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Transport of particulate organic material in streams as a function of physical processes

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With 3 figures and 2 tables in the text

Introduction

Those in search of fundamental properties of stream ecosystems have sought physical bases for comparing biological structure and function between running waters of different sizes, within basins and between basins. This endeavor has always seemed promising because the same functional groups of organisms, from microbes to fish, but consisting of different taxa, can be found in the streams and rivers of various terrestrial biomes (Hynes 1970; Cummins 1974; Whitton 1975). A number of hydraulic-geomorphic parameters, such as discharge regime or stream order (Strahler 1957) appear promising as independent variables upon which to regress the many dependent variables measured by stream ecologists, such as standing crops or the ratio of primary production to community respiration (P/R). To date, no physical or chemical parameter, or combination of parameters, has been demonstrated to adequately serve as a general organizer for lotic biotic data, although a number of classification systems have been proposed (e. g., Pennak 1971; Hawkes 1975). For the time being, stream order has proven to be a useful "bookkeeping" device for comparing ecological information within a basin (e. g., Sheldon 1968; Cummins 1977), but is of limited use in comparisons between basins which differ hydrologically and geomorphically.

It is likely that various biological characteristics of stream ecosystem structure and function will regress most reliably on different combinations of physical parameters. For example, since the transport of particulate organic matter (= POM, detritus or particles $> 0.45\,\mu m$) is dependent on the work performed by moving water, stream power per unit width of channel should be a suitable dependent variable (Leopold et al. 1964; Langbein & Leopold 1964). Stream power which takes into account the density of water, rate of discharge and stream gradient, seems to be a logical unit from which comparisons can be made between streams of different sizes.

Since sediment and water moving along a stream channel are the primary independent variables influencing channel morphology, quantitative relations have been established between water and sediment discharge (Wolman & Miller 1960). The nature and quantity of bedload and suspended sediment and all aspects of channel morphology such as dimension, shape, gradient, and pattern have been related to water discharge.

In this paper particulate organic material in transport in four different sized streams and rivers in each of four different geographical-hydrological regions in the United States are examined. The objectives are to: (1) examine POM concentration and report the percentage size composition in all streams; and (2) relate of POM transport as a function of stream power, as well as concentration of POM as a function of power, gradient, and watershed area.

Site description

Four regions are selected to provide very different hydrologic, geologic and vegetational contrasts (Fig. 1 A and B, Table 1). For each region as streams increase in size

