Dynamics of Lotic Ecosystems

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5. AN ALTERNATIVE FOR CHARACTERIZING STREAM SIZE

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ABSTRACT

Stream order is often useful in expressing relative stream and watershed size within a physiographically and climatically homogeneous basin. However, there are disadvantages when comparing stream and watershed size on a regional or national scale because of, among other things, the lack of uniform map specifications, the lack of agreement on the definition of a first-order stream, and the problem of deciding the appropriate map scale to determine stream order.

We examined published studies on 71 watershed/stream ecosystems in 31 states within major physiographic and climatic regions of the conterminous United States. Our objective was to demonstrate the value of using discharge characteristics and watershed area instead of stream order to provide a rough but useful characterization of watershed and stream sizes throughout the nation. We found that streams of a given order show vast ranges in discharge and watershed area, greatly overlapping the ranges for higher and lower order streams. Therefore we suggest using mean annual discharge per unit area and watershed area instead of stream order to quantify stream and watershed size.

INTRODUCTION

Quantification of stream characteristics is necessary to study and manage the nation's streams and to facilitate communication among a diverse group of scientists and managers throughout the United States. Currently, stream order (Strahler, 1957) is used by scientists and managers throughout the nation to relate stream characteristics. The term is commonly used to convey an understanding of stream size, watershed size, and, in some instances, even quantity of water. Although stream order has been and will probably continue to be a useful means of expressing relative size within a physiographically and climatically homogeneous basin, the term is often used beyond its capacity.

Several problems arise when stream order is used to represent stream size (Hughes and Omernik, 1981). (1) There is little agreement on how to include perennial, intermittent, and ephemeral streams in determining stream order. Are they considered as equals regardless of flow frequency? If so, note that some hydrologists use all map crenulations in a watershed although some channels only have flows during major storm or snowmelt periods. If not, how permanent must a stream be, given the short history of some stream gauging? Are Alaskan streams that freeze solid during the winter considered permanent or temporary? (2) There is little agreement as to which scale to use in determining order. For instance, depending on the map scale selected, a stream such as Oak Creek at Corvallis, OR, can be categorized as unordered, or first- third- or fourth-order. (3) All regions are not mapped to the same scale, under the same specifications, or during similar weather periods. Differences in stream density (and hence stream order) can be a function of different map compilation or field annotation processes. These differences often can be seen along neat lines between adjoining maps that have been compiled at different times under different specifications. Hence the small streams used to derive stream order are not all mapped in a uniform manner from one region to another in the United States, much less from one country to another.

Aside from the problem of determining stream order, the term provides little quantifiable information about streams and their watersheds. Stream order was developed to describe the linear geomorphic characteristics of small stream networks within a homogeneous physiographic area. It does not, nor was it intended to, address area, relief, or discharge. Smart (1972) felt that stream order was a mediocre approach even for the primary classification of stream networks, adding that watershed area may be preferable. Stream order provides no information about climate in the vicinity of a stream or annual and seasonal variations in discharge. Yet this information is useful for understanding the human uses and the community structure and function of all streams. Moreover, stream order has little or no meaning when considering distributaries, channelized or ditched streams, influent or disappearing streams, or streams arising from or flowing through alluvium, large springs, lakes, wetlands, snowfields, or glaciers. In karst and glaciated regions, streams may have discharges an order of magnitude greater than higher order streams in the same basin. Also, as pointed out by Hynes (1970), the stream order resulting from the junction of two equal-order tributaries can be increased whether a tributary is only a few hundred feet long or several miles long. Finally, the continuous addition of small tributaries of order n-1 to a stream of order n can greatly change the discharge and watershed area of a stream without changing its order. Shreve's (1966) link analysis and Scheidegger's (1965) consistent scheme of stream ordering classify each stream segment by the number of first-order streams flowing into it. This alleviates the last problem but not the others.

We suggest that using watershed area and mean annual discharge per unit area (i.e., unit discharge in cubic meters per second per square kilometer or preferably centimeters per year) rather than stream order will lead to a more accurate understanding of stream size, watershed size, and quantity of water. We believe this use will alleviate many of the difficulties described.

MATERIALS AND METHODS

We examined data on 71 streams in 31 states within most of the major physiographic regions (Fenneman, 1946) and ecoregions (Bailey, 1976) of the conterminous United States (Figure 1, Table 1). Ecoregions are large regional ecosystems with similar climate, landform, soils, vegetation, and fauna. We selected small streams that have been studied rather intensively and were covered by 1 : 24,000 scale U. S. Geological Survey topographic maps. We used these maps to determine watershed areas (by planimeter) and stream orders (from solid and broken blue lines). Unit discharges for the stream sites were determined directly from U. S. Geological Survey data, when possible, or from unit discharge isolines constructed from U. S. Geological Survey data on nearby streams. Unit discharge isolines were used to show regional patterns in runoff by the U. S. Geological Survey (1970) and by Muckleston (1979). Extrapolations from unit discharge isolines are also useful to estimate discharge in regions where watershed boundaries are difficult or impossible to define from topographic maps.

