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Seston Dynamics in Southern Appalachian Streams: Effects of Clear-cutting

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Suspended particulate matter (seston) was studied from July 1977 to July 1978 in two second-order streams in the southern Appalachian Mountains. In the first stream, which drains an undisturbed hardwood forest watershed, seston concentrations fluctuated with season (lowest during winter high flows) and with storm flows. Most organic and inorganic particles were smaller than 105 μm diameter. The second stream drains a watershed (formerly a hardwood forest) that was clear-cut in early 1977. Increased levels of both organic and inorganic seston were found in the latter stream, especially beginning 1 yr after clear-cutting (2 yr after construction of logging roads). Particles larger than 234 μm in diameter accounted for most of the increases in inorganic seston. These increases were probably due to sediments deposited in the stream bed during road building and transported downstream during periods of peak flow. Increased levels of organic seston were probably related to breakdown of debris that entered the stream during logging and reduced retention by leaf packs. We hypothesize that eventual recovery of the stream will be limited by the rate of recovery of the surrounding terrestrial ecosystem.

Key words: seston, sediment, detritus, stream, clear-cut, roads

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Une étude a été faite de la matière particulaire en suspension (seston) dans deux cours d'eau de second ordre du sud des Appalaches de juillet 1977 à juillet 1978. Dans le premier, qui draine un bassin recouvert d'une forêt non dérangée d'arbres feuillus, les concentrations de seston varient avec la saison (minimales au moment de l'abondant débit hivernal) et selon les débits de tempête. La plupart des particules organiques et inorganiques ont un diamètre inférieur à 105 μm. Le second cours d'eau draine un bassin (anciennement forêt d'arbres feuillus) ayant subi une coupe à blanc au début de 1977. On a trouvé dans ce dernier cours d'eau des niveaux plus élevés de seston, tant organique qu'inorganique, surtout à commencer un an après la coupe à blanc (deux ans après la construction de routes forestières). Des particules de diamètre dépassant 234 μm sont responsables de la plupart des augmentations de seston inorganique. Ces augmentations résultent probablement de sédiments déposés sur le lit du cours d'eau lors de la construction de routes et transportés en aval durant les périodes de débit de pointe. Les niveaux accrus de seston organique sont probablement liés à la décomposition des débris pénétrant dans le cours d'eau lors de l'exploitation forestière et à la rétention moindre des amas de feuilles. Nous émettons l'hypothèse que le rétablissement éventuel du cours d'eau sera limité par le taux de rétablissement de l'écosystème terrestre environnant.

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ORGANIC seston in small headwater streams in forested watersheds originates predominantly as allochthonous material (Cummins 1975; Hynes 1975) which, through detrital processing, is successively reduced in size to smaller particles (Boling et al. 1975). Inorganic seston is comprised of particles dislodged from the stream bed or eroded from the stream bank and surrounding watershed. Increased inorganic sediment transport associated with logging activities can often be attributed to construction and use of roads (Brown and Krygier 1971; Douglass and Swift 1977). Some methods of log re-

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moval also increase inorganic seston levels (Bormann and Likens 1970; Douglass and Swift 1977; Patric and Aubertin 1977). Alternatives such as cable logging may have less impact on stream sediment loads (Brown and Krygier 1971).

Several studies have examined organic and/or inorganic material transport in streams and rivers (e.g. Nelson and Scott 1962; Maciolek and Tunzi 1968; Berrie 1972; Fisher and Likens 1973; Sedell et al. 1978; Naiman and Sedell 1979). Bilby and Likens (1979) emphasized the complex relationship between seston concentrations and stream discharge, while others (e.g. Bormann et al. 1974) examined effects of deforestation on particulate transport.

Most seston studies to date have restricted their emphasis to two size fractions, coarse (>1 mm in diameter) and fine (0.45 μm to 1 mm) and ignored the distribution of intermediate sized particles. Particle size distribution may reflect fundamental stream ecosystem processes, including changes predicted by the river continuum hypotheses (Vannote et al. 1980), the role of leaf packs and debris dams as retention devices (Maciolek 1966; Fisher and Likens 1973; Sedell et al. 1978), and the role of detritivores in particle size reduction. Particle size distribution is especially significant to filter feeders, some of which possess fairly size-specific particle capture mechanisms (Wallace and Merritt 1980).

