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APPENDICES

QUANTITATIVE MODELING OF THE RELATIONSHIPS AMONG BASIN, CHANNEL AND HABITAT CHARACTERISTICS FOR CLASSIFICATION AND IMPACT ASSESSMENT

By

John F. Orsborn, P.E.

TIMBER/FISH
&WILDLIFE

JULY, 1990

TIMBER-FISH-WILDLIFE

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APPENDIX I.--REFERENCES

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APPENDIX II.--NOMENCLATURE

APPENDIX II. NOMENCLATURE

For a general reference on nomenclature and terminology refer to the AFS (1985) Glossary of Stream Habitat Terminology.

A	area (basin, channel, flow ....)
A_b	basin area
A_c	channel cross-sectional flow area
AF	acre-feet; volume of water; number of feet over one acre of area
a	coefficient in width equation for hydraulic geometry
b	exponent in width equation for hydraulic geometry
C	coefficient in an equation
C′	second coefficient developed from a previous equation and (C)
c	coefficient; in depth equation for hydraulic geometry
csm	cubic feet per second per square mile; unit values used to relate design flows and characteristic flows among basins of different sizes; written as cfsm in USGS annual gage records
D	geomorphic term for mean water (hydraulic) depth in a channel cross-section; density of stream or drainage networks; equivalent to hydraulic raduis (R) in wide channel (W/D > 30-40)
DD	drainage density (network; all channels, perennial and intermittent); LD/A
DR	diameter of rock
DS	diameter of sand
d	exponent in depth equation for hydraulic geometry; diameter of sediment particles
d50	mean particle diameter
E	estimated value in streamflow tables; elevation
EH	headwater elevation

EO basin outlet elevation

e coefficient in velocity equation for hydraulic geometry

f exponent in velocity equation for hydraulic geometry

g acceleration due to gravity; 32.2 fps; 9.8 m/s

H head; energy; basin relief; $A(H)^{0.5} = E_b$ = basin energy

k height of bed material; roughness height in velocity profile

L length; of basin, channel, segment, reach ....

LB length of basin along main axis or main channel

LD length of drainage (channels)

LS length of stream (blue lines of USGS topographic map); of different orders (LS1, LS2 ... LSn) or (L1, L2 ... LT)

LST total stream length (or LT)

LTT Long Term Trend channel monitoring site; USDA Forest Service

m order of magnitude of flow event

n number of years or events; exponent; Manning's resistance coefficient

n_r resistance factor due to rock

n_s resistance factor due to sand

P wetted perimeter of stream channel; precipitation (also $\overline{P}$); peak type of flood flow

p probability of occurrence, 1/RI

P:R pool to riffle ratio

Q flow; a general term; specific characteristic statistical flows and others as listed below:

- QBL bedload discharge;
- QI instantaneous water flow in sediment analysis;
- QMSA flow at maximum spawnable area;
- Q_w water flow (and QW);
- Q_s sediment flow (and QS);
- QS stream power.

R hydraulic radius; R = area (A)/wetted perimeter (P).

R^2 correlation coefficient

RI recurrence interval in flow frequency analysis; 1/p.

RP river parameter in sediment analysis (LI · LT · A · H)

S slope of channel or bed slope (S_b)

S_e slope of energy gradient

S_w slope of water surface

SD stream density; perennial solid (blue lines) stream·length per unit of area; LS/A

SO stream order

V mean velocity of flow in channel cross-section with certain flow area and discharge (V = Q/A);

- V_i incipient velocity which causes seiment movement;
- VS unit stream power.

W top width of water surface in stream channel

WB width of basin; A/LB

WY Water Year; October 1-September 30; same numbered year as January of this period

WRIA Water Resources Inventory Area

X	unknown values; horizontal scale on graph paper (abscissa)
Y	water depth (or y); vertical scale on graph (ordinate)
γ	specific weight of water; 62.4 lb/ft^3
τ	shear stress
τ_0	shear stress on boundary
Σ	summation
1.1	code numbers for USGS gaging stations in hydrologic provinces (1-9) on Olympic Peninsula (1.1 through 9.2); USGS Nos. like 12056500

APPENDIX III.--HYDROLOGY

- DATA ANALYSIS
- MODELS FOR UNGAGED STREAMFLOW ESTIMATION

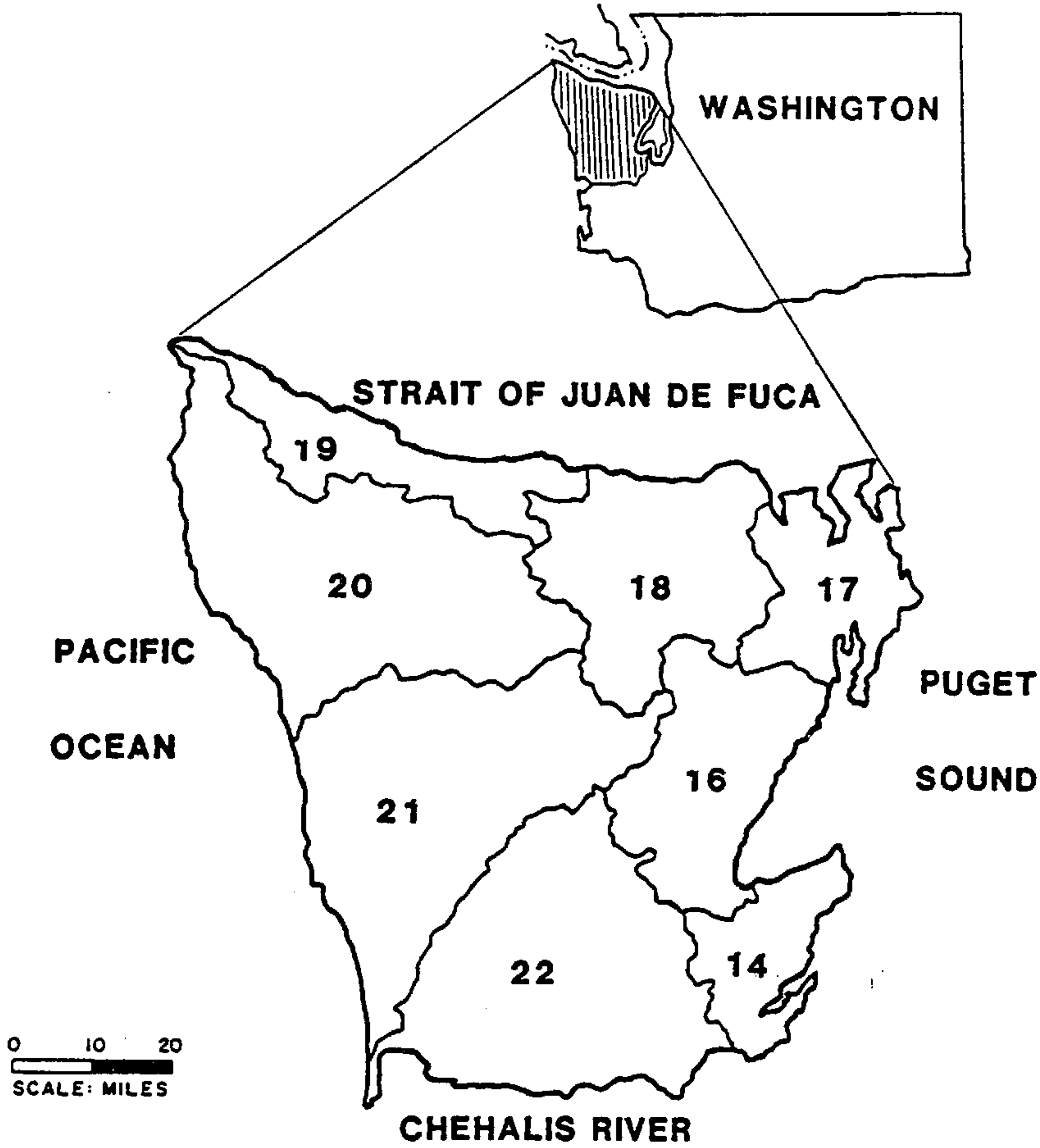


Figure III-1. Location map of Olympic Peninsula with water resources inventory areas. From Amerman and Orsborn (1987).

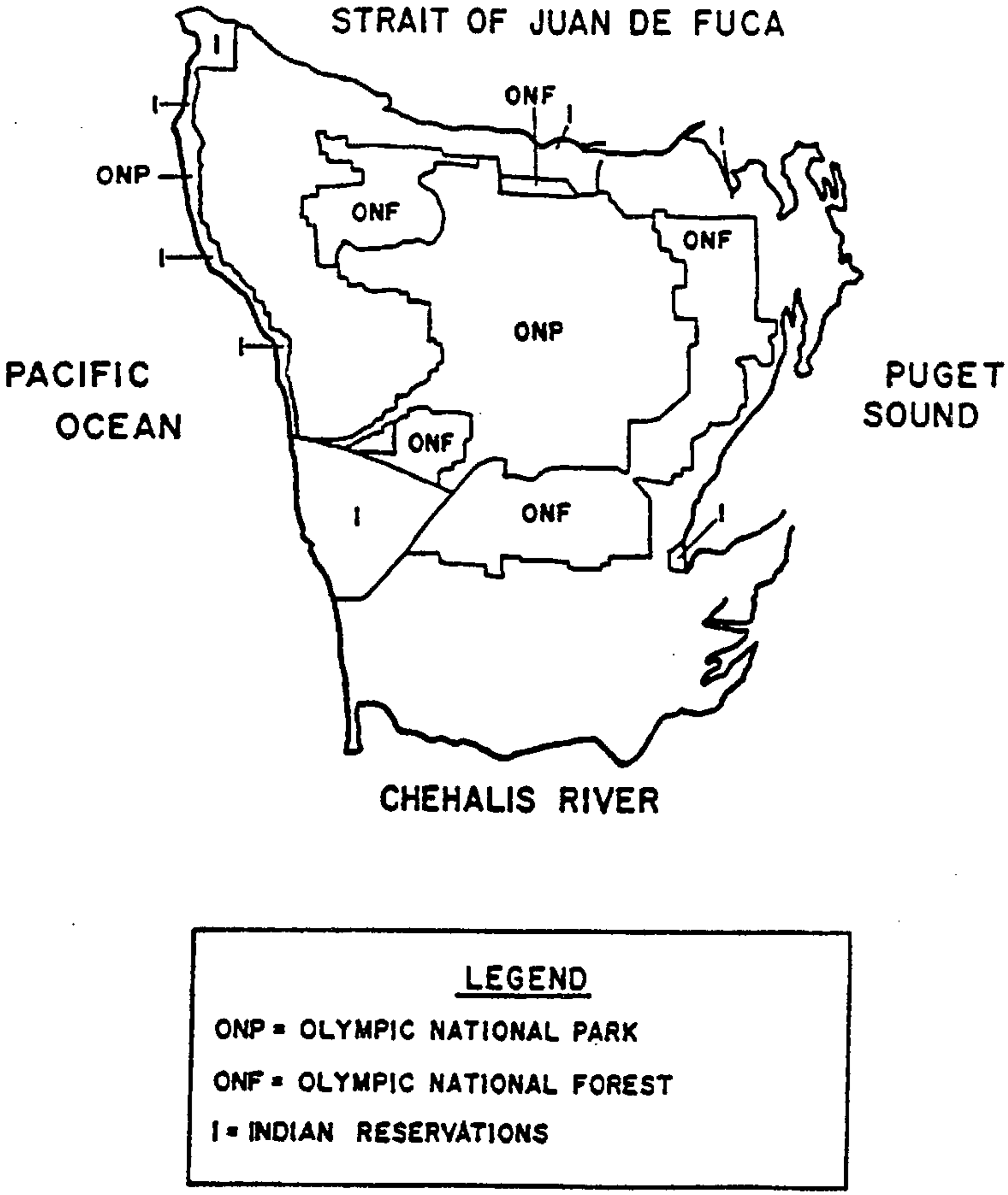


Figure III-2. Major Land ownerships on the Olympic Peninsula. From Amerman and Orsborn (1987).

Very little of the Peninsula's hydrological uniqueness and diversity have been quantified, synthesized or analyzed. The major drainages and representative streams are illustrated in Figure III-3. Some examples of the types of streamflow analyses needed for the analyses of typical water resources, land use and fisheries problems are:

Types of Flow	Application(s)
Floods, Flood Frequency (Recurrence Interval Analysis).	Design of bridges, culverts, channel capacities; flood plain inundation; risk analysis; changes in land use; impacts; sediment transport.
Average Annual Flow, Monthly Average Flows, and their variability.	Preliminary hydropower studies, studies of instream flow analysis and useable area for habitat, upstream fish passage, natural flow variability.
Low Flows, Low Flow Frequency (or Recurrence Interval Analysis).	Temperature effects, passage for some species, rearing in pools, diversions, flow reservations, waste dilution, habitat limitations.
Duration Curves: Long-Term, Annual, Seasonal, Monthly and Extended low-flow periods.	Detailed hydropower studies, habitat availability (related to duration curve shape), instream flow needs studies, fish passage and dependable water supply.

Demands on the land and water resources have increased the pressure for multiple uses of many of the river basins which form the Peninsula. Small scale hydropower, logging and urbanization all generate interactive land and/or water impacts. Unfortunately, most of the streams where information is needed are ungaged which raises the necessity for using hydrologic models.

Geologic Characteristics

The Olympic Mountains are relatively young in terms of geologic time. The Peninsula began as an oceanic plate covered with sandstone and shale formed by deposited sediments. These sedimentary deposits were covered by flowing basalt that extruded out of ocean-floor volcanic fissures, forming undersea mountains. The spreading action of the sea floor pushed these rock beds to the East colliding with the North American continent. Much of the rock was forced upward thousands of feet forming the Olympic Mountains (Leeson and Leeson 1984).

Glaciers advancing from Canada moved through the coastal lowlands, carving Hood Canal, Puget Sound and the Strait of Juan de Fuca (Leeson and Leeson 1984). Glacial debris, boulders and cobble were left throughout the range. Alpine glaciers also shaped many of the U-shaped river valleys of the Peninsula that flow radially from its center.

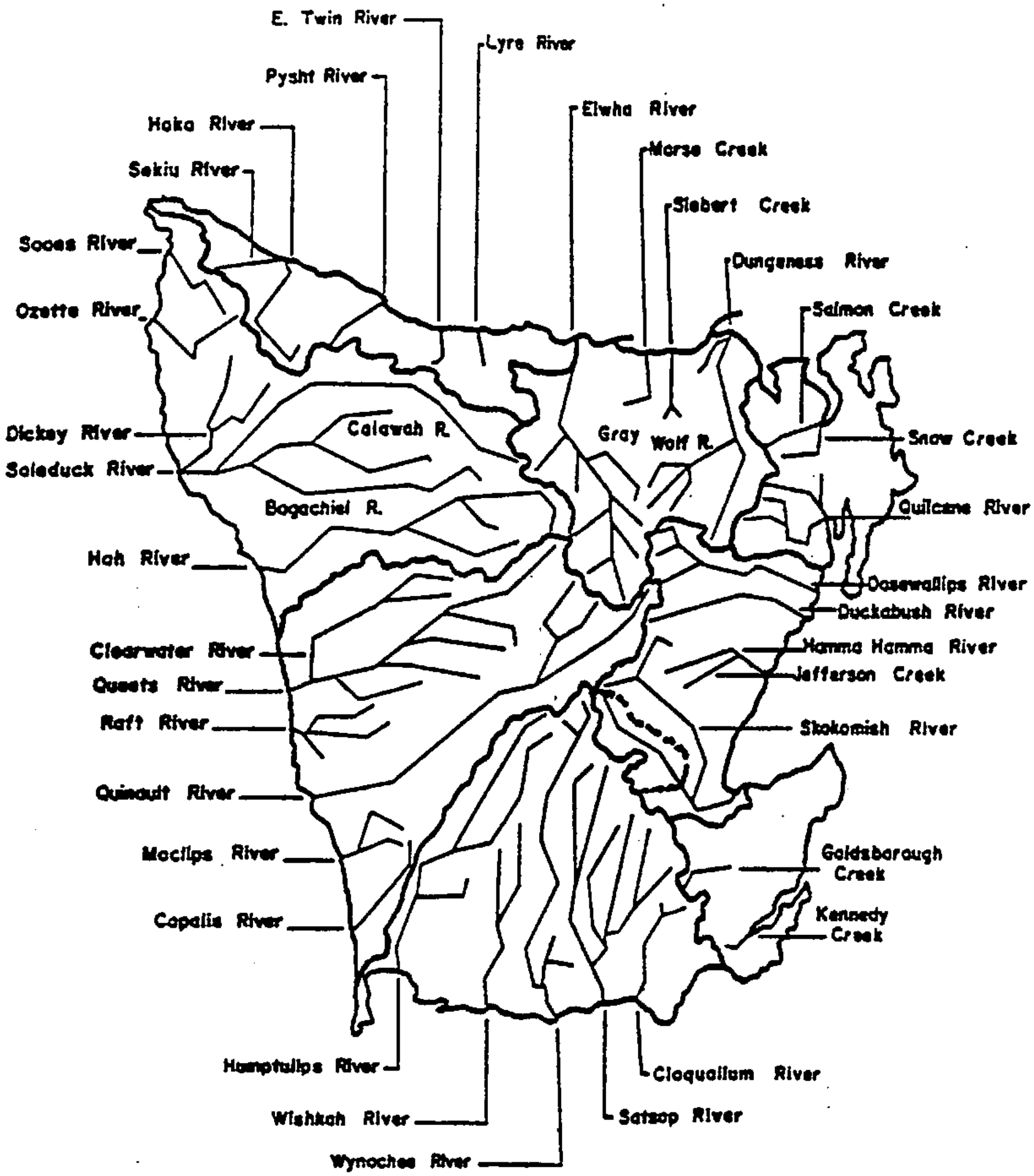


Figure III-3. Major drainage divides and representative streams on the Olympic Peninsula. From Amerman and Orsborn (1987).

Approximately 60 glaciers are found in the headwaters of some basins and provide larger low flows than basins without glaciers. Large glaciers, such as the Blue and Hoh, originate near Mount Olympus.

The interior of Olympic National Park, which contains the central core of mountains, is composed of partly matamorphosed, fine grained sedimentary rocks of marine origin. This core is classified as the EPA Ecoregion system "Cascades" (Omernik and Gallant 1986 map). The balance of the Peninsula is classified as "Coast Range." Bordering these core rocks on the north, east and south are basalt flows of volcanic origin (Walters 1970). Foothills and lowlands to the west and further south of the mountains are underlain by mostly older marine rocks, terrace deposits, and some alluvial materials along the main river valleys (Nassar 1973).

Low flows are closely related to geology in a basin, but even when field and geologic maps are examined, geologic homogeneity usually cannot be identified nor quantified for use in hydrologic analysis (Riggs 1972). Therefore, specific details of the geology of the Peninsula as described by Danner (1955) and Tabor and Cady (1978) are not included in this report. Direct measurements and/or hydrologic modeling of low flows at project sites provide the best information.

Climate as a Classification Index

The spatial distribution of precipitation is intricately related to the landforms on the Peninsula. An axial mountain barrier, dominated by Mount Olympus and the peaks of the Bailey Range, bisects the Peninsula (Fonda and Bliss 1969). As moist cool air approaches the Peninsula from the Pacific Ocean, it is forced to rise over the coastal range, except for the air flow entering by way of the Strait of Juan de Fuca, or that which flows up the low-lying Chehalis River valley. Large amounts of precipitation occur on the windward side of the mountains. As the air masses pass over the crest and descend, they are warmed and retain more moisture. This process creates a major precipitation shadow effect in the northeast corner of the Peninsula (Figure III-4).

Seasonal precipitation patterns, as described by Johnson and Dart (1982), have winter peaks in December. The mean monthly precipitation decreases to a summer minimum in July and then increases during the fall and winter months. The precipitation gage in Port Angeles, which is in a partial rain shadow, shows a slightly different pattern with the lowest monthly precipitation in April and another low value in July. Weather during the summer months brings less moisture as it approaches from a north to northwesterly direction around a high pressure area off the coast (Collings, 1971).

Mean annual temperature is fairly constant on the Peninsula, with summer temperatures on the coastal plain and lower mountains ranging from 18 to 24 degrees Celcius during the day and 10 degrees Celcius at night. Winter maximum temperatures reach approximately 4 to 8 degrees Celcius with a minimum at around minus 1 degree Celcius (Fonda and Bliss 1969).

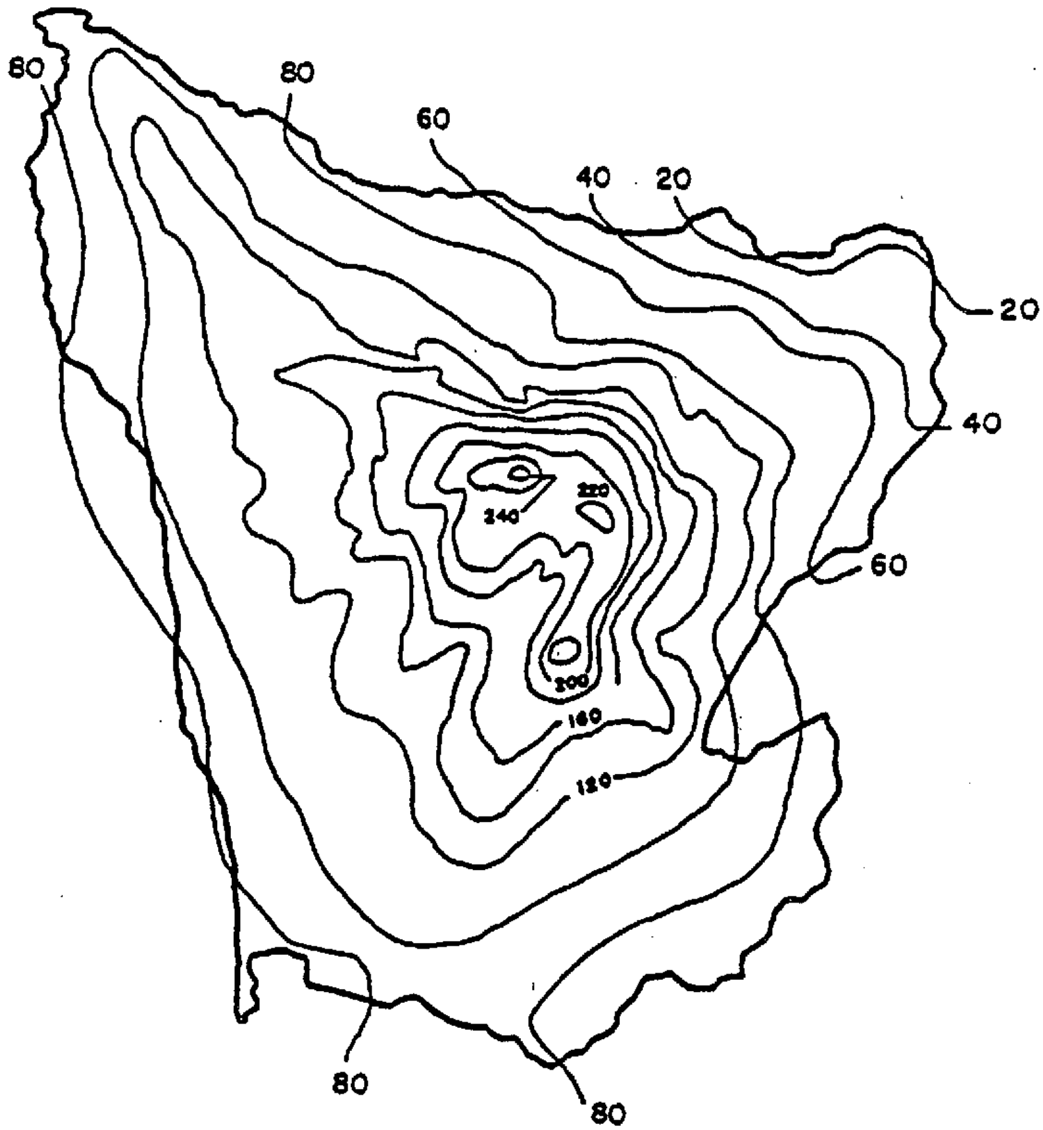


Figure III-4. Mean annual precipitation on the Olympic Peninsula in inches per year. From Amerman and Orsborn (1987).

Hydrological Provinces as Classification Regions

Streamflow hydrology reflects the net precipitation and the potential fisheries activities on the Peninsula. To provide an organizational basis for streamflow information, the major drainages and streams on the Olympic Peninsula were combined as shown in Figure III-5 based on average annual precipitation, elevation, drainage divisions (WRIA) and geology. Due to a lack of streamflow data, Provinces 6 and 7 were combined into Province 6.

A study by the U.S. Geological Survey divided the State of Washington into six classes of hydrological regions based on homogeneity in seasonal distribution of mean monthly streamflow (Moss and Haushild 1978). Based on the analysis of the annual mean flow series it was found that lower elevations have runoff distributions similar to the precipitation distribution. Mean monthly streamflows peak in winter and are at a minimum during summer months.

The lower elevation basins used in the USGS study correspond to the following hydrological privinces: Southern Mountain (Province 1), Western Coastal (Province 2), Northeast Coastal (Province 6), and Southeast Coastal (Province 9). Although Province 1 has been designated Southern Mountain implying higher elevations, the mean basin elevation of those streams used in the USGS study range from 510 to 1950 feet. The mean basin elevation for streams in the coastal provinces range from 420 to 1800 feet.

Middle and higher elevation basins have mean monthly flow peaks in both winter and spring months with either winter or spring peaks dominating. This double high flow season (such as in the Dungeness River basin) is related to high precipitation in the fall, and the accumulation and subsequent melt in the spring of snow at higher elevations. Those basins with dominant peaks in the winter are included within the Western Mountain Province (3), and basins at the middle elevations are in the Eastern Mountain Province (8). The mean basin elevations for those streams range from 2100 to 3830 feet. Basins where the spring peaks from snowmelt are dominant were included in the higher elevations of the Eastern mountain Province (8). Their mean basin elevations range from 3700 to 4700 feet.

Environmental Zones

Several physical and biological features can be combined to provide another classification descriptor of the range of conditions found on the Olympic Peninsula as an extension of the EPA ecoregion (Omernik and Gallant 1986). Henderson et al. (1989) combined the following zones of "roughly similar environments":

(1) abundance and distribution of plant indicator species;

(2) climate (wetter zones have lower numbers);

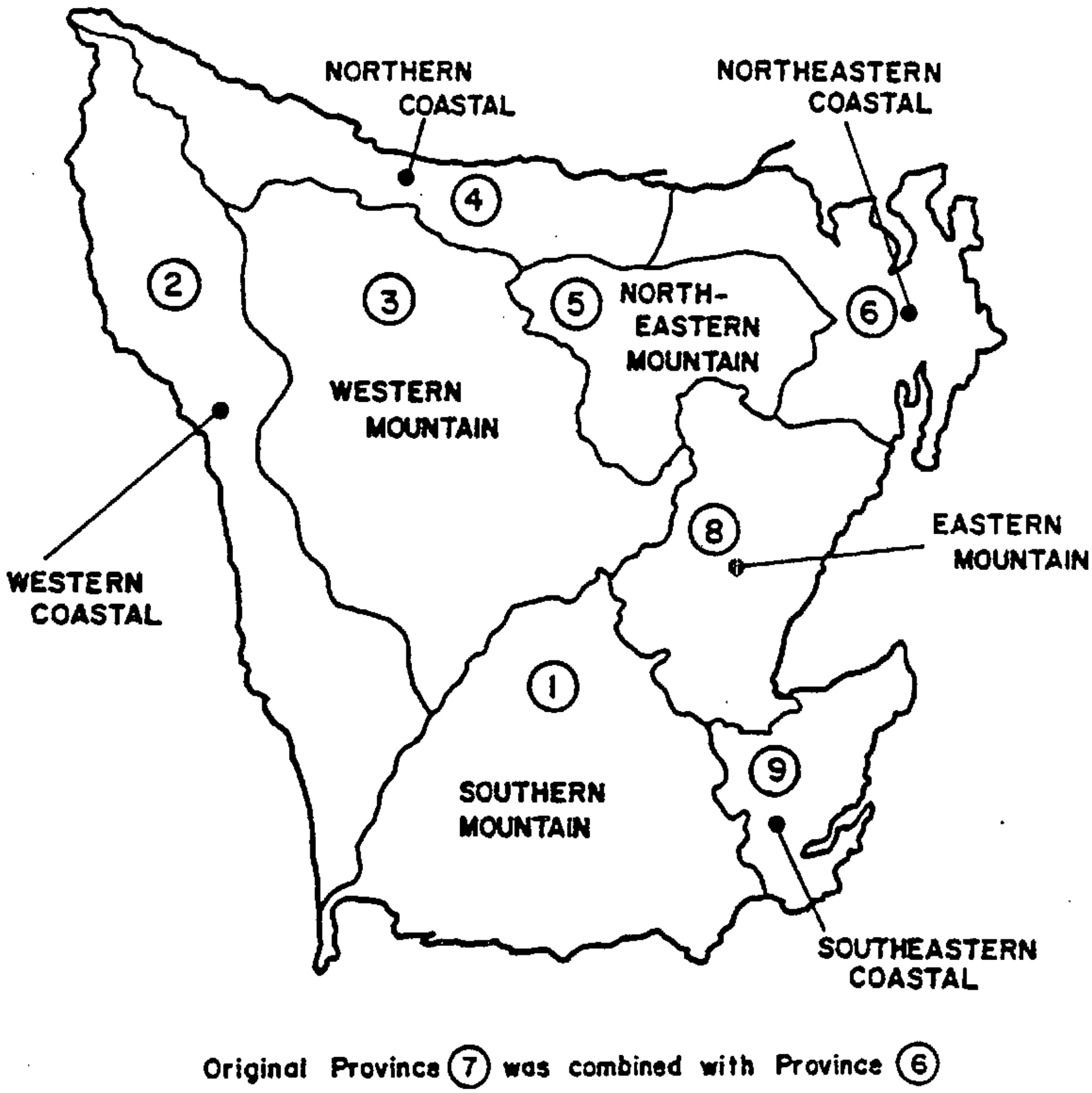


Figure III-5. Hydrological/climatic provinces on the Olympic Peninsula.

(3) mean annual air temperature;

(4) mean annual precipitation; and

(5) aspect.

The method was developed originally using silver fir as the primary indicator species, and using elevation as the primary correlation factor. Variations in the geographic location and elevation distribution of silver fir were found to be consistent. On the wetter west side of the Peninsula silver fir occurs at lower elevations than on the drier east side. The indicator species were expanded to include mountain hemlock, subalpine-fir and Douglas-fir zones. The limit on abundance was placed at 10 percent cover in old-growth stands of silver-fir and mountain hemlock. In checking the preliminary map it was found that local minor anomalies existed due to such factors as steepness of slope and cold air drainage patterns (Henderson et al. 1989). After zone maps were completed the correlations with other factors such as soils, fire history and species diversity were found to exist.

This section on environmental zones of the Olympic National Forest has been included to help describe the diversity, and the strong correlations, among geographic, physical and biological conditions on the Peninsula, and to demonstrate climatic and geological influences on streamflow, vegetation, soils, streams and fisheries.

Examples of environmental zones are demonstrated in Figures III-6 and III-7. The similarity between the mean annual precipitation map in Figure III-4 and the environmental zones in Figure III-6 is obvious.

These types of relationships lead to other relationships which provide the quantitative planning, management, analysis and interpretive tools necessary for better husbandry of our natural resources. Similar empirical relationships among numerous basin components are developed in other parts of this report to further define the interdependence and interaction of factors which affect the physical condition of the fisheries environment in a segment of a particular stream within an ecozone and/or ecoregion.

The Hydrology of Streamflow

The Data Base and Flow Variability

As was shown in Figure III-4, the average annual precipitation on the Olympic Peninsula varies from more than 200 to less than 20 inches per year from the highest mountains to the northeast part of the Peninsula. The average annual flow, as a reflection of the average annual precipitation, varies as shown in Table III-1. One needs to know the expected natural variability in those flows to provide a basis for evaluating impacts, and especially during the seasonal life-phase activities of fish to evaluate impacts on habitat. Within hydrologic regions the ratios in Table III-1 are quite consistent.

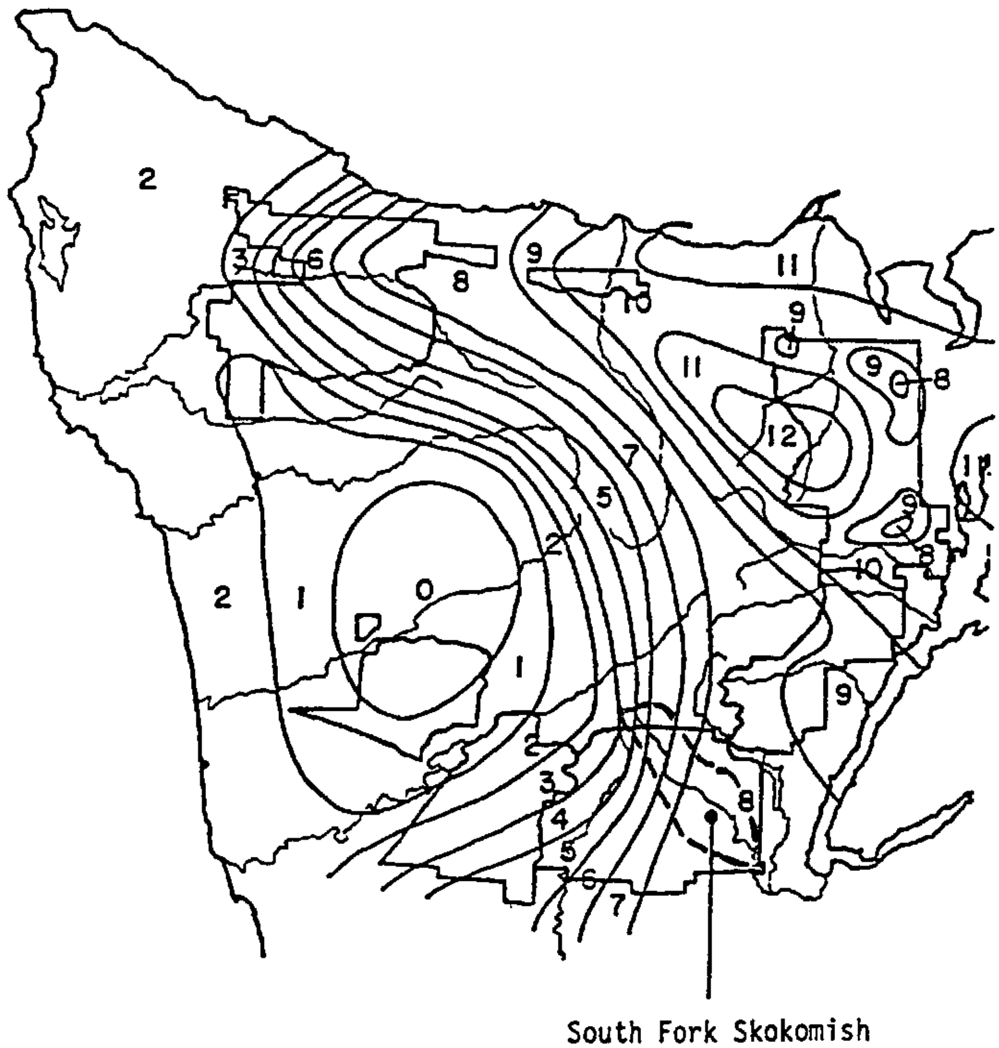


Figure III-6. Map of environmental zones. Note that the South Fork Skokomish Pilot Study area is in environmental zones 5 through 8. From Henderson et al. (1989).

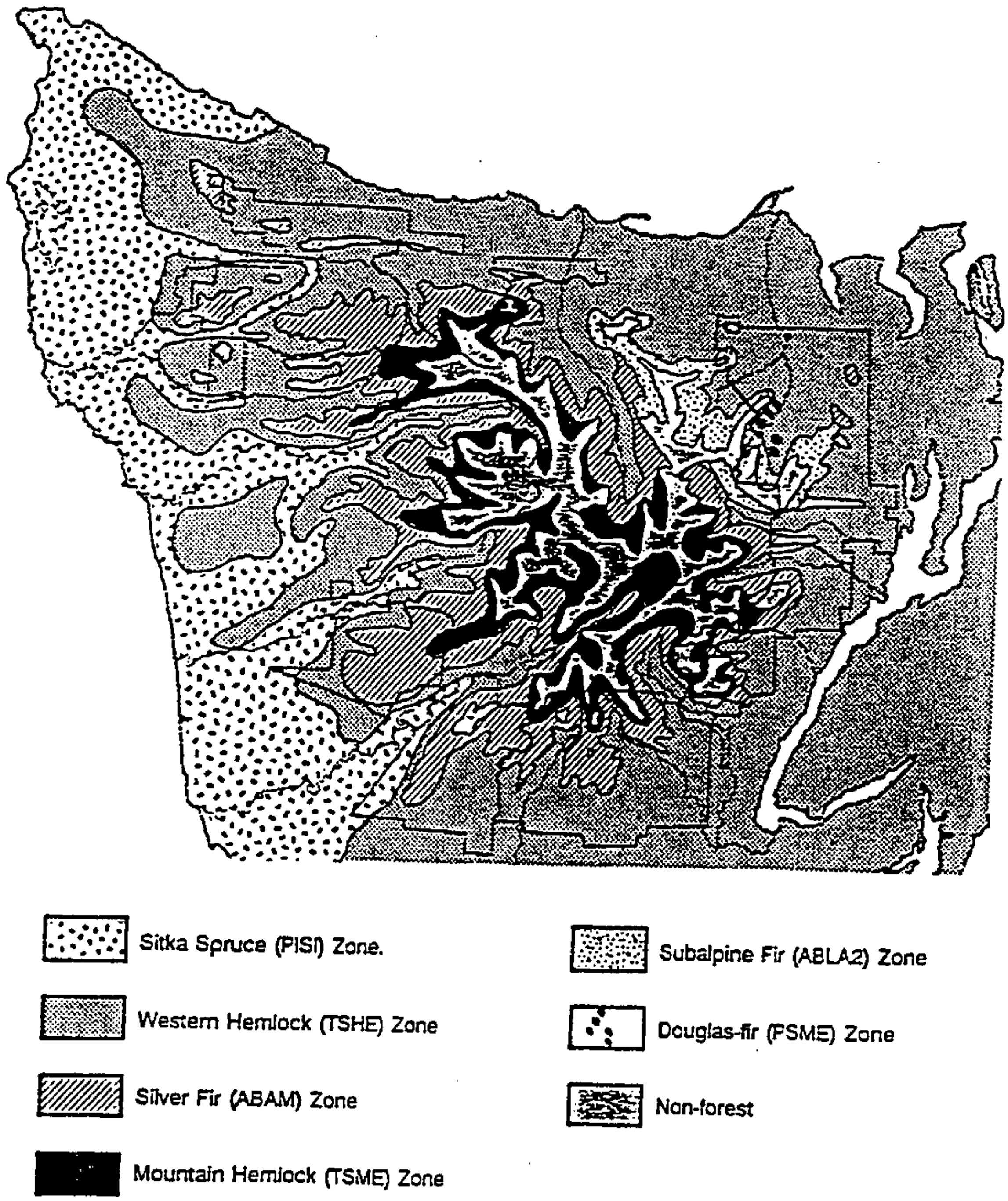


Figure III-7. Map of vegetation zones based on aspect-elevation curves and environmental zones. From Henderson et al. (1989).

Table III-1. Geographic and Yearly Variability in Recorded Average Annual Flows at Selected USGS Gaging Stations on the Olympic Peninsula.

USGS Gage No. (12-)	Stream Name	Hydrologic Province from Fig. 1	Maximum Annual Flow (cfs)	Average Annual Flow (cfs)	Minimum Annual Flow (cfs)	Ratio Max. to Min.
032500	Cloquallum	1-South Mountain	367 (1.34)*	274	205 (0.75)*	1.79
043163	Sooes	2-West. Coastal	276 (1.33)	208	135 (0.65)	2.04
039300	N. Fork Quinault	3-West. Mountain	1151 (1.34)	861	564 (0.65)	2.04
043430	E. Twin	4-North. Coastal	81 (1.25)	65	43 (0.67)	1.88
050500	Snow	6-NE Coastal	22 (1.39)	16	9 (9.55)	2.44
060500	S. Fork Skokomish	8-East. Mountain	1041 (1.42)	732	424 (0.58)	2.46
078400	Kennedy	9-SE Coastal	78 (1.28)	61	47 (0.77)	1.66

*Ratio of annual maximum and minimum flows to average for period of record at the gaging station. Periods of record are not common, which may account for some variability in the ratios. From Amerman and Orsborn (1987).

The variability of annual and monthly flows can be determined using the standard deviation about the mean (Table III-2). Because of the way the average monthly and annual flows are distributed about the mean, there is no benefit gained by consider two standard deviations. (Note parenthetic values in Table III-2). These flow ratios are used as models for estimating monthly flows at an ungaged site from the average annual flow.

We have been considering average daily flows, averaged over the time period in question (monthly, yearly or period of record). Other flows which are of interest for application to fisheries and impact studies:

- average daily annual high and low flows, and how long they last;
- instantaneous annual peak flood flows; and
- instantaneous annual minimum flows.

The extreme floods and low flows have application in:

- determining the timing and lengths of high and low flow periods to examine sediment transport and droughts, respectively;
- analyzing heights to which peak floods will rise;
- to determine fish passage conditions; and
- the analysis of causes and changes in high or low flows.

In the next section we will define the problems associated with generating and verifying streamflow information at a project site.

Options for Flow Estimation

In order to develop the desired project flows for analyzing fisheries related projects one must be able to:

1) analyze streamflow **RECORDS** at or "near" the site;

2) estimate project flows using some form of **HYDROLOGIC MODELS**;

3) make a sample of **STREAMFLOW MEASUREMENTS** at the site; or

4) install a **TEMPORARY GAGE** at the site and calibrate the gage by making streamflow measurements over a range of flows; the range will be governed by the type of project. One might combine two or three methods.

