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Transport of dissolved organic carbon in streams of differing physiographic characteristics*†

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Abstract—Transport of dissolved organic carbon (DOC) in four river systems in different physiographic regions of the United States was related to link magnitude by a power function, $\log Y = -0.84 + 1.24 \log X$. Multiple linear regression indicated that discharge, watershed area, and link magnitude explained almost all variation in DOC transport. For purposes of ecosystem comparison, link magnitude appeared superior to other classification systems, such as stream order.

In two of the river systems, the largest fraction of DOC was transported in the spring. A third had a winter transport maximum; the last had bimodal spring and fall maxima.

Streams transporting similar total amounts of DOC may vary widely in DOC concentration ($mg.l^{-1}$). Particulate organic matter concentration was not simply related to that of DOC.

Ranges and means of DOC concentration, mean DOC:POC ratios, annual load of transported DOC as well as annual watershed DOC output were tabulated for 45 streams and rivers, representing a broad range of stream systems and physiographic regions. Mean DOC concentration for these 45 waterways ranged from 0.7 to 28 $mg.l^{-1}$. The very low DOC values are found in undisturbed streams; many of the higher values are associated with larger streams influenced by human activities. Most DOC outputs fell within the range 0.21–5.42 metric tons. $km^{-2}.yr^{-1}$; mean DOC:POC ranged between 0.09 and 70.

A comparison was made among several biomes of the ratio of exported DOC to watershed gross and net primary production. DOC, while playing a major role in aquatic ecosystem organic budgets, appears to be of little significance in the nutrient balance of watersheds.

INTRODUCTION

It is well-established that the largest component of organic loading in small streams is in the dissolved state ($<0.5\,\mu m$; e.g. Wetzel *et al.*, 1972; McDowell and Fisher, 1976; Saunders, 1976) and the role of this dissolved material in the detrital food chain has been subjected to increasingly concerted investigation and speculation (e.g. Lush and Hynes, 1973). Studies of streams and rivers which report dissolved organic carbon (DOC) concentrations are still relatively few and those studies that have been conducted generally fail to compare the absolute amounts and concentrations of DOC over annual periods or along the downstream increase in size of a single river system. Differences between tributaries and main-stem branches of various physical, chemical, and geologic characteristics usually are not studied. Further, it has been shown that maximum diurnal variation in DOC may be as great as its seasonal variation (Manny and Wetzel, 1973). Comparison of transport characteristics of streams from differing physiographic regions gives rise to additional difficulties, due to a lack of uniformity in sampling, processing, reporting, and interpretation.

This study evaluates changes in DOC concentration on a seasonal basis as well as spatially through the longitudinal expansion of four river systems. In addition to stream links and orders, other physical parameters of watersheds have been employed in this study to explain the amount of DOC transported. Discharge, basin area, stream power, and annual precipitation have been included by means of multiple linear regression analysis. Annual means and ranges of DOC quantities in these systems were determined using nearly identical methods of collection, processing, and analysis. Thus, a unique opportunity was available to compare DOC transport in streams of different biomes by link analysis, while removing many of the procedural inconsistencies of previous investigations. To our knowledge, only one other study has attempted to relate drainage basin morphology to the transport of a biologically significant substance (Kirchner, 1975).

Various physical or chemical parameters or gradations of these have been proposed in order to contrast regions which may appear biologically related, but which may radically differ physically or chemically.

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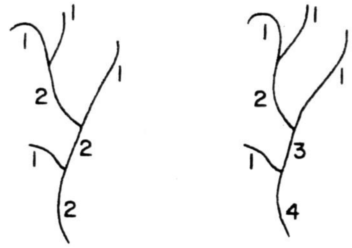

Fig. 1. (a) Hypothetical drainage network numbered according to the Strahler stream order system. (b) Same hypothetical network numbered according to link analysis.

A commonly-used criterion is that of stream order (Horton, 1945; Strahler, 1957), but this technique has maximum value in comparing ecological relationships within a given watershed (e.g. Sheldon, 1968). The method of stream link magnitude analysis is similar to traditional geomorphic–hydraulic parameters, such as stream order, but has some advantages in the examination of a single watershed (Shreve, 1966) and should be superior when conditions in different watersheds are compared. The term 'external link' refers to a section of channel reaching from a source to a confluence. Link magnitude of all stream sources is defined as 1. Thus, the link magnitude of a channel segment which is downstream of six source streams is 6; its confluence with another channel of link magnitude 5 will result in an 11-link stream (Shreve, 1966). Observations on the East Fork of the Salmon River, Idaho, and the McKenzie River, Oregon, indicate that many physical characteristics of a given stream order may be highly variable. For instance, basin area and link magnitude at the upstream end of a channel segment of a specific stream order average 50–60% of that at the downstream end. Furthermore, in a large watershed, lengths and drainage areas of streams vary substantially among streams of a particular order, and Strahler stream order is insufficiently sensitive to accommodate the influence of these basin parameters.

Strahler stream order stipulates that the joining of two same-order stream segments is necessary to form a new order. This system results in loss of information about the total number of source streams. In the hypothetical drainage shown in Fig. 1a, a second order stream exists, according to the rules of numbering. This same network, however, has a link magnitude of 4 (Fig. 1b) indicating four sources, information which is not obtainable by Strahler stream order. Much biological processing of organic material has been shown to occur in these small headwater segments, and for that reason links are considered to reveal more biologically useful information. The additional information provided by stream links for a watershed allows stream ecosystems to be compared, not only within similar, but also in contrasting physiographic regions.

The ratio of DOC:POC (particulate organic carbon) for streams and lakes has been considered over the past 5–10 yr to be a universal 10:1 constant (Wetzel and Rich, 1973). This ratio was tested in the four river systems of this study, as well as others reported. Transport of POC in the four river systems was reported elsewhere (Sedell *et al.*, 1978).

The impact of watersheds on organic matter transport is still largely unknown. This potential relationship was tested by comparing total mass and load per unit area of carbon transported annually in the dissolved state among 45 streams covering a broad range of stream systems and physiographic regions.

