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Changes in stream morphology and storm transport of seston following watershed disturbance

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Abstract. Surveys of stream morphology and measurements of particulate organic matter (seston) transport were made in four streams to examine response to forest disturbance. Seston was sampled during baseflows and stormflows in streams draining an 8-year-old clearcut, a 25-year-old clearcut, and two reference watersheds at Coweeta Hydrologic Laboratory in the southern Appalachian Mountains of North Carolina. Surveys of stream morphology indicated that there were fewer debris dams and organic matter accumulations in disturbed streams. Baseflow seston concentrations varied seasonally, ranging from 0.5 to 1.0 mg/L in winter and from 3.0 to 7.0 mg/L during summer. Baseflow seston concentrations did not differ consistently between streams. In all streams, seston concentration increased with increasing discharge during storms and was positively correlated with the rate of change of discharge during rising flows. Seston concentrations decreased during peak flows and gradually declined as discharge returned to baseflow. Average seston concentrations during storms were generally highest in streams draining disturbed watersheds, and export (g AFDW transported/m^2 stream channel) was significantly higher in streams draining disturbed watersheds. Storm transport varied with season, storm intensity, and storm duration. Our results show that baseflow seston concentrations in streams draining disturbed areas may return to normal levels within a few years following disturbance; however, concentrations during storms may remain elevated for many years.

Key words: seston, streams, disturbance, storms, logging, Coweeta.

Headwater streams are closely linked to the areas they drain (Hynes 1975, Vannote et al. 1980), thus watershed disturbance can cause severe disruption within streams. Logging has been a common disturbance to eastern deciduous forests and has resulted in a variety of long-term effects on streams. Removal of vegetation decreases transpiration and increases streamflow (Hewlett and Hibbert 1961, Kovner 1956). Streamflow may remain elevated for 30–40 years following logging, returning to predisturbance levels at a rate proportional to forest revegetation (Swift and Swank 1981). Logging may also increase stream nutrient concentrations for 10–20 years (Likens et al. 1970, Martin et al. 1984, Swank and Douglass 1975, Vitousek and Melillo 1979). Soil disturbance associated with road building and timber harvest can increase erosion and result in high sediment loading to streams (Lieberman and Hoover 1948, Paustian and Beschta 1979, Tebo 1955). Sediment yields decrease to predisturbance levels as vegetation regrows; however, instream redistribution and transport of sediment may continue for many years (Brown and Krygier 1971).

Logging also alters the energy base of stream ecosystems. When forests are cut, allochthonous leaf inputs to streams are greatly reduced (Webster and Waide 1982); however, autochthonous production may increase due to the absence of shading and increased nutrient concentrations (Hains 1981). The pulse of autochthonous production is generally short-lived and rapid regrowth of riparian vegetation returns the stream to a detritus base within a few years (Swanson et al. 1982, Webster et al. 1983). However, the composition of detrital inputs may change considerably from mostly late successional, decay-resistant, litter to rapidly decaying early successional litter (Webster et al. 1987).

Logs and other organic debris play an important stabilizing role in stream ecosystems. Leaves and twigs accumulate behind logs that are large enough to span stream channels without being displaced by streamflow. These aggregations, called dams, cause a stepped pattern of streambed morphology, which reduces stream power and sediment export (Heede 1972, Swanson et al. 1976). Debris dams also filter dissolved and suspended particulate material from the water column (Bilby 1981, Swanson and Lienkaemper 1978, Triska et al. 1982). Rapid erosion of debris dam structure following logging was reported by Bilby (1981) and Fisher and Likens (1973). Small sticks and leaves, which form the internal matrix of debris dams, decay relatively rapidly; and since allochthonous inputs are reduced, the matrix is not replaced. Breakdown in debris dam structure may account, in part, for increased baseflow seston transport observed following logging (Gurtz et al. 1980, Hobbie and Likens 1973, Webster et al. 1983). Webster and Golladay (1984) noted that increased baseflow seston concentration returned to reference levels within 10–20 years following logging, suggesting that debris dam function may be partially restored as allochthonous inputs return to predisturbance levels.