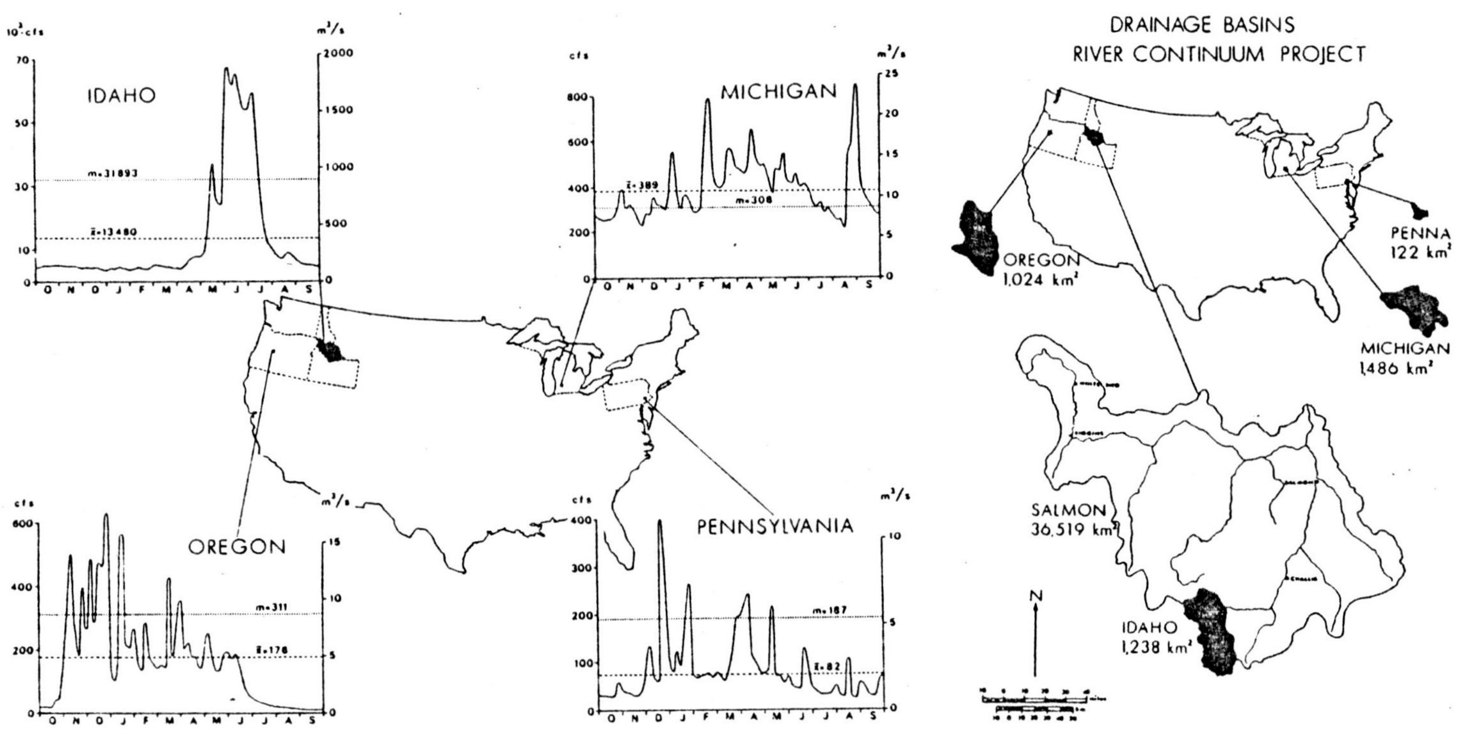

Fig. 1. A) Location and area of watersheds studied in the United States. B) Hydrographs of each watershed are shown with mean discharge and median high water flow.

Table 1. Description of sampling locations investigated in the United States.

Geographical regions	Stream order	Biome	Watershed area (km²)	Annual precip. (cm)	Mean base flow ($m^3 \cdot sec^{-1}$)	Mean annual POM concent. (mg/m^3)	Gradient (%)	Stream power	Annual range of POM (mg/m^3)
Oregon									
Devils Club Creek	1	Mesic Coniferous Forest	0.2	230	0.013	40.00	24.00	688	235— 1079
Mack Creek	3	Mesic Coniferous Forest	6.0	230	0.035	13.00	43.00	443	158— 553
Lookout Creek	5	Mesic Coniferous Forest	60.5	230	0.700	3.00	5.00	385	170— 537
McKenzie River	7	Mesic Coniferous Forest	1024.0	230	13.500	0.60	6.00	763	616— 957
Idaho									
Camp Creek	2	Xeric Coniferous Forest	0.8	38	0.012	10.65	7.00	2624	820— 7551
Salmon River (Smiley)	5	Xeric Coniferous Forest	23.3	38	0.387	1.18	2.00	3675	722— 9401
Salmon River (Obsidian)	6	Xeric Coniferous Forest	738.1	38	8.800	0.47	6.00	1159	512— 1540
Salmon River (Casino)	7	Xeric Coniferous Forest	1238.3	38	12.800	1.09	9.00	1305	506— 1984
Michigan									
Smith Creek	1	Deciduous Forest	0.4	152	0.013	1.10	0.27	5887	2624—10425
Augusta-Creek (UP-43)	2	Deciduous Forest	36.4	152	0.300	0.25	0.34	7126	2352—15025
Augusta-Creek (Kellogg)	3	Deciduous Forest	62.7	152	0.700	0.16	0.39	4766	3014— 7020
Kalamazoo River	5	Deciduous Forest	1486.0	152	13.500	0.09	0.72	4757	2154— 6906

Table 1 (continued).