SITE DESCRIPTIONS AND METHODS

Streams from four regions (Fig. 2) of the cotermінous United States were studied, representing distinctly different geologic–hydrologic regimes (Table 1). White Clay Creek in the Brandywine River watershed of southeastern Pennsylvania is considered typical of deciduous forest streams in an unglaciated setting while the Augusta Creek–Kalamazoo River system in southcentral Michigan is in deciduous forest on glaciated terrain. The Michigan streams are subject to approx 30% greater annual precipitation with substantially greater mean base discharge (Fig. 3).

The Salmon River in central Idaho arises in rugged, high mountains (2600 m elevation) of sparse coniferous forest, and then flows through broad glacial valleys. Unlike the other sites, the Salmon River receives dramatically differing amounts of annual precipitation between its high elevation headwater and lower downstream regions (Table 1) with major runoff from spring snowmelt. A 70% decrease in downstream precipitation and a 60% decrease in runoff is reflected in a shift from conifers to sagebrush (*Artemisia* spp.) as the principal terrestrial vegetation.

The McKenzie River watershed of west-central Oregon is dominated by dense coniferous forests of Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophyla*) with a riparian zone dominated by alder (*Alnus rubra*). Its 230 cm of annual precipitation is substantially greater than that of any other site. Up to 80% of the annual precipitation falls during the winter and early spring months (November–April). A bimodal runoff pattern is exhibited due to snowmelt in the Cascades Mountains and rainfall.

Runoff for the Pennsylvania and Michigan sites is quite similar, ranging from 46 to 72 cm . yr^{-1} for all but the fourth order Michigan waterway (Table 1). Except for the second-order stream (Camp Creek), Idaho's Salmon River is comparable to the eastern rivers. Only Oregon appears to exhibit a radically different runoff, ranging from 26 cm . yr^{-1} in the small order stream to 190 cm . yr^{-1} in the third order segment. Although streamflow or runoff generally increases from west to east over the United States in response to climatic characteristics, it can be as large in the western mountains as in the east (Leopold *et*

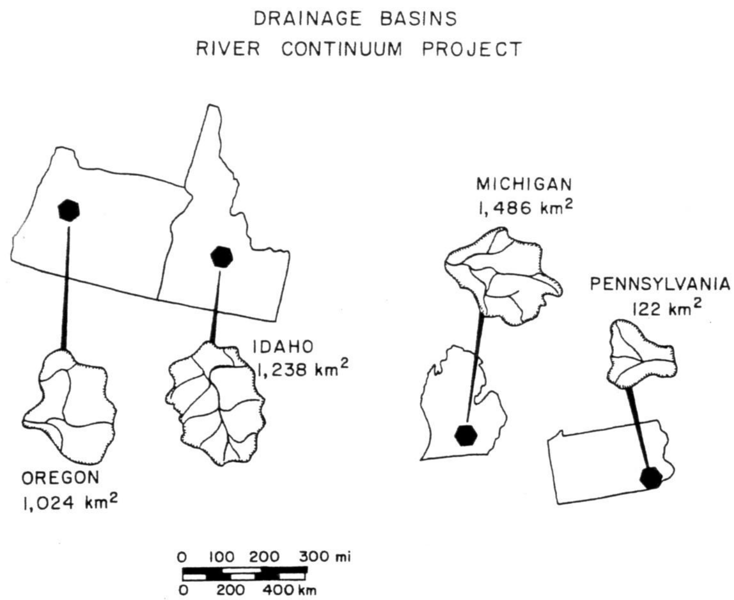

Fig. 2. Drainage basins of River Continuum Project.

al., 1964). This is seen in the calculated runoff values for the stations of this study (Fig. 3). While regional averages would show a gross trend as described by Leopold *et al.*, individual variation between the three easternmost watersheds precludes a general statement about runoff among these three sites.

Water samples were collected in the same general manner at each region. One liter of stream water was filtered through a pre-ashed GF-C glass-fiber filter under approximately 35 mm Hg pressure. GF-F glass-fiber filters were not available at the time this study began. Membrane filters leach unknown and inconsistent amounts of DOC when water is passed through them, thereby resulting in elevated DOC values. While GF-C glass-fiber filters have an effective pore size of 1.2 μm, it is felt that the difference in DOC concentrations compared to filtration through a 0.45 μm membrane filter will be small, if detectable at all. Subsequent analyses on three water samples from the Salmon River verified our initial hypothesis (Appendix A). Water was filtered through ashed (550°C) and non-ashed GF-C glass-fiber filters, Millipore® (0.45 μm) and Nucleopore® (0.45 μm) filters. Non-ashed GF-C filters gave slightly elevated DOC concentrations ($\sim$0.05 mg/l) compared to ashed GF-C filters. Although they have a much smaller nominal pore-size than GF-C filters, Millipore filters actually showed increased amounts of DOC in each

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

Geographical Region (Station)	Predominant Geology	Strahler Stream Order	Stream Link No.	Annual Precipitation (cm)	Watershed Area (km^2)	Mean Annual Discharge ($m^3.sec^{-1}$)	Unit Power ($kg \cdot m^{-1} \cdot sec^{-1}$)	Mean Annual DOC ($mg \cdot l^{-1}$)	DOC Load ($t \cdot yr^{-1}$)	DOC Output ($t \cdot km^{-2} \cdot yr$-1)
Pennsylvania										
White Clay Ck	gneiss	1	1	80	0.3	0.0056	2.31	2.6	0.46	1.53
White Clay Ck (Choates)	gneiss	2	2	80	1.8	0.029	5.99	2.6	2.40	1.32
White Clay Ck (Experimental)	gneiss	3	4	80	6.0	0.089	8.90	1.9	5.33	0.89
Buck & Doe Run	gneiss	5	59	80	122.4	2.83	24.14	2.5	223	1.82
Michigan										
Smith Ck	carbonaceous sandstone	1	1	152	0.78	0.014	10.27	3.9	1.72	2.21
Augusta Ck (Upper 43rd Site)	carbonaceous sandstone	2	5	152	36.4	0.82	33.06	3.9	100.9	2.77
Augusta Ck (Kellogg River)	carbonaceous sandstone	3	12	152	62.7	1.13	22.60	3.3	117.6	1.87
Kalamazoo R.	carbonaceous sandstone	5	80	152	1486.0	10.73	20.33	2.8	947	0.64
Idaho										
Camp Ck	granite	2	2	102	0.8	0.038	809.4	1.1	1.32	1.65
Salmon R. (Smiley)	granite	5	42	102	70.6	1.283	252.3	1.4	56.6	0.80
Salmon R. (Obsidian)	granite	6	430	38	738.1	19.69	308.5	1.5	931	1.26
Salmon R. (Casino)	granite	7	852	38	1238.3	28.47	674.6	1.6	1437	1.16
Oregon										
Devil's Club Ck	basalt-rhyolite	1	1	230	0.2	0.0017	113.3	1.6	0.09	0.43
Mack Ck	basalt-rhyolite	3	10	230	6.0	0.092	398.7	0.7	2.03	0.34
Lookout Ck	basalt-rhyolite	5	95	230	60.5	3.66	915.0	0.7	80.8	1.33
McKenzie R.	basalt-rhyolite	7	346	230	1024.0	55.0	825.0	1.1	1908	1.86