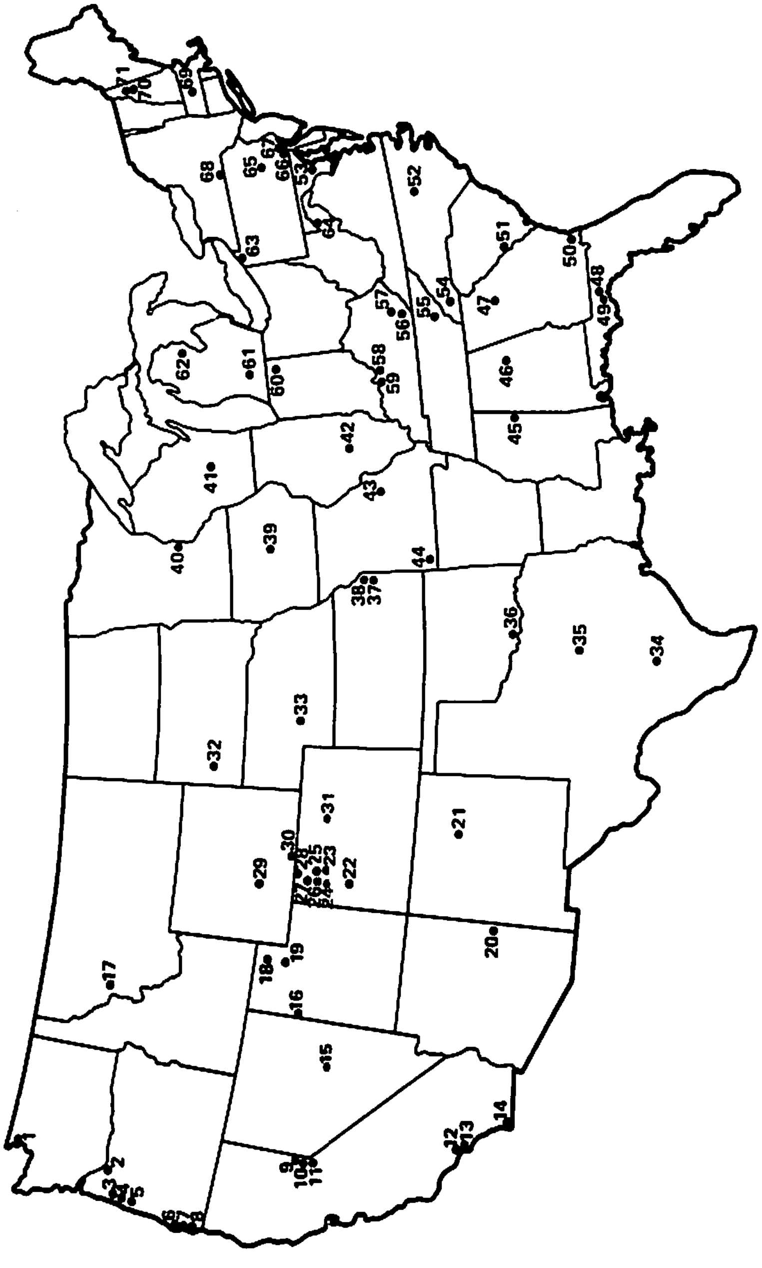

Figure 1. Locations of study sites.

Table 1. Stream Order, Watershed Area, Mean Annual Discharge, and Mean Annual Discharge per Unit Area of Selected Study Streams

Number	Stream	Investigator	Stream order	Watershed area, km^2	Mean annual discharge, m^3/sec	Mean annual discharge per unit area, cm/yr
1	Whatcum Creek	Orrell (1980)	3	145.3	9.85	213.87
2	Bull Run	Fredriksen et al. (1974)	3	277.1	24.09	274.32
3	Siletz River at Siletz, OR	Hughes and Omernik (1981)	5	523.2	45.02	271.53
4	Willamina River at Willamina, OR		5	168.4	7.00	131.06
5	Oak Creek	Kerst and Anderson (1974)	3	7.5	0.34	141.8
6	Winchester Creek	Oregon Department Fish and Wildlife (1969)	3	30.0	1.52	158.75
7	Big Creek		3	8.8	0.44	158.75
8	Two Mile Creek		3	24.1	1.21	158.75
9	Ward Creek	Leonard et al. (1979)	4	25.1	0.63	79.65
10	Blackwood Creek		4	29.0	1.89	110.49
11	Prosser Creek	Needham and Usinger (1956)	3	137.8	2.41	55.12
12	Sespe Creek	Swift et al. (1975)	4	650.1	1.42	6.86
13	Santa Ana river		4	2097.9	4.59	6.86
14	Temecula River		3	339.3	0.74	6.86
15	Hot Creek	Hubbs et al. (1974)	4	33.4	0.13	12.19
16	Thoms Creek	Winget and Reichert (1976)	3	21.2	0.25	36.83
17	Owl Creek	Oswood (1979)	3	362.6	2.97	25.91
18	Temple Fork	Pearson and Kramer (1972)	3	37.3	0.25	20.83
19	Red Butte Creek	Bond (1979)	3	18.9	0.12	20.83
20	Ord Creek	Rinne (1978)	3	21.5	0.14	20.83
21	Santa Fe River at Santa Fe, NM	Molles and Gosz (1980)	3	32.6	0.09	8.64