Geographical regions	Stream order	Biome	Water-shed area (km^2)	Annual precip. (cm)	Mean base flow (m^3 · sec^{-1})	Mean annual POM concent. (mg/m^3)	Gradient (%)	Stream power	Annual range of POM (mg/m^3)
Pennsylvania									
White Clay Creek	1	Deciduous Forest	1.8	110	0.006	0.62	0.07	2288	1680— 2883
White Clay Creek (Choates)	2	Deciduous Forest	2.0	110	0.028	0.62	0.16	1361	970— 2203
White Clay Creek (Experimental)	3	Deciduous Forest	6.0	110	0.126	0.62	0.35	1587	630— 3651
Buck and Doe Run	5	Deciduous Forest	122.4	110	1.960	0.15	0.50	3101	892— 6905

the role of the autotrophic component increases. The Kalamazoo River site and McKenzie River site are the only streams containing appreciable macrophyte communities. The Kalamazoo River site is dominated by macrophytes over its entire area in summer, while the McKenzie River has a continual 2—3 m border of moss (*Fontanalis* sp.) on either side of the stream.

The McKenzie River basin is underlain and totally influenced by basalt from very recent (1,500—50,000 yr) volcanic activity. The river drains Douglas-fir (*Pseudotsuga menziesii)*, western hemlock (*Tsuga heterophylla)* forests of which less than 10 % of the area has been cut. Predominant land use is commercial logging and recreation. Over 80 % of the precipitation falls in a six month period between November and April, most as rain, with snow above 800 m. Only the McKenzie River, the largest Oregon stream examined, exhibits a spring snowmelt runoff in addition to winter rain storms.

The portion of the Salmon River basin studied in central Idaho is dominated by granite from late Jurassic to early Cretaceous age and several recent episodes of glaciation. Higher order sites lie in broad, flat U-shaped glacial valleys while the headwater streams drop steeply off high mountain slopes (2,600 m elevation). Dominant vegetation of valley streams is willows (*Salix*) and alder (*Alnus*). Mountain slopes are sparsely covered with Douglas-fir (*Pseudotsuga menziesii)*, lodgepole pine (*Pinus contorta)* and sagebrush (*Artemisia* sp.). Forest cover is uneven with north-facing slopes being more dense than south-facing slopes. Principle watershed activities are livestock grazing and some mining. The area studied has a low density human population and less than 15 % of the forests have been cut. Precipitation is evenly distributed throughout the year but major runoff comes from snowmelt in spring.

The Kalamazoo River basin in southcentral Michigan lies in fairly recent glacial till and is characterized as poorly drained with may lakes and bogs. Riparian vegetation is mixed hardwood forests and shrubs. The watershed is rural with dairy farms, silage crops, permanent pastures and woodlots the predominant use. Precipitation is evenly distributed, with a high snow melt and runoff in April.

The Brandywine and White Clay Creek basins in southeastern Pennsylvania are underlain by geologically old formations of mica schist and gneiss. Dominant streamside vegetation is a mixture of meadow grasses and mixed deciduous trees in woodlots. This area has been occupied and farmed since the late 1600's with 70—80 % of the land in permanent pasture, silage crops and dairy farms. The remaining 20—30 % is woodlots up to 90 years old. Annual precipitation and runoff is evenly distribution throughout the year.

Methods and materials

Transport of organic detritus was sampled in the same general manner in each region with only slight modifications introduced to accomodate specific sampling problems (Table 2). All samples were divided into eight size classes by particle diameters (> 16 mm, 16—4 mm, 4—1 mm, 1 mm—500 μm, 500—250 μm, 250—106 μm, 106—53 μm, and 53—0.45 μm), ashed at 550 °C for two to four hours, and weighed. Miller plankton samplers or pumps with nested nytex bags or screens were used to sample particles in the fine particulate organic matter range (FPOM: 53 μm to 1 mm), or larger in some cases. Large nets or screens were used for coarse particulate organic matter (CPOM: > 1 mm) and very fine particulate organic matter (VPOM: 0.45 to 53 μm) was collected as grab samples. Since data represent two to four day diel samples taken in each season, only general relationship can be discerned in comparisons between the 16 sites in four biomes.

Table 2. POM sampling methods used by study region.