Our research concerned effects of perturbations associated with watershed clear-cutting on seston transport and particle size distribution. We studied two southern Appalachian streams, one that drained an undisturbed watershed and another that drained a watershed which had been recently clear-cut.

Description of Study Area

This study was conducted on two watersheds at Coweeta Hydrologic Laboratory, Franklin, North Carolina. Watershed (WS) 14, drained by Hugh White Creek, is a 61.1-ha (1 ha = 10 000 m^2) watershed with mixed hardwood vegetation that has been undisturbed since 1924 except for the chestnut blight in the early 1930's. Watershed 7, drained by Big Hurricane Branch, is 58.7 ha and is separated from WS 14 by a distance of about 1.4 km. Watershed 7 was clear-cut in 1977. Preclear-cut vegetation was similar to that of WS 14. Preclear-cut characteristics of both watersheds are summarized in Table 1.

Big Hurricane Branch and Hugh White Creek are second-order streams. Each stream is equipped with a V-notch weir for continuous recording of discharge. The hydrograph for Big Hurricane Branch during the study period is shown in Fig. 1. The hydrograph for Hugh White Creek was similar although slightly lower, as discharge in Big Hurricane Branch increased following clear-cutting. Average flow during the 13-mo study period was slightly less than the long-term average; maximum flow during the study period had a recurrence interval of about 2.5 yr.

TABLE 1. Physical and chemical characteristics of the study streams and their watersheds.

	WS 7 Big Hurricane Branch	WS 14 Hugh White Creek
Watershed area (ha)	58.7	61.1
Max. elevation of WS (m)	1060	996
Min. elevation of WS (m)	724	708
Main channel length (m)	1225	1077
Avg. bank-full width[a] (cm)	256	406
Avg. stream depth[a] (cm)	10.5	6.4
Main channel gradient ($m \cdot m^{-1}$)	0.191	0.161
Drainage density	0.0069	—
Avg. annual discharge ($L \cdot s^{-1}$)	17.7[b]	19.0[c]
Avg. annual discharge during study period ($L \cdot s^{-1}$)	22.0	16.8
Max. discharge during study period ($L \cdot s^{-1}$)	363.1	464.4
Min. discharge during study period ($L \cdot s^{-1}$)	9.6	4.0
Avg. annual elemental concentrations ($mg \cdot L^{-1}$)[d]		
NO_3-N	0.002	0.004
NH_4-N	0.004	0.004
PO_4-P	0.002	0.002
Cl	0.699	0.540
SO_4	0.475	0.362
K	0.492	0.350
Na	0.946	0.739
Ca	0.846	0.460
Mg	0.372	0.280
pH	6.82	6.61

[a]Data from first 500 m above weir.
[b]Based on 29 yr of record. All hydrologic data from Coweeta Hydrol. Lab.
[c]Based on 40 yr of record.
[d]Data from Swank and Douglass 1977; WS 7 data is preclear-cut.

As with other headwater streams in the Coweeta Basin, stream gradients of Hugh White Creek and Big Hurricane Branch vary from sections of steep exposed bedrock to short sandy reaches of low-gradient and infrequent small pools. Dense streamside vegetation (mainly rhododendron) provides heavy shading, especially in summer. Levels of autochthonous primary production in undisturbed streams are typically low (J. Hains, Clemson University, Clemson, S.C., August 1978, personal communication), and stream invertebrate communities are dominated by detritivores.

During April–June 1976 three roads were built on WS 7 for logging access. Two of these roads crossed the main stream. Approximately 5% of the watershed area was disturbed by road building. Logging began in January 1977 and was completed in June 1977. A mobile cable system was used for most logging; however, tractor skidding was used on more gentle slopes. Mineral soil was exposed on less than 10% of the total watershed area. Following logging, most of the logging