This last method could be accomplished in any of several ways, and would add greatly to the available streamflow data for ungaged areas on

Table III-2. Ratio of Monthly Flows to Average Annual Flow for a Sample of Olympic Peninsula Streams: Maximum, Minimum, Mean and One Standard Deviation Above and Below the Mean Average Annual Flow

Station	Flows	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Year
Humptulips River	Maximum	2.26	2.59	4.22	4.30	3.59	2.85	1.69	1.29	0.67	0.56	0.41	0.94	1.40
(12039000)/(1.5)[a]	+1 s.d.[d]	1.27	2.16	2.76	2.71	2.39	1.90	1.30	0.84	0.49	0.36	0.27	0.53	1.18
	Mean	0.80	1.56	2.06	1.92	1.72	1.36	0.97	0.62	0.36	0.24	0.18	0.31	1.00
1933-35, 1942-79[b]	-1 s.d.[e]	0.32	0.95	1.35	1.12	1.06	0.81	0.65	0.41	0.22	0.13	0.10	(0.09)	0.82
A = 130 mi^2[c]	Minimum	0.12	0.45	0.92	0.46	0.71	0.62	0.46	0.31	0.17	0.11	0.08	0.10	0.65
Dickey River	Maximum	2.61	2.70	3.86	3.45	2.79	2.25	1.69	0.65	0.48	0.63	0.26	1.10	1.41
(12043100)/(2.3)	+1 s.d.	1.64	2.27	2.99	3.06	2.38	1.89	1.22	0.51	0.32	0.33	0.16	0.68	1.23
	Mean	0.99	1.60	2.21	2.11	1.71	1.35	0.83	0.39	0.20	0.17	0.09	0.36	1.00
1962-73, 1977-80	-1 s.d.	0.34	0.94	1.43	1.16	1.03	0.82	0.43	0.27	0.08	(0.02)	0.02	0.05	0.77
A = 86.3 mi^2	Minimum	0.10	0.63	1.18	0.49	0.77	0.50	0.34	0.22	0.06	0.04	0.02	0.05	0.64
E. Twin River	Maximum	1.58	2.83	3.80	3.38	3.20	2.46	1.42	0.70	0.39	0.19	0.14	0.23	1.25
(12043430)/(4.2)	+1 s.d.	1.04	2.21	2.87	3.18	2.38	2.23	1.24	0.63	0.29	0.17	0.10	0.18	1.19
	Mean	0.59	1.49	2.09	2.47	1.78	1.58	0.97	0.51	0.22	0.13	0.08	0.12	1.00
1962-72	-1 s.d.	(0.14)	0.78	1.30	1.77	1.18	0.93	0.70	0.38	0.15	0.08	0.05	0.07	0.81
A = 14.0 mi^2	Minimum	0.19	0.60	1.05	1.42	1.15	0.65	0.63	0.36	0.15	0.07	0.05	0.07	0.67
Snow Creek	Maximum	1.07	1.62	3.65	5.85	4.23	3.46	2.84	2.07	1.78	1.41	0.44	0.58	1.39
(12050500)/(6.2)	+1 s.d.	0.57	1.17	2.26	3.25	2.53	2.40	1.91	1.65	1.22	0.81	0.33	0.31	1.22
	Mean	0.35	0.73	1.47	1.99	1.69	1.49	1.37	1.19	0.80	0.48	0.23	0.22	1.00
1952-72	-1 s.d.	(0.12)	0.30	0.68	0.72	0.84	0.59	0.83	0.73	0.37	(0.14)	0.14	0.12	0.78
A = 11.2 mi^2	Minimum	0.15	0.27	0.41	0.41	0.46	0.46	0.73	0.50	0.28	0.19	0.12	0.12	0.55

Table III-2. Ratio of Monthly Flows to Average Flow. (Continued)

Station	Flows	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Year
S.F. Skokomish														
River	Maximum	2.36	3.19	4.55	5.51	3.54	2.92	1.91	1.72	1.24	0.65	0.36	1.09	1.42
(12060500)/(8.8)	+1 s.d.	1.24	2.21	2.75	2.78	2.25	1.74	1.39	1.12	0.76	0.43	0.43	0.47	1.20
	Mean	0.73	1.50	1.98	1.82	1.57	1.26	1.03	0.84	0.53	0.30	0.19	0.27	1.00
1931-79	-1 s.d.	0.22	0.80	1.21	0.85	0.88	0.79	0.68	0.55	0.30	0.18	0.13	0.07	0.80
A = 76.3 mi^2	Minimum	0.12	0.10	0.73	0.33	0.57	0.61	0.47	0.41	0.22	0.14	0.11	0.09	0.58
Goldsborough														
Creek	Maximum	0.95	2.50	3.02	3.43	4.47	3.29	1.62	1.31	0.52	0.30	0.28	0.32	1.40
(12076500)/(9.1)	+1 s.d.	0.65	1.82	2.22	2.96	2.94	2.31	1.46	0.83	0.46	0.29	0.24	0.25	1.21
	Mean	0.45	1.20	1.70	2.20	2.03	1.63	1.15	0.63	0.39	0.26	0.21	0.21	1.00
1951-71	-1 s.d.	0.24	0.57	1.17	1.45	1.12	0.96	0.83	0.43	0.31	0.23	0.18	0.17	0.79
A = 39.3 mi^2	Minimum	0.16	0.21	0.86	0.83	0.79	0.90	0.62	0.40	0.29	0.20	0.17	0.15	0.68

[a](USGS Gage No.)/(Province/Stream Gage Code).
[b]Period of years utilized in statistics, not necessarily years of continuous record.
[c]Drainage area.
[d]Mean monthly value plus one standard deviation.
[e]Mean monthly value minus one standard deviation.
From Amerman and Orsborn (1987), Table 9-2, page 9-5.

the Peninsula or elsewhere in the State. The options for stream gaging include:

- **CALIBRATE AN ARTIFICIAL STRUCTURE** such as a culvert, box culvert or bridge.
- select a **STABLE REACH OF STREAM** with a uniform distribution of flow, install three (3) staff gages 50 to 100 ft. apart and calibrate for say five flows; and
- develop either of the above methods, but install an automatic **STAGE RECORDER** (plus staff gages) to take more continuous readings of streamflow.

One benefit of calibrating flows in a structure (culvert or bridge) is that the calibration will not change unless there is a major change in the streambed up- or downstream of the structure.

Analysis of Streamflow Records

The common unit of streamflow is the AVERAGE DAILY FLOW in cubic feet per second (cfs, or ft^3/s) in the United States. A typical USGS annual record is shown in Table III-3 for the South Fork Skokomish River (USGS, 1986). The detailed glossary of terms, and an explanation of how the USGS records are obtained and analyzed, are presented in the front of each annual book of records (e.g., USGS 1986).

An abbreviated discussion of a typical data sheet follows using the key numbers 1-15 in Table III-3.

1. The MAJOR RIVER BASIN in which the gage is located.
2. GAGE NUMBER, STREAM NAME and nearest community. The 12- at the front of the gage number refers to a major part of the United States.
3. DETAILED LOCATION usually referenced to the confluence of the measured stream with another downstream stream.
4. DRAINAGE AREA measured from the outline of the basin's topographic divide above the gage location.
5. PERIOD OF RECORD may be intermittent, continuous or, as noted here, discontinued as of September, 1984.
6. REVISED RECORDS: WSP is "Water Supply Paper," orange-colored, paper-bound USGS streamflow records for different parts of the U.S.; Part 12- is for Pacific Coast basins in Washington; since 1961 the annual records have been published on a state-by-state basis; the year of the change (1950) is printed right after the WSP; the type of change is either coded (M = Maximum Flow) or typed out (Drainage Area); details are explained in the front of each yearly book of records.

Table III-3. Typical Annual Discharge Record for USGS Gaging Station; South Fork Skokomish River Gage No. 120605000; Water Year 1984. From USGS, 1986

1 SKOKOMISH RIVER BASIN

2 12060500 SOUTH FORK SKOKOMISH RIVER NEAR UNION, WA

3 LOCATION.--Lat 47°20'26", long 123°16'44", in SW¼NE¼ sec.2, T.21 N., R.5 W., Mason County, Hydrologic Unit 17110017, on right bank 3.0 mi upstream from Vance Creek, 2.3 mi upstream from confluence with North Fork, and 8.5 mi west of Union.

4 DRAINAGE AREA.--76.3 mi².

5 PERIOD OF RECORD.--August 1931 to September 1984 (discontinued).

6 REVISED RECORDS.--WSP 1216: 1950. WSP 1316: 1934(M), 1938(M). WSP 1932: Drainage area.

7 GAGE.--Water-stage recorder. Datum of gage is 103.35 ft above National Geodetic Vertical Datum of 1929.

8 REMARKS.--Water-discharge records good except those for periods of no gage-height record Jan. 3 to 18, Mar. 31 to Apr. 19, which are fair. No regulation or diversion upstream from station.

9 AVERAGE DISCHARGE.--53 years, 742 ft³/s, 132.06 in/yr, 537,600 acre-ft/yr.

10 EXTREMES FOR PERIOD OF RECORD.--Maximum discharge, 21,600 ft³/s Jan. 22, 1935, Nov. 26, 1949, gage height, 11.0 ft, from rating curve extended above 11,000 ft³/s; minimum, 62 ft³/s Sept. 18, 1938; minimum gage height, 1.06 ft Oct. 3, 1965.

11 EXTREMES FOR CURRENT YEAR.--Peak discharges greater than base discharge of 6,000 ft³/s and maximum (*):

Date	Time	Discharge (ft³/s)	Gage height (ft)	Date	Time	Discharge (ft³/s)	Gage height (ft)
Nov. 3	0500	6,160	5.23	Nov. 15	1300	*13,000	*6.92

12 Minimum discharge, 88 ft³/s Sept. 27 to 30, gage height, 1.50 ft.

13 DISCHARGE, IN CUBIC FEET PER SECOND, WATER YEAR OCTOBER 1983 TO SEPTEMBER 1984
MEAN VALUES

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	149	459	893	1110	553	1360	580	934	596	313	154	105
2	145	2570	796	1720	501	1250	560	1470	544	305	154	105
3	145	4090	720	3300	459	1020	570	990	519	296	153	97
4	149	2490	654	3500	418	880	540	796	527	296	149	103
5	145	1500	616	2300	403	776	500	688	510	293	145	172
6	140	1630	550	1700	380	746	480	623	519	283	145	231
7	136	1510	560	1530	365	736	500	561	484	265	144	156
8	132	1130	1220	1350	679	736	470	596	451	258	140	168
9	132	1140	1480	1190	945	736	490	641	442	252	140	155
10	128	1820	2020	1060	1180	756	520	660	418	251	139	136
11	128	3160	1510	960	1140	746	600	901	411	249	136	127
12	124	2970	1240	870	2450	1220	830	901	411	245	136	123
13	124	3030	1870	800	2010	1290	780	788	418	236	136	118
14	120	3380	1670	710	1400	1090	780	746	451	223	134	113
15	120	10500	1220	640	1150	1250	1050	679	467	222	132	110
16	120	7940	979	580	990	1310	970	623	426	223	124	109
17	124	7030	828	520	858	1780	850	570	395	225	124	108
18	120	5120	731	493	786	1800	860	527	365	221	124	105
19	124	3620	649	459	923	1540	827	934	356	212	122	105
20	163	3670	574	426	2770	1990	756	1050	409	206	120	98
21	168	2240	512	418	1830	2340	717	786	430	195	119	98
22	467	1660	464	596	1280	1680	706	776	398	185	116	97
23	290	1380	424	727	1090	1320	651	1010	378	182	116	98
24	224	3820	392	1180	1130	1090	623	901	380	177	116	97
25	197	2890	389	2130	1010	1000	570	806	371	177	113	96
26	177	1970	414	1310	912	934	519	1000	386	177	113	92
27	168	2090	361	1040	945	848	484	890	373	172	110	92
28	158	1510	323	880	1220	786	467	817	339	171	109	88
29	149	1210	459	766	1350	717	459	806	383	167	109	88
30	403	1020	1540	688	---	660	519	776	352	163	105	88
31	501	---	1660	596	---	614	---	669	---	161	105	---
14 TOTAL	5570	88549	27718	35549	31127	35001	19230	24913	12909	7001	3982	3478
MEAN	180	2952	894	1147	1073	1129	641	804	430	226	128	116
MAX	501	10500	2020	3500	2770	2340	1050	1470	596	313	154	231
MIN	120	459	323	418	365	614	459	527	339	161	105	88
CFSM	2.36	38.7	11.7	15.0	14.1	14.8	8.40	10.5	5.64	2.96	1.68	1.52
IN.	2.72	43.17	13.51	17.33	15.18	17.06	9.38	12.15	6.29	3.41	1.94	1.70
AC-FT	11050	175600	54980	70510	61740	69420	38140	49410	25600	13890	7900	6900

15 CAL YR 1983 TOTAL 353965 MEAN 970 MAX 10500 MIN 120 CFSM 12.7 IN. 172.58 AC-FT 702100
WTR YR 1984 TOTAL 295027 MEAN 806 MAX 10500 MIN 88 CFSM 10.6 IN. 143.84 AC-FT 585200

7. The TYPE OF GAGE; its DATUM (local reference elevation) is for gage calibration;

8. Remarks describe the relative accuracy of the stream gaging records (excellent ± 5%, good, fair and poor), and how the quality of the data can change with the season due to ice, debris and other effects such as backwater from a downstream control; if there is diversion above the gage, these conditions are mentioned, but rarely are the diversions quantified.

9. AVERAGE DISCHARGE is the average daily flow for all the days (and years) of record in units of ft^3/s (cfs); inches per year equivalent of water to a certain depth over the whole watershed; and acre-feet per year for irrigators; all three sets of units are equivalent;

   NOTE: inches/year of equivalent streamflow (OUTPUT) divided by the average annual precipitation (INPUT) gives the relative amount of runoff derived from average annual precipitation (runoff coefficient, CRO); for the South Fork Skokomish River this is equal to RO = 132 in/yr divided by about 150 in/yr of precipitation (P) gives CRO = 132/150 = 0.88, or 88 percent of the measured precipitation appears as streamflow. Recall that average precipitation over a basin is very difficult to determine accurately, and the P = 150 in/yr is an estimated value from isohyetal maps based on very limited records.

10. EXTREME flow (maximum instantaneous highs and minimum instantaneous or daily average) lows are given for: (a) the period or record; and (b) for this particular WATER YEAR in Parts 11 and 12.

    The WATER YEAR 1984 (Section 13) extends from October 1, 1983 to September 30, 1984 to include fall and winter precipitation as snow which later melts and appears as streamflow.

13. These are the AVERAGE DAILY FLOWS as recorded at this gage, based on a relationship between water surface elevation (STAGE) and streamflow (DISCHARGE), a stage-discharge calibration curve. The calibrations are checked 5 to 6 times a year.

    Notice the seasonal and monthly variations in the flow. They can be most easily observed by looking at the monthly summaries (Section 14) and yearly summary (Section 15) at the bottom of the table.

14. The mean, maximum and minimum daily flows are listed for each month in cfs, as well as the total (sum) in cfs-days. The next three lines are all equivalents for the average monthly flow in:

    - CFSM -- cubic feet per second per square mile of drainage area as for October where CFSM = 180/76.3 = 2.36 cfsm (sometimes noted as csm);

- IN -- is the equivalent amount of runoff in inches spread over the basin area as discussed above for average annual runoff and precipitation; and

- AC-FT is the equivalent volume of water spread out over the basin area (in acres) to a depth of so many feet.

15. These two lines of data are summaries for the calendar year and WATER YEAR. As for the monthly summaries the values are given in TOTAL = 295027 cfs-days, the mean (806 cfs), the maximum (10,500 cfs on Nov. 15) and the minimum (88 cfs on Sept. 27-30); and the rest of the values are equivalents to the mean in units as discussed before.

It can be determined whether this was a **RELATIVELY WET OR DRY YEAR** by comparing the 1984 mean flow (806 ft^3/s) on the last line (15) with the average discharge of record (742 $ft^3/2$) on line 9. These two numbers indicate the Water Year (WY) 84 was [(806 - 742)/(742)] X (100) = 8.6% wetter than the average year. This type of a wet and dry annual analysis is very important when mixing short and long records in models, and a method for analysis is presented later.

Sources and Uncertainty of Streamflow Data

The best source of streamflow data is the U.S. Geological Survey, but there are other sources of miscellaneous records, and some short-term continuous records from:

- state agencies such as WDOE, WDOF, WDOF AND WDNR taken as part of their projects, research and operations (e.g., Canning 1988);

- power companies, municipalities or PUDs which gather streamflow information (and lake levels and reservoir storage) as part of their hydropower or water supply projects;

- instream flow studies conducted by state and federal agencies, and consulting firms;

- hydropower studies (FERC applications) wherein the applicant must monitor and model the streamflow; and

- miscellaneous streamflow measurements made for monitoring programs, such as the Forest Service long-term monitoring projects to determine the impacts of altered land use on stream channel geometry.

Because the amount of streamflow data decreases as one moves upstream, there are large voids in streamflow information on the Peninsula and elsewhere in the State. Starting at a stream gaging site and working upstream, the entire upper watershed is **UNGAGED** upstream of the first significant tributary. Depending on the tributary basin

APPENDIX III. HYDROLOGY

Introduction

This appendix contains information on two major aspects of hydrology:

(1) data for the analysis of streamflow regimes; and

(2) a series of models which can be used to estimate streamflow Ocharacteristics at ungaged sites, or to extend data with short records.

The hydrologic component is comprehensive so that it can provide the means for future AMC projects to estimate the flow regimes at monitoring and research sites.

Streamflow gages on the Olympic Peninsula are used to demonstrate analytical procedures and to calibrate the models. Precipitation records are sparse and have a high degree of uncertainty when translated any distance, so the only precipitation value used is the average annual precipitation on a basin. This information is derived from the average annual precipitation (isohyetal) map of the State (U.S. Weather Bureau 1965) and has been printed for each U.S. Geological Survey (USGS) stream gage (Williams et al. 1985).

Description of the Pilot Area

Geographic Setting of the Olympic Peninsula

The Olympic Peninsula is highly diverse with wide variations in geography, topography, vegetation, geology, precipitation and streamflow. The general description of the Peninsula as a pilot study area provides the foundation for the hydrologic details in this Appendix. One can experience a collection of landscapes including glacial mountains, alpine meadows, rain forests, and ocean shores in a span of less than 35 miles. Moisture to create these diverse regions is supplied by the Pacific marine climate. When coupled with the Olympic mountains the moisture laden clouds provide a range of average annual precipitation from 20 to 200 inches per year. The location of the Peninsula is shown in Figure III-1 as are the Washington Department of Ecology Water Resources Inventory Areas which delineate major basin systems. The southern border of the Peninsula is defined by the Chehalis River. The Peninsula contains eight of the State Water Resurce Inventory Areas (14, 16, 17, 18, 19, 20, 21, and 22).

The center of the Peninsula is dominated by the Olympic National Park which is surrounded by numerous land ownerships including the Olympic National Forest, the Washington Department of Natural Resources, Indian reservations and land owned by private industry, individuals and municipalities. Major land ownerships are shown in Figure III-2 except for Department of Natural Resources lands which comprise many dispersed smaller parcels.

geology, it may contain only 30 percent of the drainage area, but may provide 60 percent of the low flow.

In terms of making streamflow measurements for a fisheries/monitoring/research project, it is important to know how much flow is contributed by each tributary at various seasonal levels so relative impacts on subbasins can be evaluated. This can be checked in the field during a low flow period by conducting an "accretion" study. Streamflows are measured in the mainstem just above and below (or in) the tributaries, whichever two of the three branches have the best gaging sites. Measuring the flow just upstream of the tributary accounts for accretion which has accumulated below the next upstream measurement site.

It would be helpful to have more information on smaller basin streamflows. The coefficients in hydrologic models change as a function of elevation, precipitation and geology. If the model coefficients are based primarily on stream gage information from larger basins, then the application of those equations to smaller basins at higher elevations could cause errors.

Methods and Examples of Streamflow Data Analysis

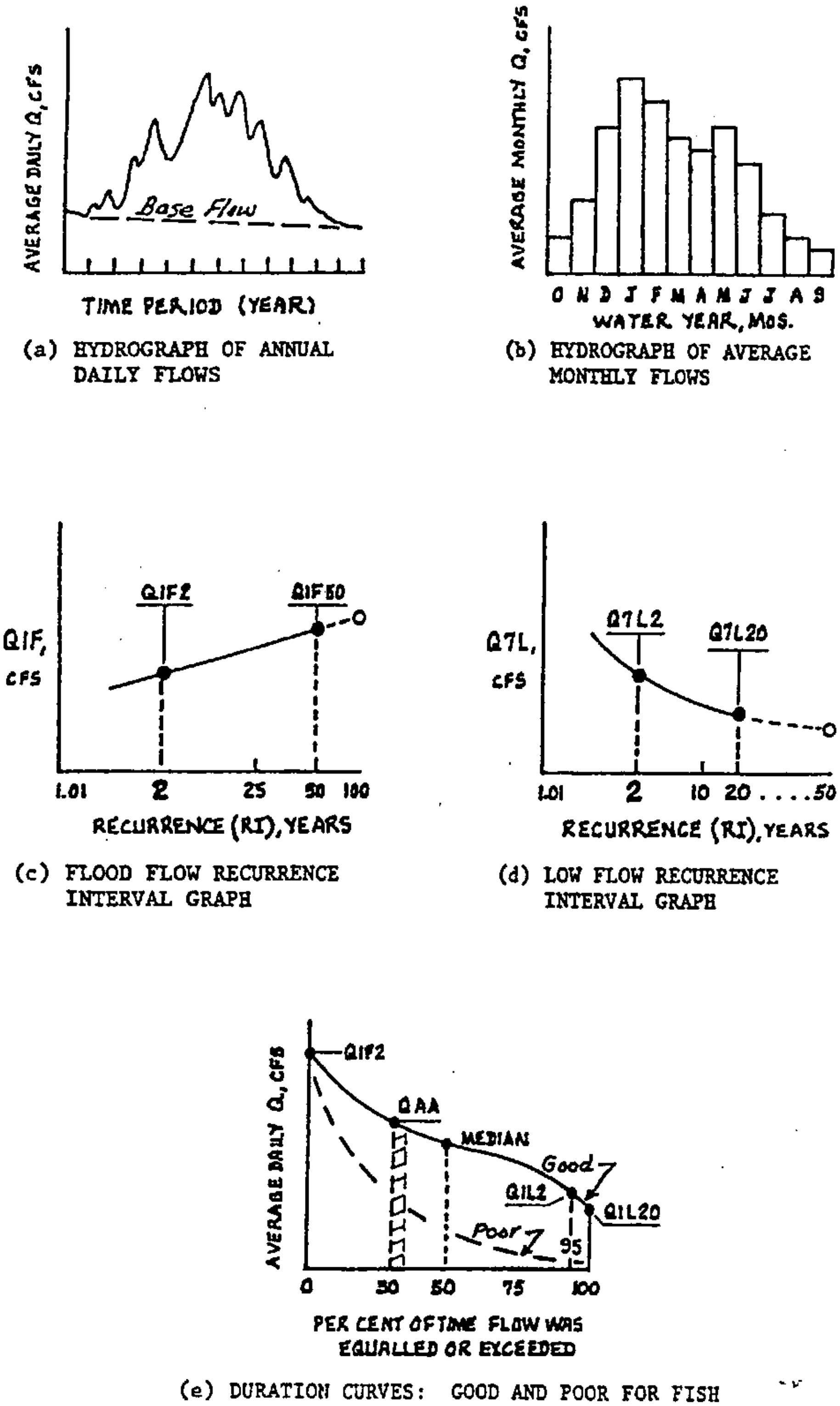
When daily streamflow records like Table III-3 are collected at a USGS gaging station for say 49 years, then the data set (the population in statistics) consists of:

- 49 instantaneous annual maximum peak flows, plus many other lesser peak flows;
- 17,897 average daily flows;
- 49 minimum daily average, and instantaneous low flows.

The average daily flow data can be analyzed by these methods:

- HYDROGRAPHS of average daily flow plotted versus calendar days;
- HYDROGRAPHS of maximum, mean and minimum monthly flows averaged over the 49 years, or for any of the separate years;
- FREQUENCY GRAPHS (probability, or recurrence interval analyses) of peak floods, annual maximum daily flows, average annual flows and annual minimum flows; and
- DURATION CURVES of flow versus the percent of time that flow was equalled or exceeded; duration curves are usually prepared for monthly, seasonal or annual time periods and are very useful in fisheries studies.

Generic examples of HYDROGRAPHS, FREQUENCY CURVES and DURATION CURVES are shown in Figure III-8. The hydrograph of monthly flows in WY 1984 for the South Fork Skokomish River is plotted in Figure III-9. A



(a) HYDROGRAPH OF ANNUAL DAILY FLOWS

(b) HYDROGRAPH OF AVERAGE MONTHLY FLOWS

(c) FLOOD FLOW RECURRENCE INTERVAL GRAPH

(d) LOW FLOW RECURRENCE INTERVAL GRAPH

(e) DURATION CURVES: GOOD AND POOR FOR FISH

Figure III-8. Typical generic hydrographs, frequency and duration curves for analyzing streamflow records.

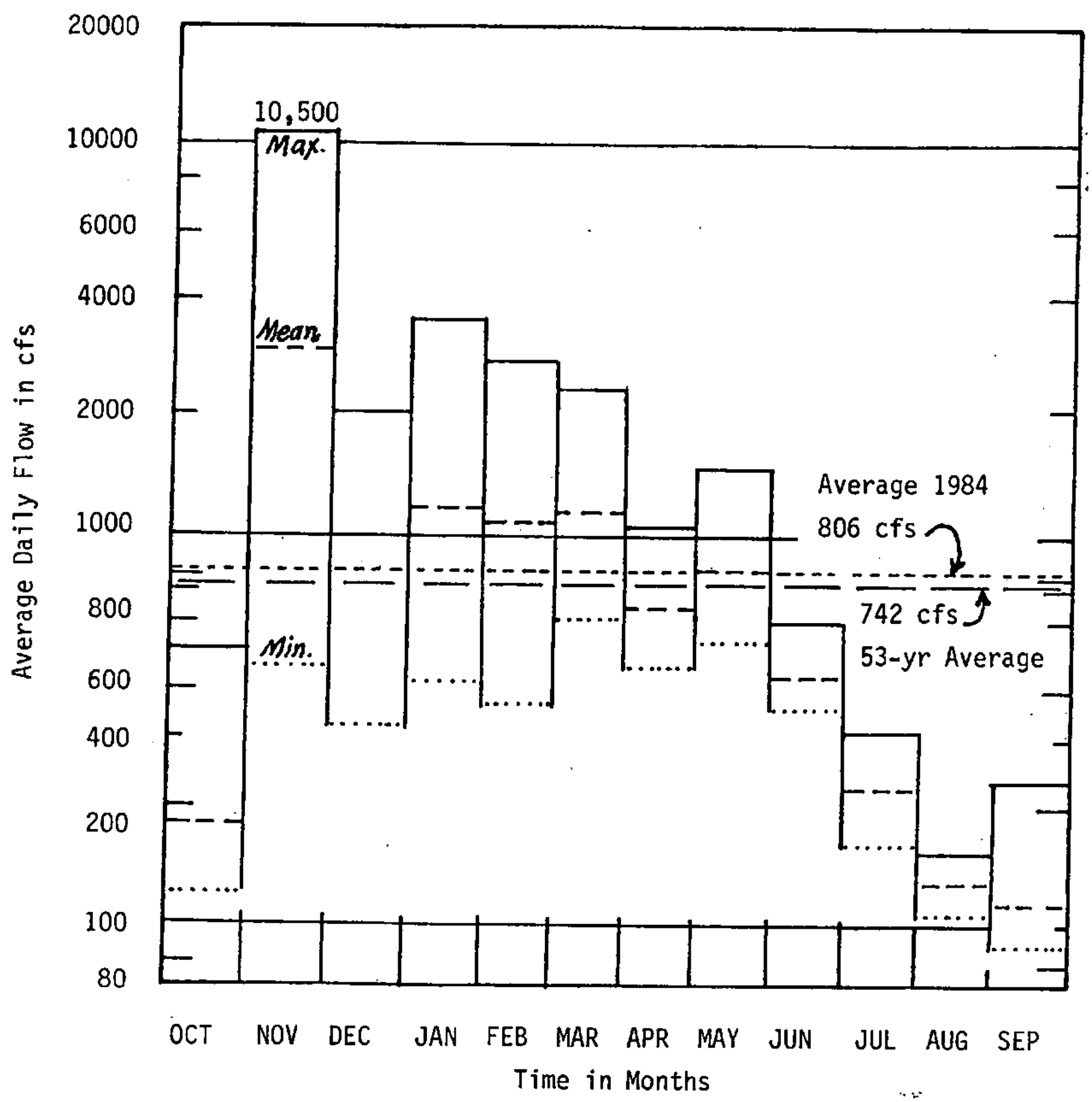


Figure III-9. Bar graph of monthly maximum, mean and minimum average daily flows for the South Fork Skokomish River at gage No. 120605000 during water year 1984.

HYDROGRAPH OF DAILY FLOWS (Figure III-8a) for a year, or the average for a typical year, is useful if you are interested in the increase or decrease in flow rates throughout the year. The MONTHLY BAR GRAPHS in Figure III-8b and III-9 show the distribution of flow for either the period of record or for a particular water year (October 1-September 30).

FREQUENCY CURVES (Figure III-8c and -8d) are developed by calculating the PROBABILITY of these historical events occurring again, assuming the flow distribution history is repeated.

The steps in flow frequency analysis are:

- gather the annual sets of either high or low daily flows for the PERIOD OF RECORD (our example has 49 years of record). Therefore the number of annual events (n) = 49.

- arrange the high and low flows and assign them each an ORDER OF MAGNITUDE (m). The largest high flow has m = 1, and the lowest low flow has m = 1. If there are several flows of the same size they receive sequential values of (m).

- calculate the PROBABILITY of occurrence (p) for each of the high and low flows where

$$p = m/(n + 1)$$

- this analysis is more commonly done using the reciprocal of probability called the RECURRENCE INTERVAL (RI) which is

$$RI = 1/p = (n + 1)/m \text{ (years)}.$$

For our example set of data (49 years) the largest high flow and the smallest low flow would have recurrence intervals of

$$RI = (n + 1)/m = (49 + 1)/1 = 50 \text{ years}.$$

The probability of occurrence in any year would be p = 1/RI = 1/50 = 0.02.

This analysis does not mean that if the highest (or lowest) daily flow of record occurred last year that it will be 50 years before another flow of the same size occurs. It means that <u>each year</u> there is a <u>2% chance</u> that a flow of this size will occur. To find an estimate of a flow of longer recurrence interval the data can be extended either graphically or mathematically as shown for the South Fork Skokomish River at USGS gage 12060500 in Figures III-10 and III-11. There is not much change in low flows beyond a recurrence interval of 20 years because of the gradual withdrawal from the groundwater or glacial low flow supply.

Figures III-10 and III-11 are plotted on what is called LOG-PEARSON TYPE III probability paper which distributes the extreme high and low

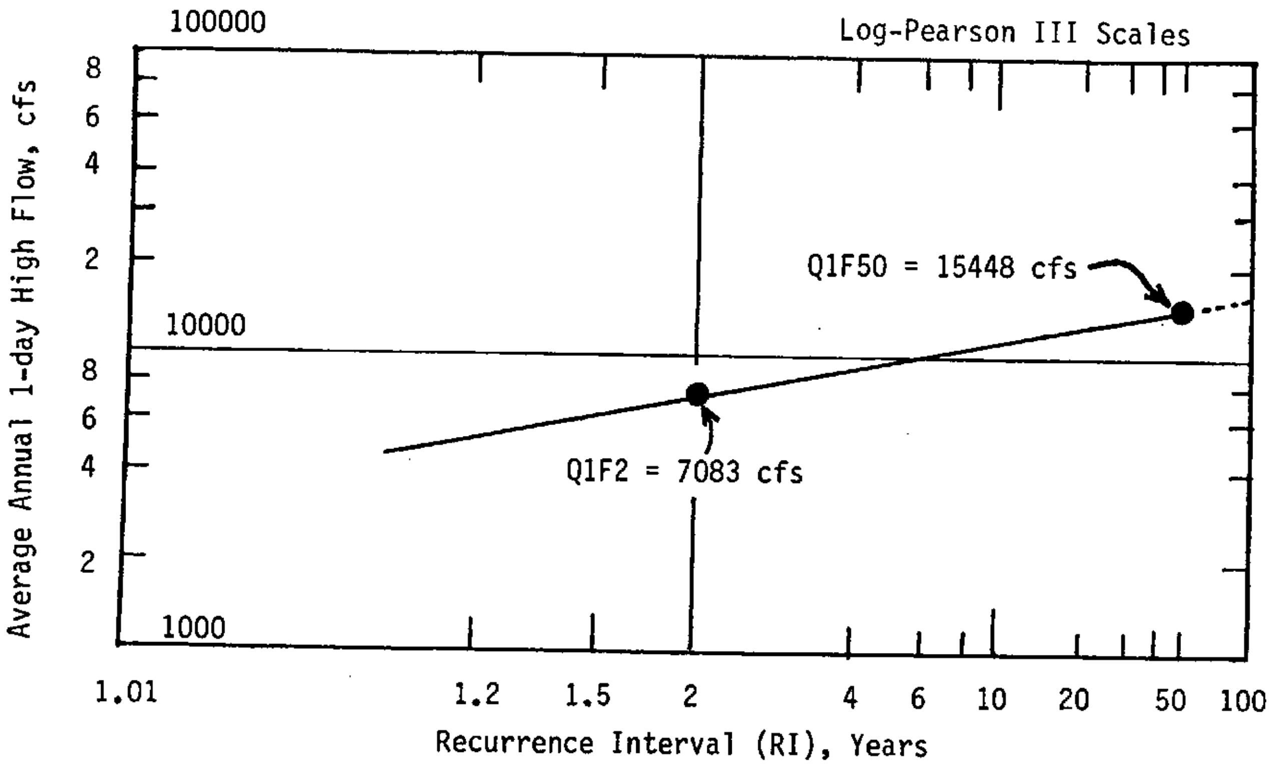


Figure III-10. Maximum annual daily flood flow recurrence interval graph for the South Fork Skokomish River Gage No. 12060500.

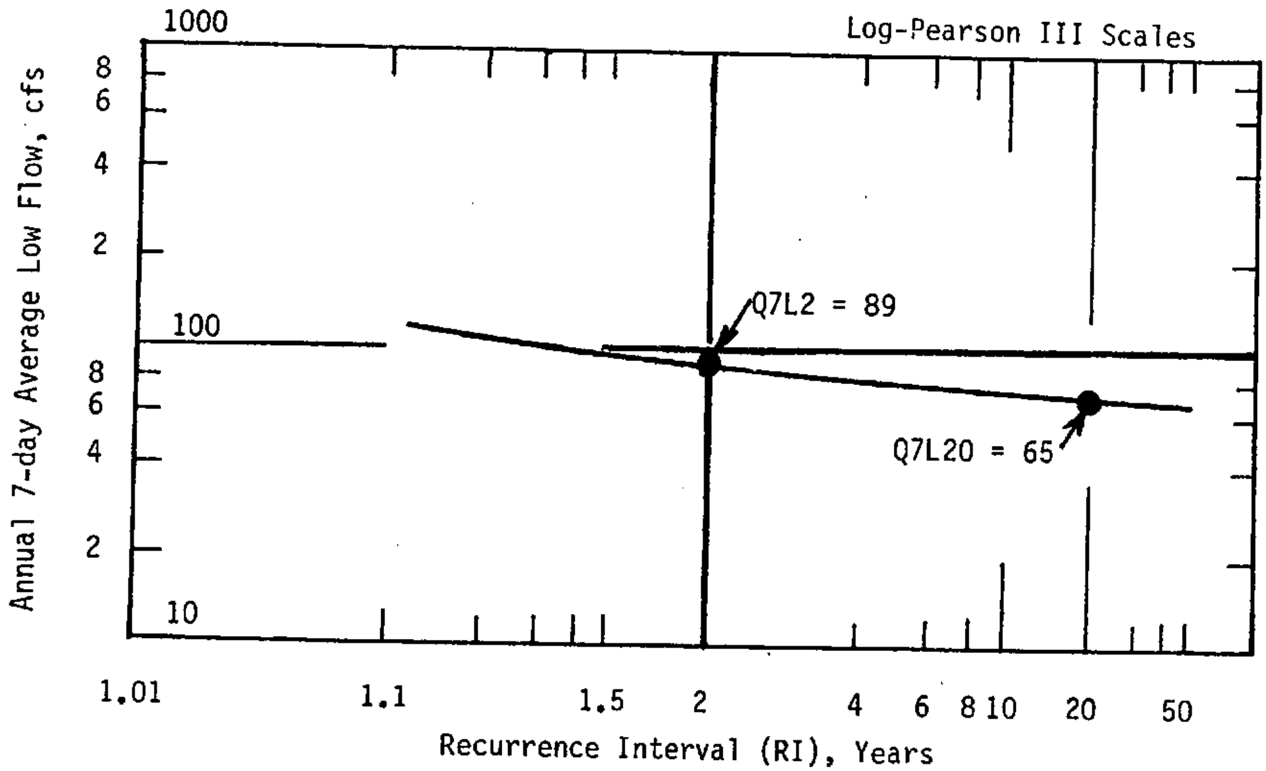


Figure III-11. Seven-day average annual low flow recurrence interval graph for the South Fork Skokomish River Gage No. 12060500.

events. Details of the mathematical analysis can be found in any technical hydrology reference.

A DURATION CURVE is developed by analyzing the daily flows over a time period (month, year or period of record) and calculating the percent of time that each flow was equaled or exceeded. For example, with 100 events, the highest flow was equaled or exceeded zero percent of the time, the second highest flow 1 percent, and the lowest flow 100 percent of the time. The steps are summarized below and demonstrated in Table III-4:

- the daily streamflow data for the period to be analyzed is arranged from highest to lowest flow;
- sizes of events are grouped into a range of flows called a "class," say for example, 2000-2999 cfs, 1000-1999 cfs, 900-999 cfs, etc.;
- the ranges of flows with the large numbers of events are divided into more classes to better define the shape of the duration curve;
- the number of events in each class is totaled and then divided by the total number of events to obtain the percentage of time that the mean flow in the class has been equalled or exceeded; and
- the area under the duration curve is the total volume of flow for the period.

The long-term average duration curve for the South Fork Skokomish River near Union (12060500) is plotted in Figure III-12. The ends of the duration curve are the average 1-day, 2-year flood and the average 1-day, 20-year, low flow. Duration curve characteristics are very important with respect to assessing habitat and potential productivity. The greater percent of time that the average annual flow is equalled or exceeded (a flatter duration curve), the greater the potential productivity. As was sketched in Figure III-8e the steep duration curve provides less opportunity for good habitat. Duration curves can be estimated quite accurately for ungaged sites by estimating just three or four flows to describe them, as labeled in Figure III-12.

<u>Development of Characteristic Flows</u>

Returning to our sample gaging station record of 49 years of average daily flows, the entire data population of 17,897 events can be depicted by the rectangle at left center in Figure III-13. All the annual high and low daily flows (49 of each) are above and below the dashed lines. The 98 annual daily high and low data points are all also part of the average annual flow calculation for each year, and for the period of record.

The AVERAGE FLOOD is the high flow that has a probability (p) of 0.50 of occurring in any year, which is equivalent to a Recurrence Interval (RI) of 2 years (RI = 1/p). The nomenclature of all the hydrologic flow terms is in Table III-5, and is developed as follows:

Table III-4. Sample Calculations for Developing a Duration Curve

Class of Discharge cfs	Occurrences in Class	Accummulated Occurrences	Percent of Total
23- 49	10	252	100.0
50- 99	54	242	96.0
100- 149	38	188	74.6
150- 199	16	150	59.5
200- 249	20	134	53.7
250- 299	14	114	45.2
300- 349	10	100	39.7
350- 399	9	90	35.7
400- 499	23	81	32.1
500- 599	11	58	23.0
600- 699	8	47	18.7
700- 799	6	39	15.5
800- 899	5	33	13.1
900- 999	4	28	11.1
1000-1999	20	24	9.5
2000-2999	4	4	1.6
	252		

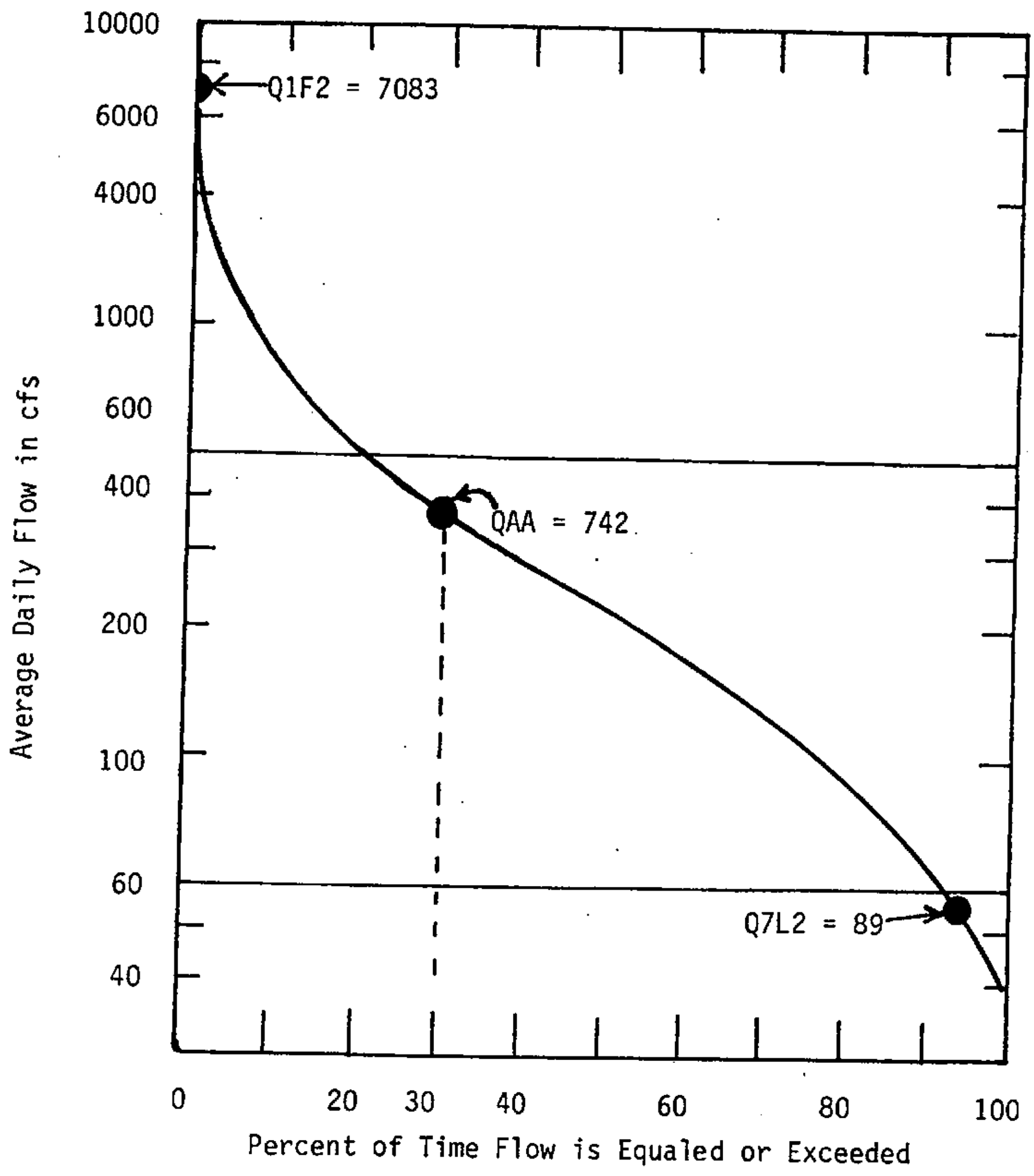


Figure III-12. Duration curve of average daily flows for the period 1932-1979 for the South Fork Skokomish River near Union at USGS gage 12060500. Three primary characteristic flows have been superimposed (Q1F2, QAA and Q7L2).

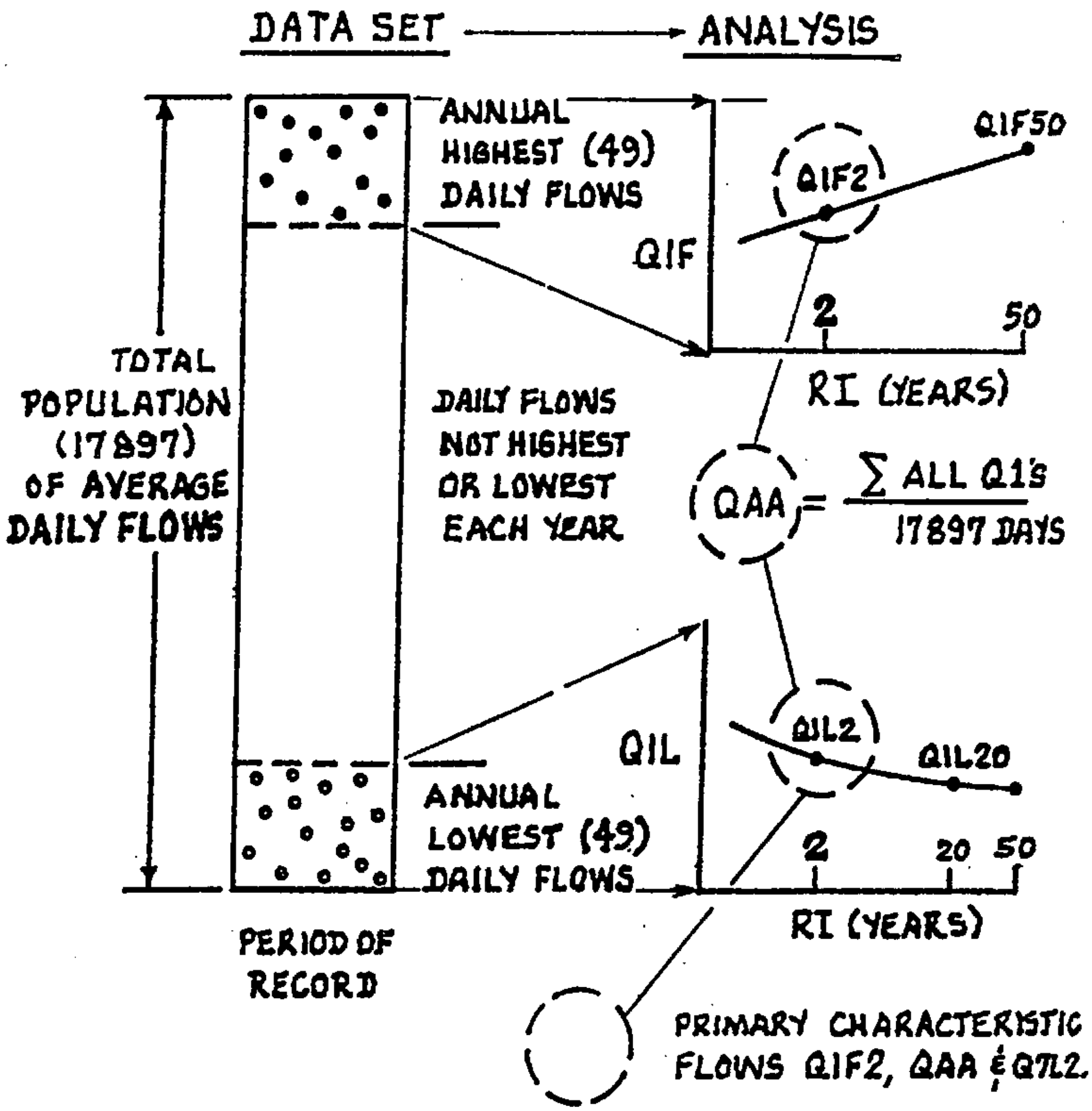


Figure III-13. Graphical representation of a 49-year data set (population) of average daily flows and their analysis by frequency (RI) analysis and the arithmetic mean to develop the three primary characteristic flows (Q1F2, QAA and Q1L2).