Table 1, continued

Number	Stream	Investigator	Stream order	Watershed area, km^2	Mean annual discharge, m^3/sec	Mean annual discharge per unit area, cm/yr
22	Cement Creek	Allan (1975)	4	69.7	0.91	41.4
23	Service Creek	Shirazi et al. (1980 draft)	3	100.5	1.26	39.62
24	Fish Creek		3	89.4	0.39	13.72
25	Grassy Creek		1	66.8	0.04	2.03
26	Yampa River at Steamboat Springs, CO	Hughes and Omernik (1981)	5	1,564.4	13.00	26.16
27	Little Snake River at Lily, CO		5	9660.7	15.85	5.08
28	Little Snake River at Slater, CO		5	738.2	5.97	25.65
29	Little Popo Agie at Lander, WY	Binns and Eiserman (1979)	5	323.8	2.3	22.35
30	Deadman Creek		2	2.3	0.02	24.13
31	North St. Vrain Creek	Pennak and Van Gerpen (1947)	3	274.5	2.25	25.91
32	Rapid Creek	Stewart and Thilenius (1964)	4	1559.2	1.70	3.56
33	Otter Creek	Van Velson (1979)	2	9.1	0.01	3.56
34	San Antonio River at San Antonio, TX	Hubbs et al. (1978)	4	2641.8	5.78	6.86
35	Bosque River at Waco, TX	Lind (1971)	4	4410.8	12.06	8.64
36	Rush Creek	Barclay (1979)	4	60.6	0.13	6.86
37	Mill Creek	Hazel et al. (1979)	4	100.8	0.72	22.35
38	Cedar Creek		4	128.5	0.91	22.35
39	Four Mile Creek	Johnson (1978)	3	50.5	0.30	19.05
40	Valley Creek	Waters (1964)	2	6.7	0.03	13.72
41	Lawrence Creek	Hunt (1969)	1	136.8	1.05	24.13
42	Kaskaskia River at Arcola, IL	Larimore and Smith (1963)	3	9137.5	84.93	29.21
43	Courtois Creek	Ryck (1974)	4	595.7	5.54	29.21
44	James River at Galena, MO	Dieffenbach and Ryck (1976)	5	2556.3	25.16	30.99

45	Luxapalila River at Columbia, MS	Arner et al. (1976)	5	2095.3	33.22	50.04
46	White Oak Creek	Lawrence and Webber (1979 draft)	4	22.0	0.36	51.82
47	Rooty Creek	North et al. (1974)	3	105.7	1.21	36.32
48	Ford's Arm	Turner et al. (1977)	3	4.4	0.07	48.26
49	Meginniss Arm		2	8.0	0.12	48.26
50	Satilla River at Brunswick, GA	Benke et al. (1979)	4	9142.7	74.98	25.91
51	Upper Three Runs	McFarlane (1976)	4	490.0	6.70	43.18
52	New Hope Creek	Hall (1972)	4	57.0	0.62	34.54
53	Rhode River	Correll (1977)	4	9.8	0.12	39.62
54	Coweeta Creek	Monk et al. (1977)	3	16.3	0.51	98.3
55	Walker Branch	Harris (1977)	3	1.04	0.02	63.75
56	Buckhorn Creek	Kuehne (1962)	4	113.4	1.61	44.96
57	Clemons Fork	Lotrich (1973)	3	5.7	0.08	44.96
58	Morgan's Creek	Minshall (1967)	1	0.5	0.01	41.40
59	Doe Run	Minckley (1963)	3	182.1	2.38	41.40
60	Black Creek	Gorman and Karr (1978)	2	54.9	0.51	29.21
61	Augusta Creek	Mahan and Cummins (1978)	3	71.5	0.71	30.99
62	Au Sable River at Mio, MI	Richards (1976)	4	4677.5	40.9	27.69
63	Linesville Creek	Coffman et al. (1971)	2	23.1	0.35	48.26
64	Fernow	Kochenderfer and Aubertin (1975)	3	14.8	0.32	69.09
65	Mahantango Creek	Pionke and Weaver (1977)	4	420.1	6.2	46.48
66	Conowingo Creek	Stauffer and Hocutt (1980)	3	278.4	3.65	41.40
67	White Clay Creek	Moeller et al. (1979)	4	122.0	1.60	41.40
68	Owego Creek	Sheldon (1968)	4	479.2	8.38	55.12
69	Roaring Brook	McDowell and Fisher (1976)	2	1.3	0.02	53.59
70	Hubbard Brook	Vitousek (1977)	4	30.8	0.67	69.09
71	Bear Brook	Fisher and Likens (1973)	2	1.3	0.03	69.09