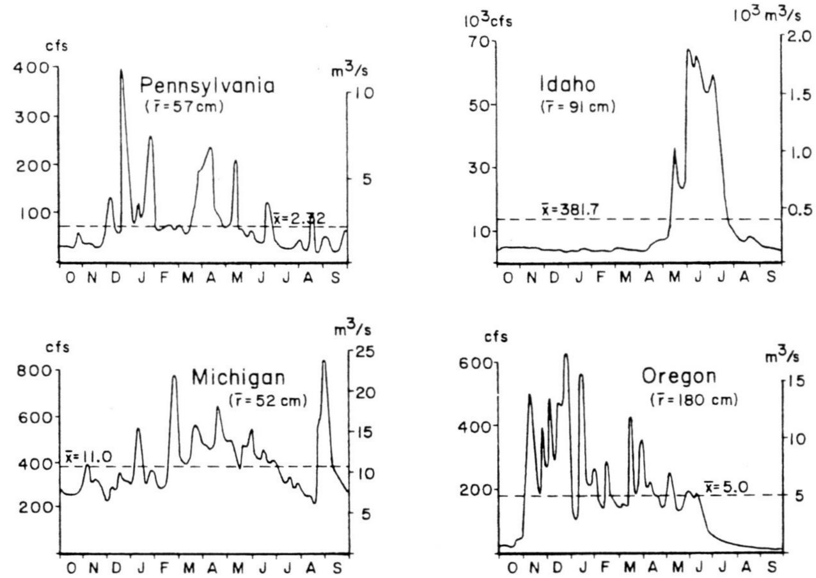

Fig. 3. Hydrographs and runoff data for each of the four river systems, 1976. Mean discharge ($\bar{X}$) and mean runoff ($\bar{r}$) are included. Runoff for Oregon determined for Lookout Ck and McKenzie River stations only.

sample ($\sim$0.10 mg/l). This is attributed to the filter matrix itself, which is organic in composition. These membrane filters were initially washed with 100 ml of sample, but they still leached small quantities of organic carbon. Nucleopore® filters yielded DOC concentrations between that of ashed GF-C and Millipore® filters. It is possible, however, that our samples are slight over-estimates of true DOC concentration. The sample was collected in an acid-washed BOD bottle, and then acidified to pH 2 or less with 2 ml of concentrated hydrochloric acid. Samples were concentrated to approximately 3 ml by freeze-drying, and three replicates of each were analyzed in a Dohrmann DC-50 Total Carbon Analyzer. Freeze-drying was recommended as a method of compensating for questionable accuracy of this instrument below concentrations of 10 ppm. The reliability of the freeze-drying technique was checked by concentrating an acidified solution with a known amount of DOC. Triplicate sub-samples gave estimates within 5–8% of the theoretical concentrations. Link magnitude was determined by tabulation of all first order streams for a given watershed on 7.5 min USGS topographic maps.

In the comparison of data of previous studies to those of this investigation, dissolved organic matter (DOM) was assumed to be 50% carbon (Birge and Juday, 1934; Wetzel *et al.*, 1972). Additionally, 1 g carbon was assumed equivalent to 10 kcal of energy (Winberg, 1971). Total annual transported DOC, if not reported, was determined with mean annual discharge and DOC concentrations either explicitly supplied by the investigator or extrapolated from figures in the text.

RESULTS

Cross-biome comparison

With the exception of the Salmon River, the general (albeit slight) trend was for the smallest order segments to have the highest concentrations of DOC (Table 1). The Michigan streams showed the greatest mean annual DOC concentration, while Oregon streams had the lowest values. Mean DOC concentrations were relatively constant throughout the river segments investigated.

Gross annual transport of DOC showed a fairly wide diversity between streams (Table 1). Whereas first and second order segments in Oregon, Idaho, and Pennsylvania carried less than 2.5 metric tons (t)$.\mathrm{yr}^{-1}$, the second order Michigan stream carried nearly 50 times as much. The Kalamazoo and McKenzie Rivers had the greatest mass of transported DOC, while the fifth order Pennsylvania stream carried only twice the annual load of the second and third order Michigan streams. Similarly, the fifth order Idaho site transported only 6% of the DOC of the same order Michigan stream.

Expression of these data on an areal basis resulted in striking similarity of DOC output. Each watershed, with the exception of Oregon and the largest Michigan site showed no more than a 2-fold difference in DOC output among its streams; the exceptions showed a 4-fold difference. Comparison between watersheds likewise yielded close results, with all sites ranging from 0.34 to 2.77 t$.\mathrm{km}^{-2}.\mathrm{yr}^{-1}$.