Table III-5. Notation for Characteristic Streamflow Abbreviations

QA	Average daily flow for a particular year (arithmetic mean)
QAA	Average annual flow (arithmetic mean) for period of record
Q1L	One-day average low flow for a particular year
MinQ1L	Minimum instantaneous low flow on a particular day
Q7L	Seven-day average low flow for a particular year
Q7L2	Seven-day average low flow with a two-year recurrence interval
Q7L20	Seven-day average low flow with a twenty-year recurrence interval
Q30L	Thirty-day average low flow for a particular year
Q30L2	Thirty-day average low flow with two-year recurrence interval
Q30L20	Thirty-day average low flow with twenty-year recurrence interval
QPF	Peak (instantaneous) flood flow for a particular year
QPF2	Peak flood flow with a two-year recurrence interval
QPF50	Peak flood flow with a fifty-year recurrence interval
Q1F	One-day average flood flow for a particular year
Q1F2	One-day average flood flow with two-year recurrence interval
Q1F50	One-day average flood flow with fifty-year recurrence interval
Q3F2	Three-day average flood with two-year recurrence interval
Q7F2	Seven-day average flood with two-year recurrence interval
Q3F50	Three-day flood with a fifty-year recurrence interval
Q7F50	Seven-day flood with a fifty-day recurrence interval
MaxQPF	Maximum instantaneous peak flood of record
MaxQ1F	Maximum one-day average flood of record
QMA#	Monthly average flow for month # (# = 10-12, 1-9 in a water year
MaxQMA#	Maximum monthly average flow for month #
MinQMA#	Minimum monthly average flow for month #

All of these flows (flood, average, low) are for average daily flow values except for QPF, QPF2, and QPF50 which are instantaneous peak flow values. Daily averages are for sequential numbers of days.

Q	1	F	2	= Q1F2
Flow	No. of Days for which Flow is Averaged	Flood-Type of Flow	Recurrence Interval, Years	

Q356A2 would be an average annual flow for one year (365) with a 2-year RI, but it is abbreviated with QA for one year of data, and QAA as average annual for the period of record (also the arithmetic mean).

Q7L2 is flow, averaged over 7 days, low type, with a 2-year recurrence interval (or Q1L2 for one day).

With 15 to 20 or more years of record, the arithmetic mean of the high, average and low flows is usually very close to the 2-year RI values (statistical means). Wet or dry annual cycles may increase the differences in the arithmetic and statistical means.

Characteristic Flows Defined

These types of statistical mean flows, and others of longer recurrence intervals, or longer periods over which they are averaged, are called **CHARACTERISTIC FLOWS**. They represent different portions of the entire population of average daily flows. Any group of "similar" basins of about the same size, and which receive about the same amount of annual precipitation, will have about the same amount of average annual flow (QAA) (Orsborn and Sood, 1973). But, their characteristic high flows and low flows will vary in size and timing as a function primarily of their geology, soils, form of precipitation and groundwater conditions. When floods come, everything is usually saturated, or the floods are due to rain on snow, or snow melt from saturated or frozen ground. The amount of low flow is being drawn from natural storage in valley soils (or snowpack and glaciers in some headwaters).

But, because the amount of input (precipitation) is, on the average, about the same in a particular sample of basins, then all of the high, average and low events each year are part of the same "population" of events as depicted in Figure III-13. If one basin has shallow or tight soils (clays), or large amounts of bedrock, then runoff will occur more rapidly, there will be less infiltrated water and lower, low flows derived from the source. Conversely, more porous (glaciated) soils will have more infiltration, lower flood flows, and higher low flows. These soils/geology conditions will be reflected in the drainage network density.

These statistical and arithmetic mean flows, as were listed in Table III-5, can be considered to represent a type of **HYDROLOGIC**

SIGNATURE which describes the hydrologic-climatic-geomorphic characteristics of a region (hydrologic province). Given a particular series of annual precipitation events over a period of time, basins within a province will tend to release these **SIGNATURE or CHARACTERISTIC FLOWS** at an order of magnitude that integrates the precipitation in a manner which reflects the dominant "geomorphic-geologic-vegetative" conditions in the basins. Ratios of characteristic flows (and others) are good indices for classification of basins (and stream size) as will be demonstrated later in Appendix VII.

Relationships Among Characteristic Flows and Their Utility

The three **PRIMARY CHARACTERISTIC FLOWS** are the two averages of the extreme events (Q1F2 and Q7L2) and the average of all the daily events, QAA (Figure III-13). But, because there is usually very little difference between the one-day average low flow (Q1L2) and the 7-day average low flow (Q7L2) the latter is used as the average low flow. Also, the Q7L10 is a water quality standard (10-year RI, probability of 0.10 in any year). In addition, the 20-year low flow (Q7L20) is considered to be a "base flow," a legal standard for natural, fair weather flows below which diversions are usually not allowed so as to protect instream, base flow values ($p = 0.05$ or 1/20 each year).

It has been found (Amerman and Orsborn, 1987) that a relationship exists among these three **primary characteristic flows** such that

$$Q7L2 = 8.0\ (QAA)^3/(Q1F2)^2$$

and also

$$Q7L2 = 50.8\ (QAA)^3/(Q1F50)^2$$

for 2- and 50-year average daily floods in gaged streams on the Olympic Peninsula.

These are called "1,2,3 POWER" relationships and were developed originally as part of the WDOE State Water Planning Program in the Lewis River Study Area (Orsborn and Sood 1973). They provide a very strong hydrologic model for flow estimation, verification and extrapolation. These power relationships are based on the longest periods of record available and are better ways for estimating floods of larger recurrence intervals than by statistically extending a short period of record using a Log-Pearson III equation.

Other important aspects of the PRIMARY CHARACTERISTIC FLOWS in a hydrologic province are their consistent plotting positions for the percent of time they are equalled or exceeded on a duration curve x-axis. This is demonstrated in Table III-6.

Knowing these percentages and the general shape of duration curves for gages in a hydrologic province, one can estimate the average annual duration curve for an UNGAGED SITE by estimating (modeling) just the three characteristic flows: Q1F2, QAA and Q7L2. The percent of time for Q1F2 can be assumed to be zero, and for Q7L20 the percent of time is

Table III-6. Percentage of Time Characteristic Flows are Exceeded for Eight Stream Gages on the Olympic Peninsula*

Province/ Stream Gage Code	Station Name	USGS No. 12-	Q7L2 (% time)	QAA (% time)	Q1F2 (% time)
1.5	Humptulips R.	039000	95.8	30.9	0.24
2.3	Dickey R.	043100	99.4	30.9	0.25
3.1	N.F. Quinault	039300	96.9	33.9	0.51
4.1	Hoko R.	043300	97.3	31.7	0.16
5.2	Dungeness R.	048000	95.8	36.0	0.36
6.2	Snow Creek	050500	97.1	32.8	0.33
8.2	Duckabush R.	054000	96.8	36.4	0.28
9.2	Kennedy Creek	078400	96.5	32.4	0.24

*Not for common periods of record, which could be increasing the variability.

Table III-7. Characteristic Flows for Twenty Stream Gages on the Olympic Peninsula: Low, Average and Flood Flows for the Period of Record at Each Station (From Amerman and Orsborn, 1987, Table 7-1, Page 7-5).

Province/ Stream Gage Code	Station Name	USGS Gage No. 12-	Q30L20 (cfs)	Q7L20 (cfs)	Q30L2 (cfs)	Q7L2 (cfs)	Min QA (cfs)	QAA (cfs)	Max QA (cfs)	Q1F1.01 (cfs)	Q1F2 (cfs)	Q1F50 (cfs)
1.1	Cloquallum River	032500	20	15	27	24	205	274	367	1074	2492	4202
1.3	Satsop River	035000	212	197	263	239	1199	2016	2908	8783	18307	39003
1.5	Humptulips River	039000	107	95	167	147	868	1337	1878	5976	13393	24278
2.1	Moclips River	039220	3.1E	2.5E	6.9E	5.5E	134E	213E	288E	1119E	2732E	5273E
2.3	Dickey River	043100	7.0E	5.7E	16E	13E	340	549E	747	3028E	7599E	14970E
2.4	Sooes River	043163	3.9E	3.3E	8.4E	6.7E	135E	208E	276E	986E	2278E	4222E
3.1	N.F. Quinault River	039300	137	115	212	161	564	861	1151	2656	6182	17463
3.5	Hoh River	041000	525	401	778	610	1396	2028	2576	6768	13054	27476
3.7	Soleduck River	041500	67	58	96	79	359	621	832	2711	6021	13723
4.1	Hoko River	043300	16	14	25	20	292	408	585	2413	4739	9561
4.2	E. Twin River	043430	3.0	2.7	4.4	3.7	43	65	81	280	595	882
5.2	Dungeness River	048000	89	77	133	114	197	376	545	613	1903	5186
6.1	Siebert Creek	047500	2.3	2.0	2.8	2.6	7.0	17	36	38	249	1263
6.2	Snow Creek	050500	1.8	1.5	2.7	2.2	9.0	16	22	59	151	478
6.3	Little Quilcene River	052000	7.4E	6.2E	11E	9.4E	26E	49E	71E	127E	365E	1136E
8.2	Duckabush River	054000	58	49	90	73	204	414	564	1093	2965	5699
8.3	Hamma Hamma River	054500	45	40	71	60	258	364	459	1013	2576	5379
8.8	S.F. Skokomish River	060500	74	68	100	89	424	732	1041	3170	7083	15449
9.1	Goldsborough Creek	076500	18	16	22	21	79	116	163	327	778	1435
9.2	Kennedy Creek	078400	2.1	1.8	3.1	2.7	47	61	78	268	563	1114

All characteristic flows based on longest period of record through 1979.
E Estimates based on correlation with one or more gages

assumed to be 100. Models for these procedures are discussed later in this appendix.

A sample of characteristic flows for the entire Olympic Peninsula is presented in Table III-7. When the ratios of these flows are developed in a region (hydrologic province) they offer an easy and powerful hydrologic set of tools for estimating ungaged stream flows at monitoring and research sites.

Hydrologic Models to Estimate Ungaged Streamflows

Introduction

To briefly recapitulate about hydrologic models, ungaged streamflows, and project design flows:

- models are ways of representing reality in the natural or modified basin;
- simpler models with fewer terms and few assumptions are usually better;
- we will use models based on relationships among basin characteristics and streamflows, and among certain streamflows;
- we will use average annual precipitation only in one model to estimate average annual flow;
- most project /control/monitoring/research (called **PROJECT SITES** from hereon) sites usually would be classified as ungaged, and it is always best to make a few flow measurements during low flow periods (when it is easier and safer) to check your model estimates;
- fisheries flows which may be impacted directly or indirectly through changes in channel geometry include:
    - passage season flows in wide and steep channel reaches;
    - passage season flows at waterfalls, chutes, cascades and culverts;
    - spawning season duration curves;
    - duration curves for critical rearing seasons such as overwintering and summer low flows; and
- land use impacts on flows could include increased highs, increased or decreased lows, and shifts in the seasonal timing of the flow regime.

Definition of the Problem

Hydrologic models can range from very simple relationships to very complicated models with many variables. But, just because a model contains numerous variables does not guarantee the best results. Models must always be calibrated and verified (determine the coefficients and the exponents in the equations) from stream gaging records. There has to be a reasonable balance between resources expended in the modeling analysis, and the amount and value of the streamflow generated by modeling and/or measurements for projects. For example, a hydrologic analysis for engineering design of culverts could just as easily check upstream passage conditions for fish during their migration seasons.

In using hydrologic models we are trying to relate the streamflow characteristics of a region to a small portion of that region as shown in Figure III-14. We are only generating the stream flows, and later we will analyze those flows with respect to the characteristics of the stream segments.

In some situations adequate streamflow information to develop regional hydrologic models may not be available. In those cases you have the option of making a series of stream measurements at the site, and then correlating those site flows against the same-day flows at a "nearby" (base) gage. Without other adequate gages for modeling you would probably have to make more measurements at the project site to improve your correlation model against the base gage.

Information Needed to Develop Hydrologic Models

The following types of information are needed for the purposes shown:

Information Source	Purposes
Long-term USGS Gaging Station Records	Statistical analysis; BASE STATIONS; characteristic flows for region; ranges of annual monthly and seasonal flows; maxima and minima
Miscellaneous and Crest-Stage Flows	To fill data gaps in a region where continuous records are not widely available.
Topographic Maps	Determine basin characteristics to correlate to regional characteristic flows at gage sites (develop models).
Precipitation Map	Determine average annual basin INPUT (or use USGS values for basins above stream gages).

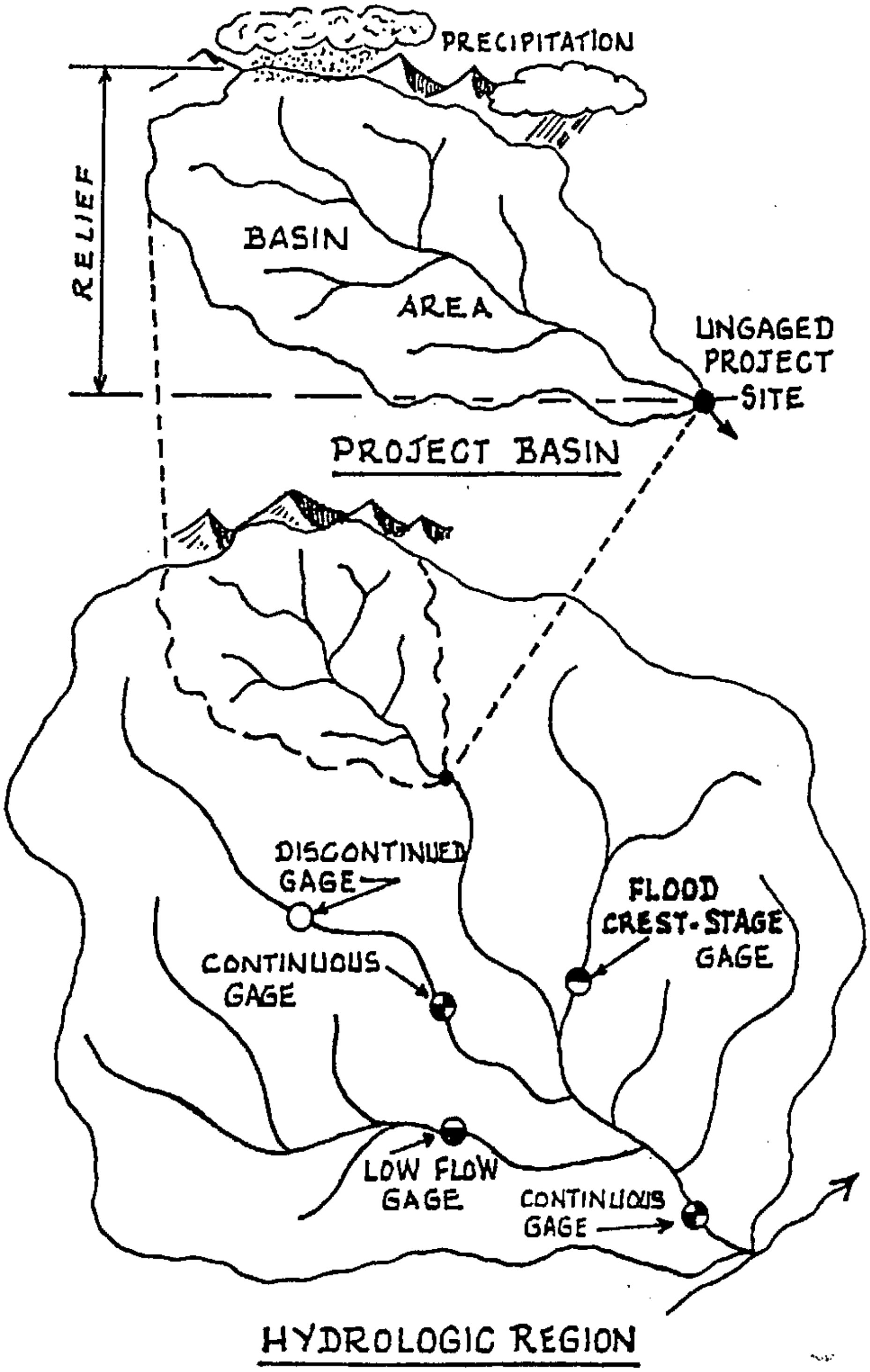


Figure III-14. Regional stream gages for modeling (estimating) streamflows at an ungaged site within the region.

The BASE STATIONS in a region are used as references to determine long-term trends and flow fluctuations, and for correlation with records from short-term gaging stations and with streamflow measurements at project sites. These base stations are fundamental to classifying streams in particular provinces or within larger ecoregions.

Methods of Data Analysis and Hydrologic Model Development

We will consider three types of hydrologic models:

1) where streamflow (output) is related to precipitation (input), OUTPUT:INPUT;

2) STREAMFLOW (dependent output) is related to physical (geomorphic) basin characteristics which regulate (independently control) the streamflow released from the basin; and

3) models which interrelate one type of streamflow (characteristic flows) to another type of streamflows, OUTPUT:OUTPUT MODELS, or flow to flow relationships.

Several specific models exist within each of these three types. They are summarized before examples are given. The general logic for all the hydrologic models is shown in Table III-8.

1) FLOW IS A FUNCTION OF PRECIPITATION (INPUT:OUTPUT):

- storm precipitation at a gage can be related to flood events;
- seasonal precipitation at a gage can be accumulated and related to a subsequent flood; or
- average annual streamflow (output) can be related to average annual precipitation (input) over a whole basin or region.

2) FLOW IS A FUNCTION OF BASIN CHARACTERISTICS (OUTPUT:CONTROLS):

- many characteristic flows are related to drainage area (A).
- using average annual flow as an example QAA = C(A), where C is a coefficient determined from the regional graph of QAA = C(A) for a series of gages with different QAA and A values.
- introduce average annual precipitation (P) values for each gaged basin either from Williams et al. (1985) or as measured from an isohyetal map (Figure III-15).
- combine the equations of QAA = C(A) by solving for (C) as a function of average annual precipitation (P).

Table III-8. Logic for the Development of Hydrologic Models

A. BASIN CHARACTERISTICS
   1. Relate area, relief, stream length, etc. to each other to reduce future measurements and to characterize geologic provinces.

B. STREAMFLOW CHARACTERISTICS
   1. Generate available streamflow data from existing and discontinued gages, and miscellaneous measurements.
   2. Establish baseline, long-term gages in each hydrologic (climatic) province.
   3. Cross-correlate short- to long-term gages to extend records and improve reliability of characteristic flows (low, average, floods, and monthly).
   4. Do computer runs of flow frequencies, durations and probability distributions, unless already completed by USGS.

C. COMBINE BASIN AND STREAMFLOW CHARACTERISTICS TO GENERATE THE REGIONAL (PROVINCIAL) HYDROLOGIC MODELS ...
   1. Select gaged basins to set aside for testing model.
   2. Relate characteristic flows to basin characteristics in part (A).

D. CHANNEL CHARACTERISTICS
   1. Select sample of channels with typical, but various, geometric shapes which are deformable (not constrained by bedrock, hardpan, etc.), in province.
   2. Relate flows to hydraulic geometry of the sample channel sections (width, depth, velocity, wetted perimeter, flow area, bankfull flows, bed materials and gradient).

E. COMBINE STREAMFLOW AND CHANNEL CHARACTERISTICS TO GENERATE CHANNEL MORPHOLOGY MODELS .... Called Hydraulic Geometry.

F. COMBINE BASIN AND CHANNEL CHARACTERISTICS TO GENERATE BASIN-CHANNEL MORPHOLOGY MODELS .... Channel geometry depends on basin geometry.

G. TEST THE HYDROLOGIC MODELS
   1. Use gaged sites that were set aside.
   2. Estimate flows at ungaged sites in each province.
   3. Verify estimates with miscellaneous measurements at ungaged sites.
   4. Expand the calibration model for easily accessible and selected remote basins.
   5. Define hydrologic and geologic anomaly areas for further study.

H. CONSOLIDATE AND ASSESS RESULTS
   1. Define stream gaging needed to complete calibration of models in anomaly areas.
   2. Make miscellaneous measurements to refine calibration.

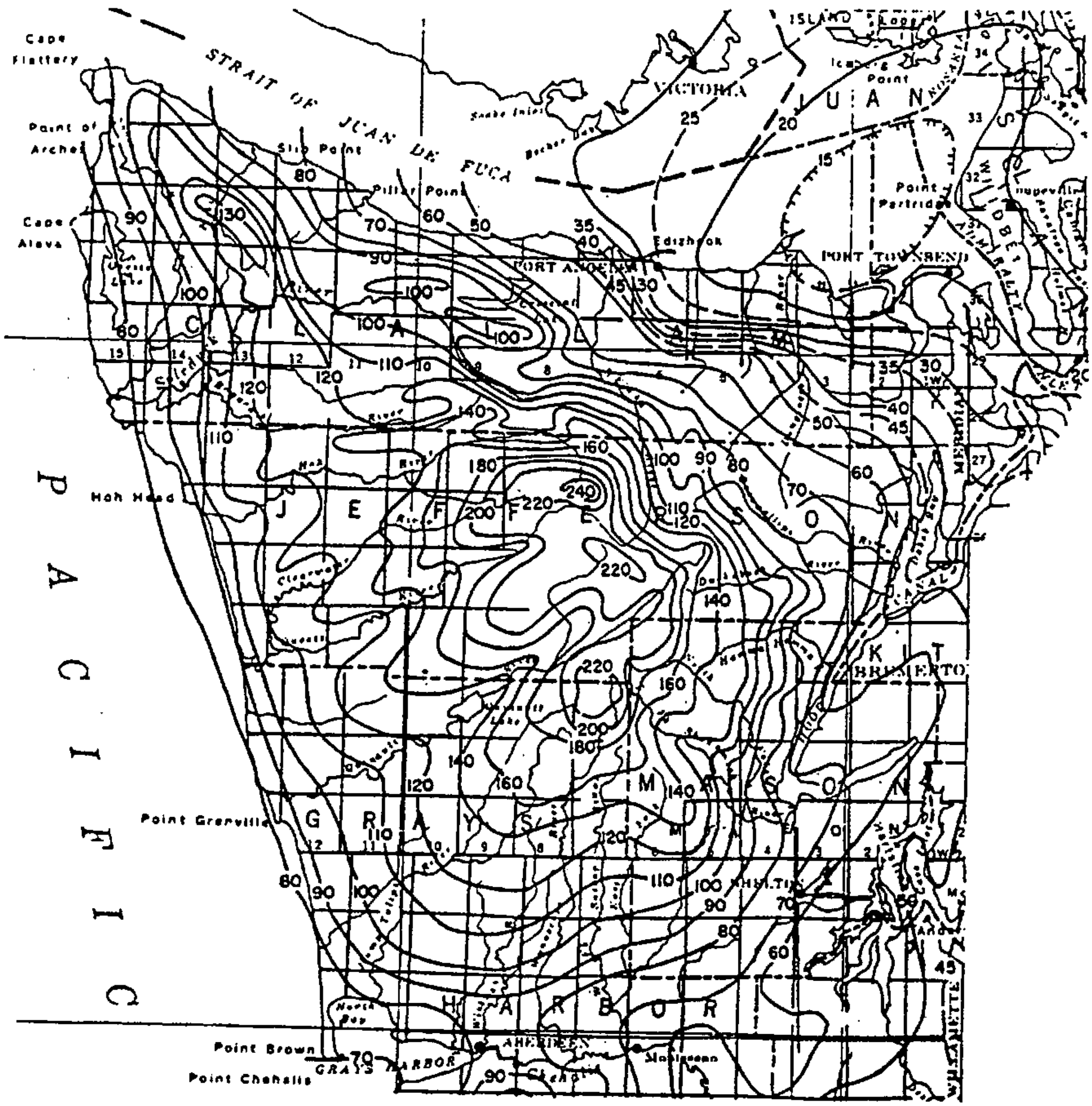


Figure III-15. Isohyetal chart of average annual precipitation on the Olympic Peninsula. Reproduced from the State of Washington chart (USWB 1965).

- this provides a general solution for $QAA = C'(P)^n(A)^{1.10}$ for any basin on the Olympia Peninsula, or for whatever region it is developed.

- the **BASIN ENERGY MODEL** is a physically (dimensionally) correct model which considers gravity forces and the potential ENERGY (RELIEF, H) of the watersheds such that any characteristic flow (Q_X where x means "unknown") at a gaging station

$$Q_X = C(g)^{0.5}\,[A(H)^{0.5}]$$

where $C(g)^{0.5}$ is combined into a coefficient for each type of primary characteristic flow (flood, average annual and low). Gravity is considered a constant, so $(g)^{0.5} = 5.67$ is in each model coefficient. The coefficients for each type of model are determined by plotting each gaged characteristic flow versus $(A)\,(H)^{0.5}$ and performing a regression analysis either mathematically or graphically. All the subsequent tables and figures in this appendix are from **Amerman and Orsborn 1987.**

3) MODELS WHICH INTERRELATE CHARACTERISTIC STREAMFLOWS **(LOW:AVERAGE: FLOOD):**

- Correlate same-day average flows at one site to another site with longer records;

- relate peak floods to average daily floods of longer duration such as 1-, 3- and 7-day average floods;

- ratios of characteristic flows such as those shown for a sample of gages on the Olympic Peninsula in Table III-9;

- ratios of monthly flows to average annual flows for determining average monthly and seasonal flows, and their variability; and

- interrelationships of low, average and flood flows such as the 1-2-3 power relationship discussed earlier.

Examples of Hydrologic Models

The rest of this part of the hydrology section deals with a detailed discussion of:

1) several types of hydrologic models; and

2) the application of these models to estimate various project flows.

Basic Information

The description and code numbers of the stream gages used in developing these models are listed in Table III-10. Not all of the gages are used in all models due to limitations on their periods of

Table III-9. Ratios of Characteristic Flows for Twenty Stream Gages on the Olympic Peninsula: Low, Average and Flood Flows for Period of Record at Each Station.

Province/ Stream Gage Code	Station Name	USGS Gage No. 12-	Q7L2 / Q7L20	Q7L2 / Q30L2	Q7L20 / Q30L20	Q7L20 / QAA	Q7L2 / QAA	QAA / Q7L2	Q1F1.01 / QAA	Q1F2 / QAA	Q1F50 / QAA	Q1F50 / Q1F2	Q1F2 / Q7L2	Min QA / QA (%)	Max QA / QA (%)
1.1	Cloquallum River	032500	1.57	0.90	0.76	0.056	0.088	11.3	3.9	9.1	15.3	1.7	103.0	74.8	133.9
1.3	Satsop River	035000	1.21	0.91	0.93	0.098	0.120	8.4	4.4	9.1	19.4	2.1	76.6	59.5	144.2
1.5	Humptulips River	039000	1.55	0.88	0.89	0.071	0.110	9.1	4.5	10.0	18.2	1.8	91.1	64.9	140.5
2.1	Moclips River	039220	2.20E	0.80E	0.81E	0.012E	0.026E	38.7E	5.2E	12.8E	24.8E	1.9E	496.7E	62.9E	135.2E
2.3	Dickey River	043100	2.21E	0.79E	0.81E	0.010E	0.023E	43.6E	5.5E	13.8E	27.3E	2.0E	603.1E	61.9E	136.1E
2.4	Sooes River	043163	2.03E	0.80E	0.85E	0.016E	0.032E	31.0E	4.7E	11.0E	20.3E	1.8E	340.0E	64.9E	132.7E
3.1	N.F. Quinault River	039300	1.40	0.76	0.84	0.130	0.190	5.4	3.1	7.2	20.3	2.8	38.4	65.5	133.7
3.5	Hoh River	041000	1.52	0.78	0.76	0.200	0.300	3.3	3.3	6.4	13.6	2.1	21.4	68.8	127.0
3.7	Soleduck River	041500	1.36	0.82	0.87	0.093	0.130	7.9	4.4	9.7	22.1	2.3	76.2	57.8	134.0
4.1	Hoko River	043300	1.43	0.80	0.88	0.034	0.049	20.4	5.9	11.6	23.4	2.0	237.0	71.6	143.4
4.2	E. Twin River	043430	1.37	0.84	0.90	0.042	0.057	17.6	4.3	9.2	13.6	1.5	160.8	66.1	124.6
5.2	Dungeness River	048000	1.48	0.86	0.87	0.200	0.300	3.3	1.6	5.1	13.8	2.7	16.7	52.4	144.9
6.1	Siebert Creek	047500	1.30	0.93	0.87	0.120	0.150	6.6	2.2	14.6	73.9	5.1	95.8	40.9	210.5
6.2	Snow Creek	050500	1.47	0.81	0.83	0.094	0.140	7.4	3.6	9.3	29.5	3.2	68.6	55.5	138.9
6.3	Little Quilcene River	052000	1.52E	0.82E	0.84E	0.130E	0.190E	5.2E	2.6E	7.5E	23.4E	3.1E	38.8E	53.5E	146.1E
8.2	Duckabush River	054000	1.49	0.81	0.84	0.120	0.150	6.5	2.6	7.2	13.8	1.9	40.6	49.3	136.2
8.3	Hamma Hamma River	054500	1.50	0.85	0.89	0.110	0.160	6.1	2.8	7.1	14.8	2.1	42.9	70.9	126.1
8.8	S.F. Skokomish River	060500	1.31	0.89	0.92	0.093	0.120	8.2	4.3	9.7	21.1	2.2	79.6	57.9	142.2
9.1	Goldsborough Creek	076500	1.31	0.95	0.89	0.140	0.180	5.5	2.8	6.7	12.4	1.8	37.0	68.1	140.5
9.2	Kennedy Creek	078400	1.50	0.87	0.86	0.030	0.044	22.6	4.4	9.2	18.3	2.8	208.5	72.0	127.9

All characteristic flows based on longest period of record through 1979.

E Ratios made with estimated flows based on correlation with one or more gages

Table III-10. USGS Continuous Gaging Stations Used in Olympic Peninsula Streamflow Models: Province/Streamgage Code, Stream/Gage Name and USGS Gage Number

Province/Stream Gage Code	Gage Name	USGS Gage No. 12-
1.1	Cloquallum River at Elma, WA	032500
1.2	E.F. Satsop River near Elma, WA	034200
1.3	Satsop River near Satsop, WA	035000
1.4	Wyoochee River at Oxbow, near Aberdeen, WA	035500
1.5	Humptulips River near Humptulips, WA	039000
2.1	Moclips River at Moclips, WA	039220
2.2	Raft River below Rainy creek near Queets, WA	039520
2.3	Dickey River near La Push, WA	043100
2.4	Sooes River below Miller Creek near Ozette, WA	043163
3.1	N.F. Quinault River near Amanda Park, WA	039300
3.2	Quinault River at Quinault Lake, WA	039500
3.3	Queets River near Clearwater, WA	040500
3.4	Clearwater River near Clearwater, WA	040000
3.5	Hoh River near Forks, WA	041000
3.6	Hoh River at U.S. Hwy 101 near Forks, WA	041200
3.7	Soleduck River near Fairholm, WA	041500
4.1	Hoko River near Sekiu, WA	043300
4.2	E. Twin River near Pysht, WA	043430
4.3	Lyre River at Piedmont, WA	044000
5.1	Elwha River at McDonald Bridge near Port Angeles, WA	045500
5.2	Dungeness River near Sequim, WA	048000
6.1	Siebert Creek near Port Angeles, WA	047500
6.2	Snow Creek near Maynard, WA	050500
6.3	Little Quilcene River near Quilcene, WA	052000
8.1	Dosewallips River near Brinnon, WA	053000
8.2	Duckabush River near Bronnon, WA	054000
8.3	Hamma Hamma River near Eldon, WA	054500
8.4	Jefferson Creek near Eldon, WA	054600
8.5	N.F. Skokomish River below Staircase Rapids near Hoodsport, WA	056500
8.6	Deer Meadow Creek near Hoodsport, WA	058000
8.7	S.F. Skokomish River near Potlatch, WA	060000
8.8	S.F. Skokomish River near Union, WA	060500
9.1	Goldsborough Creek near Shelton, WA	076500
9.2	Kennedy Creek near Kamilche, WA	078400

record. The locations of the gaging stations are shown in Figure III-16.

To determine whether a period of streamflow record is in a relatively wet or dry cycle, the year to year variation in the long-term average annual flow must be determined. This is done by comparing the average annual flow for each year of record with the long-term average flow at a **BASE STATION** in each hydrologic province. This relationship of average annual flow to long-term average flow is shown in column 3 of Table III-11 for the North Fork Skokomish River below Staircase Rapids at gage 12056500. The basin for this gage is in the Olympic National Park, is in a natural state, and there are no gaps in the records. In Table III-11 the sliding 5-year averages are tabulated for estimating wet and dry cycles for gages having short periods of record.

The fourth type of information needed to develop regional (provincial) models involves basin characteristics (Table III-12). The characteristics used in these models include: basin relief(H); drainage area (A); average annual precipitation (P); and the combined parameters of (P·A) and $A(H)^{0.5}$.

Correlation Models

Correlation procedures relate a streamflow at a project site to the same-day streamflow at a long-term gage (or just at another site). The plotted flows might be same-day, average weekly, monthly, seasonal, or annual peak or minimum flows. A typical correlation model is presented in Figure III-17 for Jefferson Creek (Sta. 8.4) as a function of the downstream gage on the Hamma Hamma River (Sta. 8.3). The characteristics of the graphical relationships in Figure III-17 are as follow, beginning with low flows in the lower left hand part of the graph:

- following the lowest summer flows, the fall increases in streamflow follow a straight, steep line (solid dots); this relationship says flows are increasing faster in Jefferson Creek than in the Hamma Hamma during the fall-winter season;

- at flows above 1000 cfs at both sites annual, high 1-day flows (floods) increase more rapidly at the Hamma Hamma gage;

- as flows recede in the spring and summer they tend to follow the curved relationship which says that Jefferson Creek has a much smaller low flow storage than does the Hamma Hamma River; and

- minimum flows are on the order of 10 cfs in Jefferson Creek and 40 cfs in the Hamma Hamma River.

This fall-winter-spring-summer correlation loop is typical of many stream relationships on the Peninsula, where one has more snowpack or glaciers to sustain low flows. Both respond similarly, as a function of size and elevation, to seasonal storms and dominant climatic patterns. By entering the long-term statistical values for the Hamma Hamma gage CHARACTERISTIC FLOWS on the x-axis, the same flows can be estimated for

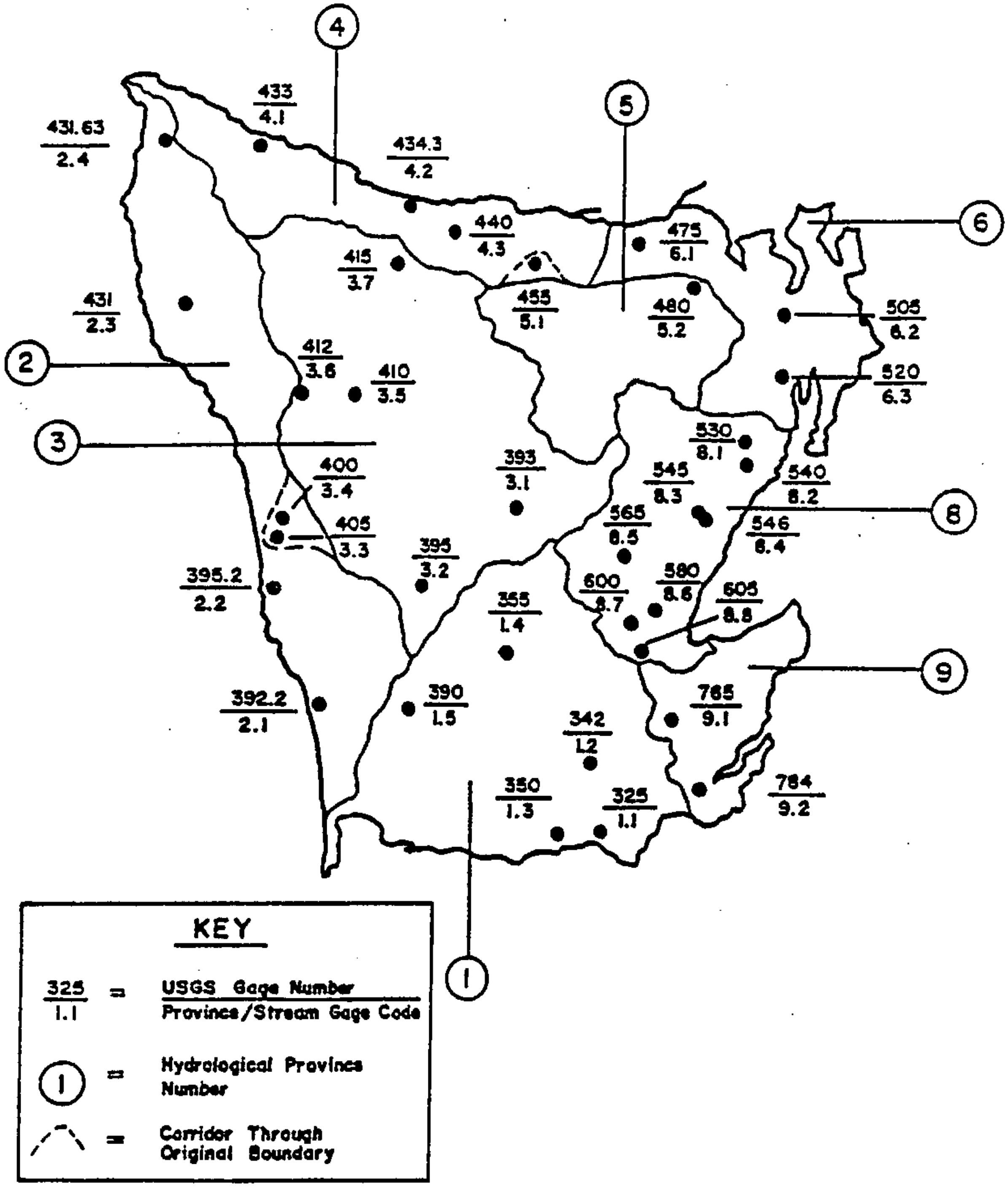


Figure III-16. Continuous USGS stream gaging stations used in study: USGS gage number, and province/stream gage code (USGS gage no. has prefix of 12-).

Table III-11. Sliding Ratios of Average Annual Flow for the Base Station on the N.F. Skokomish River at USGS Gage 12056500 for Period 1925-1984

Year	Average Flow Rate[a]	R[b]	R5[c]	R10	R15	R20	R25	R30	R35	R40	R45	R50	R55	R60
1984	552.0	1.083												
1983	671.0	1.317												
1982	640.0	1.256	1.150											
1981	505.0	0.991												
1980	563.0	1.105		1.04										
1979	340.0	0.667												
1978	607.0	1.191												
1977	292.0	0.573	0.931		1.07									
1976	645.0	1.266												
1975	487.0	0.956		1.03		1.07								
1974	755.0	1.482												
1973	442.0	0.867												
1972	603.0	1.183	1.126		1.04		1.06							
1971	627.0	1.231												
1970	441.0	0.866		1.09		1.04		1.07						
1969	567.0	1.113												
1968	650.0	1.276												
1967	600.0	1.178	1.055		1.07		1.05		1.08					
1966	488.0	0.958												
1965	381.0	0.748		1.05		1.08		1.07		1.08				
1964	542.0	1.064												
1963	513.0	1.007												
1962	406.0	0.797	1.036		1.06		1.09		1.05		1.04			
1961	649.0	1.274												
1960	528.0	1.036		1.07		1.08		1.07		1.02		1.02		
1959	548.0	1.076												
1958	530.0	1.040												
1957	477.0	0.936	1.098		1.09		1.06		1.04		1.01		1.01	
1956	688.0	1.350												
1955	555.0	1.089		1.12		1.06		1.02		1.02		1.00		1.00
1954	617.0	1.211												
1953	564.0	1.107												
1952	496.0	0.973	1.146		1.07		1.01		1.01		1.00		0.99	
1951	615.0	1.207												
1950	626.0	1.229		1.05		1.01		1.00		0.99		0.99		
1949	449.0	0.881												
1948	538.0	1.056												
1947	422.0	0.828	0.957		0.98		0.99		0.98		0.98			
1946	558.0	1.095												
1945	471.0	0.924		0.89		0.96		0.97		0.97				
1944	310.0	0.608												
1943	387.0	0.760												
1942	415.0	0.814	0.831		0.90		0.094		0.96					
1941	490.0	0.962												
1940	516.0	1.013		0.87		0.89		0.93						
1939	384.0	0.754												
1938	526.0	1.032												
1937	399.0	0.783	0.917		0.87		0.89							
1936	421.0	0.826												
1935	606.0	1.189		0.93		0.88								
1934	552.0	1.083												
1933	524.0	1.028												
1932	500.0	0.981	0.872		0.89									
1931	391.0	0.767												
1930	256.0	0.502		0.88										
1929	310.0	0.608												
1928	457.0	0.897												
1927	550.0	1.079	0.882											
1926	356.0	0.699												
1925	573.0	1.125												

[a]Long-term average flow is 510 cfs.

[b]R = Ratio of year to long-term averages.

[c]R5, etc. = Sliding five-year averages.

Table III-12. Basin Characteristics for the Twenty USGS Base Gaging Stations on the Olympic Peninsula

Province/ Stream Gage Code	Station Name	USGS Gage No. 12-	Gage Elev. (ft)	Headwater Elev. (ft)	Basin Relief, H (ft)	Basin Relief, H (mi)	Drainage Area, A (sq. mi)	Average Annual Precip., P (in/yr)	COMBINED PARAMETERS Basin Input (PA) (sq.mi-in/yr)	COMBINED PARAMETERS Basin Energy (A)(H)$^{0.5}$ (mi)$^{2.5}$
1.1	Cloquallum River	032500	20	800	780	0.15	64.9	72	4673	25.1
1.3	Satsop River	035000	30	2500	2470	0.47	299.0	128	38272	205.0
1.5	Humptulips River	039000	120	3200	3080	0.58	130.0	155	20150	99.0
2.1	Moclips River	039220	25	500	475	0.09	35.0	120	4200	10.5
2.3	Dickey River	043100	50	1000	950	0.18	86.3	95	8199	36.6
2.4	Sooes River	043163	70	800	730	0.14	32.0	116	3712	11.5
3.1	N.F. Quinault River	039300	620	4000	3380	0.64	74.1	200	14820	59.3
3.5	Hoh River	041000	320	4500	4180	0.79	208.0	167	34736	184.9
3.7	Soleduck River	041500	1060	4160	3100	0.59	83.8	99	8296	64.4
4.1	Hoko River	043300	50	1200	1150	0.22	51.2	124	6349	24.0
4.2	East Twin River	043430	10	1200	1190	0.22	14.0	90	1260	6.6
5.2	Dungeness River	048000	570	5000	4430	0.84	156.0	62	9672	143.0
6.1	Siebert Creek	047500	280	2000	1720	0.33	15.5	41	636	8.9
6.2	Snow Creek	050500	220	3400	3180	0.60	11.2	43	482	8.7
6.3	L. Quilcene River	052000	90	3600	3510	0.66	19.6	51	1000	15.9
8.2	Duckabush River	054000	240	5000	4760	0.90	66.5	113	7514	63.1
8.3	Hamma Hamma River	054500	510	4000	3490	0.66	51.3	110	5643	41.7
8.8	S.F. Skokomish River	060500	100	3400	3300	0.63	76.3	153	11674	60.6
9.1	Goldsborough Creek	076500	200	360	160	(0.030)	39.3	84	3301	6.8
9.2	Kennedy Creek	078400	110	400	290	(0.055)	17.4	59	1027	4.1

All characteristics except headwater elevation are from USGS Annual Gaging Station Records, and Williams et al. (1985).