Regions and POM categories	Sampling methods	Volume sampled or method of determination	Sampling schedule, repeated each of the four seasons
Oregon			
CPOM + FPOM [1]	Miller high speed plankton samplers; sample washed through nested sieve series	Flourescent dye	Every 3—5 hrs over 2—3 days
VPOM [1]	Grab samples	10,000—19,000 ml	Every 3—5 hrs over 2—3 days
Idaho			
CPOM + FPOM	Pumped into a sieve column	Calibrated pump	24 hrs, 2—3 days
VPOM	Grab samples	100—3,000 ml	Every 8 hrs composited over 24 hrs, 2—3 days
Michigan			
CPOM	1 m² screen frame	Calibrated with current meter	5—15 min every 6 hrs over 24 hrs once or twice each season
FPOM	Pumped into nested series of nytex bags	Calibrated pump	1 hr every 6 hrs over 24 hrs once or twice each season
VPOM	Grab samples	100—1,000 ml	Every 6 hrs composited over 24 hrs once or twice each season
Pennsylvania			
CPOM	Drift nets	Calibrated with current meter	2 hrs with seine, 3 days per season
FPOM	Pumped into nested series of nytex bags	Calibrated pump	24 hrs, 3 days per week
VPOM	Grab samples	Up to 2,000 ml	Composited over 24 hrs, 3 days per week

[1] The defined ranges are: CPOM >1 mm; FPOM <1 mm >53 μm; VPOM < 53 μm >0.45 μm.

Stream power was calculated from measurements of mean annual discharge, stream width at that discharge, and gradient at each site. Stream power $= \Omega = Qgd$ where Q = discharge ($m^3\ sec^{-1}$), g = gradient (% slope), and d = density of water (constant kg/m^3). Dividing by width of stream (m) yields power per unit width. Unit stream power was chosen as an independent variable since it is an expression of the ability of moving water to do work (LEOPOLD et al. 1964). The unit POM transport rate (mg $m\text{-}sec^{-1}$) was chosen since sediment transport rate is commonly used by geomorphologists as a dependent function of unit stream power. Unit POM transport rate $= T = \frac{Qc}{w}$, where Q = discharge ($m^3\ sec^{-1}$), c = POM concentration (mg m^{-3}), and w = stream width (m).

In comparing mean annual POM transport between sites in regions as diverse as Oregon, Idaho, Michigan, and Pennsylvania, it is critical to consider the discharge regime for the sample period (1975—1976) at each site, and place them in the longer term perspective. Based on maximum discharge for the study period, recurrence intervals (MORISAWA 1968) were in the 1 to 5 year range at all sites (Oregon 1.2; Idaho 1 + ; Michigan 4.4; Pennsylvania 1.5).

Results and discussion

Concentration levels

Highest levels of POM, and the largest ranges, are in Michigan streams with mean annual concentrations ranging from 4,757 mg · m^{-3} in the Kalamazoo River to 7,126 mg · m^{-3} in the upper portion of Augusta Creek (Table 1). Idaho sites show a greater variation in concentration during the year. Oregon sites transport the least POM; almost an order of magnitude below the other regions with narrow annual ranges.

Particle size analysis

Each of the locations investigated is quite variable in the type and amount of organic inputs received, as well as physical and chemical characteristics, but all export particulate organic matter having a mean diameter between 5 and 12 μm (Fig. 2). Although the data are annual means, the results are consistent with seasonal patterns.

POM between 0.45 and 53 μm, makes up at least 70 % of the total organic weight of particulate transport for all stream sizes, at all locations in all seasons. POM > 106 μm comprises less than 10—20 % of the total transport. These results are consistent with the reported value of SEKI et al. (1969) for the Nanaimo River in British Columbia. There they found the dominant particle size in the summer (July) to be less than 20 μm. However, in February the average particle decreased to 4 μm.

From these data, it appears that stream systems are effective at retaining CPOM inputs and processing them to FPOM and VPOM. Very little is known about the quality and origin of the VPOM fraction which makes up the vast majority of the organic weight transported. Since most transport is in the VPOM range, physical variables (e. g., gradient, unit stream power, and watershed area), are of particular importance because this size fraction is easily suspended, and because of its small size, is less influenced by streambed roughness or stream retention characteristics.