Seasonal transport

Spring transport of DOC was approximately 7–10

Table 2. Seasonal DOC concentration and transport for each stream and river. (Pennsylvania Spring data is mean DOC, station 3, Spring 1974 and 1975)

River	Season	Sample no.	Mean DOC ($mg \cdot l^{-1}$)	Mean Discharge ($m^3 \cdot sec^{-1}$)	DOC ($t \cdot yr^{-1}$)	% of Annual DOC
Buck and Doe Run (Penn.)	Winter	3	1.6	3.3	167	17
	Spring	4	4.0	2.2	277	29
	Summer	2	1.7	2.4	129	14
	Fall	2	4.2	2.9	384	40
Kalamazoo River (Mich.)	Winter	3	4.2	7.5	993	41
	Spring	2	3.2	9.0	908	38
	Summer	2	2.3	3.6	261	11
	Fall	2	1.3	6.0	246	10
Salmon River (Casino, Idaho)	Winter	3	1.3	14.0	574	8
	Spring	2	2.7	66.4	5654	74
	Summer	2	1.3	20.0	820	11
	Fall	2	1.1	16.2	562	7
McKenzie River (Oregon)	Winter	3	2.5	120.0	9461	67
	Spring	2	0.7	110.0	2428	17
	Summer	2	1.1	54.0	1873	13
	Fall	2	0.3	44.0	416	3

times greater than at any other season in the Salmon River (Table 2). This is attributable not only to higher discharge (3–5 times that of any other season) but also to concentrations of DOC which were elevated up to 100% over other seasonal values. On an annual basis, 75% of the total transported DOC was carried during spring runoff, while the remainder was evenly divided throughout the other three seasons.

Kalamazoo River DOC concentration decreased throughout the year with highest values in winter, probably reflecting DOC transport from upstream autumn leaf litter input. Even though precipitation distribution in the Augusta Creek watershed is bimodal (with spring rains substantially greater than those of autumn) nearly 80% of annual DOC transport occurs in winter and spring. This is a function of both high discharge and high DOC concentration during those seasons, as it is in the Salmon River during spring. Fall and spring DOC concentrations in the White Clay Creek watershed are 2.5 times that of the low winter value. This area shows a bimodal distribution in annual DOC transport corresponding to these higher concentrations, since discharge and precipitation are reasonably constant during all seasons. The McKenzie River delivers 67% of its annual DOC load in winter, the period of maximum precipitation. Another 17% is carried in spring; thus, all but 20% of the annual budget is delivered during the winter and spring rainy seasons.

Total transported DOC for each river system based upon seasonal estimates (Table 2) does not correspond with that of Table 1. Seasonal estimates of DOC transport were only determined for the largest link stream segment in each watershed. Each season is assumed to be 3 months; DOC transported during that season is multiplied by four in order to express DOC on an annual basis. This is a simplifying assumption, since for example, summer in Idaho may be only 1 month long, while winter, may extend through 6 or 7 months.

Geomorphic relationships

Analysis of annual DOC transport data by multiple linear regression using various geomorphic parameters as the independent variables indicates that there are strong linear correlations between stream link magnitude, stream order, watershed area and discharge and the dependent variable DOC transport (Table 3a). Correlation coefficients for each of these independent variables against DOC transport are (1) links, $r = 0.80$; (2) order, $r = 0.79$; (3) watershed area, $r = 0.89$; and (4) discharge, $r = 0.96$. It is certain that a high degree of multicolinearity (i.e. intercorrelation among independent parameters) exists among these variables, particularly with discharge. This intercorrelation may act to obscure a truly independent parameter, or tend to overestimate the importance of a non-significant variable. Link magnitude is well-correlated with other physical parameters of watersheds, having a coefficient of determination (r^2) = 0.72 with discharge and 0.71 with area.

Inclusion of all variables in the analysis shown that 63.6% of the variance in annually transported DOC is explained by links, 30.6% more by discharge and 5.4% additional by watershed area. These relationships are all highly significant ($\alpha' < 0.001$). Removal of discharge from the analysis does not change the correlation coefficient for links ($r = 0.80$), but its value is no longer significantly different from zero.

The independent variables were entered stepwise into the multiple regression, according to their capacity to explain the greatest amount of unexplained variance. Discharge was omitted in order to circumvent multicolinearity difficulties. Area, links, precipitation and order explained 89% of the variance in DOC transport, with watershed area accounting for the majority (Table 3a). With removal of area from the analysis, links account for 64% of the variance ($\alpha < 0.01$), and are seemingly quite important in predicting the quantity of DOC annually transported. Further analysis reveals that link magnitude for each

Table 3. Multiple linear regression analysis of total transported DOC vs various geomorphic parameters. Variables entered sequentially in terms of explanation of greatest variance (SPSS packaged program)

Table 3a

Variable	Multiple r	r^2	Beta	F
Area	0.893	.798	.559	11.56***
Links	0.922	.850	.324	3.59*
Precipitation	0.936	.876	.152	2.08^{ns}
Order	0.941	.886	.159	0.99^{ns}

Table 3b

Variable	Multiple r	r^2	Beta	F
Links	0.797	.636	.647	7.30**
Order	0.854	.730	.440	4.09*
Precipitation	0.875	.766	.280	2.59^{ns}
Power	0.884	.781	-.168	0.78

*** = $\alpha < 0.001$; ** = $\alpha < 0.01$; * = $\alpha < 0.05$.
Table 3a. Discharge omitted from analysis, *d.f.* = 4, 11.
Table 3b. Discharge and watershed area are omitted from analysis. Stream power calculated as $\Omega = Qqdw^{-1}$, where Q = discharge ($m^3.sec^{-1}$), q = gradient (per cent slope), d = water density ($Kg.m^{-3}$), and w = width of stream (m) (Leopold *et al.*, 1964), *d.f.* = 4, 11.

station is significantly related to annual DOC load by a power function (Fig. 4).

DISCUSSION

Toward basic generalizations regarding DOC transport

The understanding of general stream ecosystem functions requires the development of methods for the legitimate comparison of systems. In general, lotic ecological principles have been formulated and tested within single small watersheds. Often these principles are derived from first to third order headwater streams only, where field observations and experimentation may be more easily managed than in larger downstream segments. If the goal is derivation of valid generalizations for the dynamics of entire river systems, the observational and experimental scope must be expanded throughout single watersheds and through comparisons between watersheds.