Logging also results in a long-term decline in the number of debris dams in streams draining logged watersheds (Likens and Bilby 1982, Swanson and Lienkaemper 1978, Webster et al. 1987). Generally, early successional vegetation is not large enough to form stable debris dams as it dies and falls into streams. Thus, the number of debris dams declines as old logs decay, and may remain depressed for 100–400 years depending on the recovery rate of the mature forest type of the region (Likens and Bilby 1982, Swanson and Lienkaemper 1978). Low numbers of debris dams in streams can result in high transport of particulate organic matter, especially during storms. Bilby (1981) and Bilby and Likens (1980) reported that debris dam removal on a 175-m reach of an otherwise undisturbed stream increased the transport of dissolved, fine, and coarse particulate organic matter; greatest increases were observed at high discharges and were attributed to increased stream power and decreased retentiveness.

The major long-term effects of forest disturbance on streams appear to be alteration of the energy base available to stream consumers and a gradual decline in the ability of streams to retain biologically important materials. Low retention efficiency may cause catastrophic loss of organic matter and nutrients during periods of high discharge. The objective of this study was to examine the long-term effects of forest disturbance on streams. This objective was accomplished by characterizing organic matter export during baseflows and stormflows and by examining stream channel morphology in streams draining logged and reference watersheds.

Study Site

This work was conducted at Coweeta Hydrologic Laboratory, Macon County, North Carolina, USA. Four sites were selected for study; two streams draining disturbed watersheds were matched with two streams draining reference watersheds of similar size. Big Hurricane Branch (BHB) drains WS (Watershed)-7, a 58.7-ha experimental watershed, which was grazed by cattle from 1941 to 1952 and cable logged during the winter of 1976–1977. Regrowth is dominated by hardwood sprouts, herbs, vines, and seedlings (Boring et al. 1981). Carpenter Branch (CB) drains WS-13, a 16.1-ha experimental watershed. Originally mixed hardwoods, all trees and shrubs were cut in 1939–1940 and again in 1962 (Swank and Douglass 1977). No wood was removed from the site and soil disturbance was minimal (Swank and Douglass 1977). The watershed is now covered by a young hardwood forest dominated by yellow poplar (*Liriodendron tulipifera*) at lower elevations and mixed oaks (*Quercus* spp.) at higher elevations (Leopold and Parker 1985). Hugh White Creek (HWC) drains WS-14, a 61.1-ha watershed, and Grady Branch (GB) drains WS-18, a 12.5-ha watershed. Watersheds 14 and 18 are mixed hardwood forests and are long-term reference watersheds at Coweeta (Swank and Douglass 1977). Both sites were selectively logged before 1925 and, except for the chestnut blight, have been undisturbed for 60 years. Since many of the measurements we made are influenced by stream size, streams were paired based on similarities in average annual discharge and watershed area (Table 1). Hugh White Creek was selected as a reference stream for Big Hurricane Branch, and Grady Branch was selected as a reference stream for Carpenter Branch. All streams are located within 2 km of each other. They are equipped with V-notch weirs, and continuous records of streamflow are maintained by the Forest Service. Further characteristics of the study sites are presented in Table 1.

Methods

Measurements were made on each stream to assess the effect of watershed disturbance on stream morphology and hydraulics. During September and October 1985, stream width and

TABLE 1. Physical and morphological features of the study sites. Values with parentheses are means and 95% (±) confidence intervals.

	BHB	HWC	CB	GB
Watershed No.	7	14	13	18
Treatment	Disturbed	Reference	Disturbed	Reference
Area (ha)	58.77	61.1	16.1	12.5
Main channel length (m)	1225	1125	604	345
Gradient (m/m)	0.19	0.15	0.19	0.20
Streambed area (m^2)	3274	8085	1330	1116
Average annual discharge (L/s)[a]	18.52 (1.85)	19.37 (1.45)	5.39 (0.32)	4.06 (0.31)
Organic accumulations (No./25-m reach)	1.12 (0.40)	2.66 (0.55)	1.94 (0.74)	5.14 (1.39)
Logs (No./25-m reach)	2.60 (0.53)	2.34 (0.64)	0.65 (0.36)	2.29 (0.83)
Debris dams (No./25-m reach)	0.07 (0.08)	0.45 (0.21)	0.18 (0.20)	0.64 (0.54)
Roughness (Manning's n)	0.28 (0.08)	0.34 (0.10)	0.11 (0.04)	0.24 (0.10)
Average velocity (m/s)	0.13 (0.03)	0.08 (0.03)	0.19 (0.15)	0.06 (0.02)

[a] Based on Forest Service Records.

average depth were measured at three transects within 10-m reaches every 100 meters along each stream. Average velocity was measured for each 10-m reach using dye (rhodamine-B) releases. All measurements were made during stable baseflows. Bed roughness was calculated for each reach according to the Manning formula (Chow 1959).