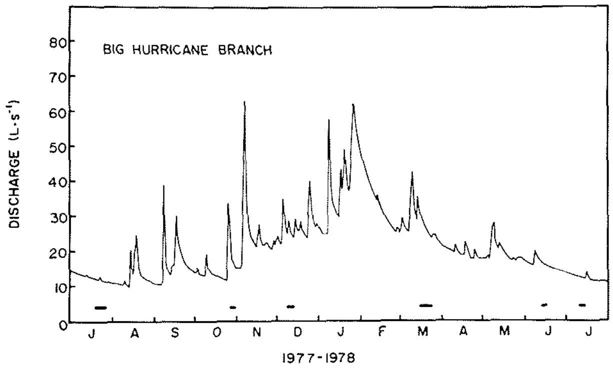

FIG. 1. Hydrograph of Big Hurricane Branch during the study period. Bars indicate times of sample collection. Data from Coweeta Hydrologic Laboratory.

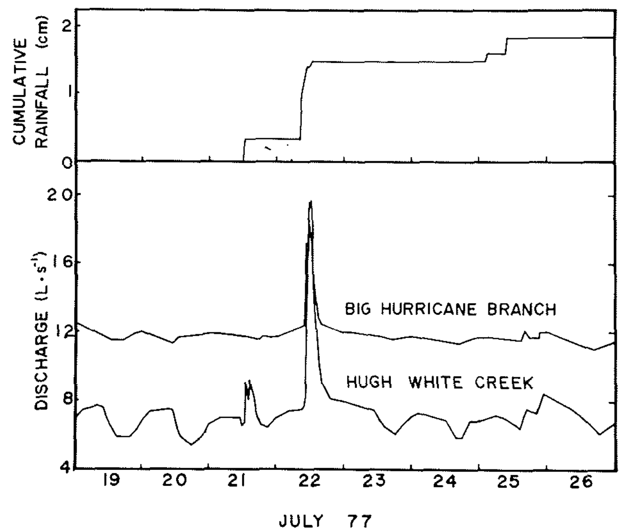

FIG. 2. Rainfall and discharge in the Big Hurricane and Hugh White Creek during the July 1977 sampling period.

debris that fell in or over the stream was removed from the channel.

Methods and Materials

A notched cutoff wall was installed in each stream for sample collection. For known time intervals, drift nets (mesh opening, 230 μm) were placed in these notches so that they caught 100% of the stream flow. These net samples were used for analysis of large particle fractions (>234 μm). Carboys of water were collected for analysis of fine particle fractions (<234 μm).

Samples were analyzed with a wet filtration system. Measured volumes of water or resuspended net samples were filtered with suction through a series of stainless steel sieves of the following size-classes: Coarse (C), greater than 5.0 mm; Large (L), 0.864–5.0 mm; Medium Large (ML), 234–864 μm; Small (S), 105–234 μm; Fine (F), 43–105 μm; and Very Fine (VF), 25–43 μm. Material collected on the screens was resuspended and collected on preashed, preweighed Gelman A/E glass fiber filters. An aliquot of material passing through the VF screen was filtered through a glass fiber filter to provide the Ultrafine (UF) fraction (0.5–25 μm). All samples were oven-dried (50°C, 24 h), desiccated (24 h), weighed, ashed (500°C, 15 min), rewetted (to restore water of hydration; Weber 1973), redried, desiccated, and weighed. From these weights, organic seston was determined as ash-free dry weight and inorganic seston as ash.

Samples were collected intensively on a seasonal basis, during both storm and nonstorm conditions. The first set of samples was collected during eight consecutive days in July 1977, ~1 mo after completion of timber removal from WS 7, and 14 mo after completion of road building. Samples were collected each 6 h initially, more frequently during storms, and less frequently after the stream had returned to base flow. Similar series of samples were collected in October and December 1977, and March, June, and July 1978 (Fig. 1).