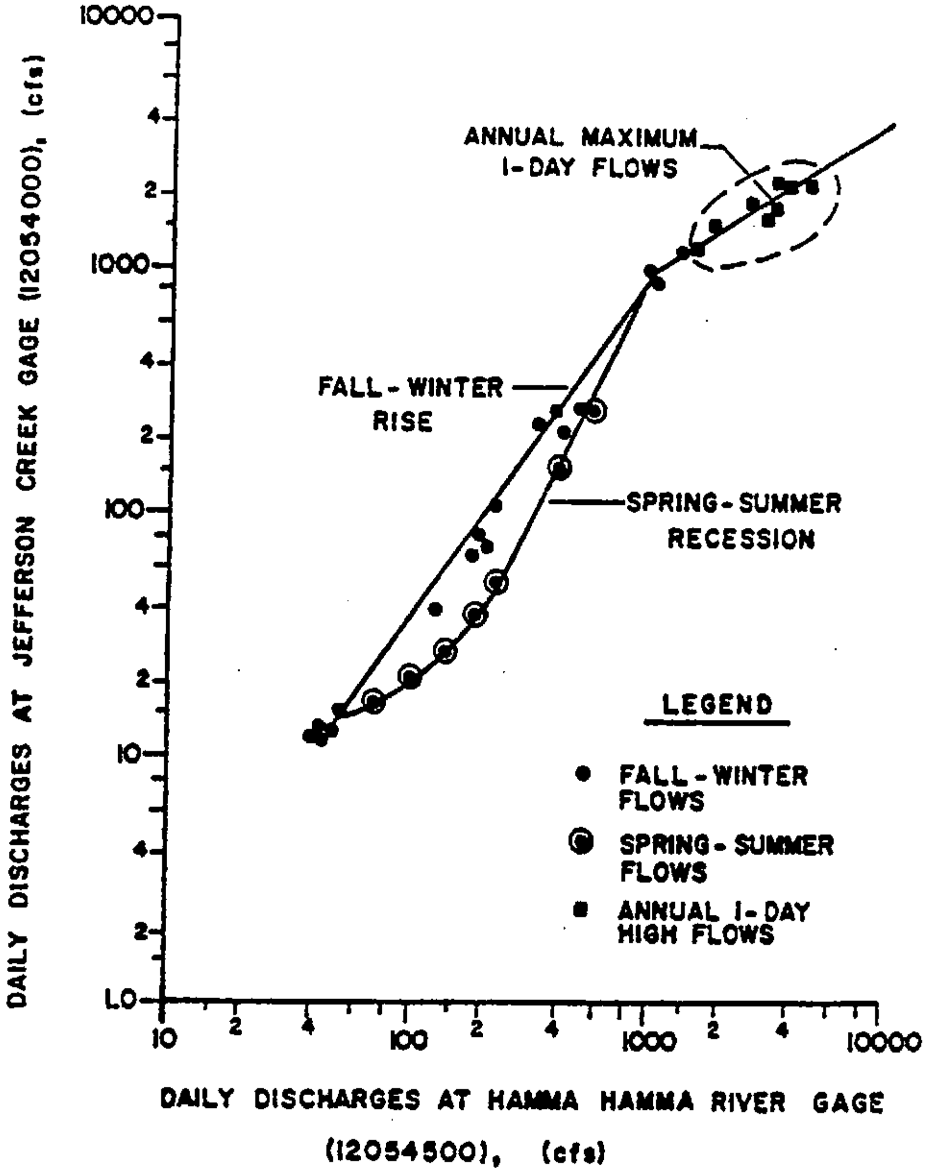


Figure III-17. Correlation of a sample of Jefferson Creek daily flows in 1970 and 1971, and annual maximum one-day flows for 1964-1971 versus same-day flows on the Hamma Hamma River.

Jefferson Creek. Dry- and wet-year correlations may vary from the average graph. Also, strong seasonal correlations may exist, such as for summer flows, even though the full range of flows may give a scattered correlation.

Models of Streamflow Using Basin Characteristics

Almost all models which use basin characteristics to estimate streamflows use drainage area (A) as the primary characteristic. We will start with area (A), then add average annual precipitation (P) on the basin area, and then consider basin relief (H). An important design flow to get an approximation of the expected upper limit of flood flows is the **PEAK FLOOD OF RECORD**. These are listed for gages on the Olympic Peninsula in Table III-13, and plotted versus (as a function of) drainage area in Figure III-18. The dashed lower lines form the most probable envelope and these lines are very similar in location to the same plot for Alaska streams. Once the drainage area exceeds about 40 sq. mi., the rate of increase in the size of peak floods decrease. For basins up to about 40 sq. mi. in area the maximum probable peak flood is

$$QPF\ (Max) = 3.50\ (A)^{2.25} \text{ and}$$

for basins larger than 40 sq. mi.

$$QPF\ (Max) = 4400\ (A)^{0.47}$$

These values would be safe estimates for most basins far from the envelope lines, but not as safe for basins in Provinces 3, 4, 6 or 8 (near the lines). Values estimated using these relationships should be considered only as preliminary flows until further analyses can be made of the 2-year and 50-year floods and their recurrence interval graph.

Relationships between the primary characteristic flows and drainage area are shown in Figures III-19 and -20.

Figure	Flow Related to Drainage Area(A)
III-19a	Fifty-year, one-day flood
III-19b	Two-year, one-day flood
III-20a	Average annual flow
III-20b	Seven-day, two-year low flow

Note that each figure has a series of parallel lines which indicate a value of "Q"/A or cfs/sq. mi., or unit values. The largest and smallest unit values which can be used as rough design flows are:

Province/ Stream Gage Code	Station Name	Drainage Area (A) (Sq mi)	Peak Flood of Record (QPF) (cfs)	(date)
1.1	Cloquallum River	64.9	5,080	12/15/59
1.3	Satsop River	299.0	46,600	1/22/35
1.5	Humptulips River	130.0	33,000	1/22/35
2.1	Moclips River	35.0	4,260	12/26/75
2.2	Raft River	76.0	17,200	12/26/75
2.3	Dickey River	86.3	17,300	1/19/68
2.4	Sooes River	32.0	3,270	11/25/77
3.1	N.F. Quinault River	74.1	26,800	11/01/77
3.3	Queets River	445.0	130,400	1/22/35
3.4	Clearwater River	140.0	37,400	11/03/55
3.5	Hoh River	208.0	38,700	11/26/49
3.6	Hoh River	253.0	46,000	1/15/61
3.7	Soleduck River	83.8	22,500	11/26/49
4.1	Hoko River	51.2	14,100	12/25/72
4.2	E. Twin River	14.0	1,220	11/19/62
5.1	Elwha River	269.0	30,000	11/26/49
5.2	Dungeness River	156.0	6,820	11/27/49
6.1	Siebert Creek	15.5	1,620	11/03/55
6.2	Snow Creek	11.2	733	1/08/59
8.1	Dosewallips River	94.0	13,200	11/26/49
8.2	Duckabush River	66.5	8,960	11/26/49
8.3	Hamma Hamma River	51.3	6,010	1/14/68
8.4	Jefferson Creek	21.6	3,160	12/13/66
8.5	N.F. Skokomish River	57.2	27,000	11/05/34
8.6	Deer Meadow Creek	1.8	445	1/15/61
8.8	S.F. Skokomish River	76.3	21,600	1/22/35
9.1	Goldsborough Creek	39.3	1,430	1/19/68
9.2	Kennedy Creek	17.4	1,380	12/11/77

Table III-13. Peak Floods of Record Related to Drainage Area for 28 Gaging Stations on the Olympic Peninsula

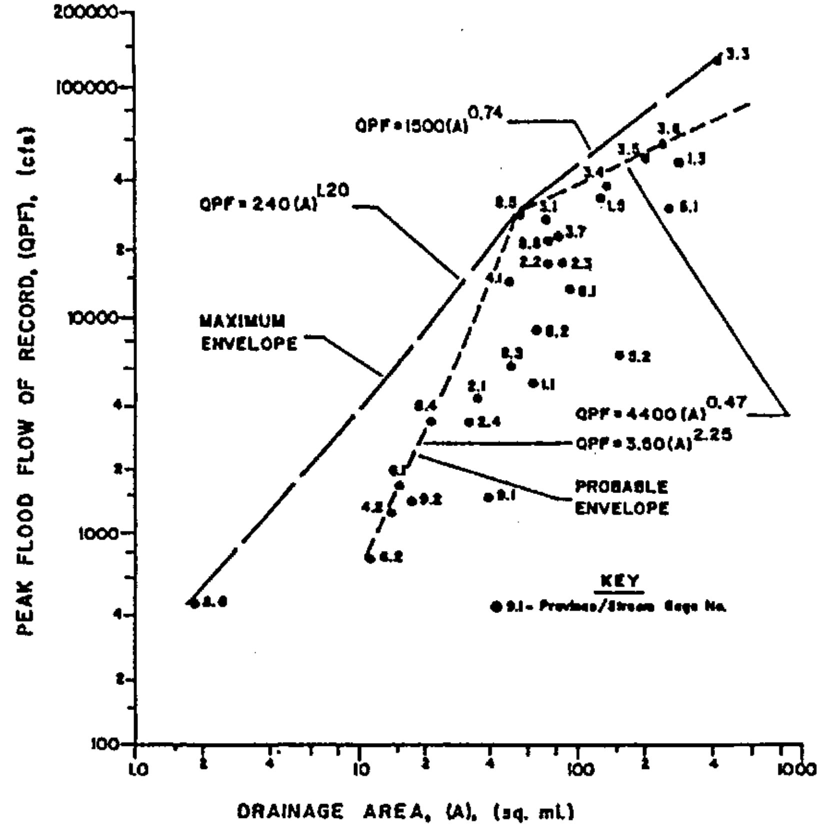


Figure III-18. Peak flood of record for USGS on the Olympic Peninsula. Records are for mixed periods.

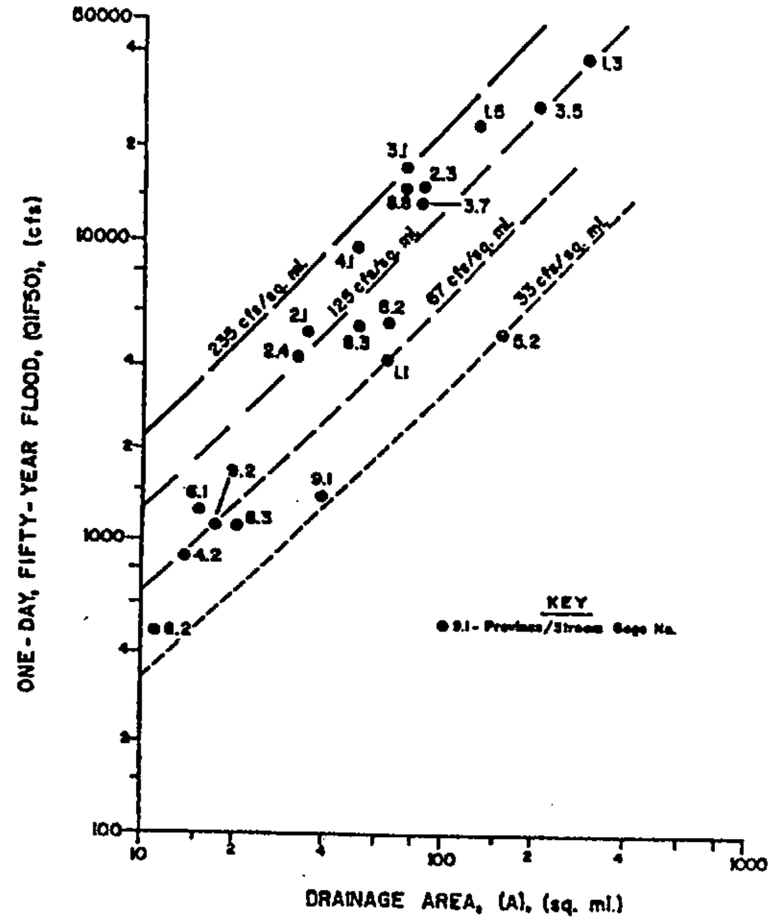


Figure III-19a. One-day, fifty-year recurrence interval floods for the 20 base gaging stations related to drainage area.

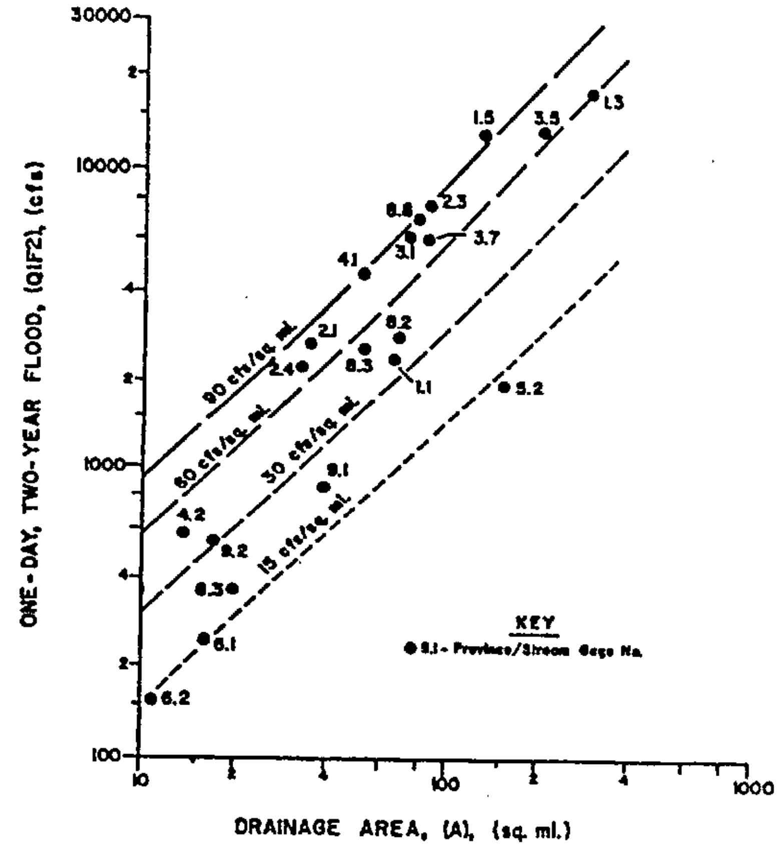


Figure III-19b. One-day, two-year floods for the 20 base gaging stations related to drainage area.

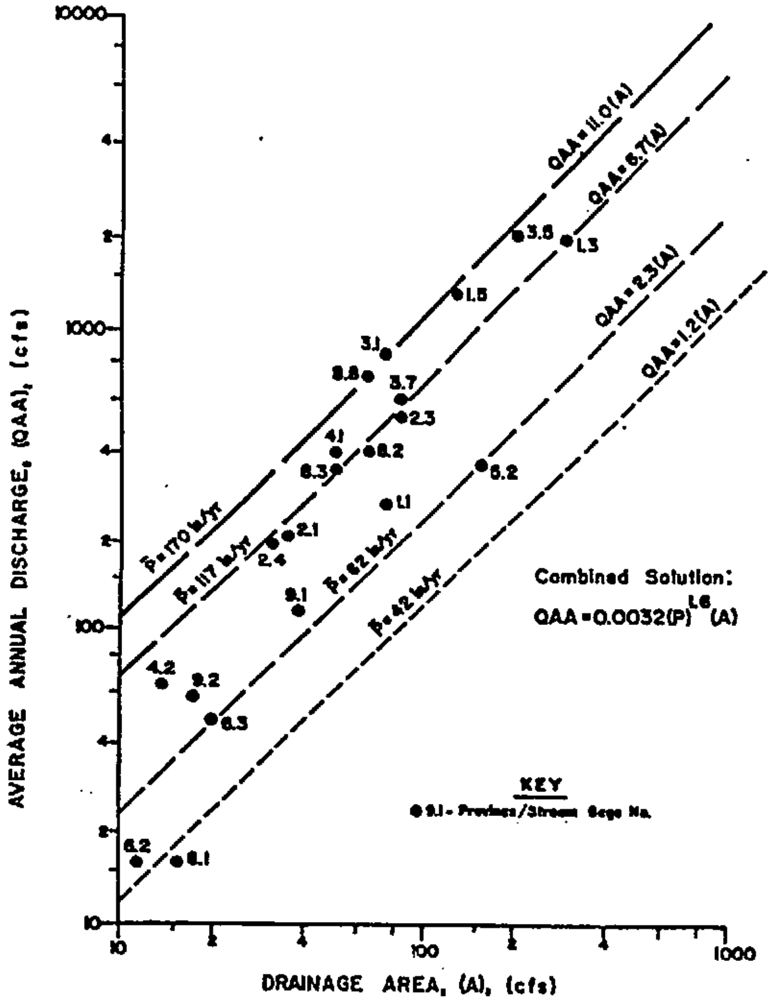


Figure III-20a. Average annual flow for the 20 base gaging stations related to drainage area.

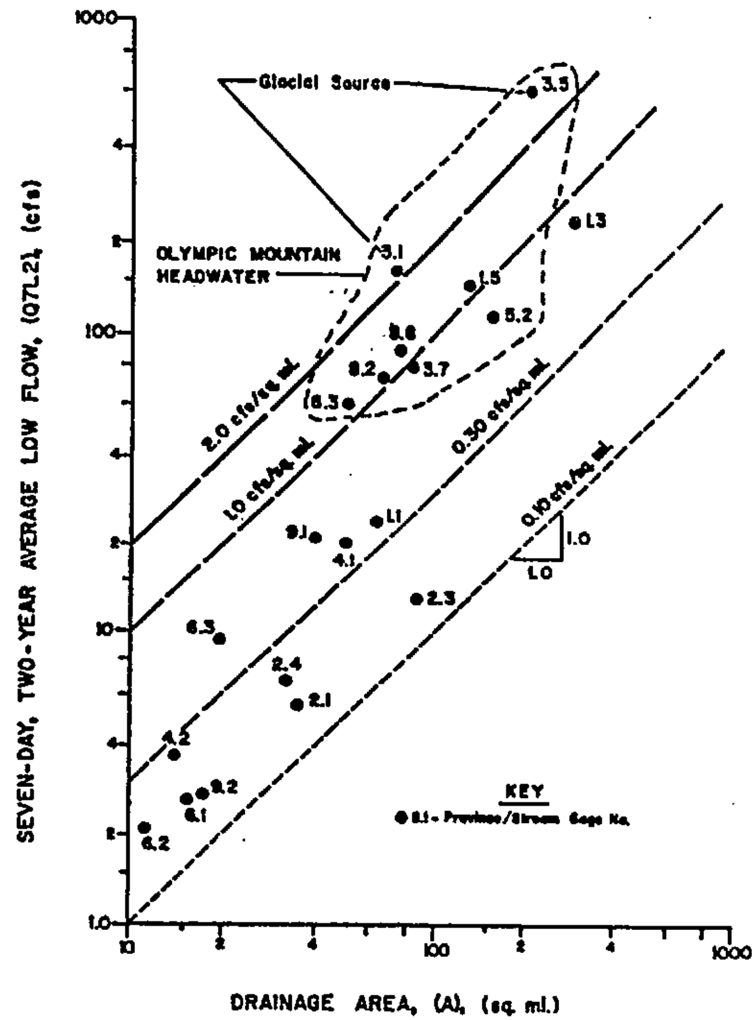


Figure III-20b. Seven-day, two-year low flow for 20 base stations related to drainage area.

Flow (Type)	Unit Values (cfs/sq. mi.)	Ratios to Largest Flow
Upper Limit		
Q1F50 (50-year flood)	235	1.00
Q1F2 (2-year flood)	90	2.61
QAA (average annual flow)	11	21.36
Q7L2 (average low flow)	2	117.50
Lower Limit		
Q1F50	33	1.00
Q1F2	15	2.20
QAA	1.2	27.50
Q7L2	0.1	330.00

These ratios indicate that:

- there is a wide range in the unit characteristic flows around the peninsula [Q1F50/A = 33 to 235 cfs sq/mi., a multiple (range) of 7.12 for 50-year floods];
- unit low flows range from 0.1 to 2.0 cfs/sq. mi., or a multiple of 20.0;
- these ranges are caused primarily by variations in precipitation, elevation and geology which regulate the amounts of water coming into and leaving a basin; and
- basins with more water have less variability between high to low flows than do the drier regions.

Notice that the station numbers for high flows (50- and 2-year floods) are consistently in the same relative position in Figure III-19a and -b. Note also that most stations that had the highest floods have the lowest low flows (such as 2.1, 2.3, and 2.4) and vice versa. In Figure III-20b those stations which have glacial and/or Olympia Mountain sources have the largest low flows. These flow ratios can be used to characterize (classify) streams in Appendix VII.

Combining Precipitation and Drainage Area Into an Input:Output Model

Referring to Figure III-20a, note that

- the average annual flow for sites within provinces can be estimated using only drainage area;

- the four graph lines are only samples of all the lines which could be drawn and they state:

$$QAA = 11.0(A) \qquad QAA = 2.3(A)$$

$$QAA = 6.7(A) \qquad QAA = 1.2(A);$$

- the slopes of the lines are all 1.0, so therefore (A) is raised to the power (exponent) of 1.0, because these are all logarithmic (power) graphs (equations);

- the coefficients (11.0, 6.7, 2.3, 1.2) in the equations are the values of QAA at A = 1.0 for each graph line;

- the main factor which causes these coefficients (or unit values of QAA/A in cfs/sq. mi.) to vary is the difference in precipitation on each basin;

- the average annual precipitation for the basins above the stream gaging stations are written on each line (170, 117, 62, and 42 inches/year); and

- by plotting the coefficient for each line (11.0, 6.7, 2.3 and 1.2) versus the precipitation for each line (170, 117, 62 and 42, respectively), then

$$C = 0.0032(P)^{1.6}$$

If this is entered in the general expression of QAA = C(A), then

$$QAA = 0.0032(P)^{1.6}(A)$$

as shown in the middle right of Figure III-20a. This is an expression which can be used to estimate average annual flow at any ungaged stream site on the Olympic Peninsula.

For example, assuming a basin with an area (A) of 10 square miles and an average annual precipitation (P) of 100 in/yr, then

$$QAA = 0.0032(100)^{1.6}(10) = 50.7 \text{ or say } 50 \text{ cfs.}$$

The coefficient $C = 0.0032(100)^{1.6} = 5.07$.

If the equation is rewritten as $QAA = C'P \cdot A$, then for 100 inches of (P), $C' = 5.07/100$ or 0.0507. Considering the average annual VOLUME OF STREAMFLOW FROM A DRAINAGE BASIN, if all of the precipitation became runoff (RO) (as from a paved surface), then 1 inch (P = RO) over one square mile in one year of time would convert to 0.0737 cfs.

So if an equation like

$$QAA = C'(P.A)$$

is used to estimate average annual flow, then if C′ is near to or greater than 0.0737 then the (P) value determined from the isohyetal map is probably too small. Runoff is too large for the amount of precipitation. Drainage area (A) can be determined much more accurately than (P). **C′Max = 0.0737 is a great check value for verifying average annual flow estimates,** and estimates of average annual precipitation.

If the runoff coefficient C′ = 0.0507 from the example is divided by 0.0737 (maximum possible), this says that (0.0507/0.0737) (100) = 69%, or 69% of the average annual precipitation appears as streamflow (on the average). But, average annual flow varies considerably from year to year as was shown in Table III-11. If the example basin was near the North Fork Skokomish basin we could expect the average annual flow of 50 cfs to vary between (ratios are 0.502 in 1930 and 1.350 in 1956) 25 and 68 cfs. Long-term average annual flow is quite stable over time and is a pivotal flow from which many other flows can be estimated.

BASIN ENERGY MODELS are displayed in Figures III-21, -22 and -23 for 2-year (average) floods, average annual flows, and 2-year, average low flows, respectively. This series of relationships have been found to be consistent for basins near the coast from Oregon to Southeast Alaska:

$$QIF2 = 230\ A(H)^{0.5}$$

$$QAA = 15\ A(H)^{0.5}$$

$$Q7L2 = 1\ A(H)^{0.5}$$

There are wide variations in these relationships around the Peninsula, due of course to the variations in precipitation and geology. But, as shown in Figure III-21, the relationships are regionalized among: West Coastal; South, Southeastern and North; East; and Northeastern Basins. Those in the rain shadow have the smallest floods for the same amount of basin energy, especially basin 5.2, the Dungeness River. The exponent of 0.96 on some of the lines comes from regression analysis and may indicate a decrease in flood contribution per square mile as basins increase in size and elevation. In Figure III-22 only two solid lines are used to show regional relationships of average annual flow and basin energy. The dashed lines show the range of variation in average flow that can be expected on a year to year basis. The dashed lines are related only to data points on the solid lines, not to other data points.

Low flow relationships to basin energy have been drawn in Figure III-23 in relatively uniform spacings, but the same inherent regionalization exists. Low flows are strongly influenced by local variations in basin geology, and there is much more variability for low flows than for floods.

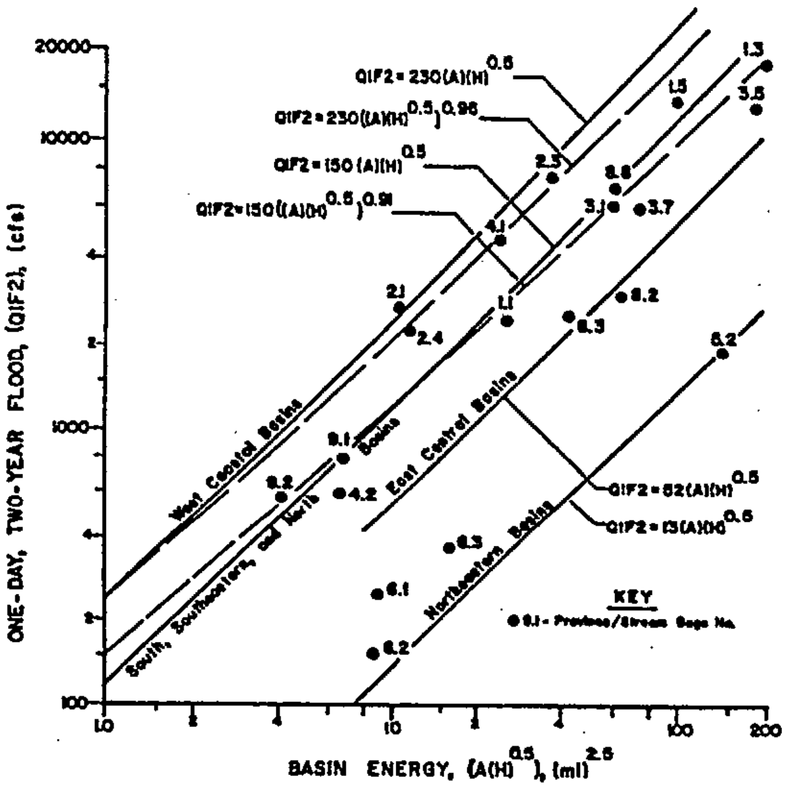


Figure III-21. One-day, two-year flood (QIF2) related to basin energy terms (A)((H)$^{0.5}$ for 20 base stations on the Olympic Peninsula.

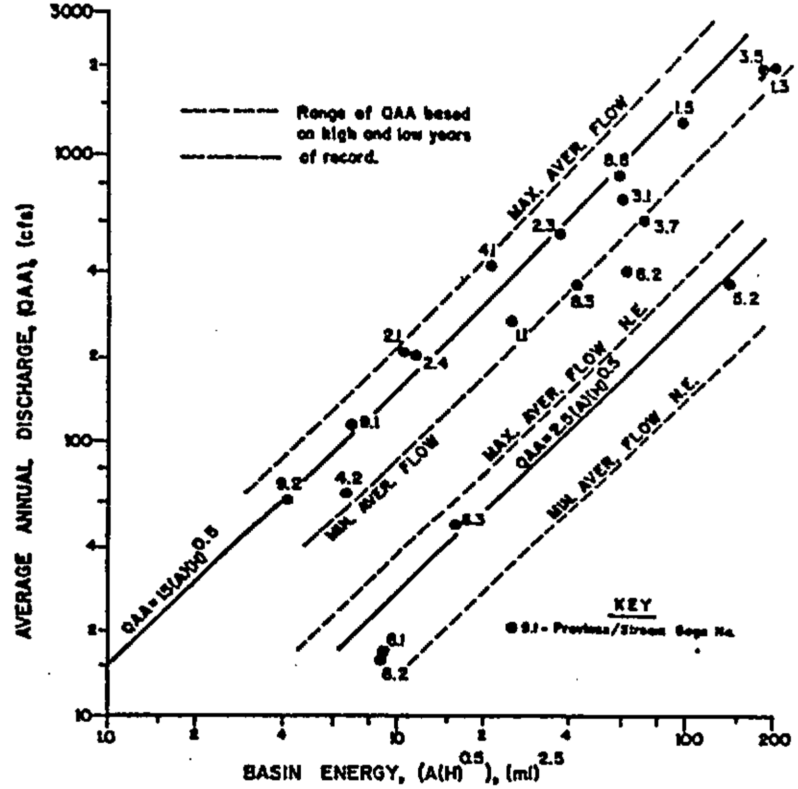
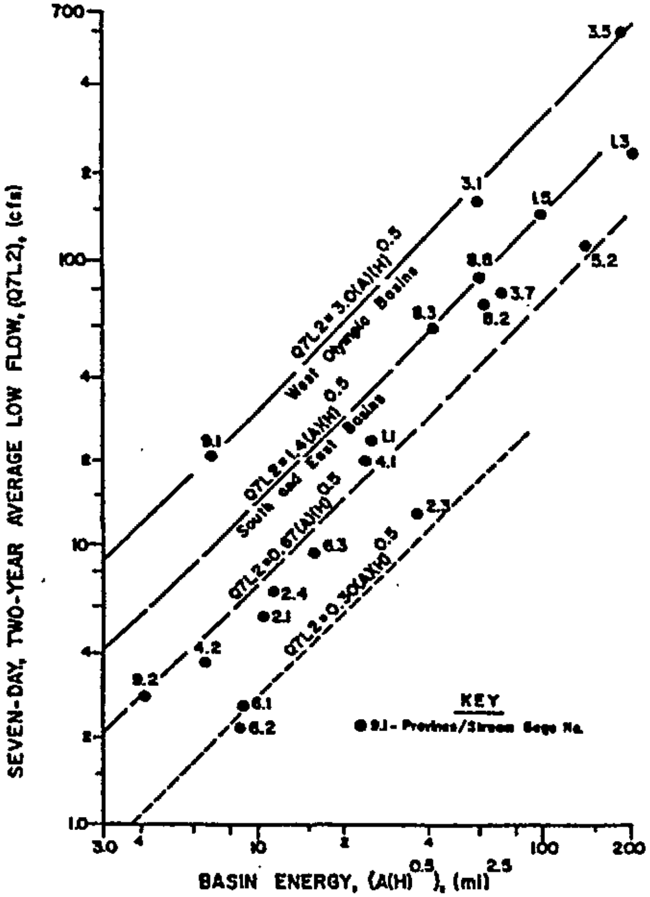


Figure III-22. Average annual discharge (QAA) related to basin energy for 20 base stations. Dashed lines are defined by average annual high and low flow years for data points on the solid graph lines.



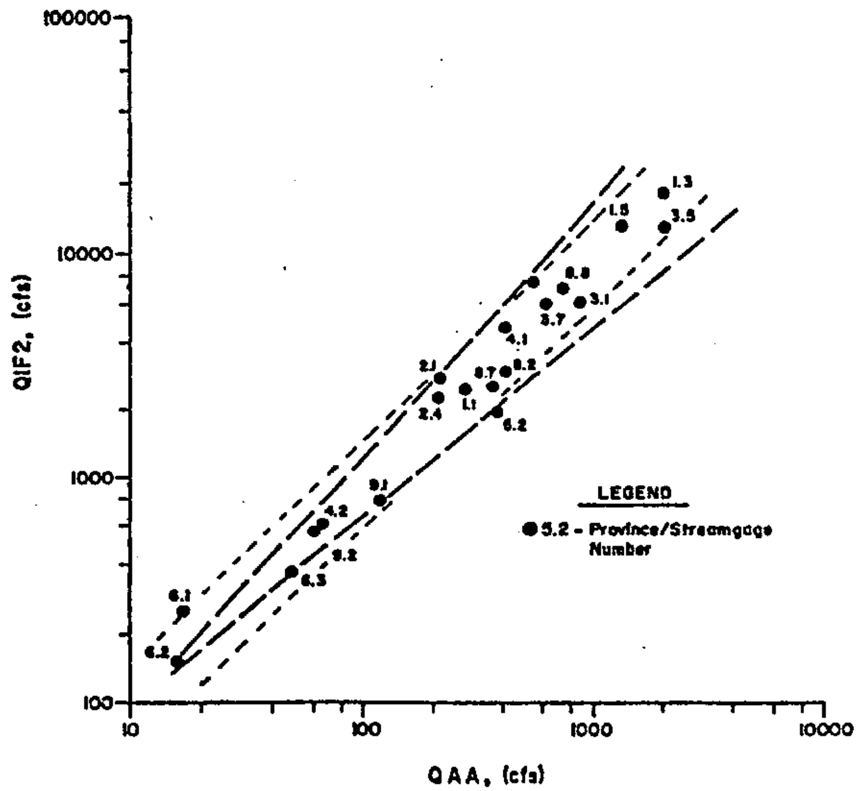


Figure III-23. Seven-day, two-year low flow (Q7L2) related to basin energy for 20 base stations.

Figure III-24. One-day, two-year flood flows related to average annual flow for 20 base gaging stations on the Olympic Peninsula.

Models of Flow to Flow Relationships

All of the daily characteristic flows are derived from the same set of measurements (population sample). Therefore, for the same amount of average annual flow from basins of "about the same size":

- streams with larger average floods should have smaller average low flows;
- ratios of characteristic flows (as shown in Table III-9) should be consistent in hydrologic provinces; and
- if the recorded natural variability and extremes are known for streamflow in a region, then estimates of ungaged project flows can be checked against those ranges of flows more accurately than by statistically projecting short records; the latter method will contain any built-in biases that exist in the collected data.

This series of models relates characteristic flows to each other, to ratios of these various flows and to other combinations. The relationship of average daily floods (Q1F2) to average annual flow (QAA), as shown in Figure III-24 indicates that the variability (defined by two parallel, short-dashed lines) is about the same for smaller and larger average annual flows. Siebert Creek (6.1) really does not belong with Stations 6.2 and 6.3 (Snow Creek and Little Quilcene), but was combined with them because of a lack of data in Provinces 6 and 7.

There are consistent relationships among peak, 1-day, 3-day and 7-day floods as shown in Figures III-25, -26, -27 and -28. If one can estimate (by model or observation) the 50-year, or 2-year, peak floods, then the 1-, 3- and 7-day average floods can be estimated from the relationships in these figures. Throughout the Peninsula these average flood ratios are about:

Fifty-Year Floods	Q1F50 / QPF50	Q3F50 / Q1F50	Q7F50 / Q1F50
Ratios	0.66	0.74	0.50
Two-Year Floods	Q1F2 / QPF2	Q3F2 / Q1F2	Q7F2 / Q1F2
Ratios	0.73	0.77	0.55

The annual variation in peak to daily average flood flows is shown in Table III-14. The flood values used in Figures III-25 through -28 are in Table III-15.

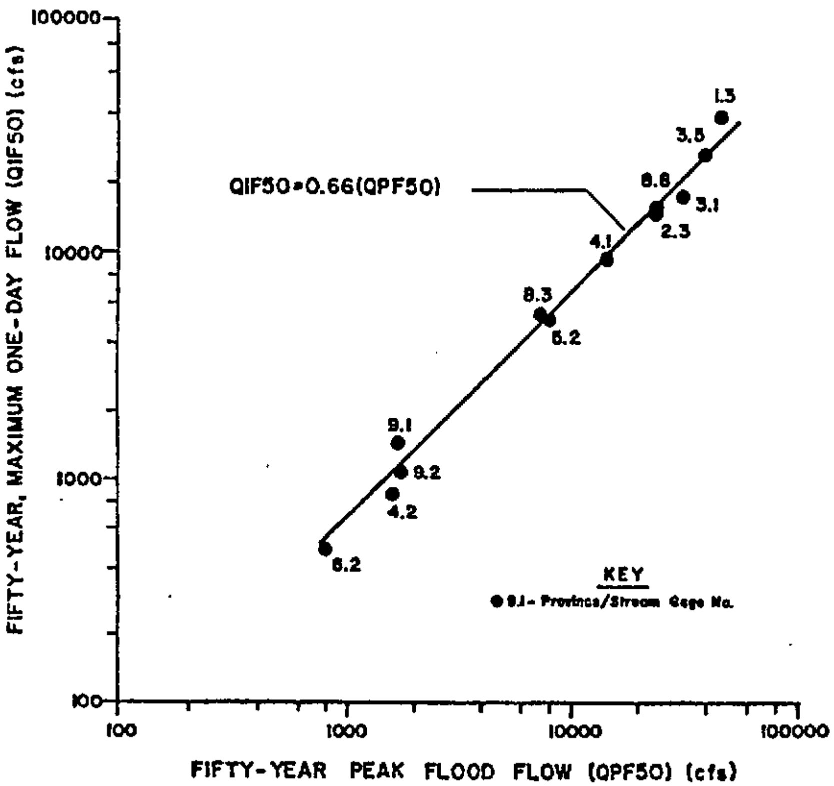


Figure III-25. Regional flood flow relationship between the fifty-year, peak and one-day average flood for stream gages on the Olympia Peninsula.

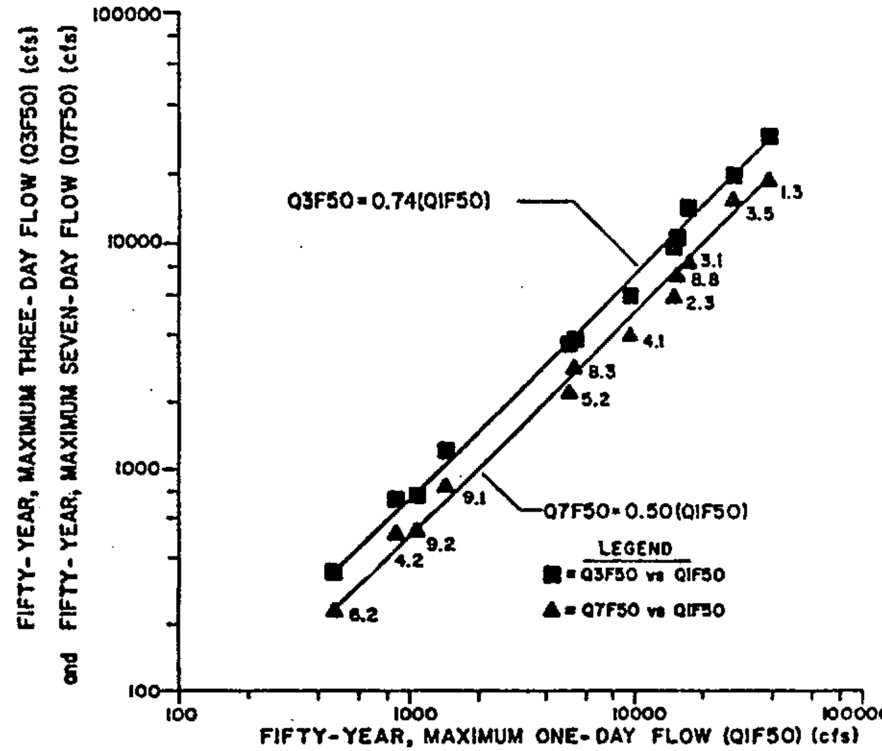


Figure III-26. Regional flood flow relationship between the fifty-year, one-day, three-day and seven-day average flood for twelve stream gages on the Olympic Peninsula.

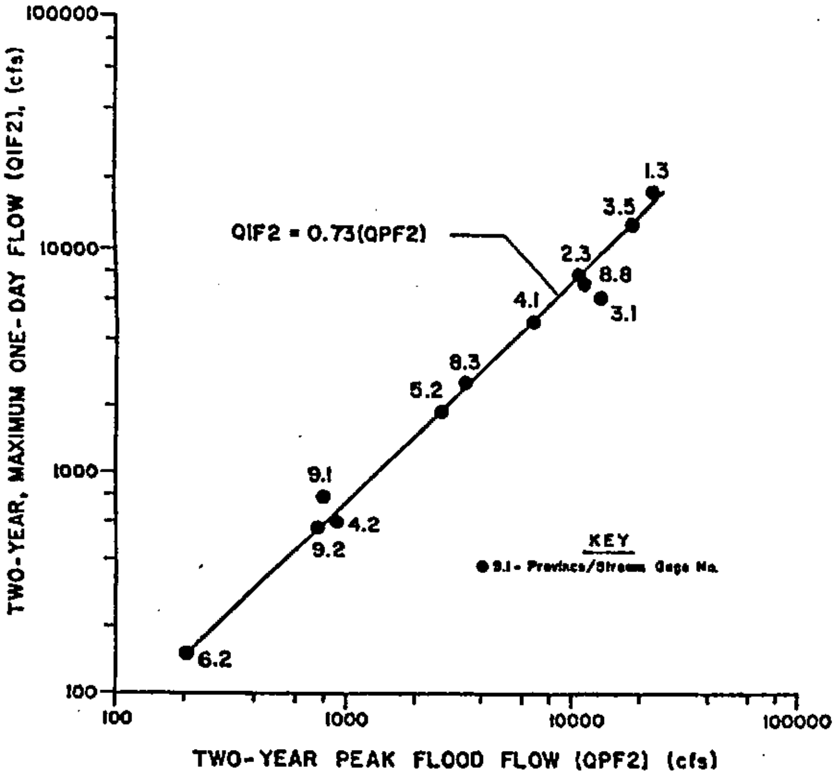


Figure III-27. Regional flood flow relationship between the two-year peak and one-day average flood for twelve stream gages on the Olympic Peninsula.

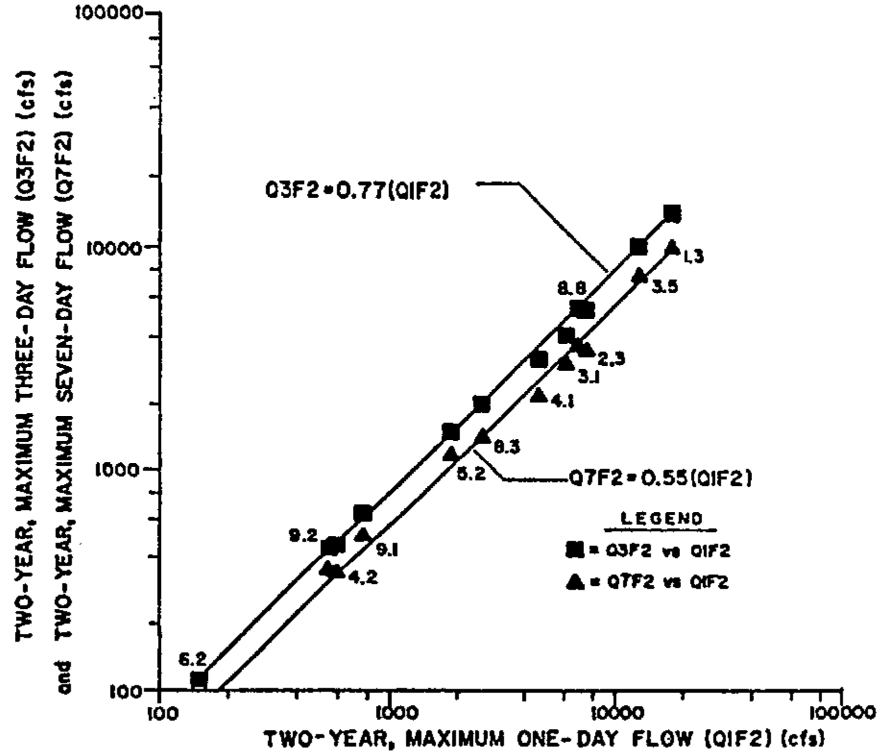


Figure III-28. Regional flood flow relationship between the two-year, one-day, three-day and seven-day average flood for twelve stream gages on the Olympic Peninsula.

Table III-14. Comparison of Annual Peak Floods with One-Day Average Maximum Flows for South Fork Skokomish River (Gage 12060500), 1959-1979

Water Year	Annual Peak Flow (QPF) (cfs)	QPF Date (Month/day)	One-Day Maximum Flow (Q1F) (cfs)	Q1F Date (Month/day)	Ratio of Values (Q1F/QPF) (%)
1979	9960	03/04	4980	03/05	50
1978	1160	11/01	6110	12/11	--*
1977	4820	12/26	3510	12/26	73
1976	13700	12/03	7500	12/03	55
1975	11500	11/20	5930	12/21	--
1974	13200	01/14	10200	01/15	77
1973	10100	12/26	6780	12/26	67
1972	13700	01/20	8440	01/20	62
1971	9560	12/07	6840	12/07	72
1970	7680	04/09	4640	04/09	60
1969	9840	12/03	5560	12/24	--
1968	11200	01/19	9560	01/19	85
1967	15600	12/12	11600	12/13	74
1966	9220	01/13	8180	01/13	89
1965	11400	11/30	8660	11/13	76
1964	10100	10/21	5900	12/23	--
1963	12200	11/25	6560	02/04	--
1962	7120	01/03	5200	01/03	73
1961	20400	01/15	15800	01/15	77
1960	16100	11/20	9930	11/20	62
1959	13500	04/29	8320	04/29	62
				Average	70%

*One-day maximum flow did not occur within one day of the annual peak flow.

NOTE: Percentage of time maximum one-day flow within one day of the annual peak flow is 76%.