During March 1986 the main channel of each stream was surveyed for channel features that represented potential obstructions to downstream transport of seston. These features were divided into three categories: 1) organic matter accumulations—accumulations of leaves and sticks supported by rocks or boulders, with no wood >5 cm diameter; 2) logs—wood alone, with an average diameter >5 cm; 3) debris dams—sticks and leaves aggregated with supporting logs >5 cm diameter. Only features that clearly affected stream morphology, i.e., created pools or stair-step patterns of flow, were included in the survey.

From June 1984 to June 1985, seston was sampled during eight storms at a single site on each stream just upstream of the weir ponding basin. Stream samples (ca. 500 ml) were collected by ISCO Model 2100 automated water samplers. Intake hoses were positioned above the streambed in well-mixed riffles. Samplers were manually turned on when rain appeared possible. Excess samples collected prior to the onset of precipitation were discarded, the sample bottles were rinsed thoroughly with water collected from below the weir (many of the particulates settle in the weir ponding basin), and bottles were returned to the sampler. All samplers were placed near the stream gaging stations, and during storms we sampled at a frequency that varied depending on how fast streamflow was changing. Sampling frequency was greatest during rising flows and continued following storms until streamflow returned to within 5–10% of original baseflow. Sampling frequency varied from 5 min during intense thunderstorms to several hours during less intense steady rains. Fifteen to 25 samples were collected from each stream during each storm. Following storms, sample bottles were returned to the lab, washed thoroughly, and rinsed with deionized water. Additional grab samples were taken between storms to measure baseflow seston concentrations in each stream.

Water samples were returned to the laboratory and filtered (ashed and tared Gelman type A/E glass fiber filters) within 48 hr of collection. Filters were dried (55°C, 24 hr), desiccated (24 hr), weighed, ashed (550°C, 20 min), rewetted to restore water of hydration, redried, desiccated, and reweighed (Gurtz et al. 1980). Organic seston concentration was determined as weight loss on ashing and expressed as ash free dry weight (AFDW). Storm export was estimated by integrating the product of seston concentration and discharge over the course of each storm.

Five throughfall collectors (1 × 400 cm pvc troughs draining into 20-L buckets) were placed over each stream to estimate inputs of particulate organic matter during storms. Immediate-

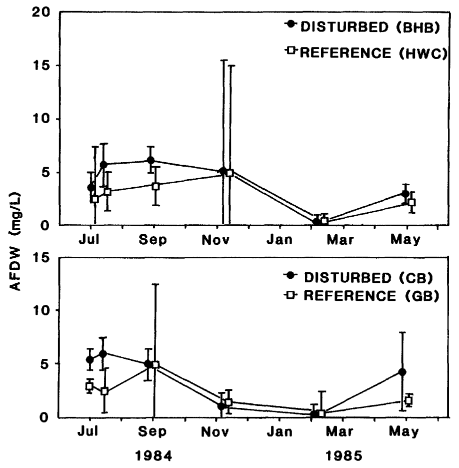

FIG. 1. Baseflow seston concentrations (mg AFDW/L) in paired Coweeta streams. Values are means and 95% confidence intervals. Solid circles represent disturbed streams, open squares represent reference streams.

ly following storms, throughfall volumes were recorded and subsamples (ca. 250 ml) were returned to the laboratory for processing as described above. Stream area, throughfall particulate organic matter concentrations, and throughfall volumes were used to estimate total organic particle inputs due to channel interception during each storm.

Results and Discussion

Effect of watershed disturbance on stream morphology and hydraulics

Organic matter accumulations and logs are common morphological features in undisturbed Coweeta streams (Table 1). Debris dams are not common owing to the rarity of streamflows of sufficient magnitude to move and consolidate large woody debris; therefore logs generally remain where they fall in the stream. A comparison of BHB and HWC revealed significantly fewer organic matter accumulations in the disturbed stream (BHB) (t-test, $p = 0.0001$), however there was no significant difference in the number of logs (t-test, $p > 0.50$). CB (disturbed) had significantly fewer organic matter accumulations (t-test, $p = 0.0003$) and logs (t-test, $p = 0.001$) than GB (reference). In Coweeta streams following logging, there appears to be a twofold disturbance to stream morphological features. An initial reduction in the numbers of stick and leaf accumulations is followed later by a more gradual decrease in the amount of large woody debris. The number of debris dams in BHB (disturbed) was significantly lower than in HWC (reference) (t-test, $p = 0.001$) but not significantly different in a comparison of CB and GB (t-test, $p = 0.10$).