Results and Discussion

EFFECTS OF STORMS

Although storms occurred during four of the six sampling periods, effects of storms on particulate concentrations are perhaps best exemplified by a short-duration, high-intensity storm during July 1977 (Fig. 2). During the first 2 d of the sampling period, a diel flow fluctuation due to evapotranspiration was observed in the undisturbed stream, Hugh White Creek, but diel fluctuation in Big Hurricane Branch was much less pronounced. A short rainfall on the 3rd d occurred on WS 14 but not on WS 7. On the 4th d an intense, short-duration rainfall occurred on both watersheds, followed by a smaller storm on the 7th d. Streamflows increased during storms, but rapidly returned to base flow following each storm. Organic and inorganic particulate material concentrations in Big Hurricane Branch were substantially higher than in Hugh White Creek (Fig. 3). During storms, particulate concentrations increased in both streams. During the storm on July 22, peak organic and inorganic particulate concentrations were 66.8 and 138.3 $mg \cdot L^{-1}$, respectively, in Big Hurricane Branch, and 21.6 and 34.5 $mg \cdot L^{-1}$, respectively, in Hugh White Creek. Following storms, particulate concentrations dropped rapidly to prestorm levels. Particle size distributions did not correspond in a consistent way to changes in discharge.

During the July 1977 storm, peak seston concentrations were reached apparently simultaneously with peak discharge. During this and other storms, a hysteresis effect was observed that shows higher seston concentrations for a given discharge on the rising limb of the hydrograph than for the same discharge on the falling limb (Fig. 4). The shape of this hysteresis loop, however, varies among the storms that occurred during sampling periods. Only once, March 1978, in Hugh White Creek, were seston dynamics similar to those described by Bilby and Likens (1979) — that is peak seston concentrations occurring prior to peak discharge. Paustian and Beschta (1979) found peak suspended

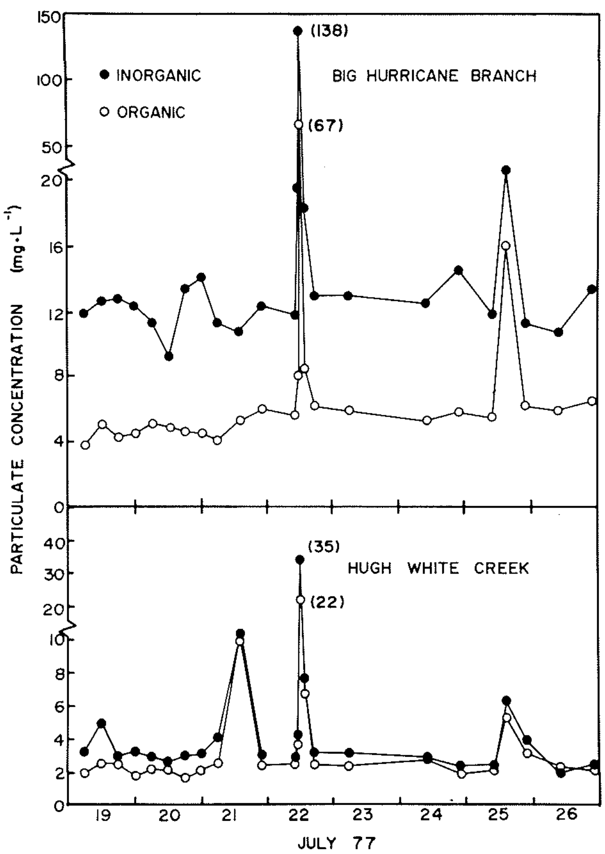

FIG. 3. Organic and inorganic particulate concentrations in Big Hurricane Branch and Hugh White Creek during the July 1977 sampling period. Note change of scale of vertical axes; numbers in parentheses indicate values of points on upper part of axes.

sediment concentrations during a given storm occurring before or at the hydrograph peak, the pattern apparently dependent upon the shape of the hydrograph prior to the storm. Bilby and Likens (1979) also noted that seston concentrations were lower after discharge returned to prestorm levels than before the storm, suggesting a "wash-out" effect. While this effect seems valid for certain sets of conditions, we did not observe it.

SEASONAL CHANGES IN SESTON CONCENTRATIONS

Mean concentrations of total inorganic and organic seston for nonstorm samples taken during each sampling period are presented in Table 2. In Hugh White Creek, high inorganic and organic seston concentrations were observed in summer whereas low concentrations occurred in winter. Factors possibly contributing to this seasonal pattern include dilution during high winter base flow; entrapment of fine particulate material in leaf packs during late fall and winter; reduced winter processing rates because of lower temperatures and insufficient leaf conditioning; and a long-term washout effect following early fall storms. Bormann et al. (1969, 1974) also found lower winter seston transport rates in smaller headwater mountain streams draining deciduous forest watersheds in northeastern United States. However, Naiman and Sedell (1979) found highest organic seston transport during winter in low-order streams in Oregon. Wetzel and Manny (1977) found highest organic seston concentrations in summer in a first-order stream draining a marsh in Michigan.