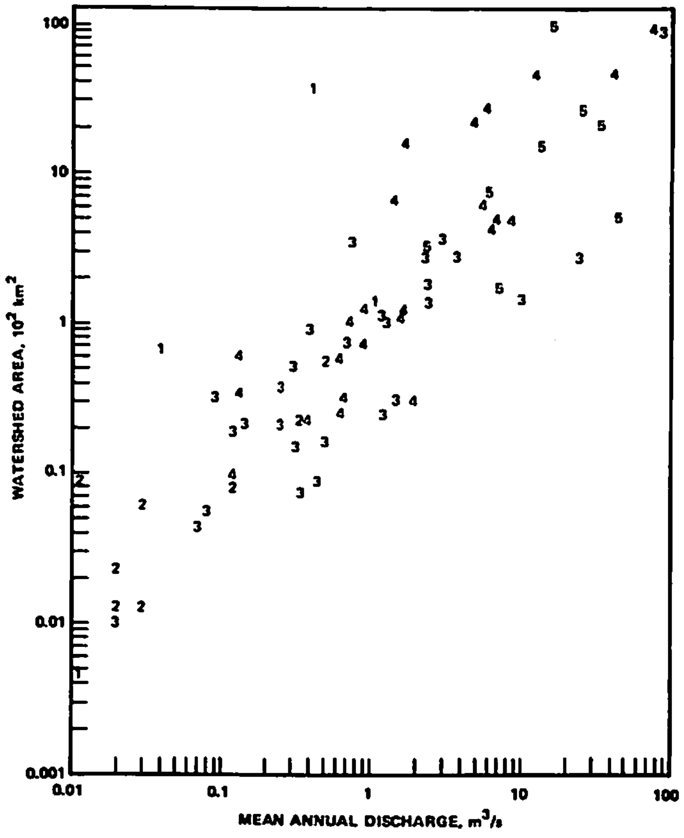

Figure 2. Mean annual discharges and watershed area relative to stream order. Numbers refer to stream order.

RESULTS

A plot of the log of watershed area against the log of mean annual discharge for first- to fifth-order streams is shown in Figure 2. Both watershed area and mean annual discharge vary over an order of magnitude within all stream orders represented. Consequently, streams of a given order may have watershed areas and mean annual discharges that are considerably greater than higher order streams. Similar variability exists even if streams within the same ecoregion (Bailey, 1976) are examined. For example, among the following pairs of streams, 22 and 23, 48 and 49, and 66 and 67, the lower order streams have greater watershed areas and mean annual discharges than the higher order streams although the unit discharges for each pair are similar or identical.

DISCUSSION

The three major advantages of using watershed area and unit discharge instead of stream order to quantify stream and watershed size are: (1) They provide a quick and fairly accurate estimate of evapotranspiration relative to precipitation. (2) They relate watershed and stream characteristics that have considerable biological significance. (3) Uniform understanding of stream size and watershed size is provided regardless of the available scale of topographic maps, the permanence of streams, or the presence of other bodies of water in the channels. This allows more meaningful comparisons of stream and watershed size.

The use of watershed size and unit discharge also leads to the use of other stream-watershed relationships. Unit discharges can be related to precipitation, evapotranspiration, and groundwater recharge when these components of the hydrologic cycle are expressed on the basis of unit area. This allows much more adequate modeling of the fate of precipitation, a very important consideration in watershed studies.

Mean annual values of low, average, and high discharges and their standard deviations, which are important determinants of habitat stability, can be estimated from the same data. Two-year flood flows, which are generally considered the major channel-forming events, can be estimated by plotting peak discharges against their recurrence intervals (Morisawa, 1968). The recurrence interval equals the number of years of record plus 1, divided by the rank of the peak discharge (the highest discharge is ranked as 1, the second highest as 2, etc.).

Minimum discharges and flow-duration curves (plots of discharge against time) can be used to classify watersheds by their water-storage capacities (Orsborn, 1976; Morisawa, 1968). Steep flow-duration curves and low minimum discharges indicate considerable direct runoff and wide fluctuations in flows. Flat flow-duration curves and relatively high minimum discharges indicate substantial storage and more equalized flows. Watershed area can be related to discharge, mean velocity, depth, and width of streams in a downstream direction (Stall and Yang, 1970). This requires gauge data. It is done by using flow frequency and the logarithm of watershed area as predictor variables and discharge, mean velocity, width, and mean depth as dependent variables. The hydraulic geometry equations are then produced by linear regression.