Stream hydraulics also appear to change following watershed disturbance (Table 1). The average velocity of BHB (disturbed) was significantly higher than HWC (reference) (t-test, $p = 0.011$), and the average velocity of CB (disturbed) was significantly higher than GB (reference) (t-test, $p = 0.014$). The roughness coefficient (Manning's n) was significantly greater for CB than for GB (t-test, $p = 0.014$), but differences in roughness were not significant between BHB and HWC (t-test, $p = 0.25$).

TABLE 2. Total rainfall and average intensity of storms sampled. Intensity was calculated by dividing total rainfall amount by the duration of a storm. Values represent averages of all sites.

Storm Date	Total Rainfall (cm)	Intensity (cm/hr)
15 Jun 84	0.50	0.15
20 Jun 84	1.57	1.05
10 Nov 84	3.27	0.55
4 Dec 84	4.04	0.23
11 Feb 85	6.30	0.48
21 Mar 85	2.10	0.06
1 May 85	1.24	0.08
7 May 85	4.19	0.10

Pattern of seston concentration during baseflows and stormflows

Baseflow seston concentrations in the four streams varied seasonally, ranging from 0.1 to 1.0 mg/L in winter and from 3.0 to 7.0 mg/L in summer (Fig. 1). Comparison of disturbed versus reference streams of similar size revealed no significant differences in baseflow seston concentration (paired t-test, $p > 0.05$).

Rainfall during the eight storms we sampled ranged from 0.5 to 7.0 cm and average rainfall intensities ranged from 0.05 to 1.05 cm/hr (Table 2). Winter and spring storms were of long duration (up to 40 hr) and moderate in intensity. Summer and autumn storms were gener-

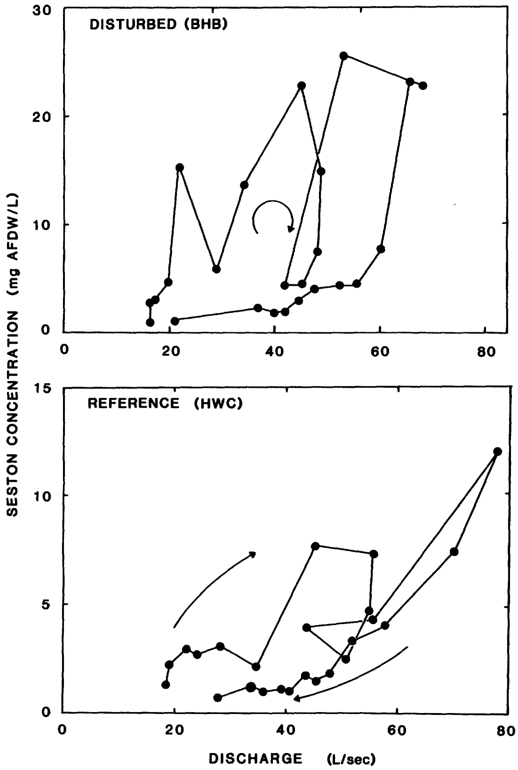

FIG. 2. Seston concentration (mg AFDW/L) versus discharge (L/s) in Coweeta streams during a storm sampled 11 February 1985. Arrows indicate the sequence of samples over the course of the storm; note difference in scale for the AFDW axes.

ally shorter (1–6 hr) and were characterized by periods of relatively intense rainfall. Rainfall amounts and intensities were similar among sites.

A typical pattern of seston concentration during stormflows is illustrated by a storm that occurred on 11 February 1985 (Fig. 2). Rainfall began at 0900 hr and intensified through the afternoon; rainfall ceased at 1700 hr but began again at 1830 hr. Rainfall was heavy through 2400 hr then stopped. Total precipitation was 6.5 cm with an average intensity of approximately 0.5 cm/hr. Seston concentration increased rapidly with increasing discharge in all streams and was highest at or slightly before peak discharge. Once streamflow stabilized, seston concentration declined and continued to decrease as discharge returned to baseflow. During this storm, two distinct peaks in seston concentration corresponded to periods of heaviest rainfall. This pattern of seston concentration was observed for each stream during all storms sampled and is similar to that observed by Bilby and Likens (1979), Fisher and Likens (1973), Gurtz et al. (1980), and Meyer and Likens (1979). In all but one case, stormflows had higher average seston concentrations in disturbed streams than in reference streams of similar size (Table 3). Differences in average concentration were significant between CB (disturbed) and GB (reference) (paired t-test, $p = 0.05$, data normalized using natural log transformation) but not between BHB (disturbed) and HWC (reference) (paired t-test, $p = 0.09$, data log transformed).