Physical differences which exist among watersheds

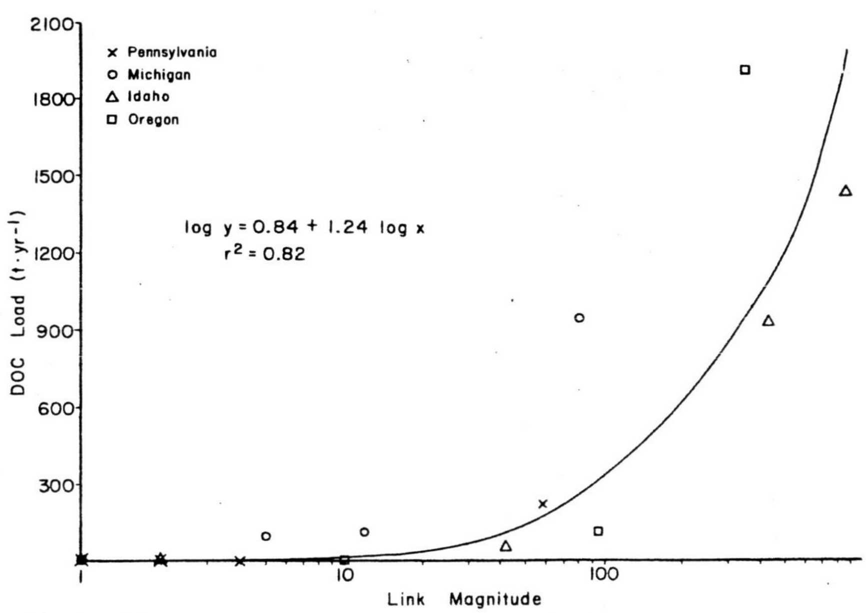

Fig. 4. DOC annual transport vs link magnitude for all stations on each stream.

Table 4. Relative physical differences of some fifth order streams. (Streams compared to Buck and Doe Run, Penn.)

Stream (Link Magnitude)	Watershed Area	Discharge	Annual Precipitation	DOC
Buck & Doe Run, Penn. (1)	1	1	1	1
Lookout Ck, Ore. (1.6)	0.5	1.4	2.1	0.4
Salmon R. (Smiley Station), Ida. (0.7)	0.6	0.2	0.9	0.1
Kalamazoo R., Mich. (1.3)	12.0	6.0	1.3	7.7

make ecological comparisons difficult. Macroclimate, precipitation regime, seasonal flow patterns, discharge and geology are often unique features of watersheds. Since many of these characteristics are integrated through channel morphometry, various attempts have been made to focus on these physical features.

Stream order has been used as a unifying technique by which to compare various biological communities, such as fishes (e.g. Kuehne, 1962; Lotrich, 1973; Small, 1975). The distribution of individual species of fish has been predicted by gradient and width variations (Trautman, 1942; Huet, 1959). Drainage area was hypothesized to influence the number of fish species present in a watershed (Thompson and Hunt, 1930). The concept of stream power evolved as a measure of the ability of moving water to do work (Leopold *et al.*, 1964). This concept was utilized to investigate the transport of particulate organic matter which was shown to be weakly correlated with stream power (Sedell *et al.*, 1978).

Stream order has been used as an independent parameter within a given physiographic area. However, it generally is unsatisfactory in comparing different areas since it does not account for small but possibly significant changes in channel width, depth and discharge; watershed area; and influx of smaller order streams. An example from the present study is indicative of the difficulties encountered with the usage of the stream order system. The fifth order stations of each river were compared by a number of physical characteristics (Table 4). The streams were arbitrarily compared to Buck and Doe Run, Pennsylvania. Watershed area is shown to vary by a factor of 24 times (Kalamazoo River vs Lookout Creek), discharge by up to 30 times, precipitation by approximately two times and DOC transport by over 70 times. Variations of this magnitude within streams of the same order obviously complicate elucidation of underlying ecological principles.

DOC–precipitation relationships

Precipitation patterns may contribute extensively to seasonal distribution of transported DOC. For example, Idaho's semi-arid conditions include substantial precipitation in the form of snow in the headwaters. Since the ground is frozen before snowfall, little runoff of water and nutrients occurs in winter. This causes the amount of DOC carried downstream to be highest during the spring thaw. Oregon has an extended winter and spring rainy season which results in a major DOC pulse during those seasons. Michigan's precipitation is distributed around spring and fall maxima yet, except for drier summer periods, DOC transport is fairly evenly distributed. Pennsylvania also receives precipitation throughout the year, and DOC transport appears low and fairly constant during all seasons. In light of these apparent trends, a correlation between transported DOC and daily precipitation may be possible, particularly if an empirically derived delay time is included. A much more intensive sampling regime than that of this investigation would be required to demonstrate this. Clearly, total annual precipitation is too coarse a parameter to explain variation in total annual DOC transported.

Role of storm runoff in transport of organic materials

Much of the DOC transported annually occurs during periods of increased flow due to runoff (Table 2), the same as has been reported for POC (Fisher, 1970; Hobbie and Likens, 1973). Our data, in general, indicate increased DOC concentration as well as increased total DOC transported during certain seasons. Identity (or even substantial similarity) in molecular composition between DOC measured in one season of a locality and that of another cannot be assumed. Variances in DOC composition will affect its ecosystem roles to an unknown extent. The flushing of large amounts of DOC from the system during periods of high discharge may serve to obscure further the role of DOC in stream ecology. If a significant percentage of DOC is removed during several concentrated periods throughout a year, a reduced amount will be available to the biota. It may be necessary to exclude these DOC surges from energy budget considerations.