Seasonal seston dynamics in Big Hurricane Branch differed from the pattern we observed in the undisturbed stream. Seston concentrations in Big Hurricane Branch were consistently higher than in Hugh White Creek, and the magnitude of difference increased toward the end of our study. While seston concentrations decreased in December, the effect of clear-cutting on seasonal seston dynamics was partially masked by the longer term trend of increasing transport (Table 2 and 3).

RELATIONSHIP BETWEEN INORGANIC AND ORGANIC MATERIAL

We found a consistent relationship between inorganic and organic material in Hugh White Creek (Fig. 5; $r = 0.96$, $n = 68$). Inorganic material averaged 57.5% of the particulate load throughout the study. A similar relationship existed in Big Hurricane Branch prior to the March 1978 samples. However, in the later (March, June, July 1978) samples, the inorganic fraction increased without a similar increase in organic material.

PARTICLE SIZE DISTRIBUTION

Distribution of inorganic and organic seston (nonstorm samples) is presented by size class in Fig. 6. In the undisturbed stream, most particles (by weight) were in the three smallest size classes, i.e. $<105\ \mu m$. This is true for all seasons and for both inorganic and organic material. Concentrations of all size fractions were lowest in winter. Organic particles larger than $234\ \mu m$ (ML and larger) were negligible except in October during leaf fall.

In Big Hurricane Branch, concentrations of both inorganic and organic particles were greater in all size fractions. Beginning in October 1977 (following removal of timber slash from the stream bed), particles larger than $234\ \mu m$ increased proportionately more than smaller particles, especially in the inorganic fraction. Thus, the increase in seston concentrations shown in Table 2 occurred mainly in the ML and L size-classes ($234\ \mu m$–5 mm).

Median particle size (by weight) generally ranged from 35 to $65\ \mu m$ (Fig. 7). Median organic particle size in Big Hurricane Branch was greater than that of Hugh White Creek except for the July 1977 sample. A continuous trend toward larger inorganic particles in suspension was apparent in Big Hurricane Branch,