Table III-15. Peak, One-, Three- and Seven-Day Average Flood Flows with Two- and Fifty-Year Recurrence Intervals at Sixteen Stream Gages on the Olympic Peninsula

Province/ Stream Gage Code	Station Name	USGS Gage No. 12-	QPF2	Q1F2	Q3F2	Q7F2	QPF50	Q1F50	Q3F50	Q7F50
1.3	Satsop River	035000	23046	18307	13784	9935	47504	39003	29551	19191
1.5	Humptulips River	039000	18651	13393	9798	6749	37392	24278	16734	10708
2.3	Dickey River	043100	11084E	7599E	5321E	3479E	24494E	14970E	9795E	5888E
3.1	N.F. Quinault River	039300	13857	6182	4000	3006	31972	17463	14486	8173
3.5	Hoh River	041000	18517	13054	9926	7381	39683	27476	20184	14597
3.7	Soleduck River	041500	9299	6021	4084	2782	22855	13723	9350	6398
4.1	Hoko River	043300	6844	4739	3144	2174	14776	9561	6020	4011
4.2	E. Twin River	043430	919	595	446	342	1627	882	726	508
5.2	Dungeness River	048000	2641	1903	1501	1176	8242	5186	3687	2255
6.1	Siebert Creek	047500	423	249	169	111	2735	1263	966	488
6.2	Snow Creek	050500	205	151	113	83	819	478	340	230
8.2	Duckabush River	054000	4226	2965	2215	1568	9354	5699	4152	2797
8.3	Hamma Hamma River	054500	3418	2576	1963	1413	7554	5379	3753	2844
8.8	S.F. Skokomish River	060500	11485	7083	5278	3655	24470	15449	10870	7199
9.1	Goldsborough Creek	076500	797	778	635	506	1762	1435	1199	839
9.2	Kennedy Creek	078400	762	563	438	348	1748	1114	757	525

All characteristic flows based on longest period of record through 1979.
E Estimated by correlation with Humptulips River (12039000)

Once an estimate has been made of the average annual flow (QAA) for an ungaged project site, then any other characteristic flow can be estimated using the flow ratios for the same province. Monthly flows can be estimated similarly from QAA based on the provincial ratios.

The 1:2:3 POWER relationship is demonstrated in Figure III-29. The gages with longest records were selected and their statistical values for Q7L2, QAA, Q1F2 and Q1F50 were combined and plotted. The relationships were solved by regression and the exponent (slope of graph) for QAA (y-axis) was consistently three (3.0).

The graphs in Figure III-30 define the relationships among the basin characteristic flows, Q1F2, QAA and Q7L2 in dimensionless ratios. Notice that when the x-scale (QAA/Q7L2) is more or less than 7.0, then the equations change.

Gage Data Summary

A complete reference list of all of the Olympic Peninsula stream gages is given in Table III-1 of Amerman and Orsborn (1987).

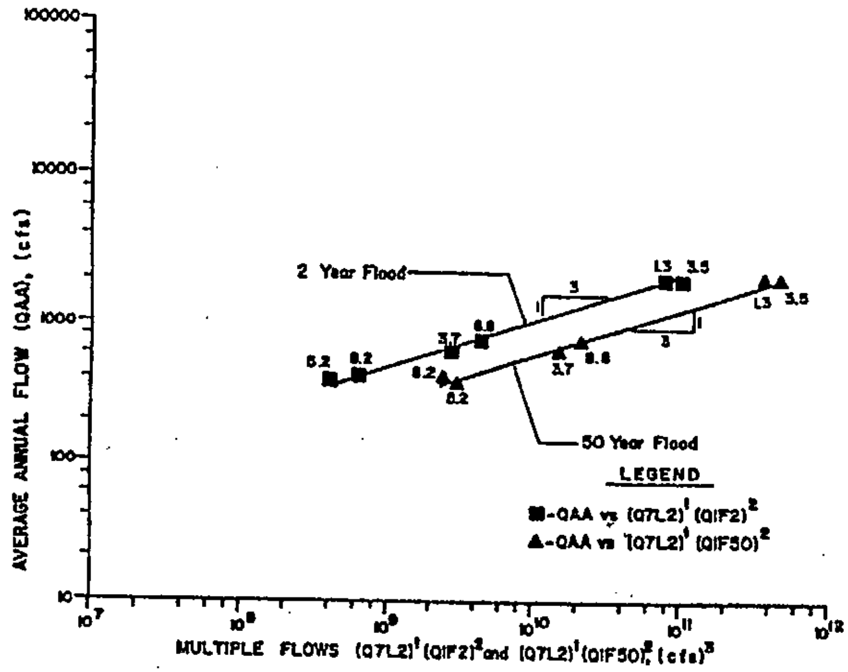


Figure III-29. Low, average and flood flows for six long-term gaging stations on the Olympic Peninsula to demonstrate the 1:2:3 power relationships.

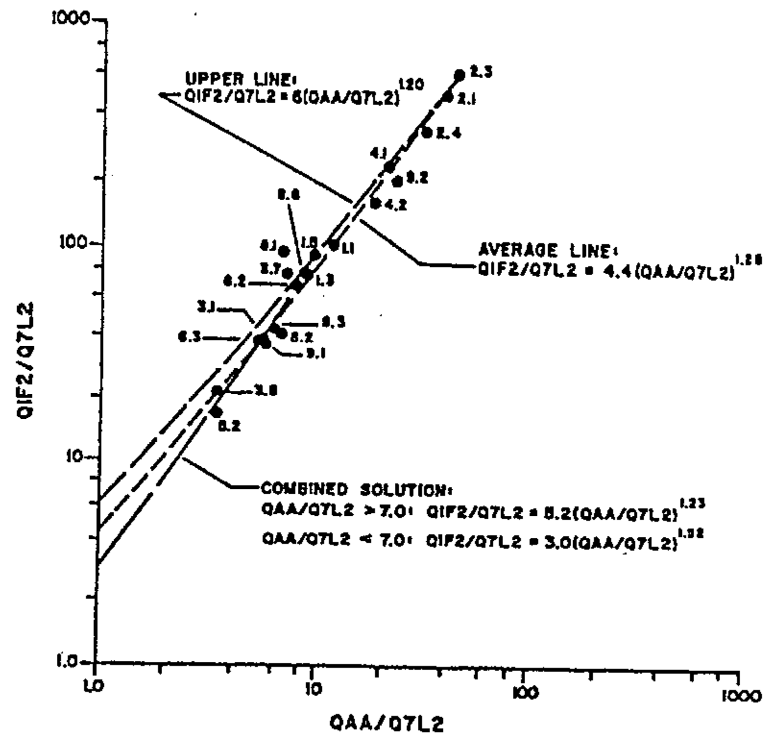


Figure III-30. Relationships of characteristic flow ratios for 20 base stations on the Olympic Peninsula.

APPENDIX IV.--DRAINAGE BASIN PERSPECTIVES, PROCESSES AND ANALYSIS

APPENDIX IV. DRAINAGE BASIN PERSPECTIVES, PROCESSES AND ANALYSIS

Introduction

This section contains several perspectives of drainage basins to provide a systematic framework for analysis and to relate basins to hydrologic and channel processes with the basins. Topics which depend on certain **BASIN CHARACTERISTICS** for their existence include: fisheries habits and habitats; precipitation and its resultant streamflow; the formation and geometric shapes of stream channels; how these basin resources interact within the basin system; and the response of fisheries to natural and artificial (man-made) limitations on their life-stage functions (spawning, incubation, emergence, rearing and migration).

Relative Degree of Basin Impacts

It is easy to visualize that for a certain size of disturbance (say a 1.0 square-mile timber harvest), that as the watershed increases in size from 1 to 10, or to 100 square miles, the downstream influence of the cut becomes less and less. Black (1970) called this the principle of inverse influence. The level of influence is also related to direct and indirect accessibility by humans and the "downstream reactions" they cause.

There are many elements in the natural basin environment which contribute to the watershed equilibrium, and which tend to maintain this balance based on a relative scale of influence. This spectrum of natural elements includes: atmospheric-climatic; geologic-geomorphic; soil-vegetative; and runoff-channel factors. The complete science of hydrology ties these factors together (Black 1970), which is why we discussed the hydrology of streams first.

Smaller basins tend to be dominated by local, high intensity storms or snowmelt which tends to dominate channel capacity. Larger basins tend to respond more to regional climatic conditions. High elevation basins may generate average flood flows of say 200 cubic feet per second (cfs) per square mile (csm) of drainage area on the Peninsula. As basins become larger, precipitation tends to be less uniform areally and less intense due to the lower elevations. The unit average floods fall off to 50-60 cfs/sq. mi. Similarly the unit values of low streamflows will vary widely as a function of basin size and elevation, but predominantly as a function of basin geology.

Watershed implies runoff (water being shed from the surface of a basin), or streamflow. But there are numerous other water components of a watershed besides surface runoff including the groundwater and/or glacial contributions to the low flow of streams.

A drainage basin implies a broader concept although drainage indicates a similar, but more controlled, release of water than did a watershed. A basin implies some kind of a partially enclosed receptacle, with sides--a container. We are dealing with natural basins defined by a topographic divide and a base level or outlet elevation. Within the basin, formed by geologic forces of uplift and subsequent erosion, numerous resources are available. The value of the resources depends on whether they are in place or transported and utilized outside the basin. For example, consider the following steps in the logic for building a road into a watershed and note the parallel results.

- Objective 1: build an access road into a basin.

- Why? To be able to remove resources.

- Why? To satisfy human needs and sustain the national economy.[1]

- Objective 2: minimize road maintenance and reduce risk of washouts.

- How? By crossing streams with adequate sized structures.

- Why? (1) to maintain stream continuity; (2) to allow floods to pass under the road; and (3) to maintain fish passage up and down stream.

- Why? (1) to minimize maintenance; and (2) to sustain the national economy.[2]

Following this line of reasoning one can visualize that, depending on your perspective, road building and fish passage through road hydraulic structures can both have the same objectives---to sustain the national economy. Therefore, consideration of road stream crossings, without considering the potential impacts on instream fisheries values in the basins is inconsistent with good resource management principles.

Components of the Basin System

Examples of ways to descriptively model and visualize the interrelations among basin components are shown in Figures IV-1 and IV-2. Beginning with the basin in the upper right of Figure IV-1, the stream network is derived from historical water, wind and ice activities. We represent stream networks from areal photographs and maps. But these are instantaneous values of stream locations and lengths which are a functions of the season. Continuing down in a hierarchy of characteristics we can select a stream segment which has similar valley and channel characteristics throughout its length (Cupp 1989). The next level of basin component in this hierarchy could be a shorter reach within the stream segment, called a riffle:pool unit in this arrangement. This unit has hydraulic significance in that the

[1] Common reason for both the road and fisheries maintenance.

[2] Common reason for both the road and fisheries maintenance.

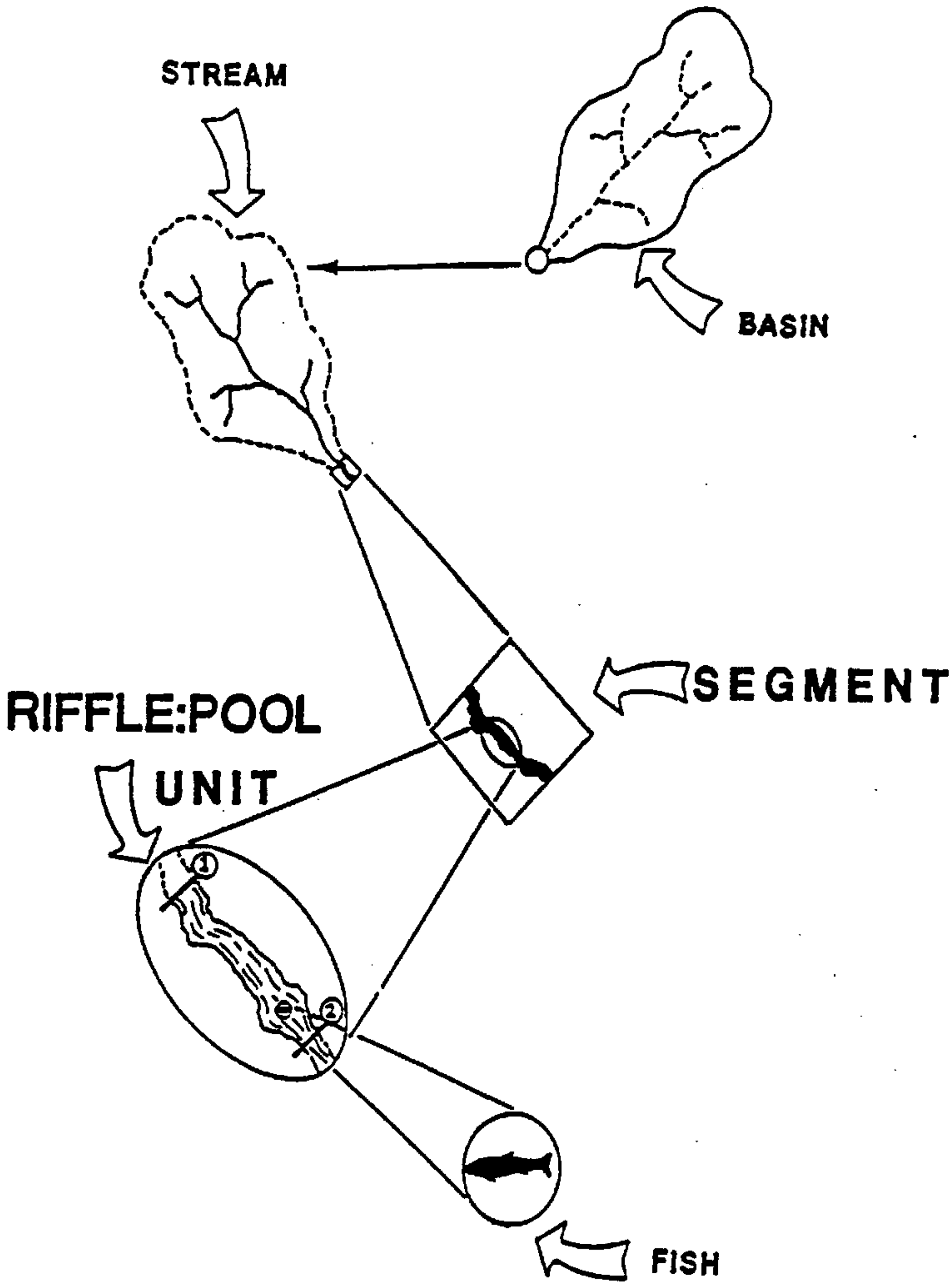


Figure IV-1. Basin, stream, segment, unit and fish subsystem hierarchy within a basin (modified from Orsborn and Anderson, 1986).

1. BASIN CHARACTERISTICS

AREA

ELEVATION: Relief, Energy

STREAM LENGTH: Stream Density, Order (Profile, Slope)

DRAINAGE NETWORK

PARAMETERS REFLECT: Soil Types; Parent Materials (Spawning Gravels), etc...

2. STREAM CHARACTERISTICS

PLAN: Geometry (Meander, Braided, Straight)

PROFILE: Slope, Velocity (Energy, Power)

CROSS-SECTION OF CHANNEL: Triangular, Trapezoidal, Rectangular; Boundary Materials (Spawning Gravels), etc...

LAND-WATER BASIN-SYSTEM

3. HYDROLOGIC CHARACTERISTICS

PRECIPITATION

LAND SURFACE: Vegetation (Interception, Infiltration, Transpiration); Evaporation

STREAMFLOW: Surface Runoff; Low Flows (Groundwater, Glaciers)

GEOLOGY: Bedrock; Soils Infiltration; (Spawning Gravels), etc...

4. STREAM LOAD CHARACTERISTICS

MASS BALANCE

STREAMFLOW

ORGANIC DEBRIS: Organisms; Drift; Woody Debris

INORGANIC DEBRIS: Sediment Transport (Spawning Gravels), etc...

Figure IV-2. Examples of interrelationships of major physical components of a land-water basin system with an example of a basic site component (spawning gravels) in each major component.

tailout sills of the pools (heads of riffles) exert a "hydraulic control" on the flow (change from slow to fast velocity, from a flat to steep slope). This break in slope is the point from which hydraulic analyses can be initiated. It also represents a point of transition from a spawning area (tailout) to a food generation and rearing area in the riffle. The final component in this basin hierarchy is our primary objective, the fish.

The second descriptive model (Figure IV-2) of the interaction of basin components deals with some of the characteristics of the basin, the streams, their hydrology and their loads (water, organic and inorganic debris). It seems rather odd that when we discuss mass wasting (debris slides) and deposition in valleys and streams, we consider them as "debris or waste material." In reality these are the very materials we consider to be the beneficial natural resources in an undisturbed basin--wood, vegetation, gravel, large rock--but the rate at which the slides arrive throws the mass (debris) balance and the hydraulic geometry out of balance in this stream segment (lower right quarter of Figure IV-2).

The major components in Figure IV-2, as part of the same basin , are interrelated and interdependent, and some of these relationships can be quantified for use in classification and process analysis. For example:

- Parts 1 and 3--there are regional (climatic, geologic) relationships between certain streamflows (say floods of a certain frequency) and the characteristics of the basin in which the floods were generated (forming hydrologic models);

  These relationships (flow to basin) become regional hydrologic models for estimating flows at ungaged project sites as developed earlier.

- Parts 2 and 3--the streamflow characteristics can be related to the cross-section of the channel (called "hydraulic geometry") at a site. Also, for a certain flow (such as the average flood) the channel geometry (width, depth and average velocity) at a series of sites can be developed into another regional hydrology:channel model.

- Parts 1 and 3 (basin and flow) are related to each other, and Parts 2 and 3 (channel and flow) are related, so therefore Part 2 (the channel characteristics) must be related to (dependent upon) Part 1 (the basin characteristics).

  Consequently it is easy to visualize that Part 4 (stream load) is dependent up (and interrelated to):

  1) basin characteristics and land use as the controllers of the amount and rate of delivery of loads;

  2) channel characteristics and stability as the network for transporting (or depositing) loads downstream; and

3) hydrologic characteristics which respond to land use changes in a transient manner, and provide the flow energy to transport (or deposit) the load as a function of channel geometry.

These interdependencies and how they affect fisheries conditions in a stream will be examined in Appendix VI on basin-water-channel component integration. But first we will quantify some watershed and channel characteristics as we have done for streamflow.

The complexity of the basin system is reflected in the various key components and subcomponents, and their applications in a verbal version of Figure IV-2 as was presented in Table 3 in the Introduction. Included in Table 3 are parameters which can be measured and provide analogies for certain watershed processes as shown by example in the last column of the table. For example, the BASINS/WATERSHEDS, whose characteristics can be measured (area, relief, etc.) and correlated again streamflow gaged records in a (geographic, hydrologic, climatic) region to produce the earlier "regional hydrologic models" in Appendix III. One analogy is that basin area represents the capability of a basin to capture precipitation. Another analogy is that relief (differential elevation) represents the available energy (due to gravity) for driving the water (downhill) out of the basin. Some examples of quantifiable basin characteristics follow.

Drainage Basin Characteristics

Introduction

The four sections which form the foundation of this report (hydrology, basins, channels and their integration) relate to the condition of the fisheries environment within the basin system as described by:

- the physical form (geomorphic) characteristics of the basin;
- the natural streamflow regime, which supports the timing of the fish runs, and the effects of altering that regime;
- how streamflows can be estimated at project sites where there is no stream gage, which is usually the case;
- the physical, hydraulic and geometric characteristics of the streamflow regime as it moves through the stream channels, and how the geometry can be related to fisheries needs; and
- the quantification of the interrelationships which exist among fisheries, basin, streamflow and channel characteristics.

Definition of the Problem

The analysis of drainage basins, the data developed and the methods applied depend on the perspective of the analyst and the type of project information needed. We are mainly interested in the interrelationships of physical geography (geomorphology) which represents precipitation, the valley and channel geometry, valley bottom and channel slopes and the streamflow regime. Some basic concepts are useful in guiding investigations into drainage basins:

- The watershed is an integrator of the forces acting on it; and
- Knowledge and experience gained in one watershed are applicable to "similar" basins (Heindl 1972).

Therefore, this leads to "regional" analyses (a type of classification) of basins with similar geology, elevation, climate and other geomorphic parameters.

The basin has been defined as having a topographic divide and an outlet elevation (base level and/or project site), and is classified as an open system ... it receives water at its surface in the form of precipitation. This water is released from the basin through evaporation, transpiration by plants, groundwater outflow and streamflow. The stream carries organic and inorganic matter and chemicals in solution. Major floods tend to cause major changes in the landscape such as landslides. But, smaller floods, which occur more frequently, move more "debris" (Orsborn 1980).

As a long-range AMC goal we want to be able to analyze a basin to meet the following objectives:

- represent the soils and geology as they relate to existing and potential land uses which can impact the channels and fisheries;
- relate the basin characteristics to stream flow characteristics in regional hydrologic models;
- evaluate the relative influence of land use changes on basin characteristics, and thus on streamflow characteristics;
- relate basin and streamflow characteristics to channel characteristics (flow plus channel geometry equals hydraulic geometry of the channel as shown in Appendix V);
- evaluate relative impacts of land use changes on the channel hydraulic geometry (flow area, width, depth, velocity, slope and stream capacity (power) to transport sediment) and changes in the load; and
- thus to be able to assess the condition of fisheries habitat in terms of the existing or anticipated condition of the basin.

The impacts (reactions) to land or water use changes (actions) are best observed in the changed stream channel. The size of the disturbance will be proportional to the relative size of the action (say a slide) with respect to the size of the stream, and the rate at which the action takes place.

In terms of fisheries the most fundamental questions have to deal with the relative condition of the basin--

- Is it in a natural, stable condition[3];
- Are there unstable conditions (such as landslides) that are triggered by high flows;
- Has it been impacted some time ago by land use changes and are the impacts arresting naturally; or
- Has it been impacted recently, is unravelling, and has not reached a new stage of equilibrium (balance between load and streamflow over time)?

The relative condition of the basin and stream capacity is an important guide to monitoring/research projects and to impact analysis.

Information Requirements for Determining Basin Characteristics

The analysis of basins for our purposes requires the evaluation of the following characteristics:

- precipitation;
- the drainage network;
- elevations; and
- the basin size and shape.

Some of the basin characteristics and the basin properties to which they relate (analogies) are displayed in Figure IV-3 and listed in Table IV-1.

The **PRECIPITATION** data are point values measured at precipitation gages which are few and far between. When all precipitation gaged values are combined with meteorological calculations (to account for elevation effects) an isohyetal map (lines of equal precipitation) is developed for average annual precipitation (USWB 1965). The analysis can be made also for storms of certain durations and frequencies.

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[3]Bank erosion is not necessarily bad, it may be part of balanced natural conditions caused by floods, and it may be the only source of substrate.

Table IV-1. Sample of Basin Geomorphic Characteristics Used in Regional Basin and Hydrologic Analyses

Property, Symbol	Dimensions*	Relates to:
Stream Length, LS	L	Perennial stream networks, percentage of input becoming surface runoff (output), soil type, geology, basin storage, contribution to low flow
Drainage Length, LD	L	All drainage channels including intermittent; floods
Basin Length, LB	L	Aspect ratio LB/WB; flood concentration time
Basin Relief, H	L	Potential energy, form of precipitation, ground cover, etc.
Basin Width, WB	L	Rectangular equivalent derived from A/LB = WB
Basin Area, A	L^2	Catchment size, ability to catch precipitation
Stream Density, LS/A	L^{-1}	Soil types and runoff conditions especially low flow; method of determination should be standardized; blue lines on USGS maps
Drainage Density, LD/A	L^{-1}	Relates to soil types and floods
Channel Slope, SC	-	Average rate of expenditure of energy as flow moves through the basin
Stream Order, SO (or drainage order)	-	Basin and stream location in the total basin; size of stream channel or basin; relates to types of fish food sources; vegetation, etc.

*L is dimension of length with units such as feet or meters.

Precipitation is usually the weakest data. One precipitation gage covers only one 80 millionth of a square mile. In the hydrologic component (Appendix III) we depended primarily on streamflow records, which are a measure of net precipitation released by the basin through the drainage network. Basins with similar climate and geology release streamflow in similar seasonal patterns and amounts.

The **DRAINAGE NETWORK** describes channel development in the basin and reflects geologic and climatic history. Significant land use changes can cause significant shifts in the size and slope of the channels. But the basic network does not change much except in small basins (with respect to the size of the impact).

The **DRAINAGE NETWORK** includes both INTERMITTENT and PERENNIAL STREAM CHANNELS. Therefore, total drainage density correlates well with flood flows, and the solid blue-line perennial streams on USGS topographic maps correlate well with low flows. Care must be taken in describing and using terms such as drainage length and stream length, and their densities, because by definition they are different. The literature contains many different methods, but as long as the method used is clearly defined and repeated throughout the analysis, the results should be consistent (Bell and Vorst 1981, Gardiner 1982). Drainage and stream density are dependent on, and represent, the soil types and geology.

The stream (or drainage) **NETWORK LENGTH** is determined from the same scale of map, preferably USGS 1:62,5000 and USGS and USFS 1:24,000 scales. The map scales can be mixed if necessary. Sometimes not all of the blue line stream lengths show because of tree cover when the aerial photographs were taken to produce the maps. Also, when matching two USGS maps, sometimes the type of stream will be shifted from perennial to intermittent, or vice versa. Also, perennial streams are sometimes randomly added to the maps in drier climates. Stream existence should be carefully checked in the field if there is any doubt.

STREAM ORDER, beginning with first-order, unbranched, tributary, perennial streams was originated by Horton (1945). Strahler (1958) simplified Horton's method of stream ordering as shown in Figure IV-3. Two, first-order streams combine to make a second-order stream; two, twos make a third-order, etc. The basic difference between Horton's and Strahler's methods is the Horton's highest order stream was the trunk stream and ran all the way from the headwaters to the basin outlet.

Stream order is very useful and can be related to the numerous physical channel features such as channel top width, but stream order is not a quantifiable property--it is an index assigned to an ordering system of stream segments. It affords a means of relating physical properties of a basin drainage system to a common index, as long as the standards for defining stream, basin or subbasin order are consistently applied.

Drainage (or stream) length can be plotted against drainage area as area increases in size. Shifts in the relationship indicate shifts in the geology, basin shape and geomorphology, and changes in soils where

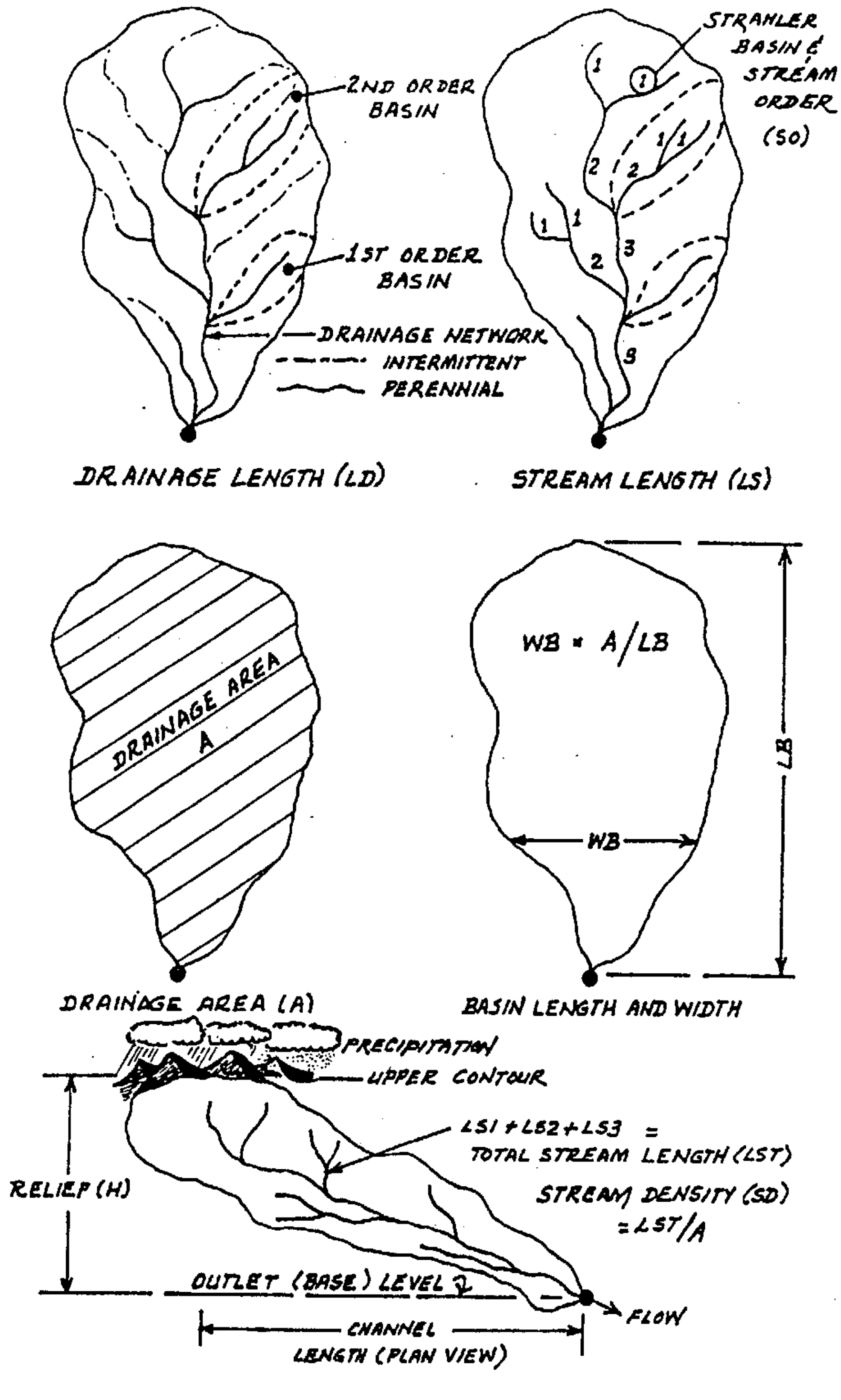


Figure IV-3. Definition sketch of basin characteristics.

bedrock is not dominant. An example of this graph is shown in Figure IV-4 for the drainages in the South Fork Skokomish River Basin (Lampard 1989). The ratio of perennial stream length (blue line) divided by drainage area is **STREAM DENSITY.** If the entire drainage system of channels is used, then this term becomes **DRAINAGE DENSITY.** Because perennial streams appear as solid blue lines on USGS maps, and are related more directly to fisheries than the entire drainage system, we will use STREAM DENSITY as the basin term even though fish seasonally use intermittent reaches. Stream density strongly correlates with average low-flow which is often a critical flow for fish.

The equation of the average line in Figure IV-4 states that **STREAM LENGTH** (by order LS1, LS2, and total, LST) is equal to

$$LST = 1.6\ (A)^{1.00} \qquad \text{(IV-1)}$$

which means the **STREAM DENSITY** is a constant (on the average) of 1.60 mi/sq mi.

For comparison the equations in some other parts of the Pacific Northwest are

$$LST = 5.6\ (A)^{0.60} \qquad \text{(IV-2)}$$

in the Deschutes River basin near Olympia where the stream density varies from 5.6 mi/sq mi at A = 1.0 sq mi to 0.9 mi/sq mi at A = 100 sq mi. (Orsborn 1976). Also,

$$LST = 1.3\ (A)^{1.00} \qquad \text{(IV-3)}$$

in the mountainous watersheds of the Coeur d'Alene River basin in Northern Idaho, and stream density is again a constant and close to the value (1.6) for the South Fork Skokomish River basin above Brown Creek (Orsborn, 1980).

Average valley and/or **CHANNEL SLOPE** over long distances (say over 2,000 to 3,000 ft) can be estimated from maps, but local slopes determined from maps can be very inaccurate and are inconsistent.

RELIEF is an important term for evaluating the relative amount of basin energy, and its average rate of expenditure (stream or valley slope) down the watershed. In Figure IV-3, relief (H) is defined as the difference in elevation between the uppermost, continuous contour in the watershed and the basin outlet, project or gage site elevation. Relief was used in conjunction with drainage area to develop regional hydrologic models for ungaged streamflow estimation.

The **SHAPE OF A BASIN**, as defined by its length to width ratio, correlates most strongly with flood flows. On the Olympic Peninsula it has been found this ratio is unnecessary to develop adequate estimates of ungaged flood flows. Shape relates to geologic structure, drainage network pattern and also low flow characteristics.

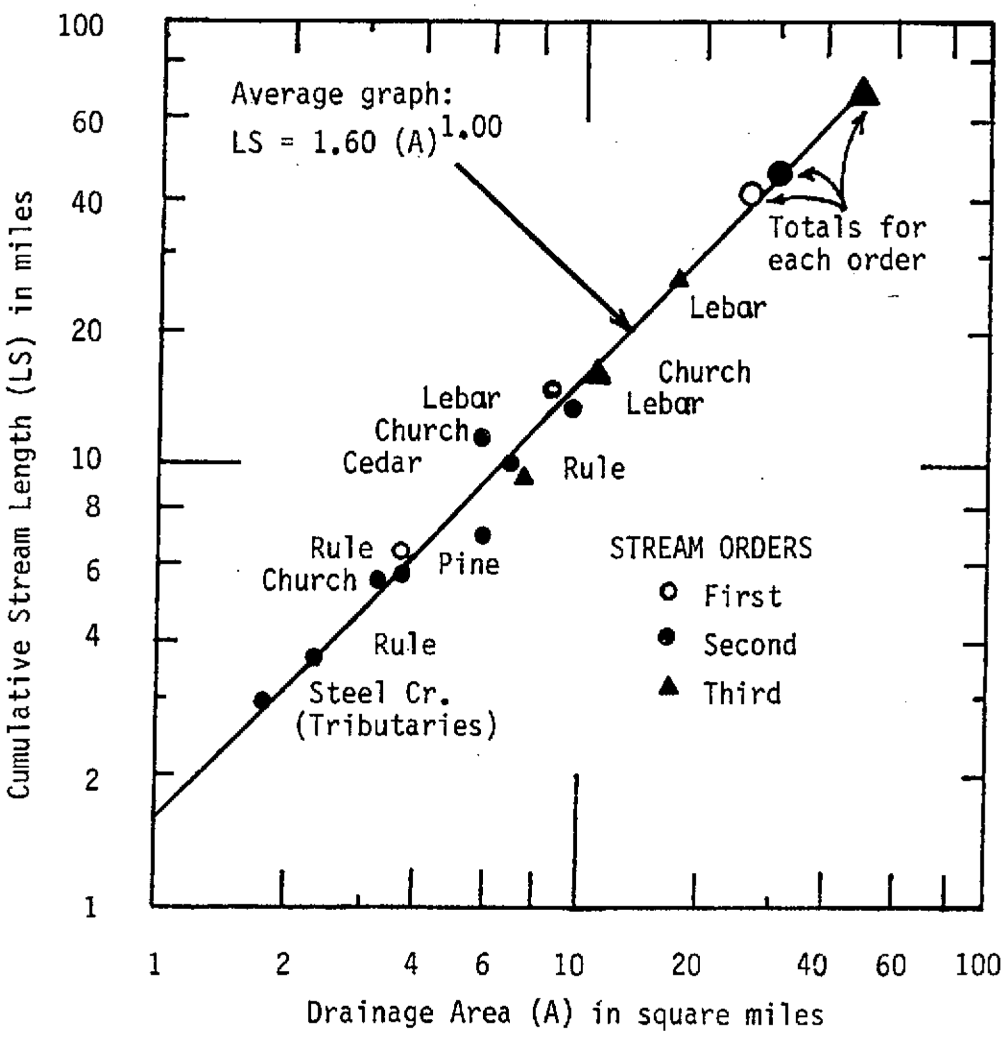


Figure IV-4. Graph of cumulative stream length for tributaries and the mainstem of the South Fork Skokomish River versus cumulative drainage area.

Basin geomorphic characteristics have been used also to develop models to estimate fish productivity in Alaska (Ziemer 1973, Swanston et al. 1977). Although the predictability of the models had wide variability the methods do hold promise. Some of these basin and channel characteristics were combined into habitat estimation models by Collings (1974) and by Orsborn (1981). Estimates of spawning habitat availability at optimum flows can be made from knowing just the wetted perimeter in a channel at bankfull flow (Orsborn 1981). The wetted perimeter (P) is the length of contact surface between the flowing water and the bed (bottom and sides) of the stream. (P) is a measure of the resistance to flow, and is a function of the level of flow and the channel shape. It will be examined further in Appendix V on channel characteristics.

Sources of Information

Depending on which characteristics of the basins you wish to analyze the information may be found from:

- the state average annual precipitation (isohyetal) chart (USWB 1965);
- 1:24,000 and 1:62,500 USGS topographic maps;
- aerial photographs and video films;
- GIS systems, depending on how the data were entered;
- USFS computerized inventory area information on land use (including roads and logged areas); and
- aerial flights and/or ground surveys.

Map and aerial photo information is easier and less expensive to develop but sometimes poor coverage may require the use of other methods such as helicopter flights, video films, low-level photographs and ground surveys.

Methods for Data Acquisition and Analysis

Unless the GIS system is designed to develop these basin characteristics, the best way to determine them is with a computerized digitizer system and topographic maps.

Elevations and relief are determined by first outlining the topographic divide of the basin on the appropriate maps. Then observe the contour just above the ends of the solid blue-line, perennial streams. This is usually adequate to define the upper basin contour, but the uppermost contour that stays within the basin may be higher. The elevation of the project site, basin outlet (base level), or stream gaging site, is also determined from the topographic map or USGS streamflow records. If a digitizer-computer arrangement is not available to measure basin characteristics, a map wheel can be used for lengths and a planimeter for areas. Make sure you account for areas which feed directly into a stream but which are not part of a stream's tributary basins. Check the sum of the parts by measuring the total basin area. Other parameters included in the project basin analysis for each subbasin are: stream order, area, relief, length, width (area/length), relief, and average annual precipitation. A more comprehensive analysis of basin characteristics and dimensional analysis was developed by Strahler (1958).

These parameters can be used in various combinations for either classification or analysis. A few examples of dimensional and dimensionless combinations are:

- (P·A): (average precipitation times drainage area) a measure of the average annual volume of water available on a basin; the maximum and minimum values can be estimated from the variability in average annual flows at gages in the region;
- (H/LB): average rate of expenditure of energy (relief, H) along the length of the basin (LB);
- (H/LS): average slope (rate of energy expenditure) of any order of stream of length (LS) or the total for the whole basin (LST);
- $(P \cdot A)/(LST \cdot H^2)$: relates average annual input to the basin to its ability to transport water (total stream length times relief squared); LST/A is stream density and the combined terms are dimensionless; has been found to be a constant in hydrologic provinces (Orsborn 1976).
- (LST/A): (total length of streams/drainage area) stream density (SD); larger values indicate more efficient runoff patterns, larger floods, less infiltration, less low flow, and vice versa.

Example Basin Geomorphic Analysis of Lebar Creek, a Tributary to the South Fork of the Skokomish River

This analysis consists of making measurements of the basic characteristics of each subbasin, such as:

- stream order (SO),
- stream length (LS, total length LST or LT),
- drainage area (A),
- headwater elevation (EH).
- basin outlet elevation (EO), and
- average annual precipitation (P).

Derived values include:

- cumulative stream length,
- cumulative drainage area,
- subbasin and cumulative stream densities (SD),
- subbasin and cumulative relief (H = EH - EO),
- subbasin and cumulative basin energy $(A)(H)^{0.5}$,
- stream length as a function of drainage area (A),
- stream length as a function of basin energy $(A)(H)^{0.50}$,
- average annual volume of precipitation on the basins (P)(A),
- stream length (LS) as a function of (P)(A),
- basin input (P)(A) as a function of basin energy $(A)(H)^{0.50}$,
- stream profile of elevation versus distance (not included),
- relief (H) as a function of the ratio of $(P)(A)/(LT)(H)^2$; this ratio represents the average annual volume of precipitation on the basin (P) (A) divided by the total basin stream length (LT), and the relief squared $(H)^2$; at a point on the mainstem.

All the basic and derived parameters (basin geomorphic characteristics) are in Table IV-2. The maps used in this analysis were USFS, 1:24000 quadrangles (1" = 2000'): (1) Mt. Tebo NW; and (2) Mt. Tebo NE. Streams were designated as the solid lines (perennial) on the maps. Stream lengths and drainage areas were measured with a computerized digitizer.

The derived map is shown in Figure IV-5 and shows the subbasins, and points on the mainstem, upstream and downstream of tributaries, where characteristics were accumulated. Lebar Creek has only 1st and 2nd order streams/basins (per Strahler's method). Stream reaches 3, 5, 7, 9 and 11 are valley segments, and their subbasin relief (H) is the mean elevation of the valley ridges minus the downstream valley elevation, and is not based on a stream headwater elevation. In terms of the subbasins cumulated above the nodes on the mainstem, then the headwater elevation applies.

The mean basin relief actually fluctuates as a function of basin geometry, and can be less at the basin outlet than it is farther upstream, or in a tributary as shown in Table IV-2. When determining the headwater elevation in a bent basin such as Lebar Creek the rule is to use the upper contour at the end of the longest line which can be drawn within the basin boundary from the outlet towards the divide. This has been verified in several studies in different parts of the country. For Lebar Creek project basin this headwater elevation is

Table IV-2. Geomorphic Characteristics for Lebar Creek Basin.

Basin No. (-)	Stream Order (-)	Stream Length LS (mi)	Cumul. Length LST (mi)	Basin Area A $(mi)^2$	Cumul. Area A $(mi)^2$	Basin Stream Density SD $(mi)^{-1}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1[a]	1	1.54	1.54	1.11	1.11	1.38
2	1	1.14	2.68	0.77	1.88	1.48
3[a]	2	1.80	4.48	1.22	3.10	1.48
4	1	1.54	6.02	0.92	4.02	1.67
5[a]	2	0.75	6.77	0.60	4.62	1.25
6	1	0.69	7.46	0.36	4.98	1.92
7[a]	2	1.37	8.83	1.12	6.10	1.22
8	1	1.30	10.13	1.11	7.21	1.17
9[a]	2	0.57	10.70	0.41	7.62	1.39
10	1	1.07	11.77	0.70	8.32	1.52
11[a]	2	2.25	14.02	1.41	9.73	1.60
Totals for Basin:		--	14.02	--	9.73	1.40

[a] Mainstem Lebar Creek valley segment, see Figure IV-5 for locations.

Table IV-2. Geomorphic Characteristics for Lebar Creek Basin--Continued

Basin No. (-)	Cumul. Stream Density SD $(mi)^{-1}$	Head-Water Elev. EH (ft)	Outlet Elev. EO (ft)	RELIEF Basin H (mi)	RELIEF Cumul. H (mi)
(1)	(8)	(9)	(10)	(11)	(12)
1[a]	1.38	4300	2000	0.44	0.44
2	1.42	4200	2000	0.42	0.44
3[a]	1.44	3000[b]	1400	0.30	0.49
4	1.50	4400	1400	0.57	0.49
5[a]	1.46	2500[b]	1300	0.23	0.53
6	1.50	2800	1300	0.28	0.52
7[a]	1.45	2500[b]	1050	0.27	0.52
8	1.40	3000	1050	0.37	0.52
9[a]	1.40	2500[b]	950	0.29	0.48
10	1.41	3000	950	0.29	0.48
11[a]	1.44	2000[b]	500	0.28	0.47
Totals for Basin:		3500	500	--	0.56

[a] Mainstem Lebar Creek valley segment.
[b] Average ridge elevation for mainstem segments.

Table IV-2. Geomorphic Characteristics for Lebar Creek Basin--Continued

Basin No. (-)	BASIN ENERGY Basin $A(H)^{0.50}$ $(mi)^{2.5}$	BASIN ENERGY Cumul. $A(H)^{0.50}$ $(mi)^{2.5}$	Aver. Precip. P (in/yr)	Basin Input (P·A) (sq mi-in/yr)	$\frac{(P.A)}{(LT \cdot H^2)}$ (in/mi/yr)
(1)	(13)	(14)	(15)	(16)	(17)
1[a]	0.74	0.74[c]	140	155	520
2	0.51	1.23[d]	138	259	499
3[a]	0.67	2.17[c]	138	428	398
4	0.69	2.81[d]	133	--	--
5[a]	0.28	3.36[c]	136	628	335
6	0.19	3.62[d]	133	--	--
7[a]	0.58	4.40[c]	134	817	343
8	0.68	5.19[d]	131	--	--
9[a]	0.22	5.28[c]	132	1005	587
10	0.38	5.76[d]	127	--	--
11[a]	0.75	6.67	130	1265	288
Totals for Basin:		7.28	130	1265	288

[a] Mainstem Lebar Creek valley segment.
[c] Just above tributary basin.
[d] Just below tributary basin.