TABLE 3. Flow weighted (average) seston concentrations (mg/L) during storms.

Date	BHB Disturbed	HWC Reference	CB Disturbed	GB Reference
15 Jun 84	8.33	7.46	8.67	3.95
20 Jun 84	40.72	10.21	24.55	15.82
10 Nov 84	17.85	30.79	12.53	18.83
4 Dec 84	4.60	3.35	2.55	2.79
11 Feb 85	6.57	2.82	4.13	3.09
21 Mar 85	3.36	2.44	4.45	2.55
1 May 85	4.74	3.10	6.85	2.90
7 May 85	5.67	4.32	6.52	4.12

During storms, stream channels expand into backwater areas where fine particles have accumulated since previous storms. Particles trapped in those areas are entrained resulting in increased seston concentrations in the streams. Once stream expansion ceases and no new sources of particles are encountered, seston concentrations decline even though discharge may remain high (Bilby and Likens 1979). Webster (1983, and unpublished data) observed a strong positive relationship between seston concentration and the rate of change in discharge during rising flows in natural and simulated storms in both natural and artificial stream channels. We have analyzed data from our study in a similar manner. Regressions of seston concentration versus the rate of change in discharge (ΔQ) during the rising limb of storm hydrographs were performed on data from six storms. Two storms with fewer than four samples taken on the rising hydrograph were excluded from this analysis. For each stream and storm, seston concentration was regressed sep-

TABLE 4. Seston concentration versus change in discharge during increasing flows. Values are coefficients of determination (r^2) (* indicates $\beta > 0$, $p < 0.05$).

	ΔQ Interval		
	5 Min	15 Min	60 Min
BHB—Disturbed			
20 Jun 84	0.88*	0.98*	0.97*
10 Nov 84	0.57*	0.67*	0.86*
4 Dec 84	0.62*	0.70*	0.84*
11 Feb 85	0.42	0.50*	0.66*
21 Mar 85	0.16	0.20	0.13
7 May 85	0.17	0.10	0.24
HWC—Reference			
20 Jun 84	0.82*	0.86*	0.40
10 Nov 84	0.71*	0.62*	0.43*
4 Dec 84	0.18	0.22	0.65*
11 Feb 85	0.57*	0.56*	0.86*
21 Mar 85	0.60*	0.68*	0.90*
7 May 85	0.25	0.32	0.59*
CB—Disturbed			
20 Jun 84	0.78*	0.77*	0.81*
10 Nov 84	0.76*	0.62*	0.61*
4 Dec 84	0.21	0.73*	0.83*
11 Feb 85	0.94*	0.94*	0.79*
21 Mar 85	0.83*	0.06	0.60*
7 May 85	0.35	0.85*	0.83*
GB—Reference			
20 Jun 84	0.85*	0.63	0.24
10 Nov 84	0.10	0.14	0.36*
4 Dec 84	0.35*	0.49*	0.85*
11 Feb 85	0.87*	0.52	0.68*
21 Mar 85	0.23	0.31	0.79*
7 May 85	0.27	0.41*	0.63*

arately against the increase in discharge over three time intervals (5, 15, and 60 min) preceding each sample time. In general, seston concentration was positively correlated ($p < 0.05$) with ΔQ in all streams (Table 4). Intense storms, with the most rapid increases in discharge, provided the strongest correlations between seston concentration and ΔQ. Furthermore, regressions of concentration versus ΔQ for 60-min intervals accounted for more of the variation in the data than regressions using ΔQ over either 5- or 15-min intervals. This analysis suggests that the origin of seston particles transported during storms is not immediately upstream from the sampling site. The median particle size for Coweeta seston ranges from 120 to 150 μm and the settling velocity for particles <150 μm ranges from 0.06 to 0.40 cm/sec (Webster et al. 1987). Once suspended, those small, slowly settling particles may travel relatively long distances in turbulent stream water. In 13 out of 72 regression analyses we found significant positive autocorrelation (Durbin-Watson test, $p < 0.05$) or serial dependence between samples. Autocorrelation was most prevalent in regressions of AFDW versus ΔQ for 5- or 15-min intervals during storms with large ΔQ values or extended periods of intense rainfall. Our experimental design did not enable us to isolate the factor causing autocorrelation in this analysis, but we feel its presence provides further evidence for relatively long particle travel distances in Coweeta streams during storms.