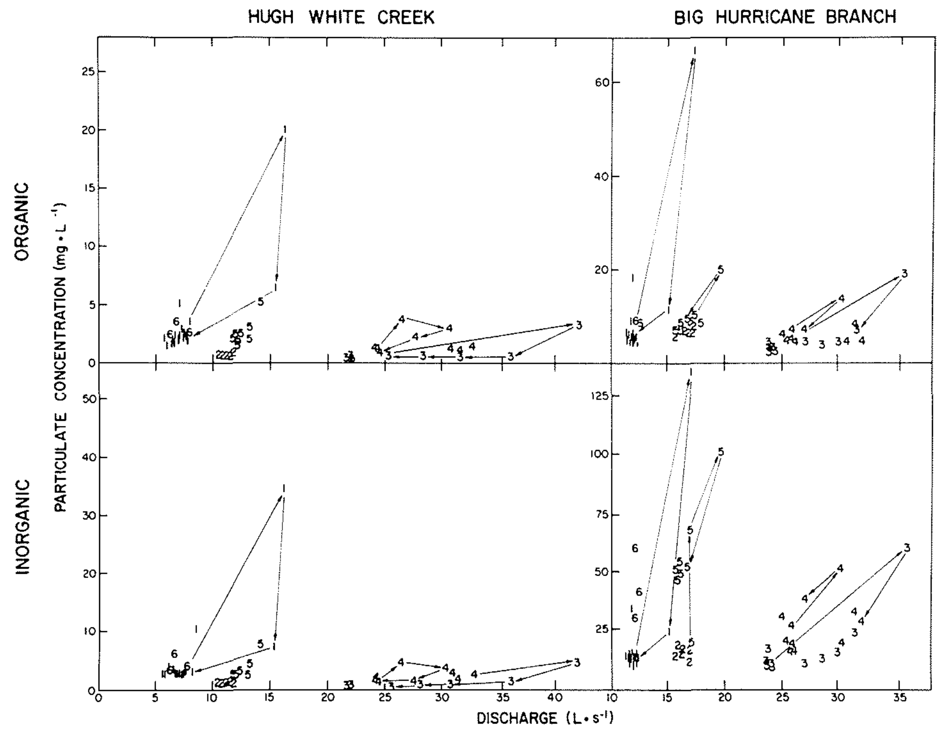

FIG. 4. Organic and inorganic particulate concentrations in Big Hurricane Branch and Hugh White Creek as functions of stream discharge. Arrows indicate the time sequence of storm samples. Numbers indicate various sampling periods: 1, July 1977; 2, October 1977; 3, December 1977; 4, March 1978; 5, June 1978; 6, July 1978. Some data points are masked.

increasing dramatically in June 1978 (Fig. 7).

Particle size of organic material in Hugh White Creek was generally larger than reported for other low-order streams by Sedell et al. (1978). Median particle size in Hugh White Creek ranged from 37 to 65 μm, whereas Sedell et al. reported median particle sizes between 5 and 12 μm. However, except for winter samples, they did not fractionate material between 53 and 0.45 μm. These figures emphasize the relative importance of small particles in all streams studied and reflect a greater importance of somewhat larger particles in Coweeta streams.

TABLE 2. Mean seston concentrations during low flow (nonstorm) conditions. S_m is standard error of the mean. n is the number of samples.

		Hugh White Creek						Big Hurricane Branch					
		July 1977	Oct. 1977	Dec. 1977	Mar. 1978	June 1978	July 1978	July 1977	Oct. 1977	Dec. 1977	Mar. 1978	June 1978	July 1978
Stream flow ($L \cdot s^{-1}$)		6.8	11.2	22.0	31.6	11.9	6.9	12.1	16.6	24.3	31.4	16.0	12.3
Particulate organic material ($mg \cdot L^{-1}$)	$\bar{x}$	2.11	0.87	0.31	1.29	2.11	3.01	4.54	6.98	2.64	6.43	7.70	8.25
	S_m	0.10	0.07	0.02	0.12	0.14	0.38	0.14	0.32	0.18	0.82	0.51	0.14
	n	9	8	6	5	4	3	9	8	6	5	4	3
Particulate inorganic material ($mg \cdot L^{-1}$)	$\bar{x}$	3.32	1.11	0.42	1.99	2.70	3.99	12.21	15.54	9.68	28.64	49.96	42.61
	S_m	0.24	0.05	0.02	0.29	0.12	0.51	0.47	0.97	0.33	2.92	1.72	9.34
	n	9	8	6	5	4	3	9	8	6	5	4	3

TABLE 3. Seston transported (kg·d^{-1}) by the two study streams during low and high flows. Low flow values are means of all nonstorm data from each collection period. High flow values represent data from the highest storm flow which occurred during the sampling period.

		Hugh White Creek						Big Hurricane Branch					
		July 1977	Oct. 1977	Dec. 1977	Mar. 1978	June 1978	July 1978	July 1977	Oct. 1977	Dec. 1977	Mar. 1978	June 1978	July 1978
Organic	High flow	30.2	—	10.9	8.2	3.4	—	99.8	—	58.7	35.6	33.2	—
	Low flow	1.2	0.8	0.6	3.5	2.2	1.8	4.7	10.0	5.5	17.4	10.6	8.8
Inorganic	High flow	48.3	—	16.8	9.5	9.1	—	206.6	—	185.2	137.0	172.6	—
	Low flow	1.9	1.1	0.8	5.4	2.8	2.4	12.8	22.3	20.3	77.7	69.1	45.3

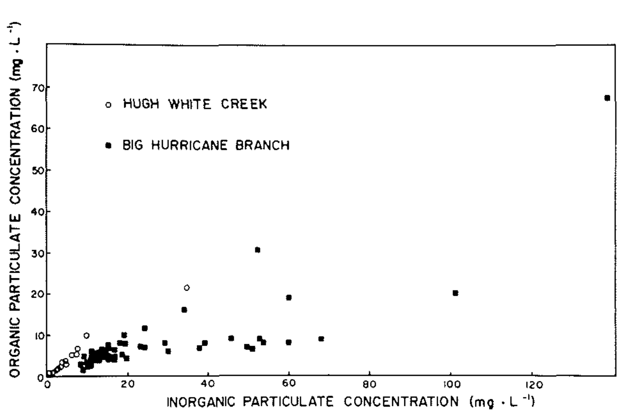

FIG. 5. Relationship between inorganic and organic seston in Big Hurricane Branch and Hugh White Creek. Some data points are masked.