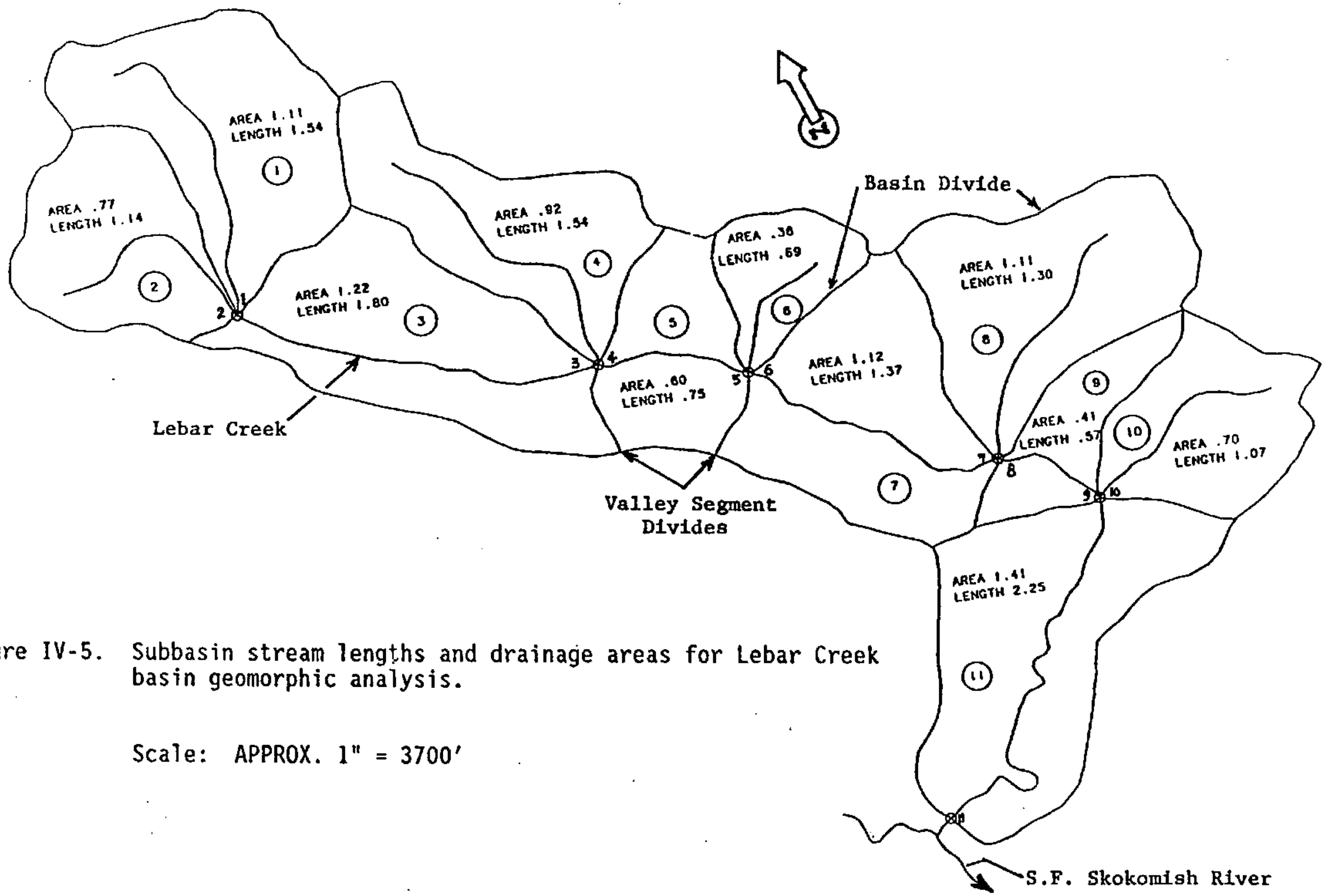


Figure IV-5. Subbasin stream lengths and drainage areas for Lebar Creek basin geomorphic analysis.

Scale: APPROX. 1" = 3700'

about 3500 ft., as opposed to an elevation of 4300 ft. in Subbasin No. 1 in Table IV-2.

The headwater elevation (EH) is taken as the highest, continuous contour that stays with the basin above the ends of the first-order streams (Figure IV-3 on page IV-11). A variation in estimated elevations of 100-200 ft. is not crucial, because the relief (H) is reduced to miles and then the square root is taken for basin energy. For example in Subbasin No. 1:

$$\left(\frac{4300 - 2000}{5280}\right)^{0.50} = 0.66$$

$$\left(\frac{4100 - 2000}{5280}\right)^{0.50} = 0.63$$

or about a 10% change in (H) causes only a 4.5% change in $(H)^{0.50}$, and the best stream gaging has an accuracy of about ±5%.

The results of the basin geomorphic analyses are plotted as follows:

- Figure IV-6: Cumulative stream length (LST) versus drainage area (A); the coefficient in the equation is the stream density.

  From the graph: $LST = 1.4(A)^{1.00}$ (IV-4)

- Figure IV-7: Cumulative stream length (LST) versus average annual precipitation volume (PA) on the watershed; this is a measure of the average annual streamflow which is $QAA = 0.0032(P)^{1.6}A$.

  From the graph: $LST = 0.0055(PA)^{1.10}$ (IV-5)

- Figure IV-8: Cumulative stream length (LST) related to basin energy $(A)(H)^{0.50}$; this equation (where $E_b = (A)(H)^{0.50}$) is:

  $LST = 2(E_b)^{1.00}$ (IV-6)

  or, if it is reversed,

  $E_b = 0.5(LST)^{1.00}$ (IV-7)

  it says that the basin energy is equal to one-half of the perennial stream length at any place along the mainstem of the creek.

As was demonstrated in Appendix III, one set of hydrologic models uses basin energy $(A)(H)^{0.50}$ to estimate such flows as the average annual flow (QAA) (or flood flows) with the equation

$$QAA = C[(A)(H)^{0.50}]^{1.00} \quad \text{(IV-8)}$$

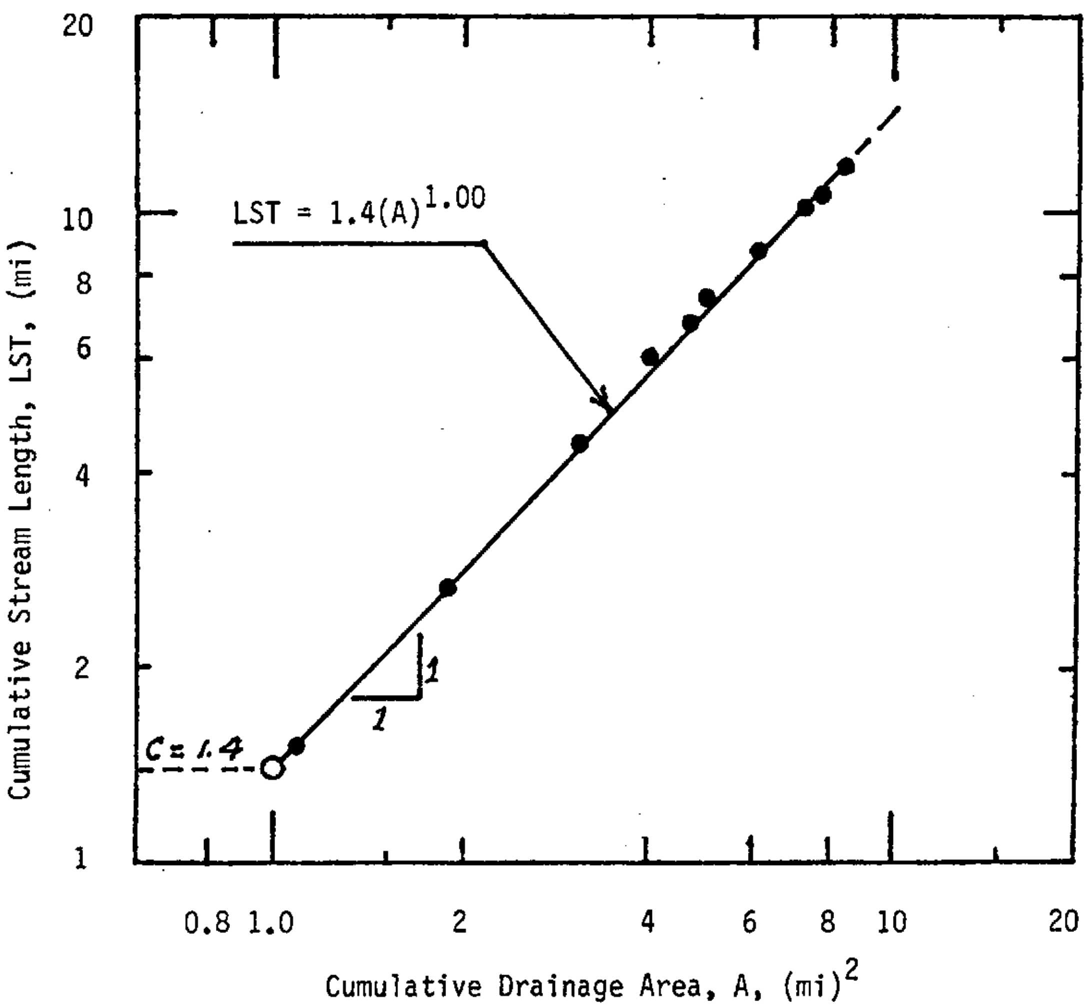


Figure IV-6. Cumulative stream length related to basin area for Lebar Creek.

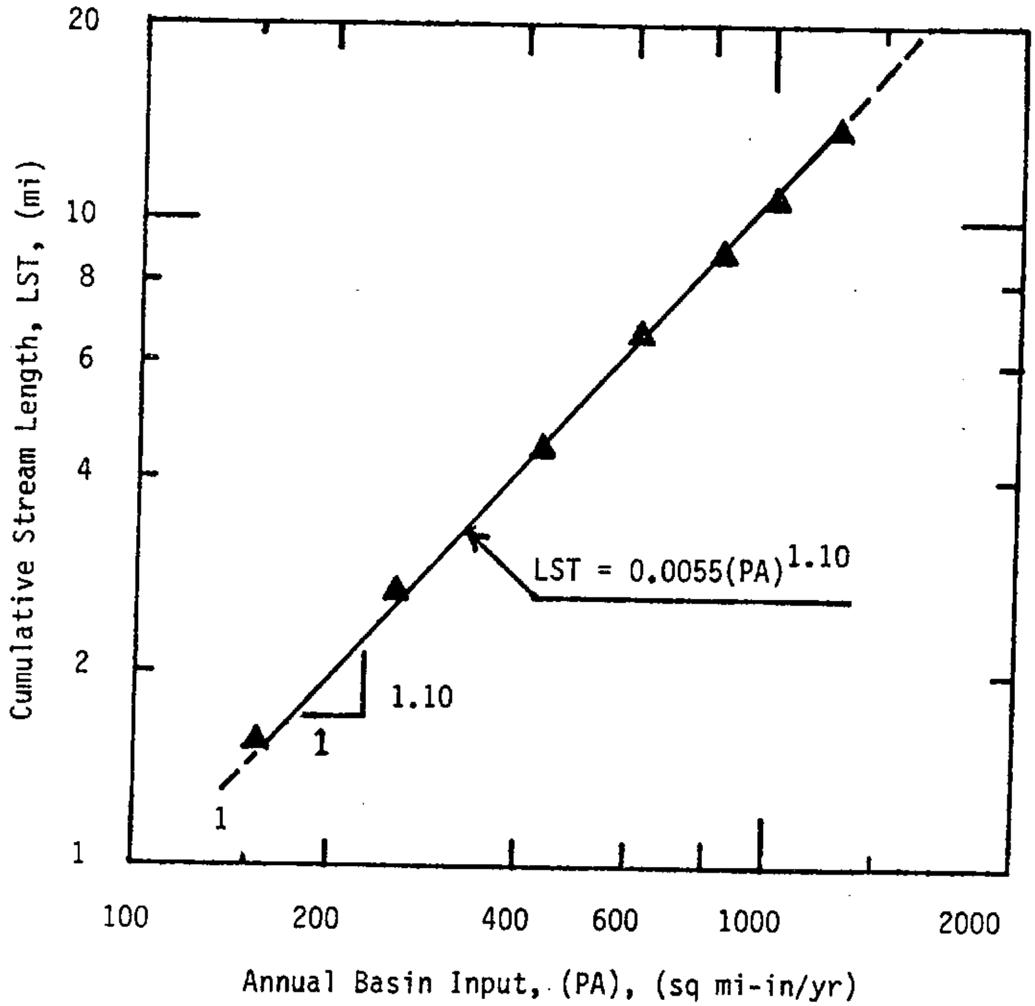


Figure IV-7. Cumulative stream length related to average annual precipitation input to the basin (P)(A) for Lebar Creek.

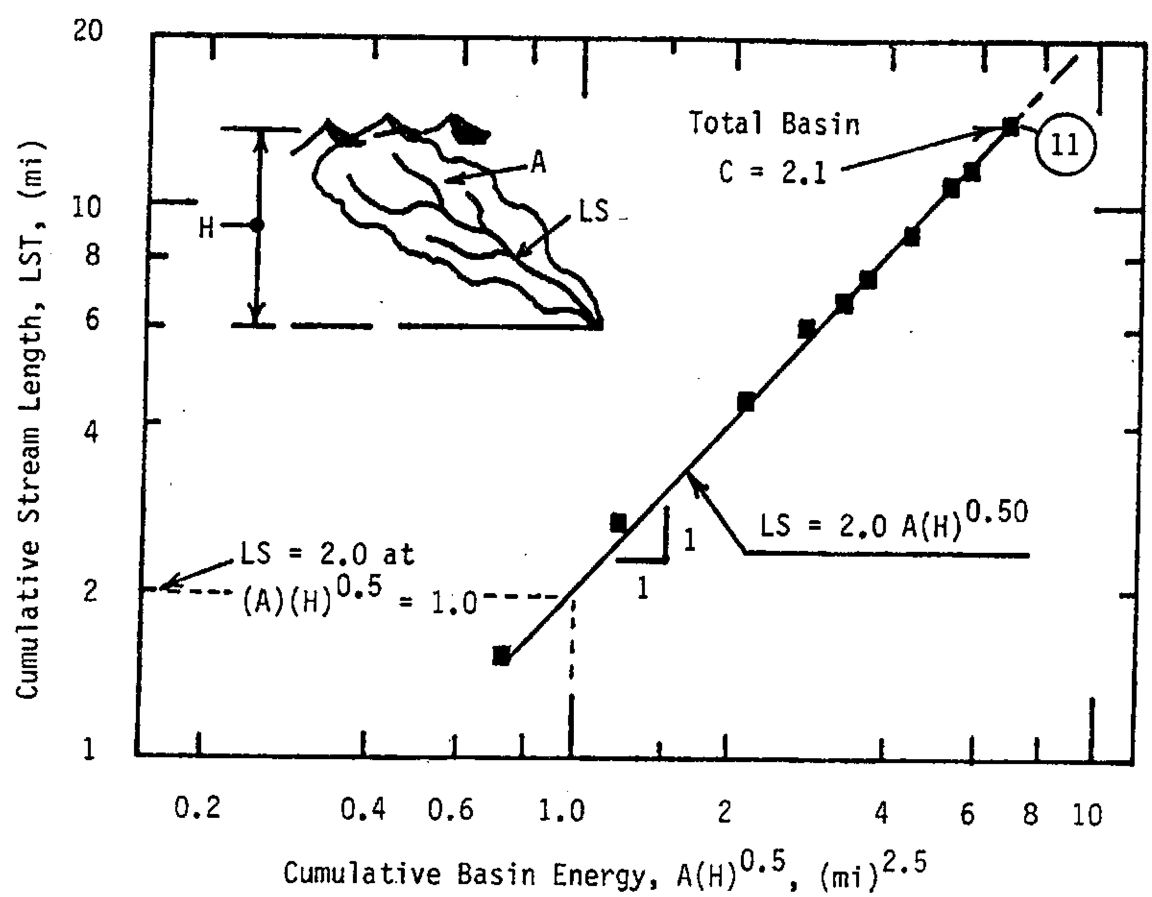


Figure IV-8. Cumulative stream length related to basin energy for Lebar Creek.

where C varies from about 20 down to 2.0 in the rain shadow, a factor of 10. This is about the same as the range of precipitation on the Peninsula, about 200 to 20 inches per year.

But, substituting Eq. IV-7 in IV-8 yields for an "average" basin:

$$QAA = 10[0.5LS] = 5(LS) \qquad \text{(IV-9)}$$

which says, when reduced, that the average annual flow is 5.0 times the length of the total perennial stream length for basins with (C) in Eq. IV-8 equal to 10. This model has been derived for this example analysis, but should be checked for other basins in the future. It means that regional equations for average annual (and average flood) flows can be calibrated to perennial stream length as shown on maps.

- Figure IV-9: gives a relationship between basin relief (H) at any point on a stream to the combined ratio of input/basin relief $(H)^2$ and the delivery system (stream) length (LS) for Lebar Creek so that

$$H = 4.5/[(PA)/(LS)(H)^2]^{0.40} \qquad \text{(IV-10)}$$

This is the same equation that was developed for a series of basins in Southwestern Washington (Deschutes, Cowlitz and Lewis basins) as part of an earlier study (Orsborn 1976). It is presented in Appendix VII (Figure VII-8) as part of the classification methods. If rearranged, and reduced

$$P = 45.0\ (LT)/A(H)^{0.50} \qquad \text{(IV-11)}$$

- Figure IV-10: shows the relationship between basin input (P)(A) and basin energy $(A)(H)^{0.50}$ for Lebar Creek. One would expect good correlation because (A) is in both sets of terms. But, the relationship can be reduced to give the precipitation (P) as a function of basin relief (H).

$$(P)(A) = 210\ [(A)(H)^{0.50}]^{0.94} \qquad \text{(IV-12)}$$

and if this is reduced

$$(P)(A) = 210\ (A)^{0.94}(H)^{0.47} \qquad \text{(IV-13)}$$

When compared with Figure VII-10 on page VII-26, the coefficient of 210 agrees the coefficient for the whole south Fork Skokomish River (Station 8.8 inside circle). Rearranging to solve for (P),

$$P = 210\ (H)^{0.47}/(A)^{0.06} \qquad \text{(IV-14)}$$

A similar analysis of the Dungeness River basin on the northeast Olympic Peninsula yielded (as in Eq. IV-13)

$$(P)(A) = 72.0\ (A)^{0.94}\ (H)^{0.47} \qquad \text{(IV-15)}$$

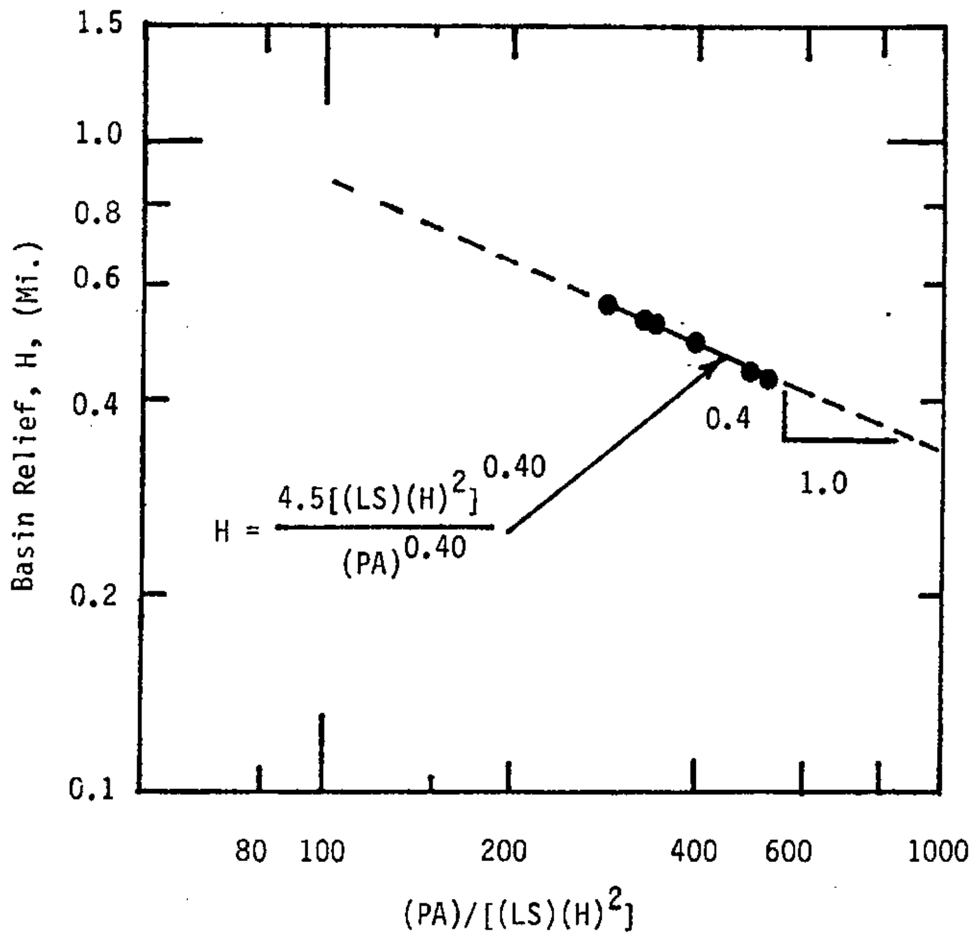


Figure IV-9. Basin relief (H) as a function of basin input (PA) divided by stream length (LS) and basin relief squared $(H)^2$ for Lebar Creek.

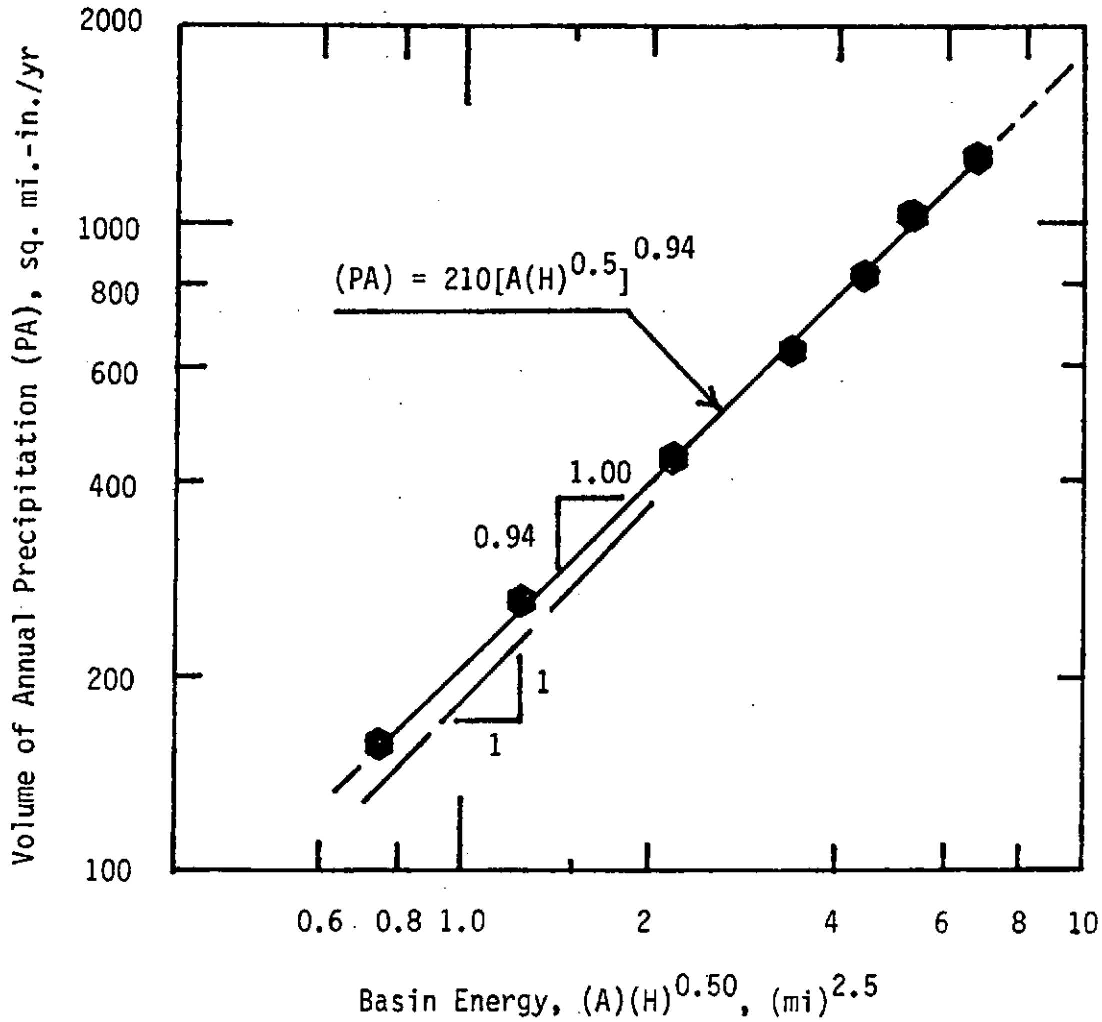


Figure IV-10. Basin input (annual volume of precipitation, PA) related to basin energy $(A)(H)^{0.50}$ for Lebar Creek.

showing that the allometric approach is verified----in physical relationships, holding the exponents constant and calibrating the coefficients by region is a reasonable method of analysis.

Now we have a set of geomorphic equations which we can use separately, or in combination, to group and classify the variations in stream length, area, relief, basin energy and average annual water supply to the basin. These, and other flow, basin and channel parameteric combinations are discussed in Appendix VI on integration of these components just before their incorporation into classification systems in Appendix VII. To prepare for that integration, the next section of the report presents a discussion of the physical aspects of stream channels to complete the description of the three major components in this project synthesis----hydrology, basins and channels.

APPENDIX V.--STREAM CHANNEL CHARACTERISTICS

APPENDIX V. STREAM CHANNEL CHARACTERISTICS

Introduction

The analysis of stream channel characteristics from the basin-fisheries perspective we must describe:

- the geometry of the channel at the site from three perspectives: plan, profile and cross-section (**CHANNEL GEOMETRY**);

- the amount and timing of flow (and sediment and organic matter) entering the stream segment (or study site) as derived from the hydrologic analysis (**HYDROLOGIC INPUT**);

- the interaction of the flow with the channel boundary (**HYDRAULIC ANALYSIS**); and

- the interaction of isolated objects in the flow (such as boulders) using **FLUID MECHANICS** (depth changes, flow patterns, scour deposition, sediment transport, vortices, habitat ...).

These aspects of the interaction can be viewed from several perspectives by:

1) combining streamflow with channel cross-sectional shape into **HYDRAULIC GEOMETRY**;

2) combining streamflow with the channel profile (slope, S) to yields **STREAM POWER** which relates to the sediment transport capability of the flow, channel deposition and the size of armor layer of bed material after high flows; and

3) combining streamflow with combinations of habitat features (depth, velocity, cover, substrate, etc....) which analyze habitat availability as a function of streamflow, and thus **HABITAT SUITABILITY INDEX** or **HABITAT DURATION CURVE**.

Assume we are dealing with a riffle:pool sequence over a reach or segment of stream as shown in the lower half of Figure V-1. The segment of stream has repeating riffle and pool sequences controlled at each end of the segment by horizontal and vertical geologic structures. The reach is in balance so the riffle:pool sequences will be adjusted during high flows, but will return to its pre-flood geometry ... it is in balance, or EQUILIBRIUM ... the work done on the boundaries (shear, friction) and in moving SEDIMENT, is balanced by the rate of expenditure of ENERGY (SLOPE of the channel between CONTROLS). Cross-sections 1 and 2 in Figure V-1 are local controls which regulate the depth of flow for lower flows.

If for some reason any of the **INPUTS** to the **RIFFLE:POOL SUBSYSTEM** are changed, then the subsystem will go "out of balance" and adjust accordingly---increased flow without increased debris or sediment load can cause increased erosion of banks, filling and widening of the channel.

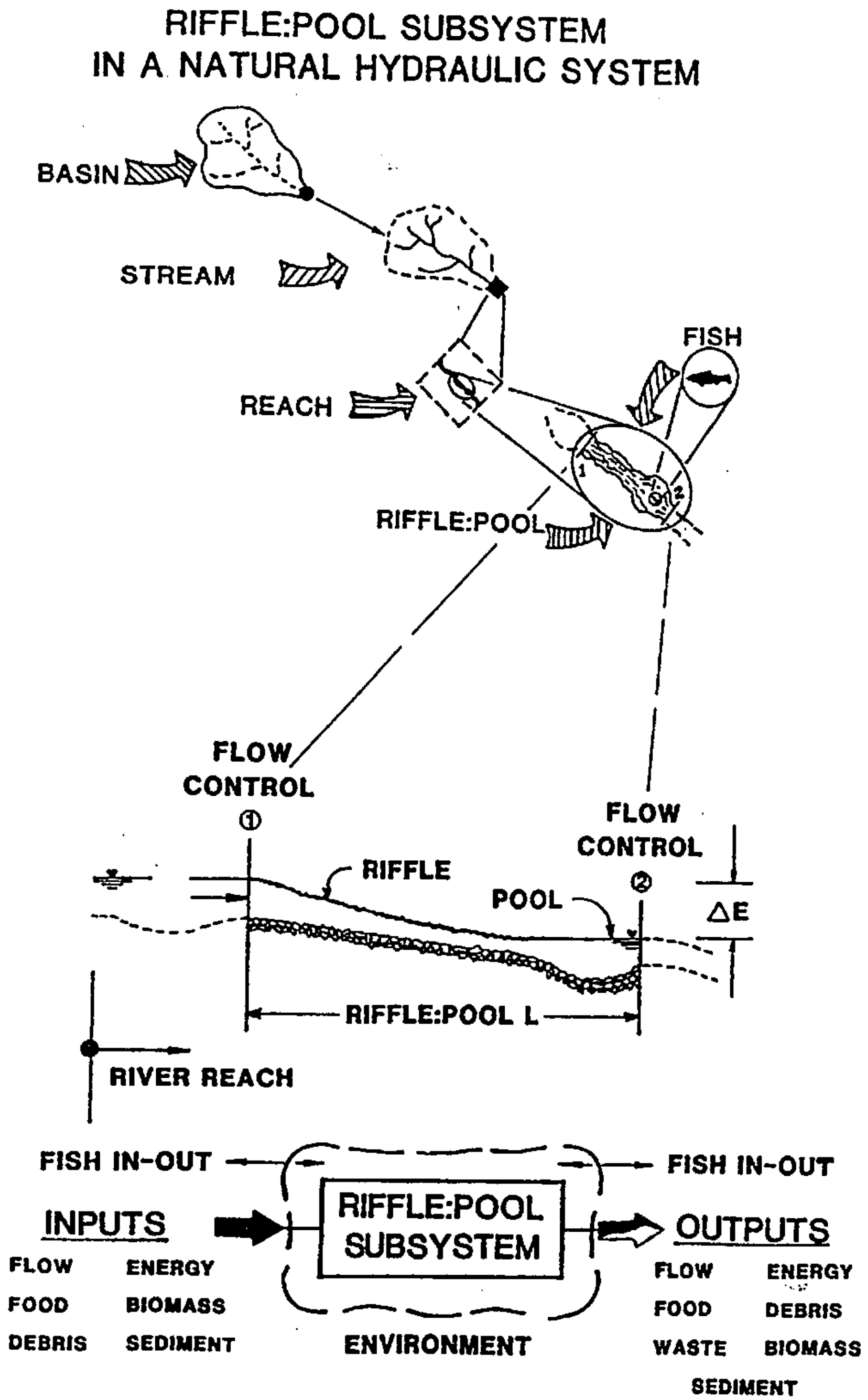


Figure V-1. A riffle:pool subsystem model within the reach, stream and basin environmental showing general inputs and outputs.

This general description of the potential interactions of the basin-stream system leads to a definition of the problems associated with interrelating flow, geometry and fisheries conditions in a segment of stream.

Definition of the Problem

With respect to anadromous salmonids, stream channel characteristics have limiting habitat conditions at both ends of the slope spectrum. Channels which are steep (3-5%) can have substrate which is too large for spawning, but pools and substrate pores may provide holding and rearing habitat. Spawning gravels would be limiting in this type of channel. At the other extreme of slope, such as in the lower reaches of the Skokomish River mainstem, where the bed slope is flatter (less than 0.5%), the bed materials are sandier. There is some intermediate range of channel described by slope and channel size within which most fisheries-channel problems can be considered. Depending on basin geology and morphology and migration barriers, some of the best steelhead rearing habitat may be in relatively small headwaters. Depending on valley size and shape, off-channel habitat may exist. These off-channel habitats are related to channel and valley geometry, and their utility is a function of how those geometries change hydraulically in relation to changes in streamflow.

Subsystem interrelationships in the reach-segment system are described schematically in Figure V-2 as an extension of Figure V-1. Considering the right side of Figure V-2, it takes the map view from the left side, and considers the site in cross-section and profile. All the physical components are interrelated subsystems, or parts of the larger basin-channel network-site system. The channel slope and cross-section, assuming they are readily deformable, will adjust according to the load of water and debris imposed on the channel.

The problem lies in being able to analyze, quantify and predict these impacts and responses to natural or man-made influences on the basin. And, separating the combined impacts of both man-made and natural influences on channel geometry, which governs fisheries habitats, is even more complex. A baseline of unaltered conditions should be part of the monitoring program, such as a comparable, well-monitored, undisturbed basin and stream segment.

HYDRAULIC GEOMETRY is derived from what is called the continuity equation (you have to account for all the flow, and changes in flow area which result in opposite changes in velocity)

$$Q = AV \tag{V-1}$$

Q is the <u>volume rate of flow</u> (ft^3/s or cfs); A is the wetted cross-sectional (flow) area of the channel (ft^2); and V is the mean velocity of the flow (ft/s or fps). (NOTE: Q IS <u>NOT</u> the volume of flow; it is the volume rate of flow.)

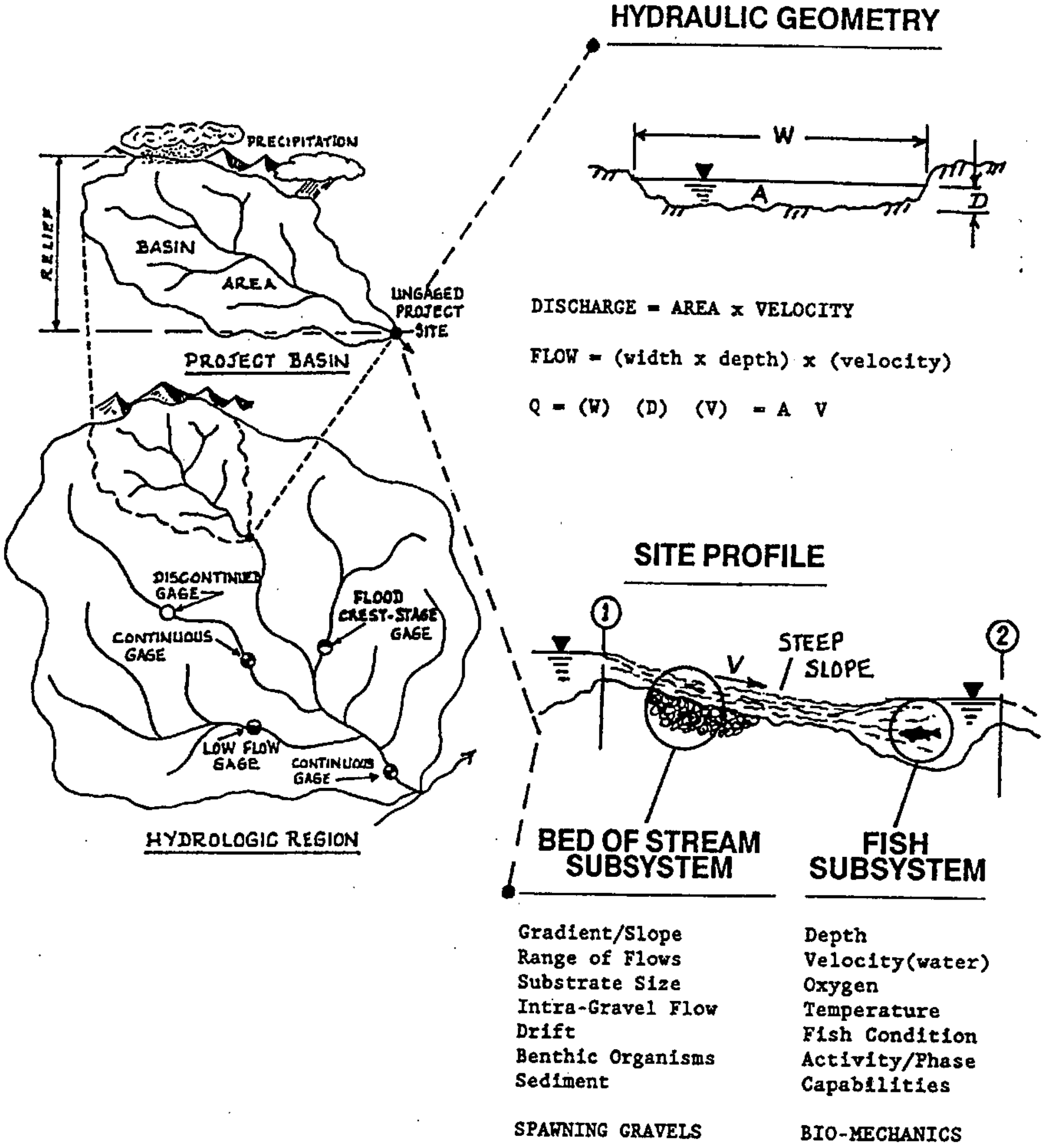
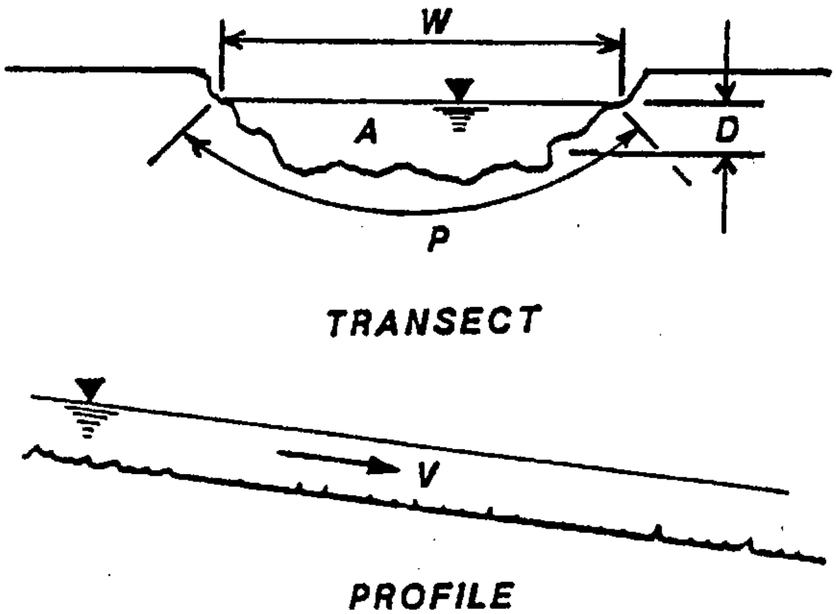


Figure V-2. Interrelationships of regional hydrologic, basin, channel hydraulic and fish subsystems.

For a particular flow, the flow area can be rewritten as A = WD where: W is the top width at the water surface (ft); and D = A/W which is called the mean hydraulic depth. In hydraulic energy calculations the symbol y is used instead of D by convention, due to the y-direction being vertical in graphical and coordinate systems. The symbol D is a convention in the geomorphic literature. The nomenclature for hydraulic geometry is shown in the sketch.



Sketch of nomenclature for hydraulic geometry.

Rewriting Eq. (V-1) as

$$Q = W \cdot D \cdot V, \qquad \text{(V-2)}$$

this equation can be divided into three parts. As the flow (Q) at a site changes, then W, D and V will change as a function of flow and channel shape such that

$$W = a(Q)^b \qquad \text{(V-3)}$$
$$D = c(Q)^d \text{ and} \qquad \text{(V-4)}$$
$$V = e(Q)^f \qquad \text{(V-5)}$$

Because the coefficients and exponents in Eq. (V-2) all equal 1.0, then by substituting the equations for W, D, and V into Eq. (V-2) yields

$$Q = a(Q)^b \cdot c(Q)^d \cdot e(Q)^f \qquad \text{(V-6)}$$

and this means that (a) (c) (e) = 1.0 and (b + d + f) = 1.0.

These equations are evaluated at project sites or gaging stations by doing streamflow measurements. Changes in these relationships over time indicate changes in the water and/or sediment and debris loads. If the W, D and V values are calculated for any particular characteristic flow (such as the average annual flow, QAA) for a series of sites in a region, then a regional channel geometry model can be developed for that flow. This hydraulic geometry is called "in a downstream direction" and shows how W, D, and V change as QAA increases with the size of the basins. Recall that as basins get larger the average flow contribution per square mile gets smaller. But, channel size increases. This method of regional modeling is explained later. All gages do not have to be in the same basin to build a regional model.

Other channel geometric characteristics which should be included in the hydraulic geometry analysis are:

A the flow area rather than using W and D separately;
P the wetted perimeter; and
R the hydraulic radius = A/P.

The wetted perimeter (P) and hydraulic radius (R) come from Manning's equation for mean flow velocity (V) in Eq. (V-1) which states

$$V = (1.49/n)\ R^{0.67}\ S^{0.50} \qquad \text{(V-7)}$$

where

1.49 = a conversion factor from metric to English units (1.0 in metric);
n = Manning's flow resistance coefficient, which usually varies inversely with flow (as Q increases, n decreases);
R = a measure of flow efficiency, area/resistance surface (A/P); and
S = will be called the slope of the streambed (S_b) for now.

Substituting Eq. (V-7) (Manning's equation for velocity) into Eq. (V-1) (Q = AV) yields

$$Q = A[(1.49/n)\ R^{0.67}\ S^{0.50}]. \qquad \text{(V-8)}$$

or as more usually seen $Q = (1.49/n)\ AR^{0.67}\ S^{0.50}$.

Sources of Hydraulic Geometry Data

1) USGS streamflow gaging station calibration data; only Q, W, D, V and A can be developed from the USGS data sheets called Form 9-207.

2) Calibration data from any stream gaging site (in operation or discontinued) operated by agencies, companies, tribes or other entities or consulting firms. WDNR has gaging stations in certain parts of the state, and WDOE makes numerous measurements in conjunction with its instream resources protection program.

3) Streamflow and channel geometry information collected at: (a) AMC monitoring sites, (b) U.S. Forest Service LTT sites, and (c) instream flow study sites.

Problems associated with the last two types of data are:

- many times the data are residing in a file and have not been reduced;
- the data may have been lost or tossed if they were not part of a formal database program; or
- the channel characteristics at the gaging site may have changed due to land-use changes on the basin, debris jams, extreme flooding, encroachment due to road construction or due to an unnoted shift in the gaging location. But this pre-impact data would be valuable for comparison with existing post-impact channel geometry.

Analysis of Hydraulic Geometry Data

A typical set of hydraulic geometry information is shown in Table V-1 for the South Fork Skokomish River. The wetted perimeter (and thus hydraulic radius, $R = A/P$) are not available from USGS gage calibration data (Form 9-207) from which this data set was derived. It is better, of course, to have a measured value of (P) and a calculated value of (R), but they can be estimated well within the range of the best stream gaging accuracy ($\pm$ 5%).

One of the major problems associated with analyzing natural channel hydraulic geometry is the changes in the relationships due to flooding and/or debris. These influences usually are most noticeable at low flows where the thalweg channel may change in size. This affects the W, D, and V relationship as shown in Figure V-3 for the Sooes River. (Note that after the 1982 flood the channel width decreased and according to the continuity equation [$Q = AV = WDV$], velocity increased in the low flow range around 8 to 20 cfs.)

When the data from Table V-1 for the South Fork Skokomish River are plotted in Figure V-4, you can see the effects of shifting measurement sites between lower and higher flows. Note the locations of the three characteristic flows (Q7L2, QAA and QIF2).

Also, hydraulic geometry relationships can be used to check for changes over different sequential periods of time to determine the effects of upstream land use changes. Typical "at-a-station" hydraulic geometry relationships for a sample of USGS gaging stations on the Olympic Peninsula are shown in Table V-2 for the three basic characteristic flows (Q7L2, QAA and QIF2). These were calculated from the at-a-station equations for each site in the Olympic Peninsula streamflow study (Amerman and Orsborn, 1987).