Relationship of DOC content to link number

The non-linear relationship between DOC transport and link magnitude may be due to the absence of intermediate-to-large size watersheds (100–1000 links) in this study. The three streams that have large link values may be insufficient to reveal a more nearly linear relation between DOC and link magnitude. In

Table 5. Summary of DOC mean concentrations, DOC annual transport, DOC output and DOC:POC ratio for reported streams and rivers

Location	Area (km^2)	DOC ($mg \cdot l^{-1}$) Annual Range	(Mean)	DOC load ($t \cdot yr^{-1}$)	DOC output ($t \cdot km^{-2} \cdot yr^{-1}$)	Mean DOC:POC	Method	Reference
Devil's Club Ck, Ore.	0.20	1.5-1.8	(1.6)	0.09	0.43		1	This study
Hubbard Bk - W6, N.H.	0.13	0.2-4.8	(1.0)	0.13	1.0		2	Hobbie and Likens, 1973
Hubbard Bk - W2, N.H.	0.16	0.1-3.1	(1.0)	0.16	1.0	(3.9)	2	Hobbie and Likens, 1973
Tecopa Bore, Calif.	spring		(<3-4)	0.28		(2.2)	1	Naiman, 1976
Inlet Stream 1, Stn. A (Lawrence Lk, Mich.)	0.15	1.2-4.8	(2)[d]	0.29	1.93	(10.0)	2	Wetzel and Otsuki, 1974
Inlet Stream 2, Stn. B (Lawrence Lk, Mich.)	0.087	1.4-6.5	(3.5)[d]	0.31	3.56	(7.0)	2	Wetzel and Otsuki, 1974
White Clay Ck, Penn.	0.3	1.9-3.4	(2.6)	0.46	1.53	(0.29)	1	This study
Camp Ck, Idaho	0.80	0.6-2.1	(1.1)	1.32	1.65	(0.13)	1	This study
Bear Bk, N.H.	1.3	0.38-3.78	(1.1)	1.7	1.31	(2.3)	5	Fisher and Likens, 1973
Smith Ck, Mich.	0.78	2.7-5.1	(3.9)	1.72	2.21	(0.18)	1	This study
Mack Ck, Ore.	6.0	0.5-0.9	(0.7)	2.03	0.34		1	This study
White Clay Ck (Choates), Penn.	1.8	2.4-2.8	(2.6)	2.4	1.32	(0.64)	1	This study
White Clay Ck (Exper.), Penn.	6.0	1.3-3.9	(1.9)	5.33	0.89	(0.3)	1	This study
Roaring Ck, Mass.	1.2	0.5-3.6	(1.1)	6.5	5.42	(5.5)	5	McDowell and Fisher, 1976
Station 2 Deep Ck, Idaho	spring	7.3-19.8[a]	(5.9)	16			5	Minshall et al., 1975
White Clay Ck (3rd order), Penn.	7.25	2.0-18.4	(6.4)	37	5.10		3	Larson, 1978
Stream 1 - Char Lk, N.W.T., Can. (1972 & 1973)	0.27		(1.8)	43	159.2	(17.3)[c]	8	deMarch, 1975
Hog Creek, Texas	222.7	0.3-3.4	(0.75)[a]	48	0.21	(3.2)[a]	5	Lind, 1971; Lind (pers. comm.)
Salmon R. (Smiley), Idaho	70.6	0.6-2.4	(1.4)	56.6	0.80	(0.09)	1	This study
Lookout Ck, Ore.	60.5	0.4-1.2	(0.7)	80.8	1.33		1	This study
Augusta Ck (UP 43), Mich.	36.4	3.0-5.1	(3.9)	100.9	2.77	(0.14)	1	This study
Augusta Ck (Kellogg Forest), Mich.	62.7	2.4-3.9	(3.3)	117.6	1.87	(0.19)	1	This study
Middle Basque R., Texas	492.1	0.2-3.1	(0.75)[a]	121	0.25	(4.0)[a]	5	Lind, 1971; Lind (pers. comm.)
Augusta CK (Kellogg Forest), Mich.	62.7	1.8-8.5	(4.4)	150	2.39	(2.8)	2	Wetzel and Manny, 1977
Stream 3 - Char Lk, N.W.T., Can. (1972 & 1973)	1.03		(1.9)	180	174.76	(21.8)[c]	8	deMarch, 1975
Buck & Doe Run, Penn.	122.4	-	(2.5)	223	1.82	(1.9)	1	This study
Fort R. (Site 1), Mass.	105	0.8-7.4	(3.0)	280	2.67		1	Fisher, 1977
South Basque R., Texas	290.1	0.3-5.0	(1.1)[a]	344	1.19	(2.7)[a]	5	Lind, 1971; Lind (pers. comm.)
Salmon R. (Obsidian), Idaho	738.1	0.9-2.2	(1.5)	931	1.26	(0.32)	1	This study
Kalamazoo R., Mich.	1486.0	1.3-4.2	(2.8)	947	0.64	(0.15)	1	This study
N. Basque R., Texas	3286.7	0.6-6.8	(1.9)[a]	1040	0.32	(3.3)[a]	5	Lind, 1971; Lind (pers. comm.)
Salmon R. (Casino), Idaho	1238.3	1.0-3.9	(1.6)	1437	1.16	(0.30)	1	This study
N. Fork, Col.	1241		(10.0)	1600	1.29	(3.6)	4	Ward, 1976; Ward (pers. comm.)
M. Oconee R., Ga.	1030.8	4 - 24	~(7.5)	1900	1.84		4	Nelson and Scott, 1962
McKenzie R., Ore.	1024.0	0.3-2.5	(1.1)	1908	1.86		1	This study
S. Platte Stn. 1 (below dam), Col.	4538		(28.0)	3030	0.67	(70.0)	4	Ward, 1976; Ward (pers. comm.)
Sopchoppy R., Fla.	264.2	6.2-52	(27.0)	6400	24.22	(23.5)	2	Malcolm and Durum, 1977; Billingsley (pers. comm.)
S. Platte Stn. 4, Col.	6680		(17.7)	6900	1.03	(8.0)	4	Ward, 1976; Ward (pers. comm.)
L. Miami R., Ohio	4545	2.5-12.5	(6.4)	9900	2.18	(2.65)	7	Weber and Moore, 1967

(Continued)

Table 5 (*continued*)