In a final analysis, regressions of seston concentration versus ΔQ were combined by season for each stream. The seasons were December–February ("winter") and March–November ("summer"). The data were combined based on the similarities in slope from the preceding analysis. For each season, analysis of covariance was used to compare the slopes of regression lines for the pairs of disturbed and reference streams. For each season and stream, seston concentration was positively correlated with ΔQ ($p < 0.05$) (Table 5). In the larger streams, BHB and HWC, the correlation between seston concentration and ΔQ was generally strongest for the 60-min interval. For 15- and 60-min ΔQ the slopes of the regression lines for BHB were significantly steeper (analysis of covariance, $p < 0.05$) indicating that a unit increase in discharge resulted in the downstream transport of more material in the disturbed (BHB) compared to the reference (HWC) stream. A similar relationship was found between seston concentration and ΔQ during storms in the smaller streams; however, there was no distinct best ΔQ interval for predicting seston concentration. In all comparisons except 60-min ΔQ during summer storms, the slopes of regression lines were significantly steeper (analysis of covariance, $p < 0.05$) for the disturbed stream (CB) than for the reference stream (GB).

Seston export during stormflows

CB (disturbed) had significantly higher export of seston during storms than GB (reference) (paired t-test, $p = 0.002$, data normalized

TABLE 5. Regressions of seston concentration and ΔQ for storms combined by season. Values are slope as mg/L increase in Q per interval, with n, r^2 in parentheses. All regressions are significant ($p < 0.05$), * indicates slopes are significantly different (analysis of covariance, $p < 0.05$).

	Mg/L per ΔQ per Interval			Mg/L per ΔQ per Interval		
	BHB Disturbed	HWC Reference	Comparison of Slopes	CB Disturbed	GB Reference	Comparison of Slopes
Winter						
5 min	5.07 (17, 0.42)	2.19 (20, 0.43)	N.S.	29.68 (14, 0.83)	6.68 (12, 0.38)	*
15 min	2.84 (23, 0.42)	0.94 (21, 0.51)	*	8.37 (18, 0.91)	3.82 (17, 0.35)	*
60 min	1.60 (24, 0.68)	0.46 (22, 0.85)	*	4.29 (18, 0.84)	1.51 (12, 0.38)	*
Summer						
5 min	25.14 (31, 0.84)	21.12 (37, 0.65)	N.S.	98.06 (30, 0.75)	55.26 (28, 0.47)	*
15 min	9.71 (36, 0.92)	6.99 (45, 0.66)	*	37.40 (33, 0.61)	20.60 (34, 0.49)	*
60 min	5.03 (48, 0.92)	2.06 (52, 0.62)	*	9.70 (40, 0.63)	8.60 (38, 0.31)	N.S.

using a natural log transformation). In a similar comparison of BHB (disturbed) and HWC (reference), there was no significant difference in seston export during storms (paired t-test, $p = 0.20$, data log transformed). The absence of a significant difference was due to the effect of an unusual storm (10 November 1984) where export from the reference stream (HWC) was substantially higher than from the disturbed stream (BHB) (Fig. 3). If the 10 November 1984 storm was excluded from the analysis, seston export from the disturbed stream (BHB) was significantly higher than from the reference stream (HWC) (paired t-test, $p = 0.03$, data log transformed).

To clarify differences between the streams, seston export during storms was divided by the bankfull stream area to correct for differences in stream size and to permit statistical comparison of treatments (Fig. 4). In paired comparisons of all storms, storm export (g AFDW/m^2 stream/storm) was significantly higher in CB (disturbed) compared with GB (reference) (paired t-test, $p = 0.01$, data log transformed), and significantly higher in BHB (disturbed) compared with HWC (reference) (paired t-test, $p = 0.0001$, data log transformed). When combined by treatment, storm export from disturbed streams was significantly higher than from reference streams (ANOVA-followed by Duncan's Multiple Range test, $\alpha = 0.05$). This analysis indicates that disturbance (i.e., logging) has resulted in increased export of seston in BHB and CB.