Using these values of W, D, V and A for each gaging station then **REGIONAL HYDRAULIC GEOMETRY MODELS** are developed for each characteristic

Table V-1. Input Data for At-A-Station Hydraulic Geometry Model for S.F. Skokomish River: August 1979-October 1984 (Gage No. 12060500) (from Amerman and Orsborn 1987)

OBS	NAME	STATION	WIDTH (FT)	AREA (FT**2)	VELOCITY (FPS)	DISCHARGE (CFS)	DEPTH (FT)
1	S F SKOKOMISH RIVER	12060500	235.0	304	2.16	657.0	1.29362
2	S F SKOKOMISH RIVER	12060500	240.0	363	1.56	565.0	1.51250
3	S F SKOKOMISH RIVER	12060500	225.0	357	1.56	558.0	1.58667
4	S F SKOKOMISH RIVER	12060500	236.0	238	0.96	229.0	1.00847
5	S F SKOKOMISH RIVER	12060500	226.5	212	2.88	610.0	0.93598
6	S F SKOKOMISH RIVER	12060500	187.0	340	0.90	307.0	1.81818
7	S F SKOKOMISH RIVER	12060500	199.0	336	0.99	332.0	1.68844
8	S F SKOKOMISH RIVER	12060500	180.0	245	0.63	154.0	1.36111
9	S F SKOKOMISH RIVER	12060500	224.0	246	1.33	328.0	1.09821
10	S F SKOKOMISH RIVER	12060500	155.0	432	3.89	1680.0	2.78710*
11	S F SKOKOMISH RIVER	12060500	155.0	465	3.91	1820.0	3.00000*
12	S F SKOKOMISH RIVER	12060500	221.0	255	2.17	554.0	1.15385
13	S F SKOKOMISH RIVER	12060500	177.0	301	1.65	496.0	1.70056
14	S F SKOKOMISH RIVER	12060500	180.0	221	1.17	259.0	1.22778
15	S F SKOKOMISH RIVER	12060500	166.0	163	0.55	89.6	0.98193
16	S F SKOKOMISH RIVER	12060500	187.0	154	0.80	123.0	0.82353
17	S F SKOKOMISH RIVER	12060500	160.0	682	4.06	2770.0	4.26250*
18	S F SKOKOMISH RIVER	12060500	155.0	425	4.54	1930.0	2.74194*
19	S F SKOKOMISH RIVER	12060500	155.0	570	5.16	2940.0	3.67742*
20	S F SKOKOMISH RIVER	12060500	182.0	282	1.86	521.0	1.54945
21	S F SKOKOMISH RIVER	12060500	180.0	207	1.05	218.0	1.15000
22	S F SKOKOMISH RIVER	12060500	183.0	211	1.38	292.0	1.15301
23	S F SKOKOMISH RIVER	12060500	120.0	366	3.06	1120.0	3.05000*
24	S F SKOKOMISH RIVER	12060500	161.0	1043	6.82	7110.0	6.47826*
25	S F SKOKOMISH RIVER	12060500	206.0	338	2.38	805.0	1.64078
26	S F SKOKOMISH RIVER	12060500	179.0	305	1.51	462.0	1.70391
27	S F SKOKOMISH RIVER	12060500	133.0	374	3.74	1400.0	2.81203*
28	S F SKOKOMISH RIVER	12060500	208.0	327	2.75	900.0	1.57212
29	S F SKOKOMISH RIVER	12060500	201.0	214	1.71	367.0	1.06468
30	S F SKOKOMISH RIVER	12060500	162.0	161	0.67	108.0	0.99383

*Probable cable measurements.

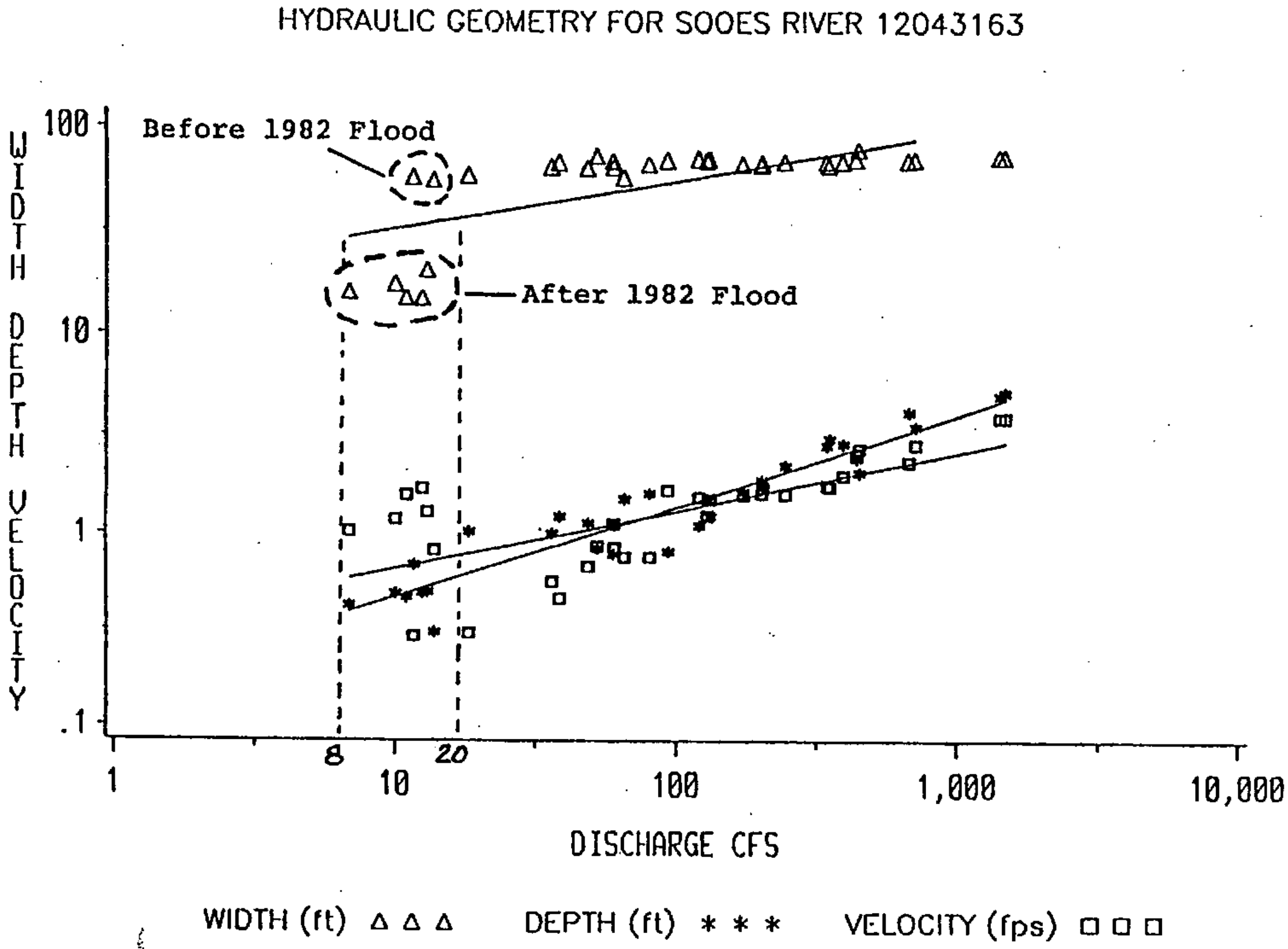


Figure V-3. Graph of hydraulic geometry for Sooes River to show effects of large floods on low flow channel geometry: September 1980-October 1985 (from Amerman and Orsborn 1987).

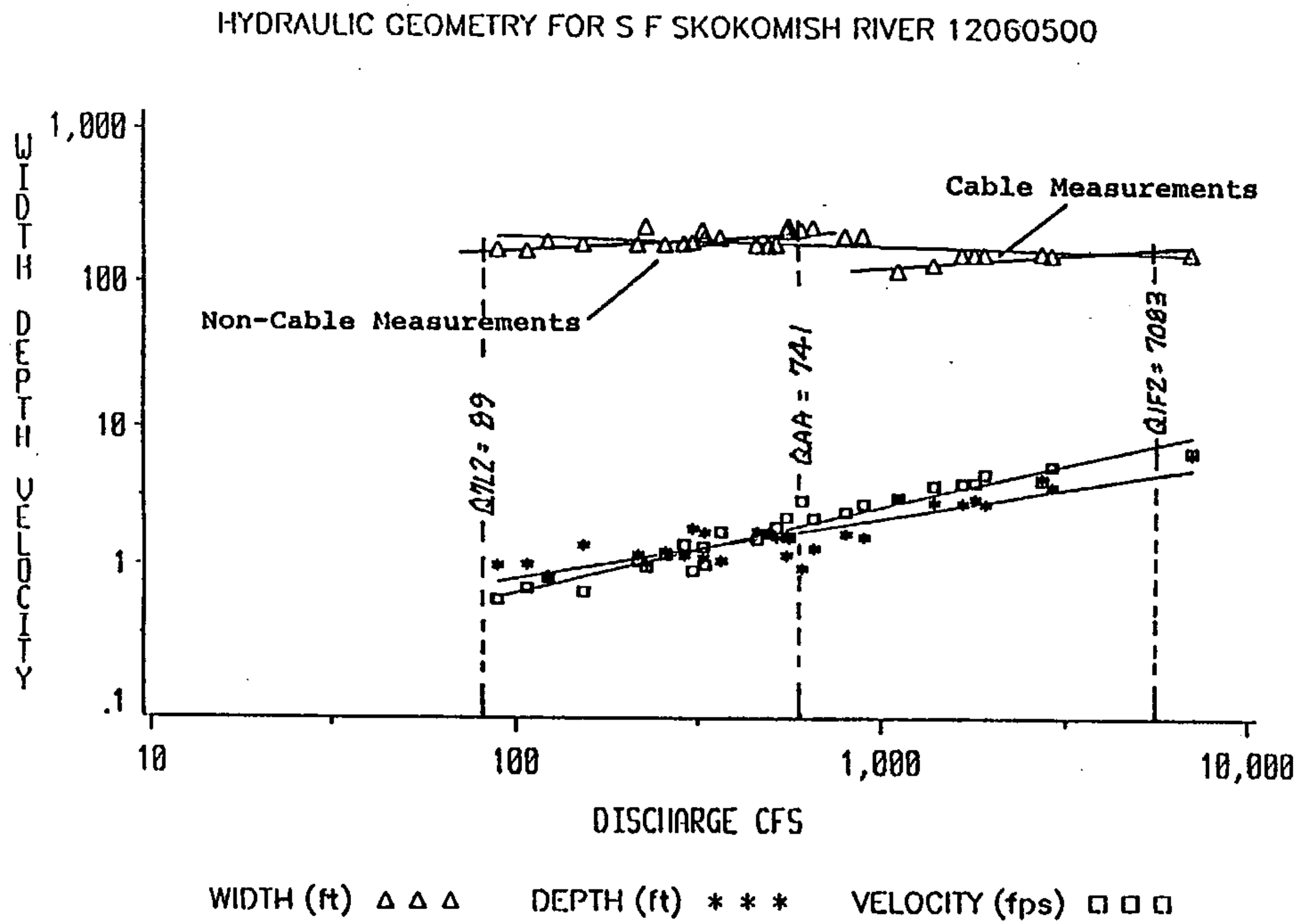


Figure V-4. Graph of at-a-station hydraulic geometry for S.F. Skokomish River to show effect of high flow measurements taken from cable way some distance from gage transect: August 1979-October 1984 (from Amerman and Orsborn 1987).

Table V-2. Calculated Values of At-A-Station Hydraulic Geometry for the Three Basic Characteristic Flows at Twenty Base Gaging Stations on the Olympic Peninsula (from Amerman and Orsborn 1987).

Province/ Stream		Characteristic Flows			Calculated Values of Width, Depth, Velocity and Area at Characteristic Flows											
					For Q7L2				For QAA				For Q1F2			
Gage code	Station Name	Q7L2 (cfs)	QAA (cfs)	Q1F2 (cfs)	W (ft)	D (ft)	V (fps)	A (ft)	W (ft)	D (ft)	V (fps)	A (ft)	W (ft)	D (ft)	V (fps)	A (ft)
1.3	Satsop River	238.7	2035	18307	212.6	1.20	0.93	255.1	252.3	2.33	3.44	587.8	300.8	4.61	13.14	1386.7
1.5	Humptulips River	146.7	1337	13393	160.1	0.96	0.95	153.7	186.9	2.70	2.63	504.6	219.6	7.99	7.60	1754.6
2.1	Moclips River'	5.5E	213E	2732E	26.5E	0.50E	0.41E	13.2E	57.2E	1.40E	2.62E	80.1E	97.7E	2.87E	9.62E	280.4E
2.2	Raft River	45.5E	546E	7770E	81.6E	0.93E	0.60E	75.9E	107.2E	2.45E	2.08E	262.6E	143.6E	6.91E	7.85E	992.3E
2.3	Dickey River	12.6E	549E	7599E	64.6E	0.78E	0.26E	50.4E	81.1E	2.52E	2.76E	204.4E	94.9E	5.68E	14.46E	539.0E
2.4	Sooes River	6.7E	208E	2278E	60.6E	0.45E	0.24E	27.3E	69.5E	1.89E	1.56E	131.4E	76.5E	5.17E	5.70E	395.5E
3.1	N.F. Quinault River	161.1	887	6182	110.2	2.17	0.67	239.1	133.0	3.56	1.87	473.5	164.6	6.25	5.98	1028.8
3.5	Hoh River	610.0	2028	13053	106.4	2.48	2.30	263.9	128.9	3.65	4.30	470.5	173.7	6.62	11.31	1149.9
3.7	Soleduck River	79.3	621	6021	80.1	1.82	0.54	145.8	85.2	3.74	1.95	318.6	91.2	8.29	7.98	756.0
4.1	Hoko River'	19.5	408	4739	52.2	0.63	0.60	32.9	93.0	1.93	2.28	179.5	148.2	4.79	6.71	709.9
4.2	E. Twin River	3.7	64.7	595	14.8	0.55	0.46	8.1	33.1	1.00	1.96	33.1	61.6	1.59	6.08	97.9
5.2	Dungeness River	113.6	393	1903	75.4	1.31	1.14	98.8	80.2	2.08	2.35	166.8	86.8	3.73	5.87	323.8
6.1	Siebert Creek	2.6	17.1	249	12.8	0.48	0.42	6.1	17.7	0.75	1.29	13.3	27.8	1.38	6.44	38.4
6.2	Snow Creek	2.2	16.2	151	15.4	0.36	0.40	5.5	21.7	0.63	1.19	13.7	31.6	1.17	4.06	37.0
6.3	Little Quilcene River'	9.4E	48.6E	365E	19.9E	0.62E	0.75E	12.3E	25.9E	0.97E	1.92E	25.1E	35.7E	1.67E	6.06E	59.6E
8.2	Duckabush River	73.4	422	2965	65.4	1.01	1.11	66.1	72.6	2.14	2.71	155.4	81.6	4.95	7.31	403.9
8.3	Hamma Hamma River'	59.9	364	2576	79.2	0.83	0.91	65.7	88.3	1.68	2.45	148.3	99.3	3.59	7.20	356.5
8.8	S.F. Skokomish River	88.8	741	7083	168.7	1.00	0.53	168.7	213.1	1.55	2.24	330.3	273.1	2.50	10.38	682.8
9.1	Goldsborough Creek	20.6	116	778	33.5	0.80	0.75	26.8	38.2	1.62	1.81	61.9	44.1	3.52	4.77	155.2
9.2	Kennedy Creek	2.7	61.3	563	11.4	0.35	0.62	4.0	29.0	1.05	1.86	30.4	56.4	2.28	4.05	128.6

Water surface width (W).
Mean hydraulic depth (D).
Mean velocity (V).
Cross-sectional area (A) = (WxD).

E Characteristic flows (Q7L2, QAA, Q1F2) estimated by correlation with one or more gages

' Calculated values of W, D, V, and A, based on these estimated characteristic flows.

flow (Q7L2, QAA and Q1F2). Values for the gaging stations from all over the Olympic Peninsula have been plotted in Figures V-5, -6, -7 and -8, so one would expect a considerable amount of variability in the relationships. This variability can be reduced by using data only from geologically similar subregions. The most variability occurs in Figure V-5 for low flows as would be expected. The variability (scatter) in the data points decreases as flow is increased to average annual flow in Figure V-6 and to average annual flood in Figure V-7. Note that for the South Fork Skokomish River (data point 8.8 inside circles) width and depth consistently show over- and under-sized values respectively compared to the average graphs. This probably reflects changes in channel size due to increased sediment loads from the basin in the past 40 years.

The regional relationships of channel flow area (A) to average annual flow and average annual floods in Figure V-8 show much less scatter than individual plots of (W) and (D). This is partially due to the fact that (D = A/W) and calculating (D) this way reduces (A) to an equivalent rectangular cross-section. The graphs and equations shown in Figure V-5 through V-8 represent only the average conditions for the set of gaging stations used in the analysis, and their average shapes for the period of record used in the analysis. Both points 3.5 (Hoh River) and 3.7 (Soleduck River) are influenced by bedrock; the Hoh along the left bank, and the Soleduck across the entire cross-section.

Examples of estimations using the regional models for QAA and Q1F2 for five sites not used in model development are shown in Table V-3. As expected, there is a large variation in some of the values developed from on-site equations compared to those estimated by the regional equations. Subregional equations developed for basins and channels of similar size and geology would certainly provide better results. The use of equations for such a large and diverse region would not be accurate enough to estimate the integrated effects of land use impacts on the response of the stream channel and demonstrated by changes in its hydraulic geometry.

But, by setting up a series of natural (unaltered) monitoring sites within a geologic-hydrologic province, very good hydraulic geometry models could be developed for assessing land use impacts on stream channel geometry, and thus fisheries habitat. This indirect method would be more accurate than trying to compare a series of channel geometry and flow study sites downstream of the altered basin areas.

In order to monitor the in-basin direct cause and effect impacts on the streams, one would have to monitor precipitation (input) over time as well as changes in land-use, flow and channel geometry. All of the major interrelated independent and dependent variables would have to be monitored which is currently impossible and unreasonable. As mentioned earlier the land-use changes, changes in precipitation and flow relationships and changes in channel responses are all transient variables. Therefore, comparison of impacted site channel geometry with unaltered, natural channels within similar (or the same) geo-hydrologic

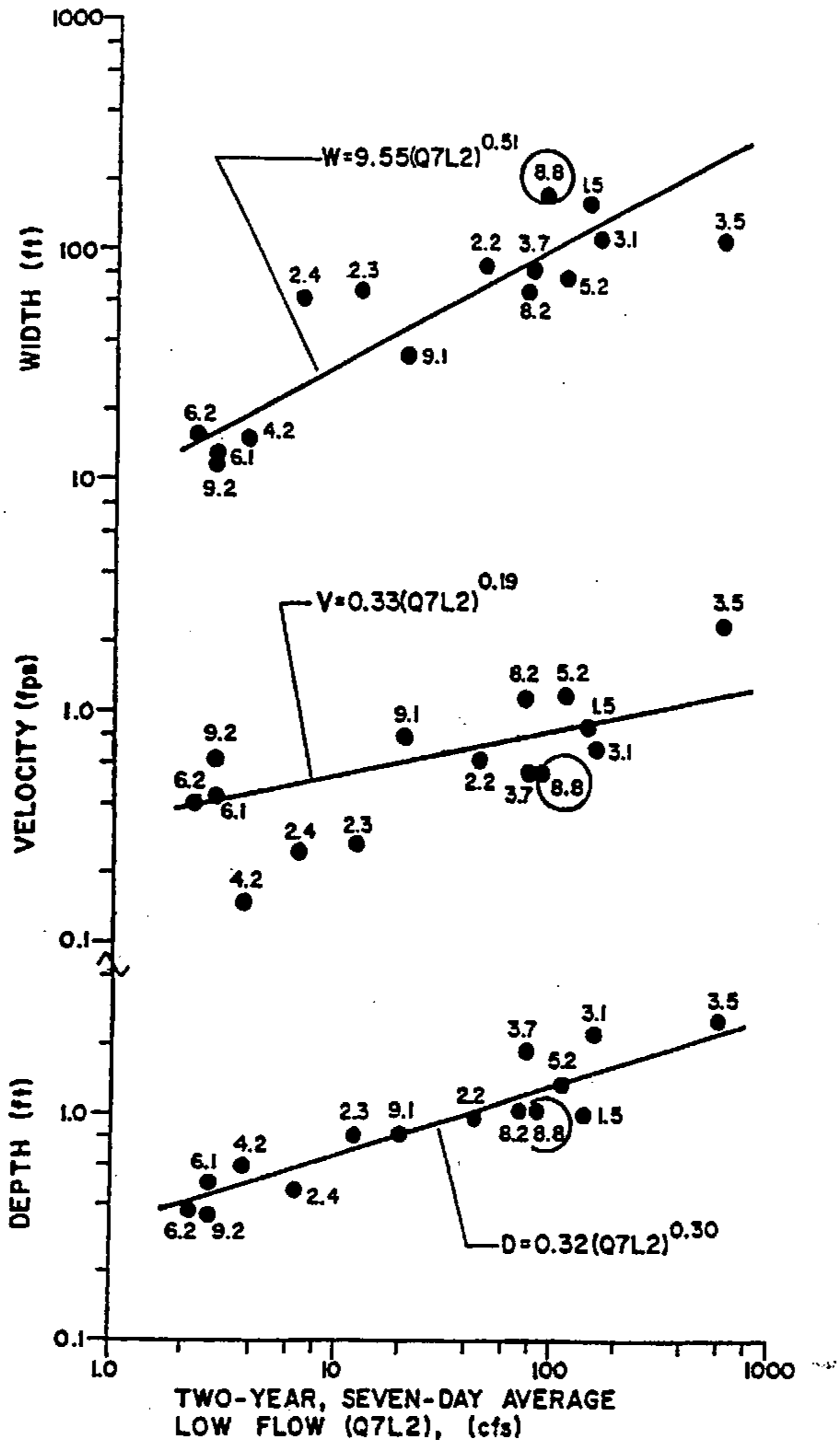


Figure V-5. Regional hydraulic geometry for Olympic Peninsula stations: width, depth and velocity versus two-year, seven-day average low flow (from Amerman and Orsborn 1987).

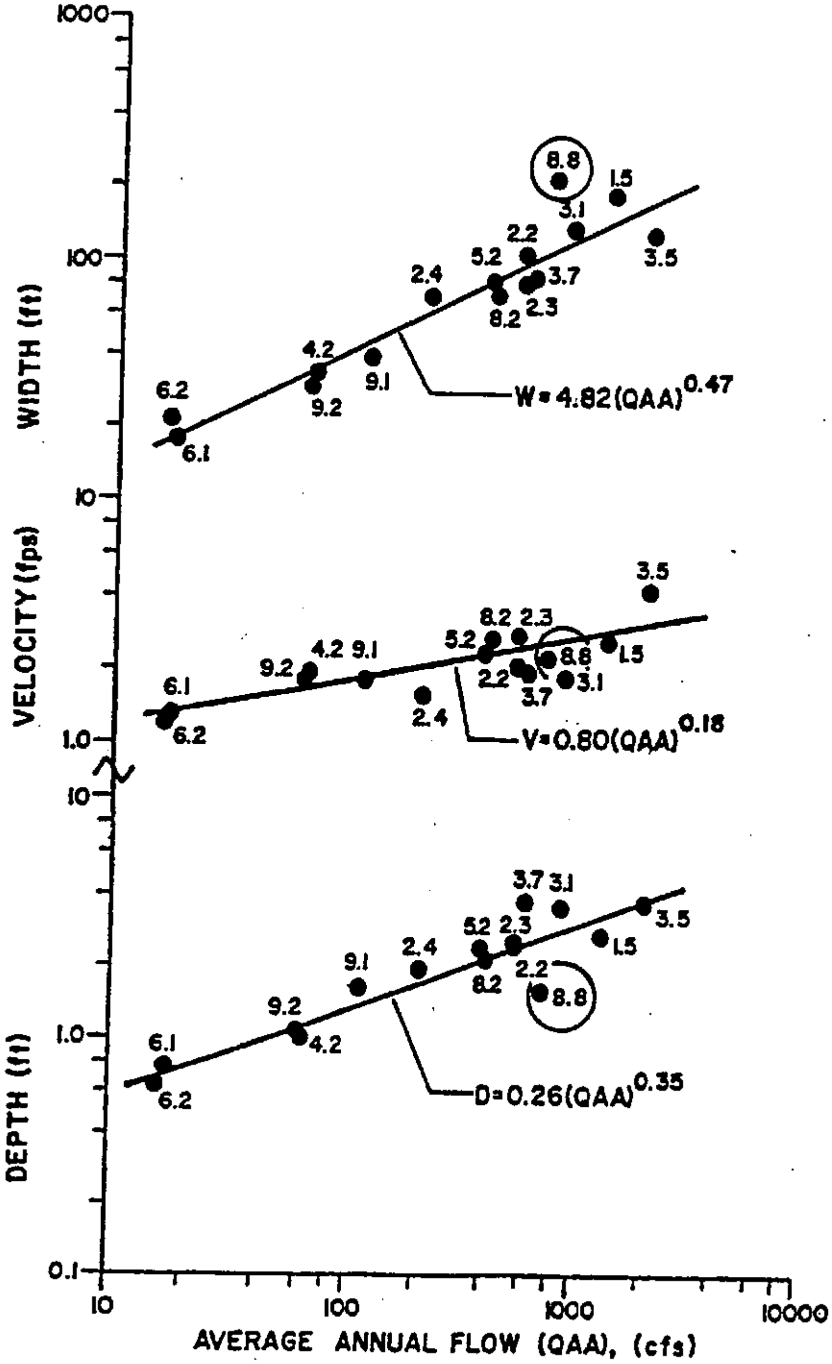


Figure V-6. Regional hydraulic geometry for Olympic Peninsula stations: width, depth and velocity versus average annual flow (from Amerman and Orsborn 1987).

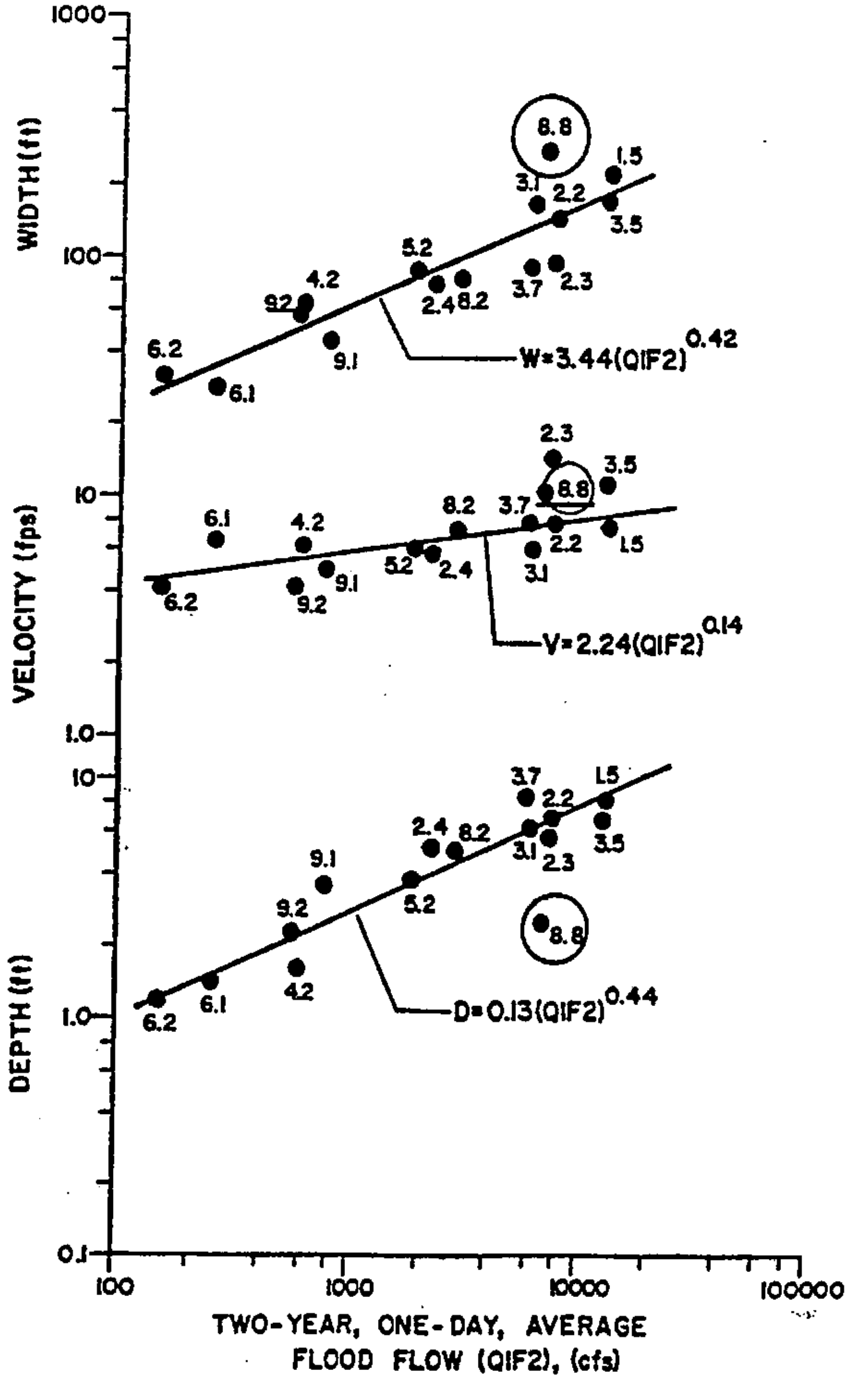


Figure V-7. Regional hydraulic geometry for Olympic Peninsula stations: width, depth and velocity versus the two-year, one-day average flood flow (from Amerman and Orsborn 1987).

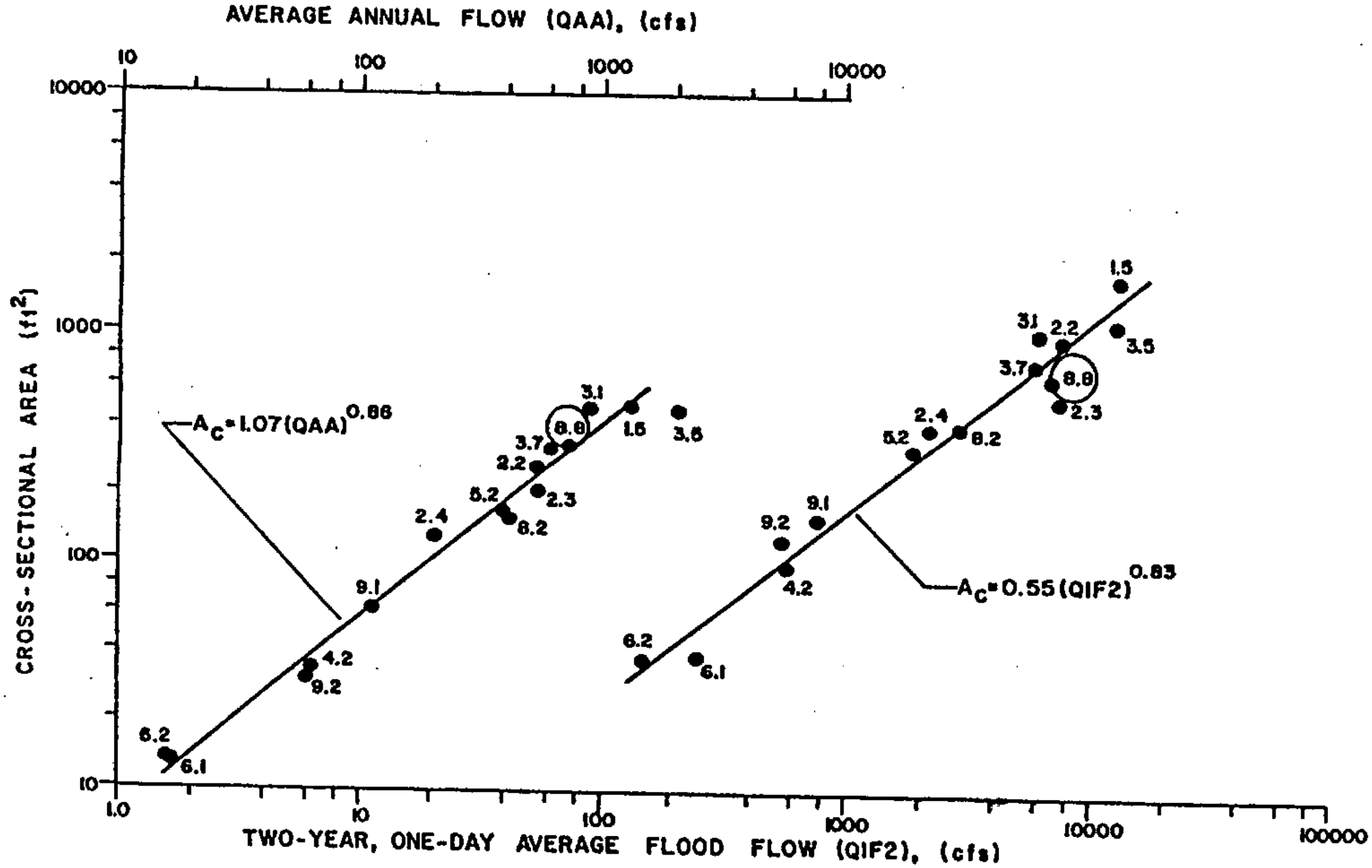


Figure V-8. Regional hydraulic geometry: cross-sectional flow area versus average annual flow and the two-year, one-day average flood flow (from Amerman and Orsborn 1987).

Table V-3. Estimates of Width, Depth, Velocity and Cross-Sectional Area for Five Test Stations Using Regional Hydraulic Geometry Models for Average Annual Flow, and the Two-Year, One-Day Average Flood (from Amerman and Orsborn 1987).

		Average Annual Flow (QAA)				Two-Year, One-Day Average Flood Flow (Q1F2)			
Test Gage and No.	Method/ % Difference	Width (ft)	Depth (ft)	Velocity (fps)	Area (ft^2)	Width (ft)	Depth (ft)	Velocity (fps)	Area (ft^2)
Satsop River (12035000) 1.3[a]	Regional Model	173.0	3.74	3.15	749.5	212.2	9.76	8.85	1898.2
	Site Analysis[b]	252.3	2.33	3.44	587.8	300.8	4.61	13.14	1386.7
	% Difference	31%	60%	8.4%	28%	30%	112%	33%	37%
Moclips River (12039220) 2.1	Regional Model	59.9	1.70	2.10	107.6	95.5	4.23	6.78	391.4
	Site Analysis	57.2	1.40	2.62	80.1	97.7	2.87	9.62	280.4
	% Difference	4.7%	21%	20%	34%	2.3%	47%	30%	40%
Hoko River (12043300) 4.1	Regional Model	81.3	2.13	2.36	188.2	120.3	5.39	7.33	618.3
	Site Analysis	93.0	1.93	2.28	179.5	148.2	4.79	6.71	709.9
	% Difference	13%	10%	3.5%	4.8%	19%	12%	9.2%	13%
Little Quilcene River (12052000) 6.3	Regional Model	29.9	1.01	1.61	30.2	41.0	1.74	5.12	73.6
	Site Analysis	25.9	0.97	1.92	25.1	35.7	1.67	6.06	59.6
	% Difference	15%	4.1%	16%	20%	15%	4.2%	16%	24%
Hamma Hamma River (12054500) 8.3	Regional Model	77.0	2.05	2.31	170.6	93.1	4.12	6.73	372.8
	Site Analysis	88.3	1.68	2.45	148.3	99.3	3.59	7.20	356.5
	% Difference	13%	22%	5.7%	15%	6.2%	15%	6.5%	4.6%

[a]Province/Stream Gage Code.
[b]At-a-station hydraulic geometry relationships.

province may be the "best" and only reasonable way to determine land-use impacts on stream channels.

A series of important factors which are useful in the analysis stream channel hydraulics, geometry and habitat conditions are discussed in the next section.

Some Other Factors for Evaluating Stream Channel Geometry

Horizontal and Vertical Controls

When stream channels issue from confining channels they tend to respond to the unconstrained side boundaries by forming an irregular "meandering" pattern, similar to the path of water flowing from an unconstrained garden hose lying on a driveway. This happens to many of the tributaries to the South Fork Skokomish River such as Church and Cedar Creeks. Additional water, sediment and organic debris loads caused by logging and road building have destabilized the channels downstream of the South Fork valley bedrock wall. Bedload fan (delta-like) deposits near the confluence of the tributaries and the South Fork infiltrate low flows making fish passage impossible.

Lane (1955) introduced two very fundamental fluvial, geomorphic concepts into the hydraulic literature regarding stream load and vertical adjustment:

1) the general concept of balance (equilibrium) between the sediment load and the stream's power to move that load; and

2) the concept of base level, or vertical controls, which regulate the shape of a stream's profile.

The equilibrium concept states that

$$Q_s d \sim Q_w S \qquad \text{(V-9)}$$

or, the product of sediment discharge (Q_s) times the mean sediment size (d) is proportional to the product of water discharge (Q_w) times the channel slope (S), or stream power.

Waterfalls, rapids, receiving streams, lakes and reservoirs are examples of base levels. Lane (1955) grouped bed profiles into six (6) classes which are summarized in Table V-4 and depicted in Figure V-9.

Variations in Manning's "n"

Manning's so-called roughness coefficient (n) is really a resistance coefficient related to anything which causes resistance to flow: bends, constrictions, large roughness elements, bed roughness, bank roughness, channel cross-sectional shape (wide and shallow, or deep

Table V-4. Summary Description of Lane's Six Classes of Stream Profiles (Lane 1955).

Class of Profile	Governing Conditions	Changes in Conditions	Examples in Class
1	Channel in equilibrium with basin supply; bed aggrades.	Increase in sediment load, sediment size and/or decrease in high flows which reduces sediment transport. Streambed rises above original "grade."	Fig. V-9a; water diversions; return of sediment to river from irrigation water; hydraulic mining; logging; road building; landslides; tributary loads.
2	Channel in equilibrium; actions result in lowering streambed.	Deposition or removal of sediment from stream; clear-water (scour) downstream of dam; increase in flow.	Fig. V-9b. Return flow from down stream power plants; a Yellow River change was 9 mil cu yds in 12 hrs. Debris jam removal.
3	Rapid increase in streambed elevation such as debris jam, landslie or construction of dam. Channel was in equilibrium.	Streambed will rise due to sediment or LOD deposition; channel seeks new equilibrium; lake forms upstream; coarser sediments deposited upstream; suspended fines carried downstream.	Fig. V-9c. Dam building; landslide; debris jam; backwater effects are function of bedslope and height of barrier; low weirs for habitat improvement reflect these conditions in a minor way with upstream depo sition and downstream scour; deposi tion in channel upstream of new culvert or bridge.
4	Balance is disrupted by temporary lowering of base level. Similar to change in Pt. C, Class 2, Figure V-9b.	Rapid headcutting upstream to reestablish original gradient of streambed.	Fig. V-9d. Reservoir or river draw down. Like geologic knickpoint process or sudden debris jam removal.
5 and 6	Balance between base levels and loads; changes caused by horizontal shift in base level.	Gradual or rapid translation of base level up or downstream; gradual or rapid filling or cutting.	Figs. V-9e and -f. Culvert discharge cuts new pool and channel and shifts streambed control downstream; shift in location of debris jam.

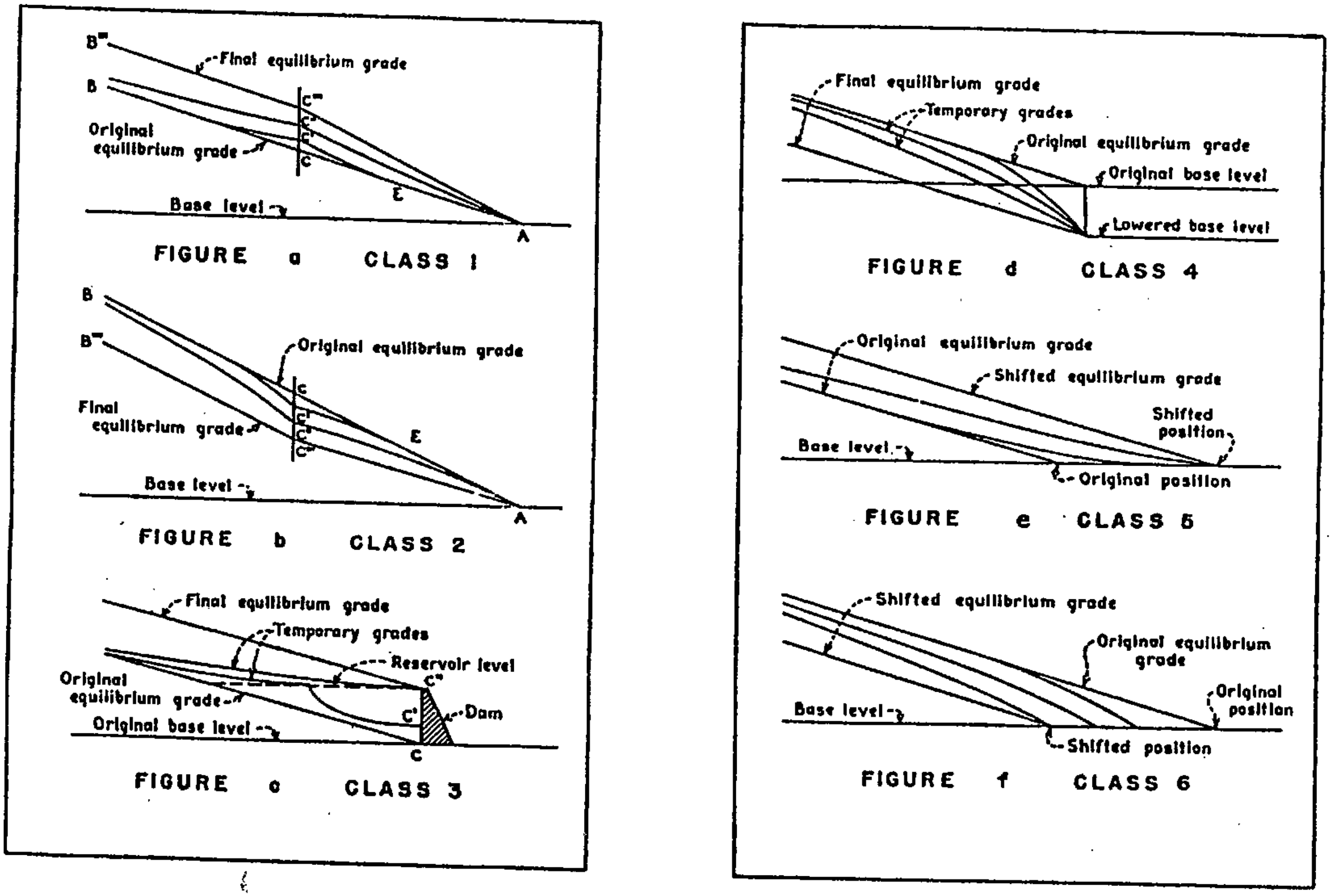


Figure V-9. Classes of channel changes and the resulting streambed profiles (from Lane 1955). Changes are summarized in Table V-4.

and narrow), large organic debris, boulders ... anything which breaks up the flow, or causes it to change direction, contract and/or expand. Energy is lost in each one of these activities, and thus the higher the (n) value, the greater the energy loss, and the less flow a channel can accommodate at a given depth according to the continuity equation, or Manning's form of it:

$$Q = (1.49/n)\ AR^{0.67}\ S^{0.50} \qquad \text{(V-8)}$$

Resistance to flow (n) varies inversely as a function depth, or relative smoothness (D/k), where (D) is the depth of flow and (k) is the height of the bed material. This was demonstrated by Simons et al. (1979) using Barnes' (1967) field data and other laboratory and field observations as shown in Figure V-10. Some comments about the use of Manning's resistance coefficient (n) follow (Simons et al. 1979):

- rapid and large sediment loads, due to slides or bank cutting, which exceed the capacity of the flow, can fill the pores of a cobble (rock) bed, result in a reduced (n), accelerate the flood velocity, and increase channel capacity.

- the relationship of roughness to depth of flow with 3- to 6-inch rock (cobble) and with sand covering the rock is about

  $$n_s = n_r\ (D_S/D_R)^{1.67} \qquad \text{(V-10)}$$

  for a "wide" channel where W/D > 20.

- based on test results by $n_s = 0.31\ n_R$, or the excess sand reduced the resistance by a factor of three (Simons et al. 1979).

- assuming (n) is a constant can cause errors of 100-300% in calculations of channel hydraulic geometry as shown in Figure V-10.

- when calibrating a stream monitoring or gaging site, measure the discharge 4 or 5 times, calculate (n) for each flow and plot (n) as a function of (Q) in a log-log, power expression like hydraulic geometry, but with a negative slope (exponent), n varies inversely with Q.

- substitute $n = aQ^{-b}$ into Eq. (V-8) to get

  $$Q = (1.49\ Q^b/a)\ AR^{0.67}\ S^{0.50} \qquad \text{(V-11)}$$

  which can be reduced for future use at a site.

- (n) also varies at a function of (W/D); for a constant flow, as (W) gets wider, D decreases and (n) increases.