Discharge, mean velocity, width, and mean depth are more meaningful than stream order for predicting changes in production, respiration, particulate organic matter, and community structure along the stream continuum (Vannote et al., 1980). For example, for a total of four rivers in Oregon, Idaho, Michigan, and Pennsylvania, Moeller et al. (1979) stated that mean annual discharge, watershed area, stream links, and stream order have correlation coefficients of 0.96, 0.89, 0.80, and 0.79, respectively, with dissolved organic carbon (DOC) transport. There is considerable intercorrelation among all these parameters. When mean annual discharge was omitted from the stepwise multiple regression analysis, watershed area explained 80% of the variance. Correlations with the first canonical variable (which accounted for 83.5% of the among-group variability in a discriminant analysis) indicated that mean annual precipitation ($r = -0.88$) and watershed area ($r = 0.78$) were the two most important variables out of 15 for explaining the classification of 27 streams in Europe and North America (Cushing et al., 1980). The other variables considered were phosphate, total dissolved solids, langleys per year, maximum diurnal water temperature fluctuation, annual degree days, summer and winter base flows, gradient, nitrate, annual number of storms 5 and 10 times greater than base flow, terrestrial litter input, and stream length/watershed area. Also, where stream order is meaningless, such as in distributaries or disappearing streams or where surface and subsurface watersheds differ, at least discharge can be measured and the data compared with that from more typical streams.

On the other hand, there are three important disadvantages of using watershed area and unit discharge rather than stream order to characterize the size of streams: (1) Watershed area and unit discharge estimates may include considerable error in small, arid, poorly defined, and topographically complex watersheds or where surface and subsurface watersheds differ. (2) Estimates of average discharge may include considerable bias when developed from short-duration gauge data. (3) Watershed area and unit discharge take more effort to determine.

We caution stream ecologists to use watershed area and unit discharge together to characterize watershed and stream size; these parameters have less meaning alone than combined. To better understand the distribution, abundance, and functions of stream biota, we also encourage stream ecologists to incorporate other discharge characteristics into their studies (mean annual values of low, average, and high discharges and their standard deviations and mean velocity, depth, and width and their standard deviations). We are not advocating the use of unit discharge and watershed area in all hydrological or stream ecology models or as descriptors of channel networks. Like stream order, these terms should not be extended into areas for which they were not designed. We only emphasize that unit discharge and watershed area provide a simple, universally useful, and relatively accurate general characterization of stream and watershed size.

REFERENCES

Allan, J. D., 1975, The Distributional Ecology and Diversity of Benthic Insects in Cement Creek, Colorado, *Ecology*, 56(5): 1040-1053.

Arner, D. H., H. R. Robinette, J. E. Frasier, and M. H. Gray, 1976, *Effects of Channelization of the Luxapalila River on Fish, Aquatic Invertebrates, Water Quality and Fur Bearers*, Report FWS/OBS-76-08, U. S. Fish and Wildlife Service, Department of the Interior, Washington, D.C., NTIS, Springfield, VA.

Bailey, R. G., 1976, *Ecoregions of the United States* (map), Forest Service, U. S. Department of Agriculture, Intermountain Region, Ogden, UT.

Barclay, J. S., 1979, The Effects of Channelization on Riparian Vegetation and Wildlife in South Central Oklahoma, in *Strategies for Protection and Management of Floodplain Wetlands and Other Riparian Ecosystems*, Proceedings of a Symposium, Dec. 11-13, 1978. Callaway Garden, GA, Report #GTR-WO-12, pp. 129-138. Forest Service, U. S. Department of Agriculture, Washington, DC.

Benke, A. C., D. M. Gillespie, F. K. Parrish, T. C. Van Arsdall, Jr., R. J. Hunter, and R. L. Henry III, 1979, *Biological Basis for Assessing Impacts of Channel Modification: Invertebrate Production, Drift, and Fish Feeding in a Southeastern Blackwater River*, Environmental Resources Center, Report # ERC 06-79, Georgia Institute of Technology, Atlanta.

Binns, N. A., and F. M. Eiserman, 1979, Quantification of Fluvial Trout Habitat in Wyoming, *Trans. Am. Fish. Soc.*, 108(3): 215-228.

Bond, H. W., 1979, Nutrient Concentration Patterns in a Stream Draining a Montane Ecosystem in Utah, *Ecology*, 60(6): 1184-1196.

Coffman, W. P., K. W. Cummins, and J. C. Wuycheck, 1971, Energy Flow in a Woodland Stream Ecosystem. I. Tissue Support Trophic Structure of the Autumnal Community, *Arch. Hydrobiol.*, 68(2): 232-276.

Correll, D. L., 1977, An Overview of the Rhode River Watershed Program, in D. L. Correll (Ed.), *Watershed Research in Eastern North America, A Workshop to Compare Results*, Feb. 28-Mar. 3, 1977, Edgewater, MD, Vol. I, pp. 105-123, Smithsonian Institution, Washington, D.C.