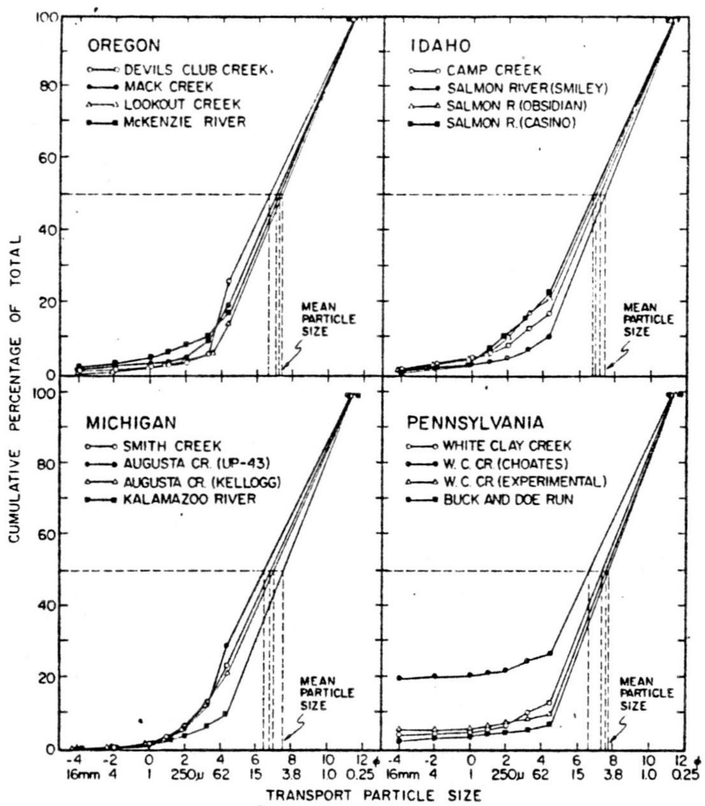

Fig. 2. Particle size analysis of mean annual particulate transport for each stream and river. Mean particle size is determined from the graph where ϕ = $-\text{Log}_2$ (particle size, mm).

Although no general relationship exists between watershed area and POM transport when all sites are viewed collectively, there is a relationship within regions (Fig. 3 A). POM concentrations exhibit two orders of magnitude differences between regions. The Michigan streams have the highest POM concentrations of the three regions but show no correlation with watershed area (r^2 = 0.22). Oregon streams also show no correlation (r^2 = 0.01). Pennsylvania streams show a slight positive relationship (r^2 = 0.53), and Idaho streams a slight negative relationship with watershed area (r^2 = 0.59). Within a regional basin, total particulate organic concentrations in transport do not exhibit much variation between stream orders and are probably determined by concentrations in small headwater streams of the drainage net, or type of land drained as exemplified by the boggy Michigan watersheds.

Kirchner (1975) showed a correlation between dissolved P export and drainage density (km of stream channel/watershed area [km^2]) for 18 forested watersheds underlain by the same lithology. Kirchner explains this relationship on the basis of retention of P by terrestrial systems and the increase in P export due to greater surface runoff that accompanies greater drainage density. Since