Location	Area (km^2)	DOC ($mg \cdot l^{-1}$) Annual Range	(Mean)	DOC load ($t \cdot yr^{-1}$)	DOC output ($t \cdot km^{-2} \cdot yr^{-1}$)	Mean DOC:POC	Method	Reference
Neuse R., N. Car.	6190	4.1-10.0	(7.1)	14100	2.28	(3.0)	2	Malcolm and Durum 1977; Billingsley (pers. comm.)
Brazos R., Texas		0.5-5.2	(3.3)	21800		(0.87)	2	Malcolm and Durum, 1977
Missouri R., Nebr. (@ Nebraska City)	1061900	1.9-9.0	(4.6)	155400	0.15	(0.27)	2	Malcolm and Durum, 1977; Billingsley (pers. comm.)
Nanaimo R., B. Col., Can.		<1-3	~(1.7)[b]	243000		(6.7)	6	Seki et al., 1969
Lower Fraser R., Can.	223100	2.0-4.9	(3.7)	309600	1.33		2	Albright, 1977; Albright (pers. comm.)
Mississippi R.	2926182	2.2-4.5	(3.4)	1563600	0.53	(0.86)	2	Malcolm and Durum, 1977; Billingsley (pers. comm.)

1 Total Carbon Analyzer; 2 Wet oxidation (after Menzel and Vaccaro, 1964); 3 Wet oxidation (after Slater, 1954); 4 Filtration and evaporation; 5 Dichromate oxidation (Maciolek, 1962); 6 Phenolsulfuric acid (after Handa, 1966; for sol. carbohydrates); 7 Combustion (after Van Hall *et al.*, 1963); 8 Gas chromatography (after Stainton, 1973).

[a] June–December (mean adjusted for missing data based on discharge).

[b] Soluble carbohydrates only.

[c] Fine particulate organic carbon only.

[d] Conc. derived from figures in text.

addition, local geomorphic conditions may create anomalies which prevent accurate determination of link magnitude. The McKenzie River, for example, arises in volcanic rock and may actually be equivalent to a fifth or sixth order stream upon surfacing; upwards of 300 km^2 of the basin have not developed a surface drainage net. Link analysis should be expanded to other large river systems, preferably undisturbed by man. Consideration of rivers which have not been dammed, channelized, or dredged is necessary in order to remove additional confounding variables from the analysis. The application of link analysis to streams of an even greater physiographic variety will aid in its ultimate acceptance or rejection as a comparative tool. Since it appears to be a useful method in comparing total DOC transport in running waters, further work on other dissolved components, such as dissolved inorganic carbon, dissolved organic nitrogen, phosphate, nitrate and other major ions, would be useful.

However, there are drawbacks to widespread usage of link analysis. The small-scale topographic maps required to determine link magnitude often do not exist for more remote areas. Link lengths, which may also have significant biological implications, are subject to large errors due to difficulty in obtaining accurate measurements from topographic maps (Jarvis, 1976). Appropriate computer techniques and reasonably accurate relationships between watershed area and link magnitude must be developed in order to eliminate the tediousness and potential error involved in tabulating the link magnitude of a large river.

Annual transport of DOC

The smallest streams of this study annually transport 0.09–1.7 metric tons (t) of organic carbon in the dissolved state (Table 1). This compares favorably to other small streams in a wide variety of geographic locations (Table 5). Arbitrary comparison of those streams which carry less than 2.5 t DOC annually shows a wide range of DOC concentrations and annual means in spite of fairly similar DOC loads. Bear Brook and Camp Creek have very low annual mean concentrations (1.1 $mg.l^{-1}$), whereas Tecopa Bore (a thermal stream), Lawrence Lake Inlet 2, and Smith Creek have annual DOC mean concentrations of 3.5 or greater. These small streams have annual DOC outputs ranging from 0.34 to 3.6 $t.km^{-2}.yr^{-1}$. Oregon streams carry the smallest quantity of DOC on an areal basis (0.34–0.43 $t.km^{-2}.yr^{-1}$), while the Michigan streams carry the largest, 1.9–3.6 $t.km^{-2}.yr^{-1}$.

The next set of streams (Table 5) includes those carrying annual DOC loads of 5–125 t. Although clustered arbitrarily, mean DOC concentrations vary even more widely than in the first grouping, ranging from 0.7 to 6.4 $mg.l^{-1}$. Hog Creek and Middle Basque River and Lookout Creek have annual mean DOC concentrations less than 1 $mg.l^{-1}$; White Clay Creek and Deep Creek have means exceeding 5.9 $mg.l^{-1}$. With the exception of Char Lake inlet stream 1, DOC output for this group is similar to the smaller streams, ranging from 0.21 to 5.1 $t.km^{-2}.yr^{-1}$. In contrast, the Char Lake inlet has a huge DOC output, in excess of 159 $t.km^{-2}.yr^{-1}$, presumably due to permafrost melting.

In general, those streams which transport between 150 and 1100 t DOC annually have more similar mean DOC concentrations than those of both larger and smaller loads. With one exception (Augusta Ck—Kellogg Forest, Michigan), mean annual DOC concentrations ranged from 1.1 to 3.0 $mg.l^{-1}$. This group includes streams from Pennsylvania, Massachusetts, Texas, Idaho, Michigan, and Northwest Territories,

Table 6. Estimates of watershed gross primary production (GPP), net primary production (NPP), litter production, and the ratios of exported DOC to these data. DOC, GPP, NPP, and litter expressed as $t.ha^{-1}.yr^{-1}$. All ratios expressed as percentages

Site	DOC	GPP[a]	NPP	Litter	DOC:GPP	DOC:NPP	DOC:Litter
White Clay Ck.	0.014	33.8	16.9[d]	3[j]	0.041	0.083	0.47
Augusta Ck.	0.019	27	13.5[b]	3[j]	0.070	0.141	0.63
Salmon R.	0.012	6	3[b,c]	0.5[k]	0.200	0.400	2.4
McKenzie R.	0.010	124.0	8.0[e]	3.9[f]	0.008	0.125	0.26
Coweeta[g] (Watershed 18)	<0.020	17.4	8.7		0.115	0.230	
Hubbard Br.	0.010	23[i]	11.5		0.043	0.087	
Findley Lake Ecol. Reserve	0.018[m]	75[n]	5[p]	3[p]	0.024	0.36	0.60