An exception to the general pattern of seston export occurred during a relatively intense, short-duration storm on 10 November 1984 (Table 2). This was the first large storm following leaffall and 6–8 weeks of relatively dry weather. Seston export was higher in reference streams than in disturbed streams. Although maximum seston concentrations were highest in BHB and CB, the disturbed streams, average seston concentrations were highest in HWC and GB, the reference streams. Similar large increases in seston transport during the first large storms following leaffall were observed by Wallace et al. (1982). Fisher and Likens (1973) observed debris dam shifting, depending on storm intensity, which resulted in increased transport of organic matter. Heede (1972) also noted that submergence or movement of debris dams during storms greatly reduced their efficiency. At Coweeta, accumulations of organic debris are more abundant in reference streams than in disturbed sites (Table 1); therefore a storm powerful enough to shift organic debris could cause release of more material in reference streams.

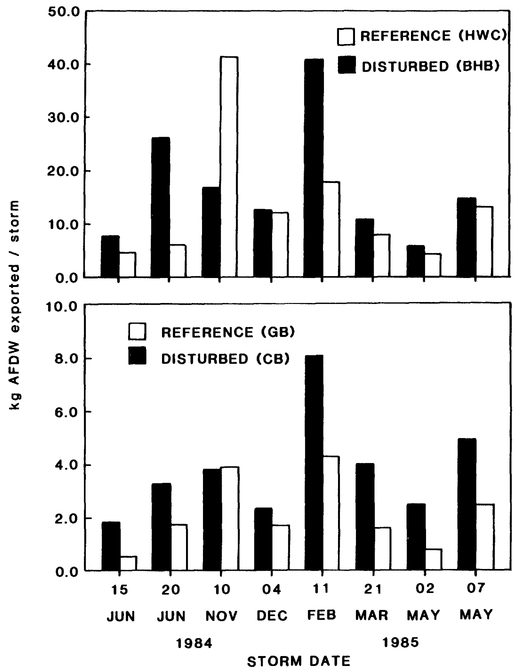

FIG. 3. Seston exported (kg AFDW) from Coweeta streams during storms. Solid bars represent disturbed streams, open bars represent reference streams; note difference in scale for the export axes.

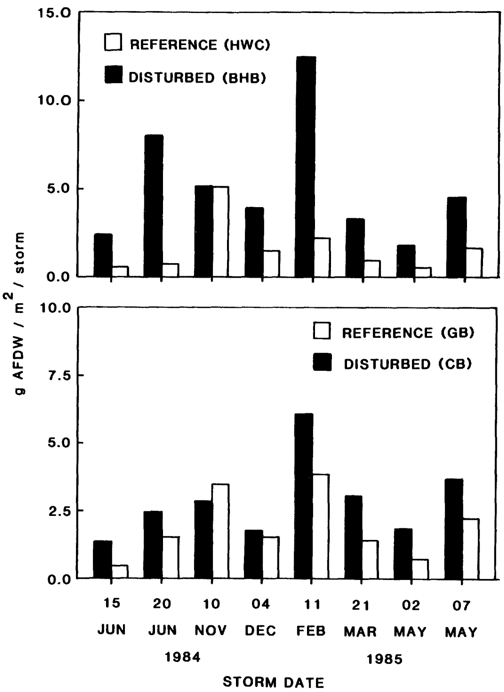

FIG. 4. Seston exported (g AFDW/m^2 stream) from Coweeta streams during storms. Solid bars represent disturbed streams, open bars represent reference streams; note difference in scale for the export axes.

Intense storms may also cause a rapid flushing from disturbed streams, resulting in short periods of very high seston concentration followed by lower concentrations as transportable material is depleted.

Origin of material transported during storms

Estimates of the input of fine organic material (<1 mm) to the streams were made for each storm. Possible external sources of particulate organic matter include soil water, springs, overland flow, and throughfall. Concentrations of particulate organic matter in soil water and springs are extremely low (Webster and Golladay 1984, Golladay personal observations) and can be excluded from calculations. Soils at Coweeta are highly permeable and infiltration rates can exceed 125 cm/hr; thus overland flow is not a common occurrence (Douglass and Swank 1975). Average throughfall inputs for all storms were 0.21 g/m^2 in BHB, 0.27 g/m^2 in HWC, 0.25 g/m^2 in CB, and 0.36 g/m^2 in GB. Throughfall contributions were highest during spring and summer when leaf area in the forest canopy was greatest (Table 6). Contributions of throughfall tended to be inversely related to storm intensity. During long or intense storms the potential throughfall contribution to total export was generally less than 20%. However, during low intensity storms, particularly in spring, the potential contribution was as high as 83% of total export. Contributions of throughfall were generally a higher proportion of total export in reference streams. This pattern may result from greater scavenging of material in the well developed canopy of reference sites or may be partially an artifact of the generally lower seston export in reference streams, particularly during low intensity storms. In general, most of the material transported during storms originates within streams; however, during low intensity storms substantial amounts of fine particulate organic material may be transferred from forest canopies to streams.