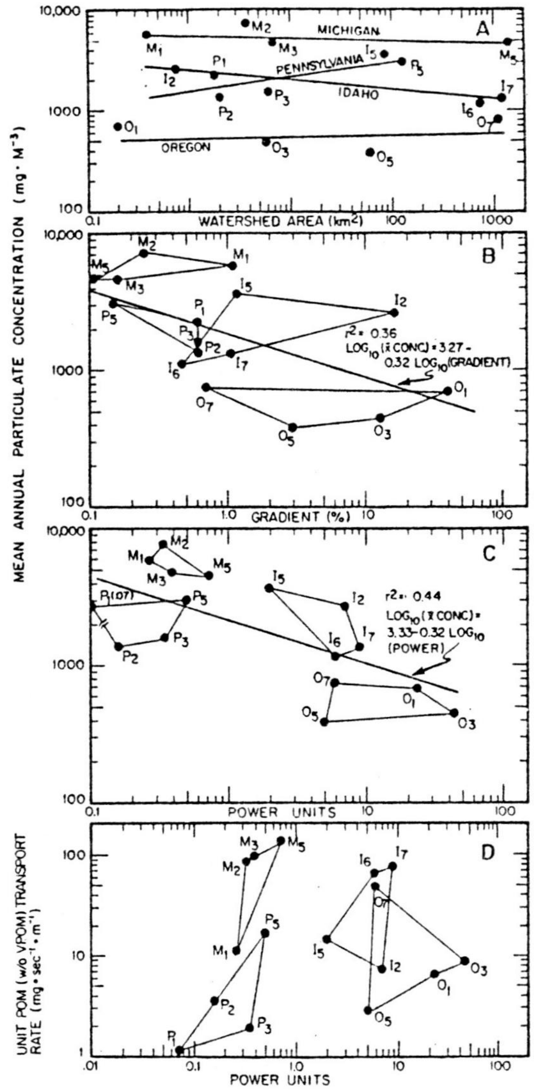

Fig. 3. Mean annual particulate transport concentration is shown as a function of (A) watershed area, (B) stream gradient, and (C) stream power. In (D) total movement of particles greater than 53 μm per meter of stream width (unit POM transport rate) is plotted as a function of unit stream power. Sampling sites are designated as: O — Oregon, I — Idaho, M — Michigan, and P — Pennsylvania. Numbers with site designations are stream order.

drainage density reflects the availability of stream channels to the watershed, and therefore, potential terrestrial inputs, the relationship described by KIRCHNER (1975) might also be expected for POM transport. Since no relationship between POM concentration and drainage density found within or between regions, channel geometry is probably more significant than basin morphology in determining POM transport characteristics in streams.

When regressed against POM concentration there is only a weak relationship with gradient ($r^2 = 0.36$) or unit stream power ($r^2 = 0.44$) (Fig. 3 B and 3 C). However, relationships within each regional basin form relatively tight clusters.

The relationship between unit stream power and unit POM (without VPOM) transport rate is shown in Fig. 3 D. VPOM is excluded from Fig. 3 D for two reasons: 1. this size fraction comprised over 70 % of the POM for all sites and seasons but it may not be nutritionally as important to the biological community as CPOM or FPOM. 2. This fraction is moved with very little energy expended. In examining the use of stream power we feel it would be more realistic to plot power versus larger particles not as easily transported in order to evaluate the ability of power to overcome retention structures. Again, the regional stream systems cluster together and, in addition, the eastern and western United States systems are separated. Eastern streams (Michigan and Pennsylvania) show a greater increase in POM discharge per unit width with increasing unit stream power than western systems (Oregon and Idaho). Since gradient changes very little with stream order in eastern systems, increasing power with stream size is primarily a function of increased discharge. In western streams, greatly increased gradient with decreasing stream order is a major factor contributing to higher unit stream power values. The second order Idaho stream probably did not cluster with the remainder because of increased retention of particulates primarily in accumulated woody debris and boulder stair steps. Oregon streams export lower amounts of POM for the same reason; large woody debris accumulations retain particulates. The seventh order McKenzie River, which did not cluster with the remainder, has little woody debris, relative to the width of the channel, and armored sediments provide few interstitial spaces for retention of particulate organics.

Conclusion

The most consistent feature of POM transport is the dominance of VPOM in all stream sizes of the four regions during all seasons. The relative importance of terrestrial (watershed) and in-stream contributions to the VPOM pool has yet been determined for any system but, undoubtedly, both are important.

Although a weak general relationship is shown between POM transport rate and unit stream power and gradient, it is clear each region is distinct, both in terms of total POM transport and physical setting. Nevertheless, unit stream power is a theoretically sound physical variable against which to examine particulate transport. The problem is that organic particulates do not behave in the same manner as inorganic sediments; they have low specific gravities and higher surface to volume ratios. Further scaling of unit stream power with retention indicies, that is the ability of the system to store POM, should provide a better index of POM transport.

Development of adequate indices for retention devices in streams is a necessity since the present state of knowledge for natural channels remains chiefly an art. Indices for such characteristics as interstitial and crevice spaces, bed roughness, retention by woody debris and boulders in streams, as well as such biological retention features as macrophytes, filamentous algae, and filter feeding invertebrates have been developed through experience rather than through quantitative relationships. Habitat rating schemes have been developed in recent years. While selection of coefficients is classified as an art, accuracy of many selections can be evaluated in exact engineering or statistical terms (BAILEY & RAY 1966).

Development of quantitative procedures for determining retention characteristics, coupled with the unit stream power, will provide a valuable tool for examining organic storage and transport characteristics of running waters.

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