Whole-stream sampling methods, which were difficult and expensive in our small CHL streams, are even more impractical in larger rivers. Therefore, the affects of using grab samples to estimate annual POM export in large rivers cannot be measured directly. However, preliminary work in a fifth-order Coastal Plain stream of the southeastern United States indicates that floodplains add 39.6×10^6 kg AFDM of POM to the river each year (Cuffney 1988). Estimates of annual export using grab methods indicate an annual POM export of only 3.2×10^6 kg AFDM from this river. A substantial portion of the missing 34.6×10^6 kg AFDM may be moving undetected through the system due to the use of grab sampling techniques. This difference represents a hugh potential error in export measurement and indicates that large rivers are even more vulnerable to underestimates associated with grab techniques than are small streams.

Relationship to Stream Ecosystem Theory

Construction and analysis of organic matter budgets has been an important component in the construction of stream ecosystem theory. Problems associated with estimating POM export have important implications for organic matter budgets and the body of stream ecosystem theory which depends on accurate budgets. Organic matter budgets based on the mass balance approach will be in error if POM is underestimated, as will most of the ecological parameters derived from budgets (e.g. benthic storage, characterizations of microbial respiration, POM processing rates, and temporal, geographic, and longitudinal patterns). For example, our grab samples underestimated annual export from the three study streams by 29–71% (i.e. [barrel estimate − grab estimate] ÷ barrel estimate; Table 5). Spiralling lengths (Newbold et al. 1981) calculated using seston barrel estimates are 2–3 times longer than those calculated using grab sample estimates. Errors of this magnitude (i.e. >100%) must be considered significant and should be addressed when stream ecosystem theories are developed. However, because of the difficulty and expense, it is unreasonable to routinely advocate continuous sampling. Data obtained by grab sampling should be carefully evaluated and sampling schemes constructed to minimize the errors produced by these techniques. Careful attention must be given to infrequent and unpredictable events which occur over very small percentages of time but which have major impacts upon total export (i.e. storms).

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