Cushing, C. E., C. D. McIntire, J. R. Sedell, K. W. Cummins, G. W. Minshall, R. C. Peterson, and R. L. Vannote, 1980, Comparative Study of Physical-Chemical Variables of Streams Using Multivariate Analyses, *Arch. Hydrobiol.*, 89: 343-352.

Dieffenbach, W., and F. Ryck, Jr., 1976, *Water Quality Survey of the Elk, James and Spring River Basins of Missouri, 1964-1965*, Aquatic Series No. 15, Missouri Department of Conservation, Jefferson City.

Fenneman, N. M., 1946, *Physical Divisions of the United States* (map), U. S. Geological Survey, Reston, VA.

Fisher, S. G., and G. E. Likens, 1973, Energy Flow in Bear Brook, New Hampshire: An Integrative Approach to Stream Ecosystem Metabolism, *Ecol. Monogr.*, 43(4): 421–439.

Fredriksen, R. L., D. G. Moore, and L. A. Norris, 1974, The Impact of Timber Harvest, Fertilization and Herbicide Treatment on Streamwater Quality in Western Oregon and Washington, in B. Bernier and C. H. Winget (Eds.), *Forest Soils and Forest Land Management*, Proceedings of the Fourth North American Forest Soils Conference, Aug 1973, pp. 283-313, Les Presses de L'Universite, Laval, Quebec.

Gorman, O. T., and J. R. Karr, 1978, Habitat Structure and Stream Fish Communities, *Ecology*, 59(3): 507-515.

Hall, C. A., 1972, Migration and Metabolism in a Temperate Stream Ecosystem, *Ecology*, 53: 585-604.

Harris, W. F., 1977, Walker Branch Watershed: Site Description and Research Scope, in D. L. Correll (Ed.), *Watershed Research in Eastern North America, A Workshop to Compare Results*, Feb. 28-Mar. 3, 1977, Edgewater, MD, Vol. 1, pp. 5-17, Smithsonian Institution, Washington, DC.

Hazel, R. H., C. E. Burkhead, and D. G. Huggins, 1979, *The Development of Water Quality Criteria for Ammonia and Total Residual Chlorine for the Protection of Aquatic Life in Two Johnson County, Kansas Streams*, Kansas Water Resources Research Institute, University of Kansas, Lawrence.

Hubbs, C. L., R. R. Miller, and L. C. Hubbs, 1974, Hydrographic History and Relict Fishes of the North-Central Great Basin, *Mem. Calif. Acad. Sci.*, No. 7.

Hubbs, C., T. Lucier, G. P. Garrett, R. J. Edwards, S. M. Dean, E. Marsh, and D. Belk, 1978, Survival and Abundance of Introduced Fishes near San Antonio, Texas, *Texas J. Sci.*, 30(4): 369-376.

Hughes, R. M., and J. M. Omernik, 1981, Use and Misuse of the Terms, Watershed and Stream Order, in L. Krumholz (Ed.), *Warmwater Streams Symposium*, Mar. 9-11, 1980, Knoxville, TN, pp. 320-326, Southern Division, American Fisheries Society, Bethesda, MD.

Hunt, R. L., 1969, Effects of Habitat Alteration on Production, Standing Crops and Yield of Brook Trout in Lawrence Creek, Wisconsin, in T. G. Northcote (Ed.), *Proceedings of a Symposium on Salmon and Trout in Streams*, H. R. MacMillan Lectures, 1968, pp. 281-312, University of British Columbia, Vancouver.

Hynes, H. B. N., 1970, *The Ecology of Running Waters*. University of Toronto Press, Toronto.

Johnson, H. P., 1978, *Development and Testing of Mathematical Models as Management Tools for Agricultural Nonpoint Pollution Control*, Annual Report 1977-1978, EPA Grant No. R-804102, Department of Agricultural Engineering, Iowa State University, Ames.

Kerst, C. D., and N. H. Anderson, 1974, Emergence Patterns of Plecoptera in a Stream in Oregon, USA, *Freshwater Biol.*, 4: 205-212.

Kochenderfer, J. N., and G. M. Aubertin, 1975, Fernow Experimental Forest, West Virginia, in *Municipal Watershed Management*, Symposium proceedings, General Technical Report NE-13, pp. 14-24, Forest Service, U. S. Department of Agriculture, Upper Darby, PA.

Kuehne, R. A., 1962, A Classification of Streams, Illustrated by Fish Distribution in an Eastern Kentucky Creek, *Ecology*, 43(4): 608-614.

Larimore, R. W., and P. W. Smith, 1963, The Fishes of Champaign County, Illinois, as Affected by 60 Years of Stream Changes, *Ill. Nat. Hist. Survey Bull.*, 28(2): 299-382.

Lawrence, J. M., and C. Webber, 1979 draft, Annual Report on Evaluation of Selected Chemical, Physical, and Biological Characteristics on White Oak and Wesobulga Creek Prior to Construction of Site No. 17A, Crooked Creek, Watershed, Department of Fisheries and Allied Agricultures, Auburn University, Auburn, AL.