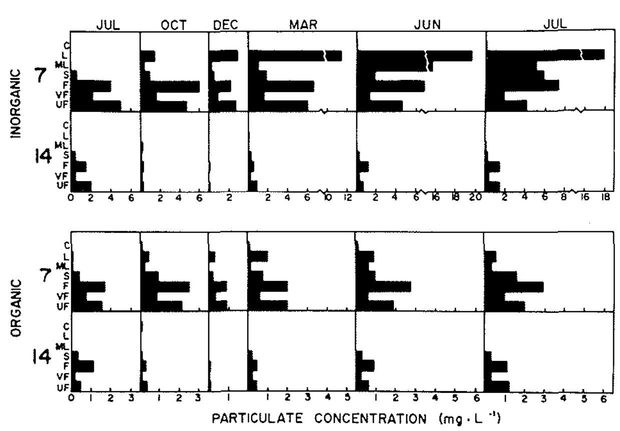

FIG. 6. Particle size distribution in Big Hurricane Branch and Hugh White Creek, July 1977 through 1978. Values are means of nonstorm samples. 14 refers to Hugh White Creek, the undisturbed stream, and 7 to Big Hurricane Branch, which drains the clear-cut watershed. Size-classes are C, >5.0 mm; L, 0.864–5.0 mm; ML, 234–864 μm; S, 105–234 μm; F, 43–105 μm; VF, 25–43 μm; and UF, 0.5–25 μm.

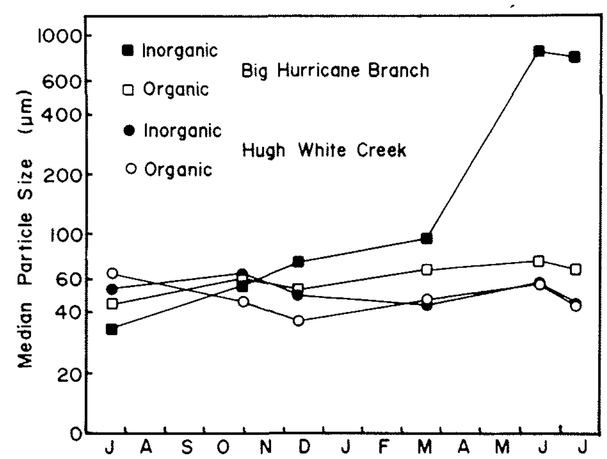

FIG. 7. Median particle sizes, by weight, in Big Hurricane Branch and Hugh White Creek during nonstorm conditions.

AVERAGE SESTON CONCENTRATIONS AND TRANSPORT

Table 4 presents mean annual particulate organic concentrations for low-order streams. Hugh White Creek had levels of organic seston within the range of other unperturbed forest streams. Big Hurricane Branch had an annual mean organic seston load nearly five times as high as Hugh White Creek and greater than most other streams. Streams higher than Big Hurricane Branch include low-gradient brown water Michigan streams and streams that have undergone some changes from their natural condition, e.g. Stampen Stream which flows through some agricultural land and is eutrophic (Malmqvist et al. 1978), and the Rhode River which drains low-gradient, multiple-use watersheds that are less than 50% forested (Pierce and Dulong 1977).

Inorganic seston concentrations in Big Hurricane Branch rose abruptly during the second summer after clear-cutting, a finding similar to that reported by Bormann et al. (1974). At Hubbard Brook, however, there were no roads and regrowth vegetation was inhibited

TABLE 4. Mean annual particulate organic matter (POM) in low-order streams. Stream order in parentheses.