[a]If GPP not reported or estimated, assumed GPP = 2 X NPP.
[b]Woodwell and Whittaker, 1968.
[c]Assume NPP = desert grassland NPP.
[d]NPP Penn. est $\approx$ 25%> Michigan NPP.
[e]Grier and Logan, 1977.
[f]Coniferous forest litter = 3.5 $t.ha^{-1}.yr^{-1}$ (Millar, 1974); litter = 4.3 $t.ha^{-1}.yr^{-1}$ (Grier and Logan, 1977); $\bar{X}$ = 3.9 $t.ha^{-1}.yr^{-1}$.
[g]J. Webster, pers. comm.
[i]Whittaker *et al.*, 1974.
[j]Jensen, 1974.
[k]Assume litter = $\frac{1}{2}$ X arctic-alpine forest.
[m]From data provided by J. Ritchie (pers. comm.).
[m]GPP assumed 15 X NPP as per Oregon estimate of Grier and Logan, 1977.
[p]C. Grier (pers. comm.).

Canada. DOC output varies from 0.32 to 2.67 $t.km^{-2}.yr^{-1}$, again with the exception of a Char Lake inlet stream.

The remaining streams carry at least 1400 t DOC per year. DOC output shows the smallest range of any grouping, 0.67–2.18 $t.km^{-2}.yr^{-1}$. In general, these are large rivers with high mean annual DOC concentrations, although the seventh order Salmon River, seventh order McKenzie River and Nanaimo River have concentrations less than 2 $mg.l^{-1}$.

The studies cited have employed at least eight different methods of DOC concentration analysis. These have been performed under a wide variety of conditions, with an unknown number of modifications. Variations in methods may cause considerable variation in the amount of detected DOC. The annual loads of DOC reviewed in Table 5 may vary widely according to sampling, processing, analysis, and seasonal or annual variations in water quality and quantity.

As nearly as can be determined, the investigators in all of these studies have defined POC as that which is greater than approximately 0.45 μm. It should be apparent from this diverse collection of streams that a DOC:POC ratio which is considered to be universally 10:1 (Wetzel and Rich, 1973) is inaccurate and misleading. Annual means are shown to vary from 0.01:1 (Salmon River, Smiley Station) to 70:1 (South Platte River). The rivers of the present study have DOC:POC ratios less than one as do the very large Brazos, Missouri, and Mississippi Rivers. All but five of these streams and rivers have DOC:POC ratios less than 10:1. Many of the ratios calculated in Table 5 are based upon annual or seasonal transport of organic carbon. Comparisons of annual or seasonal DOC and POC are indicative of relative amounts of organic loading. Weekly or daily concentrations would be preferable, and these would almost certainly tend to accentuate the DOC:POC ratios. Although there is strong desire to formulate such generalities, it is unwarranted to consider DOC:POC ratio as a universal constant for running waters.

DOC export–terrestrial primary production relationships

Finally, it is of interest to compare the amount of carbon lost in the dissolved state from a watershed to that which is terrestrially fixed (primary production). DOC export for each watershed of this study ranged from 0.010 to 0.019 $t.ha^{-1}.yr^{-1}$ (Table 6). This narrow range is remarkable in light of differences in gross primary production (GPP) and net primary production (NPP) among the sites. While GPP ranges from 6 to 124 $t.ha^{-1}.yr^{-1}$, the large value for Oregon is primarily due to very high autotrophic respiration of old-growth forests. The resultant NPP is comparable to that of other biomes for which production has been estimated.

DOC:GPP ratios vary from 0.008 to 0.20%; these values are in the general range of other watersheds as are DOC:NPP ratios ranging from 0.083 to 0.40%. Another parameter which is indicative of allochthonous carbon production is leaf litter accumulation. Estimates of annual litter accumulation are relatively similar for the sites, with the obvious exception of Idaho's high desert. As in the comparison with primary production, DOC export consists of less than 1% of litter production for all sites but Idaho (= 2.4%).

Within a watershed it is reasonable to expect an increase in DOC output for a corresponding increase in production. However, DOC:GPP, DOC:NPP, and DOC:litter accumulation ratios all appear to be inversely related to primary production. Thus a watershed with high primary production appears to export relatively less DOC than a watershed with low-carbon fixation. This finding is consistent with others which have indicated the highly-retentive characteristic of watersheds for nutrients, especially those which are essential to floral development and reproduction (e.g. Odum, 1969; Likens *et al.*, 1970).

It has been hypothesized that mature or very young ecosystems will have greater nutrient losses than those of intermediate successional stages (Vitousek and Reiners, 1975). Watersheds of this study (including those of second-growth forests) are storing material and are considered mature. It appears that among mature ecosystems, watersheds with relatively large primary production may be capable of utilizing or retaining more DOC, thereby permitting less to escape. This relationship, as well as DOC export values for the widely diverse set of streams and rivers reported in Table 5, strongly suggest that DOC is also tightly retained by watersheds and that terrestrial primary production may be a controlling factor among mature systems. Thus, DOC export constitutes a consistently small amount of production, in spite of a wide range in terrestrial primary production. Whereas annual DOC transport serves a major role in organic budgets in aquatic ecosystems, it represents but a minute portion of the total carbon fixed annually in the watershed.

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Appendix A.

Table A1. Comparison of DOC in Salmon River water subjected to various filters. Mean of three determinations; variance in parentheses (all values in mg/l)

Sample \ Filter	Non-ashed GF-C	Ashed GF-C	Millipore® (0.45 μm)	Nucleopore® (0.45 μm)
1	1.069	1.036	1.128	1.076
	(0.00012)	(0.00021)	(0.00019)	(0.00043)
2	1.133	1.062	1.202	1.112
	(0.00058)	(0.00041)	(0.00159)	(0.00003)
3	1.304	1.280	1.316	1.304
	(0.00050)	(0.00149)	(0.00034)	(0.00091)