Leonard, R. L., L. A. Kaplan, J. F. Elder, R. N. Coats, and C. R. Goldman, 1979, Nutrient Transport in Surface Runoff from a Subalpine Watershed, Lake Tahoe Basin, California, *Ecol. Monogr.*, 49(3): 281-310.

Lind, O. T., 1971. The Organic Matter Budget of a Central Texas Reservoir, *Reserv. Fish. Limnol. Spec. Publ.*, 8: 193-202.

Lotrich, V. A., 1973, Growth, Production, and Community Composition of Fishes Inhabiting a First-, Second-, and Third-Order Stream of Eastern Kentucky, *Ecol. Monogr.*, 43: 377-397.

McDowell, W. H., and S. G. Fisher, 1976, Autumnal Processing of Dissolved Organic Matter in a Small Woodland Stream Ecosystem, *Ecology*, 57: 561-569.

McFarlane, R. W., 1976, Fish Diversity in Adjacent Ambient, Thermal, and Post-Thermal Freshwater Streams, in G. W. Esch and R. W. McFarlane (Eds.), *Thermal Ecology II*, ERDA Symposium Series, CONF-750425, pp. 268-271, NTIS, Springfield, VA.

Mahan, D. C., and K. W. Cummins, 1978, *A Profile of Augusta Creek in Kalamazoo and Barry Counties, Michigan*, Technical Report No. 3, W. K. Kellogg Biological Station, Hickory Corners, MI.

Minckley, W. L., 1963, *The Ecology of a Spring Stream Doe Run, Meade County, Kentucky*, Wildlife Monograph No. 11.

Minshall, G. W., 1967, Role of Allochthonous Detritus in the Trophic Structure of a Woodland Springbrook Community, *Ecology*, 48(1): 139-149.

Moeller, J. R., G. W. Minshall, K. W. Cummins, R. C. Petersen, C. E. Cushing, J. R. Sedell, R. A. Larson, and R. L. Vannote, 1979, Transport of Dissolved Organic Carbon in Streams of Differing Physiographic Characteristics, *Organ. Geochem.*, 1: 139-150.

Molles, M. C., Jr., and J. R. Gosz, 1980, Effects of a Ski Area Development on the Water Quality and Invertebrates of a Mountain Stream, *Water, Air, Soil Pollut.*, 14: 187-205.

Monk, C. D., D. A. Crossley, Jr., R. L. Todd, W. T. Swank, J. B. Waide, and J. R. Webster, 1977, An Overview of Nutrient Cycling Research at Coweeta Hydrologic Laboratory, in D. L. Correll (Ed.), *Watershed Research in Eastern North America, A Workshop to Compare Results*, Feb. 28-Mar. 3, 1977, Edgewater, MD, Vol. I, pp. 35-50, Smithsonian Institution, Washington, DC.

Morisawa, M., 1968, *Streams—Their Dynamics and Morphology*, McGraw-Hill Book Company, New York.

Muckleston, K. W., 1979, Water, in R. M. Highsmith, Jr., and A. J. Kimerling (Eds.), *Atlas of the Pacific Northwest*, pp. 67-75, Oregon State University Press, Corvallis.

Needham, P. R., and C. L. Usinger, 1956, Variability in the Macrofauna of a Single Riffle in Prosser Creek, California, as Indicated by the Surber Sampler, *Hilgardia*, 24(14): 383-409.

North, R. M., A. S. Johnson, H. O. Hillestad, P. A. Maxwell, and R. C. Parker, 1974, *Survey of Economic-Ecologic Impacts of Small Watershed Development*, Technical Completion Report ERC-0974, Institute of Natural Resources, University of Georgia, Athens.

Oregon Department of Fish and Wildlife, 1969, Stream Surveys of Winchester, Big and Two Mile Creeks, unpublished reports, Research Division, Charleston, OR.

Orrell, R., 1980, *Report to Maritime Heritage Center Technical Committee Members*, Department of Fisheries, Burlington, WA.

Orsborn, J. F., 1976, Drainage Basin Characteristics Applied to Hydraulic Design and Water-Resources Management. in *Proceedings of the Geomorphology and Engineering Symposium*, Sept. 24-25, 1976, State University of New York, Binghamton, pp. 141-171, Dowdere, Hutchinson, and Ross, Inc., Stroudsburg, PA.

Oswood, M. W., 1979, Abundance Patterns of Filter-Feeding Caddisflies (Trichoptera: Hydropsychidae) and Seston in a Montana (U. S.) Lake Outlet, *Hydrobiologia*, 63(2): 177-183.

Pearson, W. D., and R. H. Kramer, 1972, Drift and Production of Two Aquatic Insects in a Mountain Stream, *Ecol. Monogr.*, 42(3): 365-385.