Stream	POM ($mg \cdot L^{-1}$)	Reference
Bear Brook, New Hampshire (2)	0.32	Fisher and Likens (1973)
Mack Cr., Oregon (3)	0.59	Naiman and Sedell (1979)
Convict Cr., California (2)	0.67	Maciolek (1966)
Devils Club Cr., Oregon (1)	0.97	Naiman and Sedell (1979)
Hugh White Cr., North Carolina (2)	1.14	This study
White Clay Cr., Pennsylvania (2)	1.36	Sedell et al. (1978)
White Clay Cr., Pennsylvania (3)	1.59	Sedell et al. (1978)
Camp Creek, Idaho (2)	2.62	Sedell et al. (1978)
Big Hurricane Branch, North Carolina (2)	5.15	This study
Smith Cr., Michigan (1)	5.89	Sedell et al. (1978)
Augusta Cr., Michigan (2)	7.13	Sedell et al. (1978)
Stampen Stream, Sweden (2)	4–22	Malmqvist et al. (1978)
Rhode R. tributaries, Maryland (2)	3.7–19.4	Pierce and Dulong (1977)

by herbicides. Bormann et al. (1974) attributed increased sediment load to increased erodibility in the surrounding watershed. In the present study, we attribute the delayed response to larger particle (>234 μm) inorganic material that entered the stream primarily during road construction and was transported during flood conditions. Then, after 2 yr this material began to reach our collection point near the base of the watershed (W. Swank and L. Swift, U.S. Forest Service, May 1979, personal communication).

With higher seston concentrations and higher summer flows, export of material from WS 7 by Big Hurricane Branch was substantially higher than export from the control watershed (Table 3). During low flows, export of inorganic material from WS 7 was as much as 25× that from WS 14. During peak storm flows the greatest difference we found was 19× that of WS 14. Export of organic material was also higher in Big Hurricane Branch, as much as 11× during nonstorm flows and 10× higher during storms.

Conclusions

The importance of small particles in seston of flowing waters has only recently received attention (Sedell et al. 1978; Naiman and Sedell 1979). Our studies showed that an undisturbed headwater stream in the southern Appalachians carries in suspension particles that are mostly less than 105 μm in diameter. For the organic fraction, this indicates that allochthonous inputs are comminuted within the upper reaches of the stream through physical and microbial processes and detritivore feeding. Large particle detritivores (shredders) feeding on coarse material generate particles mainly in the ML range (234–864 μm) (J. O'Hop, Univ. of Georgia, GA, May 1979, personal communication). Further breakdown occurs as this material settles out or becomes trapped and is ingested by other organisms, consistent with the "spiralling" concept (Webster 1975; Wallace et al. 1977).

We found a greater relative abundance of larger organic seston particles in these streams than has been reported for comparable North American streams (Sedell et al. 1978; Naiman and Sedell 1979). While available information is insufficient to explain the differences, we suggest that the roles of shredders and retention mechanisms are major factors.

The clear-cutting experiment, including associated road building, resulted in increased export of both organic and inorganic seston. The increase in the inorganic fraction seemed to be a delayed effect related to sediment inputs that occurred during road construction. However, the increased levels of organic seston are more difficult to interpret. Possible effects of logging debris input and its subsequent partial removal from the stream confound interpretation. Debris in the stream represents both a source of seston and a mechanism for seston retention (Naiman and Sedell 1979). Thus, breakdown of logging debris in some channel areas may lead to increased levels of organic material in transport. Further, the observed decline in leaf pack abundance in Big Hurricane Branch represents a loss in retention devices for trapping particles. Either of these factors would lead to increased organic seston transport.

In this paper we have documented a significant alteration of the magnitude and timing of seston transport resulting from watershed clear-cutting. Inorganic seston concentrations remain high, even though inputs of sediment to the stream bed have declined tremendously. Continued flushing activity, especially during periods of peak flow, will be required to reduce inorganic seston to preperturbation levels. Return of organic seston quantity and quality may take longer. Webster and Patten (1979) suggested that stream ecosystems have low resistance to perturbation but high resilience following perturbation. However, a major aspect of stream resilience is replenishment of biomass through allochthonous inputs. Recovery of allochthonous input (quantity, quality, and timing) to preperturbation levels depends on the resilience of the forest ecosystem, not the stream. Hence, recovery of streams from watershed perturbation is limited by the rate of recovery of the surrounding terrestrial ecosystem.

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