Conclusions

Seston concentration should be strongly correlated with stream power, i.e., the ability of a

TABLE 6. Contributions of throughfall (g AFDW/m² of stream area) to streams during storms and percent of total organic export that could be attributed to throughfall.

	BHB—Disturbed		HWC—Reference		CB—Disturbed		GB—Reference	
	Input	% of Export	Input	% of Export	Input	% of Export	Input	% of Export
15 Jun 84	0.05	1.19	0.04	7.02	0.09	6.52	0.04	8.51
20 Jun 84	0.38	2.70	0.16	21.92	0.20	8.13	0.26	16.77
10 Nov 84	0.24	2.64	0.24	4.70	0.37	12.89	0.39	11.17
4 Dec 84	0.09	1.32	0.12	8.05	0.17	9.60	0.17	10.97
11 Feb 85	0.23	1.04	0.42	19.91	0.32	5.27	0.29	7.53
21 Mar 85	0.11	1.87	0.21	21.88	0.14	4.65	0.19	13.29
1 May 85	0.35	11.25	0.43	82.69	0.38	20.43	0.52	72.22
7 May 85	0.35	4.40	0.58	35.80	0.32	8.63	0.76	34.08

stream to do work (Bagnold 1966), and many studies have indicated a positive relationship between seston concentration and either stream power or stream discharge (Bormann et al. 1969, Fisher 1977, Fisher and Likens 1973, Meyer and Likens 1979, Webster 1983, Webster and Patten 1979). However, other studies have shown only weak correlation between seston concentration and stream power (Naiman 1982, Naiman and Sedell 1979, Sedell et al. 1978). In headwater streams, seston concentrations are hysteretic during storms, i.e., higher during the rising limb of storm hydrographs than during the descending limbs (Bilby and Likens 1979, Fisher and Likens 1973, Gurtz et al. 1980, Webster et al. 1983). Therefore power might best be considered a measure of potential transport in headwater streams. Actual transport is highly dependent on instream factors such as particle availability and channel retentiveness (Bilby and Likens 1979, Fisher 1977, Naiman 1982).

Disturbance of forests by logging should greatly affect instream factors (particle availability, channel retentiveness) that influence seston transport during storms. Because allochthonous inputs decline following logging, and shift from slowly decaying leaf-species to rapidly decaying ones (Webster et al. 1987), one would expect a decline in rates of particle generation immediately following logging followed by a gradual decline in particle availability. However, our own preliminary observations indicate that fine benthic organic matter levels are similar in the four streams, though slightly lower in BHB and higher in CB compared with reference sites. Therefore, differences in transport that we observed during storms cannot be readily attributed to differences in particle availability alone. Channel retentiveness is greatly influenced by the presence of debris dams and organic matter accumulations in stream channels and a decline in the efficiency, number, and size of debris dams following logging has been well documented (Fisher and Likens 1973, Gurtz et al. 1980, Likens and Bilby 1982). At our study sites, disturbed streams have fewer organic matter accumulations and debris dams and higher average velocities than reference streams (Table 1). Observed increases in seston export probably resulted from reduced efficiency and number of retention structures in disturbed streams following logging.

Buffer strips, i.e., zones of undisturbed riparian vegetation, have been advocated as a means of maintaining stream water quality in logged areas. As a management tool they have been used primarily to reduce sediment movement from logging roads and disturbed soils to streams, and to maintain normal stream temperatures (e.g., Haupt and Kidd 1965, Trimble and Sartz 1957). More recent studies have demonstrated the effectiveness of buffer strips in maintaining salmonid fisheries (Burns 1972) and normal insect community structure in streams draining logged areas (Newbold et al. 1980). Streamside logging also causes long-term changes in the quality and quantity of allochthonous inputs to streams, which alter the energy base and also reduce the ability of streams to retain biologically important materials. Buffer strips, in addition to maintaining water quality, should reduce the long-term effects of logging by maintaining the predisturbance numbers of debris dams and organic matter accumulations in streams.

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