Pennak, R. W., and E. D. Van Gerpen, 1947, Bottom Fauna Production and Physical Nature of the Substrate in a Northern Colorado Trout Stream, *Ecology*, 28(1): 42-48.

Pionke, H. B., and R. N. Weaver, 1977, The Mahantango Creek Watershed—An Interdisciplinary Watershed Research Program in Pennsylvania, in D. L. Correll (Ed.), *Watershed Research in Eastern North America, A Workshop to Compare Results*, Feb. 28-Mar. 3, 1977, Edgewater, MD, Vol. I, pp. 83-103, Smithsonian Institution, Washington, DC.

Richards, J. S., 1976, Changes in Fish Species Composition in the Au Sable River, Michigan, from the 1920's to 1972, *Trans. Am. Fish. Soc.*, 105(1): 32-40.

Rinne, J. N., 1978, Development of Methods of Population Estimation and Habitat Evaluation for Management of the Arizona and Gila Trouts, in J. R. Moring (Ed.), *Proceedings of the Wild Trout—Catchable Trout Symposium*, Feb. 15-17, 1978, pp. 113-125, Oregon Department of Fish and Wildlife, Eugene, OR.

Ryck, F. M., Jr., 1974, *Water Quality Survey of the Southeast Ozark Mining Area, 1965-1971*, Aquatic Series No. 10, Missouri Department of Conservation, Jefferson City.

Scheidegger, A. E., 1965, *The Algebra of Stream Order Numbers*, Professional Paper 525B: 187-189, U. S. Geological Survey, Washington, DC.

Sheldon, A. L., 1968, Species Diversity and Longitudinal Succession in Stream Fishes, *Ecology*, 49(2): 193-198.

Shirazi, M. A., R. M. Hughes, and J. M. Omernik, 1980 draft, Land and Water Quality Interrelated by Broad Geographic Characteristics—A Feasibility

Study, Corvallis Environmental Research Laboratory, U. S. Environmental Protection Agency, Corvallis, OR.

Shreve, R. L., 1966, Statistical Law of Stream Numbers, *J. Geol.*, 74: 17-37.

Smart, J. S., 1972, Channel Networks, in V. T. Chow (Ed.), *Advances in Hydroscience*, Vol. 8, pp. 305-346, Academic Press, Inc., New York.

Stall, J. B., and C. T. Yang, 1970, *Hydraulic Geometry of 12 Selected Stream Systems of the United States*, WRC Research Report No. 32, Water Resources Center, University of Illinois, Urbana.

Stauffer, J. R., Jr., and C. H. Hocutt, 1980, Inertia and Recovery: An Approach to Stream Classification and Stress Evaluation, *Water Resour. Bull.*, 16(1): 72-78.

Stewart, R. K., and C. A. Thilenius, 1964, *Stream and Lake Inventory and Classification in the Black Hills of South Dakota, 1964*, Job Nos. 14 and 15, D-J Project F-1-R-13, Department of Game, Fish and Parks, Pierre, SD.

Strahler, A. N., 1957, Quantitative Analysis of Watershed Geomorphology, *Trans. Am. Geophys. Union*, 38: 913-920.

Swift, C. C., A. W. Wells, and J. S. Diana, 1975, *Survey of the Freshwater Fishes and Their Habitats in the Coastal Drainages of Southern California*, Inland Fisheries Branch, California Department of Fish and Game, Sacramento.

Turner, R. R., T. M. Burton, and R. C. Harriss, 1977, Lake Jackson Watershed Study: Description of Sites, Methodology and Scope of Research, in D. L. Correll (Ed.), *Watershed Research in Eastern North America, A Workshop to Compare Results*, Feb. 28-Mar. 3, 1977, Edgewater, MD, Vol. 1, pp. 19-33, Smithsonian Institution, Washington, DC.

U. S. Geological Survey, 1970, *The National Atlas of the United States of America*, Washington, DC.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing, 1980, The River Continuum Concept, *Can. J. Fish. Aquat. Sci.*, 37: 130-137.

Van Velson, R., 1979, Effects of Livestock Grazing upon Rainbow Trout in Otter Creek, Nebraska, in O. B. Cope (Ed.), *Proceedings of the Forum—Grazing and Riparian/Stream Ecosystems*, Nov. 3-4, 1978, pp. 53-55, Trout Unlimited, Denver, CO.

Vitousek, P. M., 1977, The Regulation of Element Concentrations in Mountain Streams in the Northeastern United States, *Ecol. Monogr.*, 47: 65-87.

Waters, T. F., 1964, Recolonization of Denuded Stream Bottom Areas by Drift, *Trans. Am. Fish. Soc.*, 93: 311-315.

Winget, R. N., and M. K. Reichert, 1976, Aquatic Survey of Selected Streams with Critical Habitats on National Resource Lands Affected by Livestock and Recreation, unpublished final report, U. S. Bureau of Land Management, Salt Lake City.