Interrelationships of Water Surface Top Width Depth, Wetted Perimeter and Flow Area

As was shown in the hydraulic geometry nomenclature sketch:

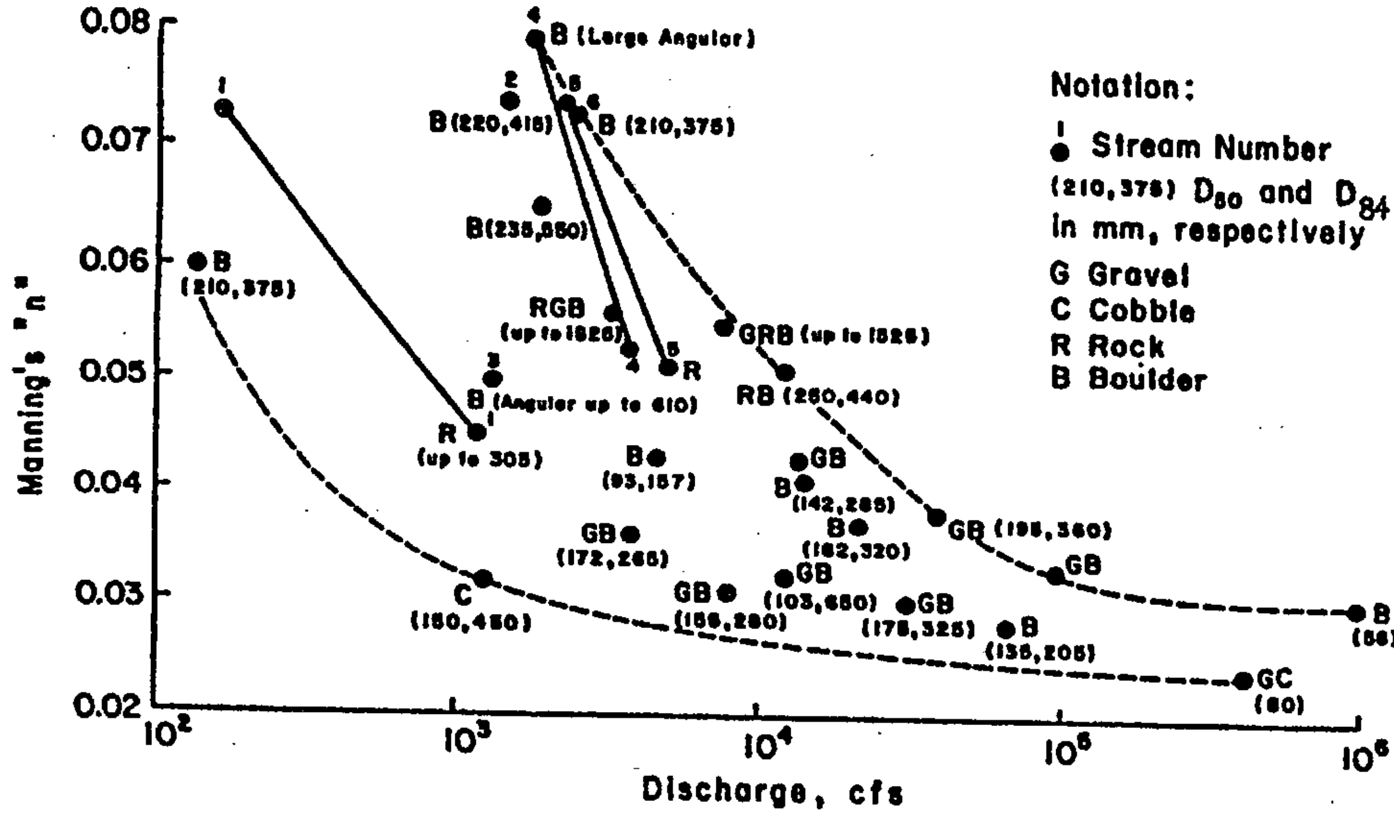


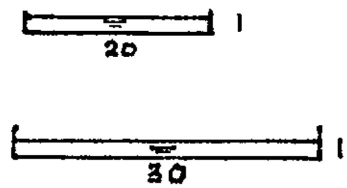
Figure V-10. Variation of Manning's resistance coefficient as a function of discharge and bed material size (from Simons et al. 1979 with data from Barnes 1967).

W is the water surface width;
D is the mean depth of (A/W);
P is the wetted perimeter; and
A is the cross-sectional flow area.

Physically, these terms can be used to represent (are analogs for) other aspects of channel hydraulics and fisheries, such as:

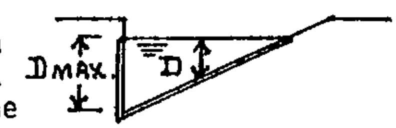
- W (top width): represents the surface area that receives solar heating; for wider channels, when W/D is greater than about 20, then (W) is almost equal to the wetted perimeter (P).

  For example, if W/D = 20, in a rectangular channel, then A = WD = 20; P = 20 + 1 + 1 = 22. Also the hydraulic radius (R = A/P) almost equals the mean hydraulic depth because A/P = 20/22 = 0.91 or within 9% of 1.0 ft. At W/D = 30, A = 30, D = 1, P = 32; R = 30/32 = 0.94 or within 6% of 1.0 ft.

  This is why an assumption is made that the "channel is wide," so that (D) or (y) can be used in Manning's equation for (R) to simplify calculations. The sides become insignificant compared to the bed in terms of flow resistance.

- D (mean hydraulic depth): approaches the hydraulic radius at W/D = 30 (within 6%, above); represents an equivalent rectangular channel, but in triangular cross sections such as on bends, mean D = 0.5 DMAX; W/D ratio is a dimensionless measure of habitat; also D is one of the criteria for spawning.

- P (wetted perimeter): a measure of the contact surface between the streamflow and the bed/banks of the stream; therefore, it is a measure of the resistance to the flow; also an index of rearing habitat at lower flows; and

- A (flow area): a measure of the stream flow, or capability to convey water; A = Q/V, so velocity is represented by A for a certain Q.

As noted by Orsborn and Stypula (1987), W/D can be calculated and plotted versus P^2/A as a dimensionless relationship that totally describes the interrelationships for channel geometry. This **SHEAR-SHAPE** relationship is shown in Figure V-11 for natural channels and for rectangular channels. Note in these relationships the general solution of the curved lines is

$$W/D = P^2/A - [\text{VARIABLE}] \qquad \text{(V-12)}$$

The variable for rectangular channels is (4 + 4D/W) and for natural channels it is (2 + 2D/W). This means that W/D is larger for natural channels with loose bank materials. But, for vertical banks with high clay content natural channels approach a rectangular shape and have a smaller W/D. As channels get wider and W/D approaches 30, the D/W becomes small, W approaches P, and W/D is equal to P^2/A minus 4 or 2, as seen in Figure V-11 in the upper part where the data points coincide. Note that at W/D = 2.0, P^2/A is a minimum for rectangular channels. This is the most efficient rectangular section with a maximum flow area and minimum wetted perimeter (it approaches a semicircular section). For natural channels, the minimum P^2/A occurs at W/D = 1.5. The radius r = depth, D, and the hydraulic radius R = A/P = WD/(W + 2D), and W + 2D. Therefore, $R = 2D^2/4D = D/2$, or the hydraulic radius (R) equals one half the depth (D). This relationship of channel size and shape (W/D), to flow resistance and efficiency, is used in the next section on **SEDIMENT TRANSPORT and STREAM POWER**, and is also a major component in evaluating certain fish habitats.

Stream Power Related to Sediment Transport

We have discussed stream power (Q_wS), the capability of the stream to do work and Lane (1955) used it to balance flow equilibrium with sediment transport and grain size in Eq. (V-9). Jackson and Van Haveren (1984) used stream power indirectly to design stable channels by relating: (1) median particle size to bed slope at a design flow; and (2) using the shear stress on the boundaries, $\tau_o = \gamma RS$, where γ is the unit weight of water (62.4 pcf). This can be rearranged so that $S = \tau_o/\gamma R$, or for a wide channel $S = \tau_o/\gamma D$. Therefore,

$$Q_wS = Q_w\ (\tau_o\ /62.4\ D) = Q_sd \qquad \text{(V-13)}$$

Yang (1976) develop a concept of minimum unit streampower for sand bed streams with various bed forms (dunes, antidunes and ripples, and plane beds). More importantly he showed that the minimum unit stream power, VS, is related to sediment size. VS has the units of foot-pounds per second per pound of water flowing. Numerous other authors discuss stream power and sediment transport in Wang (1989). Orsborn et al. (1985) used the stream power to bed material size relationships from Jackson and Van Haveren (1984) to redesign the gold-dredged channels in Crooked River, Idaho, for restoration of meanders and fisheries spawning habitat. The median diameter material in mm for stable channels was related to channel slope by

$$d50 = 4054\ (S)^{1.13} \qquad \text{(V-14)}$$

and to unit stream power in m/s by

$$d50 = 800\ (VS)^{0.81} \qquad \text{(V-15)}$$

These were checked against equations for gravel bed streams in Canada as developed by Kellerhals (1967) and found to give very comparable values for width, depth and velocity of stable channels (Orsborn et al. 1985).

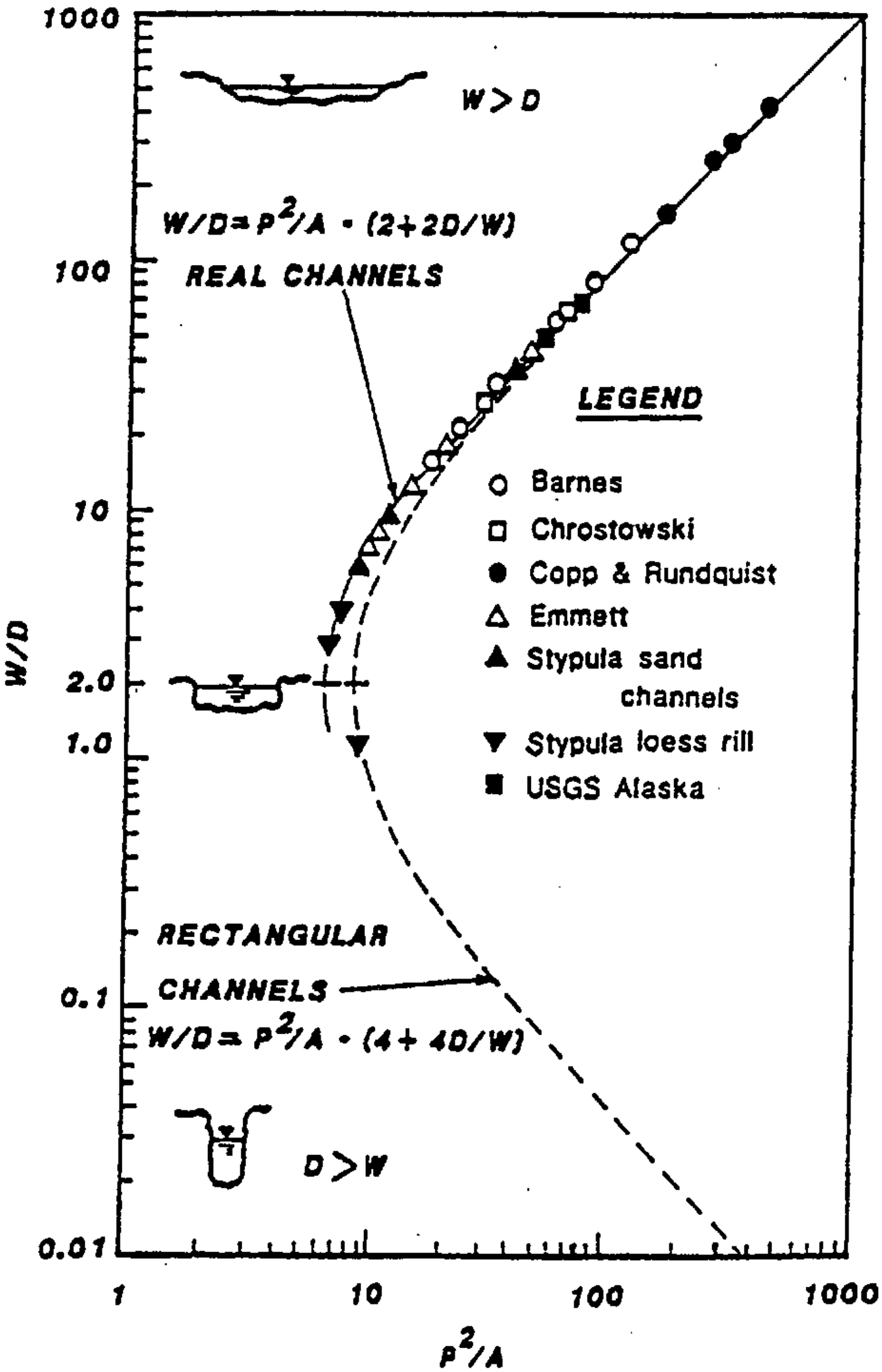


Figure V-11. Shear-shape relationships for natural and rectangular channels (Orsborn and Stypula 1987).

The dimensionless shear-shape relationship in Eq. (V-12) would be a much stronger tool than just W/D for monitoring channel changes, because it is an analog model of stream power (Q_wS) and boundary shear (τ) as follows:

$$W/D = P^2/A \text{ - Variable} \qquad (V\text{-}12)$$

Assuming the channel is wide (W/D > 30-40), then

$$W/D = P^2/A \text{ - } (c = 4 \text{ or } 2) \qquad (V\text{-}16)$$

We can write, as part of the hydraulic geometry, $W = a(QF)^b$ for a particular flood flow (such as 2-year bankfull flow) on a regional basis, or for any common high flow. Also, the shear on the bed is

$$\tau_0 = \gamma RS_e \qquad (V\text{-}17)$$

where R = D in a wide channel, and S_e is the energy slope. The **SLOPE** of the channel bed (S_b) represents the rate of change (gradient of the potential energy of the flow above some datum), or the gravitational attraction acting on the flow. When water surface slope (S_w) is parallel to the slope of the channel bed (S_b) they are equal to the slope of the energy gradient (S_e), and the flow is classified as uniform, normal flow. This condition rarely occurs in natural, irregular channels, except in straight sections on flatter gradients with fine grained bed materials.

Rearranging and substituting D for R,

$$D = \tau_0/\gamma S_e \qquad (V\text{-}18)$$

Substituting this and the hydraulic geometry equation into the original, dimensionless **SHEAR-SHAPE** relationship and incorporating the constant γ into the coefficient (a) yields

$$a'(QF)^bS_e = \tau_0(P^2/A) = W/D \qquad (V\text{-}19)$$

The coefficient (a′) is a function of channel size and the exponent (b) is a function of channel shape. If b = 0, or a small decimal at a site, the channel is rectangular. The regional relationship used in Eq. V-19 always has (b) $\approx$ 0.50. Mean flow velocity (V) and mean depth (D) could be built into these relationships based on regional channel hydraulic geometry as was the water surface top width (W).

All of this is represented (modeled) in the original equation for shear-shape (Eq. V-12) by W/D, and points to the importance of these terms for calibration and monitoring sites. This streampower, width to depth relationship has obvious application to the sediment transport system as well, as was shown in Eqs. (V-14) and (V-15) for bed material size.

Classification and Stability of Stream Channel Patterns

Stream channel patterns in plan view can be classified as straight, meandering, transitional and braided (Shen et al. 1979). As shown in Figure V-12 the stability and sediment CHARACTERISTICS of the various channel patterns can be related to their W/D ratios and their relative stability.

Kellerhals et al. (1976) further classified channels in three main categories:

1) extended patterns (between gradient controls) of straight, sinuous, irregular, irregular meander and tortuous meander;

2) dominant, channel islands: either as occasional, frequent, split or braided islands; and

3) channels with bars: none, side bar, point bar, channel junction bars, midchannel bars, diamond bars, diagonal bars and sand waves. These classifications by Kellerhals et al. (1976) in Figure V-13 and by Brice (1984) in Figure V-14, are oriented to structure within the stream as well as channel pattern. Therefore, with respect to fish habitat and channel changes due to altered loads, the latter two classifications seem more complete and appropriate than just the classification in Figure V-12. The classifications in Figures V-13 and V-14 are about a level above the style and scale of the habitat descriptions. The classification in Figure V-12 can be utilized in stability analysis as related to changes in flow and sediment load.

Hydraulics of Steep Stream Channels During High and Low Flows

As part of the AFS Symposium on "Small Hydropower and Fisheries" in 1985, Humphrey et al. summarized the hydraulic analysis of how steep mountain streams, and their associated fish habitats, can be characterized during low and high flows.

The following points summarize the hydraulic and habitat aspects of steep mountain streams from Humphrey et al. (1985):

- describes changes in pool and boulder-rapid fish habitat during extreme high flows;
- also considers habitat pool volume during low flows;
- during high flows a boulder rapid may provide more habitat than a pool;
- pools provide major habitat during low flow;

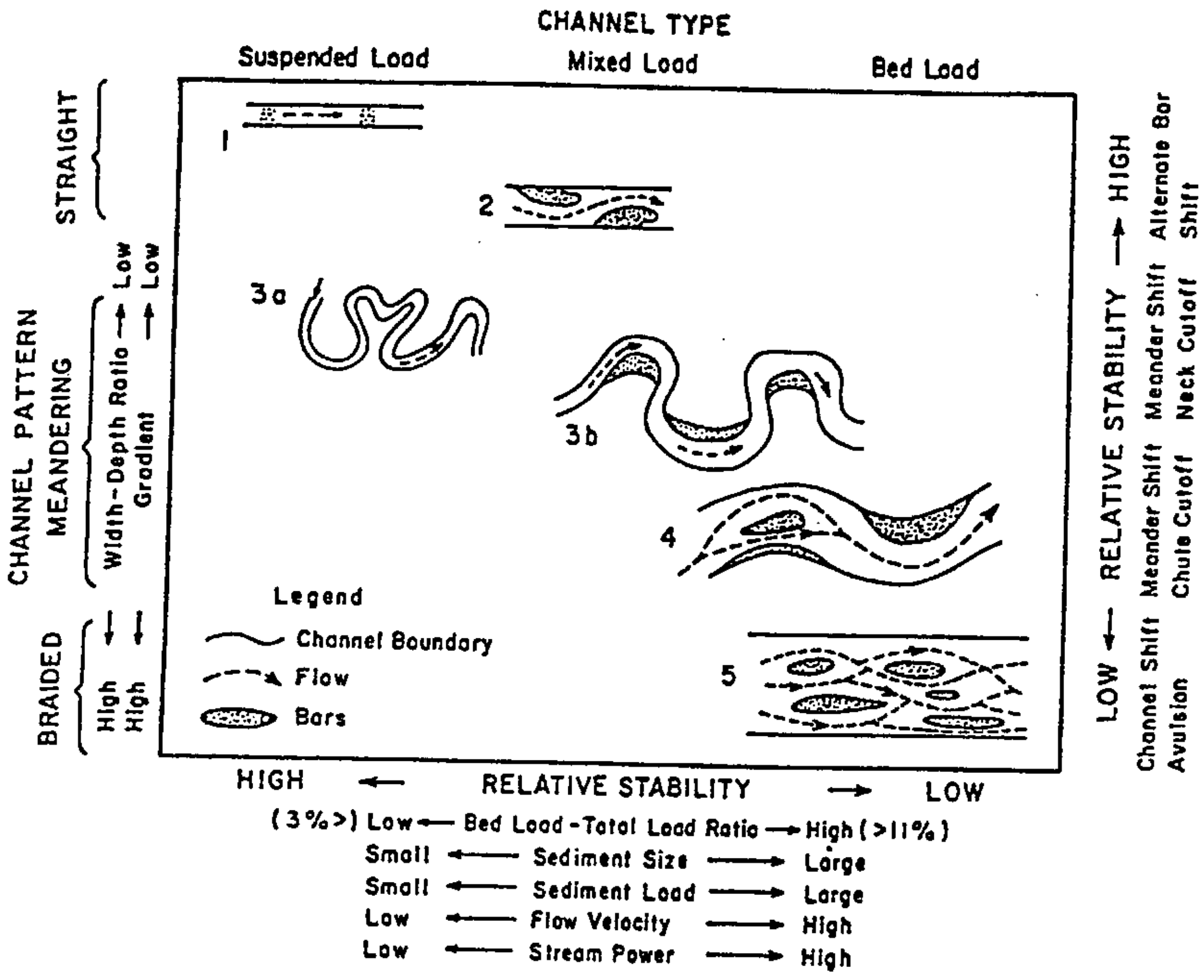
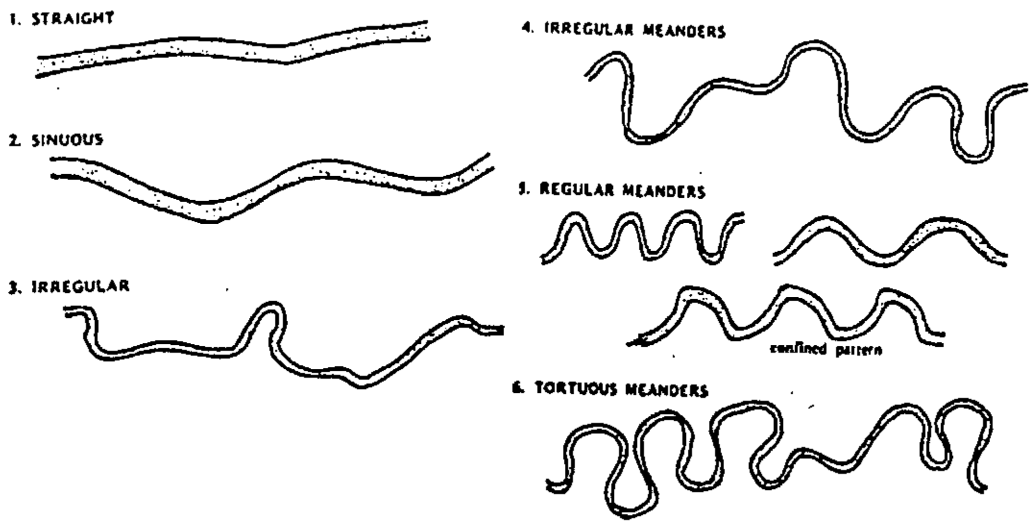
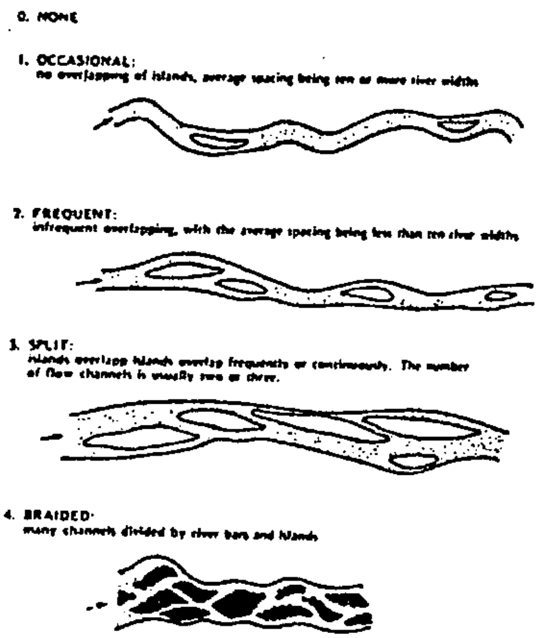


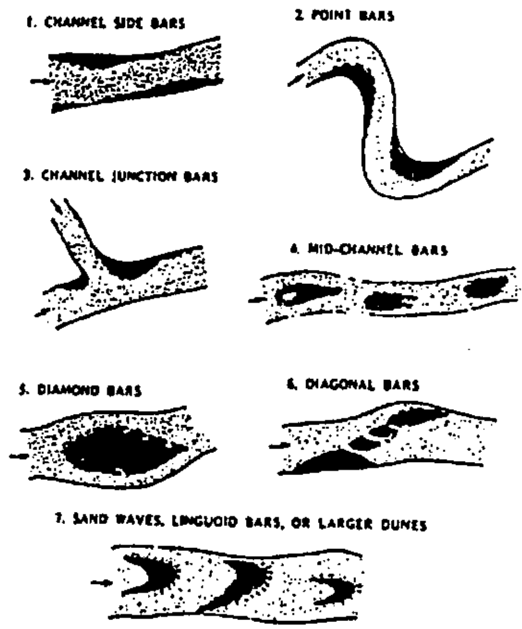
Figure V-12. Classification and stability of alluvial channels in plan view (Shen et al. 1979).



–Codification of River Channel Patterns



–Codification of Islands



–Codification of River Channel Bars

Figure V-13. Codification of river channel patterns, islands and bars (Kellerhals et al. 1976).

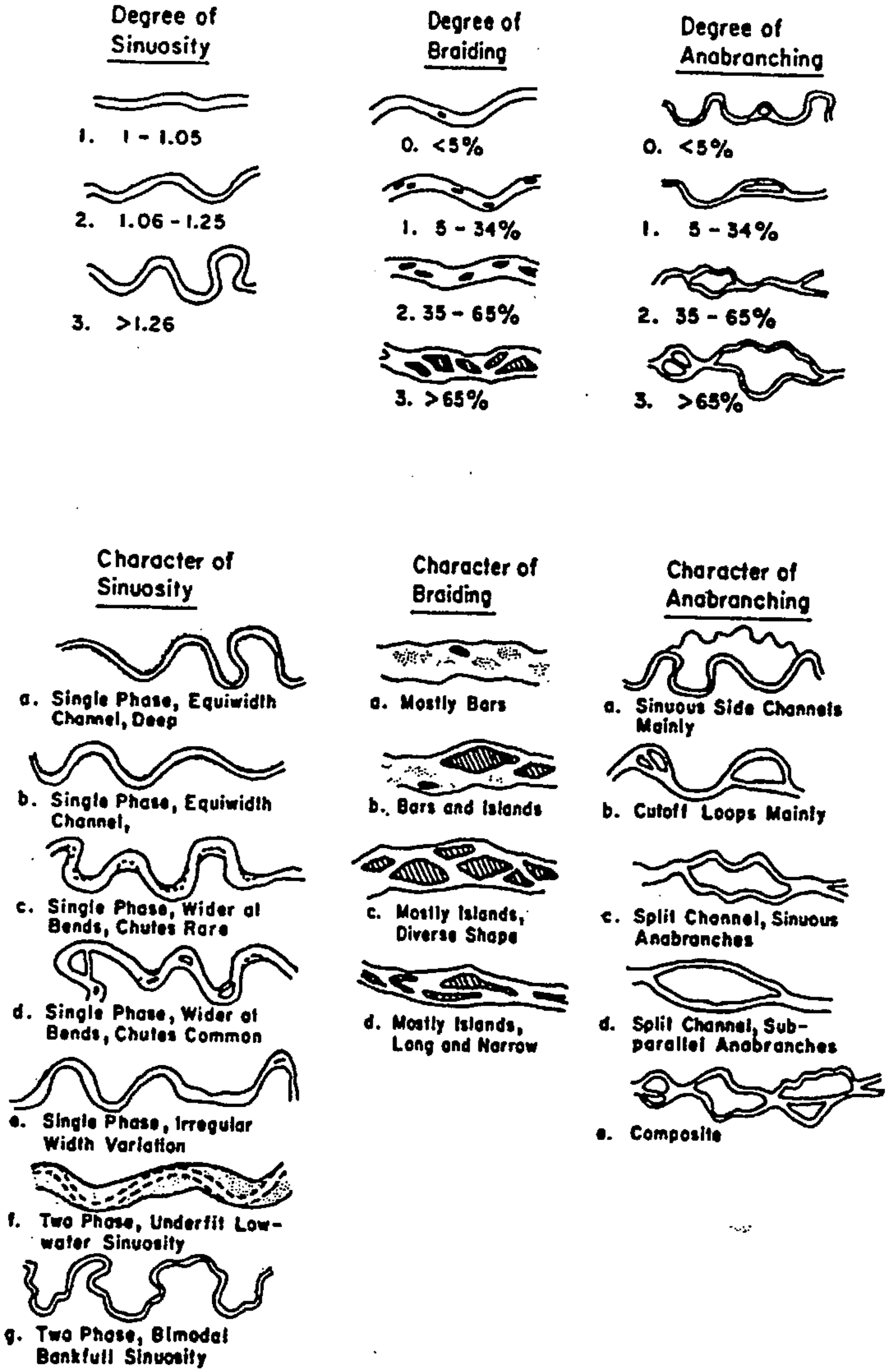


Figure V-14. Channel types based on sinuosity, braiding and anabranching (Brice 1984).

- water quality, temperature or food supply may be limiting during low flow;
- velocities in "pools" in excess of fish preferences cause fish to seek downstream wakes behind boulders;
- boulder rapids and pools were measured in the field and analyzed hydraulically;
- at lower approach flows in the rapids the high velocity energy is dissipated within the pools;
- at higher approach flows the volume of the pool cannot absorb the velocity from the chute, and the pool is swept out;
- eventually, at extreme high flows, there is so much excess kinetic energy (velocity not dissipated in pools) that the stream flows over the pools and tailouts (controls) as a continuous open channel;
- Manning's resistance coefficient (n) varied between 0.20 at D = 2 ft. to 0.09 at D = 13 ft. in the boulder channels;
- at D = 5 ft. and flow over the tops of the boulders, the cross-section consisted of 40% boulders, 40% flow area and 20% boulder wakes;
- as flow overtops boulders, the overflow plunging into the wake helps dissipate velocity (Cullen, 1989);
- under lower flow conditions the tailouts of the pools exert "control" of the flow by dissipating the approach velocity in the pool;
- velocity which will just cause movement of particles (incipient motion from literature data) is about

$$V_i = 2.5(d_g)^{0.50} \quad \text{(V-20)}$$

where V_i is the incipient mean velocity in fps, and d_g is the grain diameter in inches. The coefficient of 2.5 varies between 2.0-3.0 within 90% confidence limits for all the experimental data used in analysis, or $\pm$ 20%. Also,

- the sweep-out of short pools on steep gradients by high flows accounts for the lack of sediment in pools;
- large boulders which form pool tailouts limit the size of pools, and thus the amount of energy dissipation at higher, channel-forming flows;
- extreme high flows remove most boulders from smaller pools; and

- this analysis demonstrates the changes in limiting factors as a function of season and flow in steep streams with large bed materials.

Other Sediment Considerations

Sediment routing through natural channels, which is being driven by variable streamflow, and with sediment being derived from various sources at different rates, is complex to say the least. An alternative to "routing" the sediment would be to estimate total amounts over each annual period of sediment transport using sediment rating equations as a function of flow, and sediment duration curves. Another approach would be to analyze "CRITICAL SEGMENTS" of stream which would tend to deposit certain sediment fractions, and impacts of sediment on fish habitat in that segment. Sampling and calibration of rating curves (sediment as a function of water discharge) are very difficult, especially when trying to sample bed load or suspended load in high-gradient streams in flood stage. Even well-measured suspended load curves vary by one to two orders of magnitude depending on whether the samples were taken on the rising or falling limb of the hydrograph.

For AMC/TFW purposes we want to be able to determine which parameters need to be measured so that the characteristics of stream segments can be determined which will define a segment's capability to pass or store sediment. If one visualizes a sediment source upstream of a "critical" monitoring site, the supply of sediment to the site will be a function of the rate of streamflow, the nearness of the source to the stream, the size distribution of the source, transport and storage characteristics of the intermediate reach of stream, and the hydraulic geometry of the site. The term "critical" is applied here to mean a site where sediment will "significantly" impact a habitat feature based on the sediment transport capabilities of the site. Two objectives of the stream segment monitoring program are to: (1) monitor the response of streams after the impact has occurred; (2) to predict how streams will react to the new sediment source.

Sediment Transport Theory and Applications

A recent study by Bhallamudi (1989) did a complete analysis of the available literature on sediment transport, aggradation and degradation. Using numerical analysis he was able to predict:

(1) aggradation due to overloading;

(2) degradation due to underloading or the lowering of the "base level" (Begin et al. 1981; Lane 1955); and

(3) several other channel responses to changing stream conditions.

But, as yet, no one has been able to incorporate transient deformable (loose) side boundaries into the analysis, nor significant variations in boundary geometry. Numerous routing and transport models are used to analyze prototype systems, but these are on relatively flat gradients in streams transporting sands and finer sediments. Also, computer modeling of a prototype stream is very field data intensive.

A promising component which assists in prediction capability is the use of coefficients of aggradation, degradation and diffusion (Soni et al. 1980). These help reduce the complexity of the solution. Even through there are large fluctuations in the load due to natural variations in flow, there is still a decline in the sediment supply from a single source. Begin et al. (1981) were able to estimate the bed response to lowering of the base level using dimensionless relationships, including a degradation coefficient, but data variability was on the order of plus or minus 25 percent.

Wesche (1989) made numerous measurements of bedload over a wide range of flows to develop empirical relationships between bedload, stream flow, basin and channel CHARACTERISTICS. Bed load was of interest because even at low flows the mean velocities required to move sand grains and finer materials are found in flatter, wider sections where the sands are deposited from upstream steeper sections during higher flows.

In other applied studies, Orsborn et al. (1975) developed a sediment duration curve for the Deschutes River which enters Capitol Lake in Olympia. Components of the model included:

(1) basin characteristics (L1, LT, H and A) where L1 and LT are first-order and total blueline stream lengths above a sediment and discharge gage;

(2) sediment discharge rating curves for the USGS gages at La Grande, Rainier and Olympia (bedload was estimated by the USGS); and

(3) streamflow records at these three gages from which long-term flow duration curves could be generated.

The basin parameters used are shown in Table V-5. The resulting relationships between QS and QI at each gage are in Table V-6.

The estimated bed load transported by the Deschutes River amounts to only about 10 percent of the suspended load. The basin-sediment parameter combines first-order stream length (L1), total stream length (LT), basin relief (H), and drainage area (A) at each station. These combine the length of the delivery system with the basin energy. Considering the instantaneous river discharge (ranging from 1000-7000 cfs) then sediment value for each flow can be written as:

$$QS = C[(L1)\ (LT)\ (H)\ (A)]^{-n} \Big|_{1000}^{7000} \qquad \text{(V-21)}$$

Using the abbreviation (RP) for the river parameters [(L1) (LT) (H) (A)], the above equation for each river discharge is

Table V-5. River Basin Parameters of Deschutes River, Washington (Orsborn, et al. 1975)

Gage Station (No.)	L1 (mi)	LT (mi)	Upper Elev. (ft)	Gage Elev. (ft)	Relief H (mi)	Basin Area, A (sq mi)
La Grande (12078902)	38.6	61.5	2550	549	0.38	56.2
	Σ=38.6	Σ=61.5				
Rainier (12079000)	11.2	24.1	2550	350	0.42	89.8
	Σ=49.8	Σ=85.6				
Olympia (12080000)	8.9	29.1	2550	95	0.47	160.0
	Σ=58.7	Σ=114.7				

Nomenclature:

L1 = length of first-order (unbranched perennial streams);
LT = total length of perennial streams;
Upper Elevation = highest average contour around headwaters;
H = Relief--difference in elevation between headwaters and gage (or outlet, for ungaged basin); and
A = drainage area defined by topographic divide above gaging station or basin outlet.

Table V-6. Suspended Seiment Concentration and Discharges at Three Stations in the Deschutes River Basin (Orsborn, et al. 1975)

Station QS (mg/liter)	QI (cfs)						
	1000	2000	3000	4000	5000	6000	7000
LaGrande $QS = 0.00034(QI)^{1.83}$	105.4	374	785	1374	1999	2788	3719
Rainier $QS = 0.02\ (QI)^{1.55}$	89.7	274	492	788	1080	1436	1828
Olympia $QS = 0.000082(QI)^{1.93}$	49.4	187	411	742	1102	1564	2112

$$QS = C/(RP)^{n} \tag{V-22}$$

Solving for C and n yields

$$QS = 0.35 \times 10^{-6}\ (QI)^{2.31}/(RP)^{1.10/(QI)^{0.17}} \tag{V-23}$$

This geomorphic method of estimating sediment discharge holds promise in terms of estimated existing sediment duration curves and potential increases. Regional calibration data would have to be obtained. Potential duration loads and curves could be estimated based on regional basin geomorphic characteristics. Studies like the one by Peak Northwest (1986) may help provide sediment source documentation and model data. Further investigation of the relationships between sediment load and basin characteristics may show that stream density and (LS/A) and basin energy in the form of $(A)(H)^{0.5}$ may correlate better than the "river parameter" [(LI)(LT)(H)(A)] used in the original Deschutes River study (Orsborn et al. 1975).

Two recent studies by Gomez and Church (1989) and Reiser et al. (1989) provide a considerable amount of guidance in terms of the best sediment transport equations and flushing flow characteristics of steep streams. Gomez and Church (1989) found, after thorough testing of numerous equations, that the equations which worked best included stream power and grain size distribution, but no equation works consistently well. Reiser et al. (1989) have thoroughly reviewed all the factors necessary for consideration of impacts due to increased sediment loads, or decreased streamflows. Although their central topic was flushing flows on regulated streams, the principles would be the same for altered basins which cause changes in the flow and sediment regimes.

Another paper by Lisle (1989) presents detailed results of his studies of sediment deposition in spawning gravels in northern California coastal streams. His observations provide considerable insight into the interrelationships of flow level, infiltration of fines into the substrate, bridging of pores by larger fines, and bed scouring and sealing at deeper levels.

The integration of various basin, streamflow and channel parameters are examined for their possible use in classification systems in the next appendix.

APPENDIX VI.--INTEGRATION OF THE COMPONENT PARTS OF THE WATER-BASIN SYSTEM

APPENDIX VI. INTEGRATION OF THE COMPONENT PARTS OF THE WATER-BASIN SYSTEM

Introduction

The previous three appendices of this report have dealt primarily with: (1) the hydrologic, (2) the basin, and (3) the stream channel components of a water-basin system. Reviewing these components briefly:

(1) **HYDROLOGIC:** information on the water supply component; its diversity and variability on a regional basis; how streamflows can be modeled in terms of basin characteristics, or in terms of their own characteristic flows; estimating ungaged flows; ....

(2) **BASIN:** the geology and stream network, and their interrelationships and influences on precipitation and streamflow were described in terms of quantifiable parameters, indices and analogies; drainage area, for example is analogous to a basin's potential to receive precipitation; ... and the

(3) **STREAM CHANNELS:** form a self-adjusting conveyance system for water and debris; habitat for fisheries; respond to changes in loads due to changes in the hydrologic input due to natural variability or man-caused changes in land cover.

Examples were drawn from basins and streams on the Olympic Peninsula which has a high degree of diversity in natural and man-made conditions. In order to demonstrate that these three natural system components (hydrology, basins, and stream channels) and fisheries are interdependent parts of the same system, then common linkages (interfaces between the components) must be developed. To meet basic classification objectives the linkages must be demonstrated using relatively stable, easily determined and repeatable parameters and procedures (AMC 1989). In evaluating land use impacts the stream parameters must be response variables which exhibit change due to upstream changes, and which adequately represent the physical fisheries environment.

Several linkages among these, and other components of the entire problem, will be demonstrated and then integrated before they are applied to classification systems.

Perspectives on System Interaction and Integration of the Parts

We are going to use several perspectives to lead towards quantification of classification system parameters. The perspectives include:

- a general conceptual description of the physical, chemical and biological components, and the aquatic ecosystem response to flow modification (Sale 1985);

- a description of the relationships of logging and road construction impacts to fish, and the various process and structural changes in the system, plus direct impacts, habitat changes, and changes in fish populations (McCrea 1984);

- an analysis of fisheries life-stage functions, and how those functions are affected by various natural and man-induced activities (Orsborn 1981); and consideration of seasonal life stages of fish, how streamflow regime alternations can adversely affect the life-stage needs of the fish and how all the components can be linked quantitatively..

Interactions and Flow Modifications

Sale (1985) approached his systematic analysis of ecosystem response with the question "is flow modification biologically important?" He then described the interactions among the components of lotic (open, flowing) ecosystems as shown Figure VI-1. We are dealing primarily with the top three boxes and the two along the right edge (physical habitat and fish populations). But, the other components certainly interact with physical changes in the amount and timing of the flow regime.

Sale (1985) presents a very thorough discussion about the status of our ability to adequately describe the lower seven components in Figure VI-1. Although he was focusing on the impacts of flow modification due to hydropower development, there are similarities among the impacts caused by any instream or offstream source of flow modification ... any impact which causes changes in the sizes of extreme flows, or which causes changes in the flow time distribution. To answer various hypotheses associated with flow modification, Sale (1985) suggested five types of study designs to examine biological response to flow modifications:

- baseline studies;
- so-called natural experiments;
- process studies;
- experimental management; and
- retroactive studies.

Some of the benefits and problems associated with these types of studies are:

- large amounts of resources are spent on baseline studies, but they rarely are able to define ecosystem response to perturbations;

- process studies (laboratory or small-scale) can identify response mechanisms, but suffer when scaled-up to the real-world;

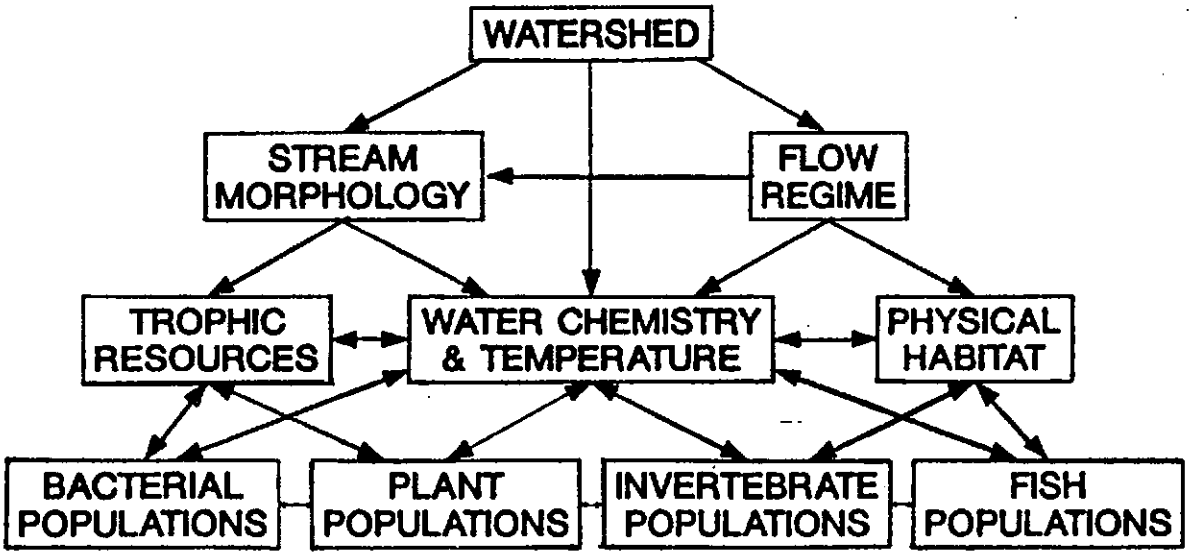


Figure VI-1. A conceptual organization of the components of lotic ecosystems (Sale 1985).

- observations of organisms in their natural environment are useful for testing hypotheses, but man-made perturbations often exceed natural fluctuations in the environment (Sale 1985, Hilborn and Walters 1981).

There is a strong need for pre- and post-impact monitoring to improve management decisions.

Direct and Indirect Impacts Due to Changes in Basin Processes and Structure

The potential and sequential changes and impacts due to logging and road construction are described in Figure VI-2 (McCrea 1984). The hydrologic and basin changes in the water balance and surface structure result in stream channel deposition or scour. Consequent habitat changes can include modification of cover type, diversity and extent, resulting in fish population shifts.

McCrea's (1984) thrust was to demonstrate why and how unregulated logging across intermittent streams in headwater areas adversely affects perennial higher-order streams. The basin energy factor ($AH^{0.5}$) was used by McCrea to demonstrate that protection of first-order (Type 5) streams in turn protects third-order streams. She estimated flood values using basin energy, and then estimated stream power (QS) for a series of first- and second-order basins in Childs and Mill Creek basins, tributaries to the Skagit and Samish Rivers, respectively. Stream power was highest in second-order basins and rapidly decreased in third-order basin due to the significant decrease in stream channel slope. The largest stream power in first-order subbasins was slightly more than the smallest values in third-order streams. Stream power in these first-order tributaries is small because of the small amount of flow generated on the narrow, steep drainages.

General Relationships Among Natural and Man-Made Conditions and Fisheries

In evaluating relationships between velocity and fish during their various life phases, Orsborn (1983) developed the following analysis of interrelationships among functional activities in natural and man-modified stream systems (Figure VI-3).

The graph on the right side of Figure VI-3 represents a generalized evaluation of how man's modifications can stress or eliminate the fisheries. The ordinate in the graph denotes the percentage of success attained by a particular species (or group of species) in a stream (or series of streams). Average conditions are considered equivalent to 100 percent success for each function. The percentage of success in one function will directly impact the next function and so on in time and space, and any percentage modification to the system must influence one, and therefore all the sequential functions.

LOGGING AND ROAD CONSTRUCTION

PROCESS CHANGES:	Water balance Energy balance Nutrients Sediments
STRUCTURES CHANGES:	Soil structure/stability Vegetation and debris Drainage network Channel shape
DIRECT IMPACTS:	Mass wasting Surface erosion Channel erosion Introduction of organic debris Damage to stream banks/bed Loss of streamside vegetation
HABITAT ELEMENTS CHANGES:	Water velocity/depth Water quality Bed composition Banks Cover type/extent Riparian vegetation Migration barriers
FISH POPULATION CHANGES:	Numbers Species Health Distribution

Figure VI-2. Relations of logging and road construction to fish (adapted from Chamberlin 1982, by McCrea 1984).

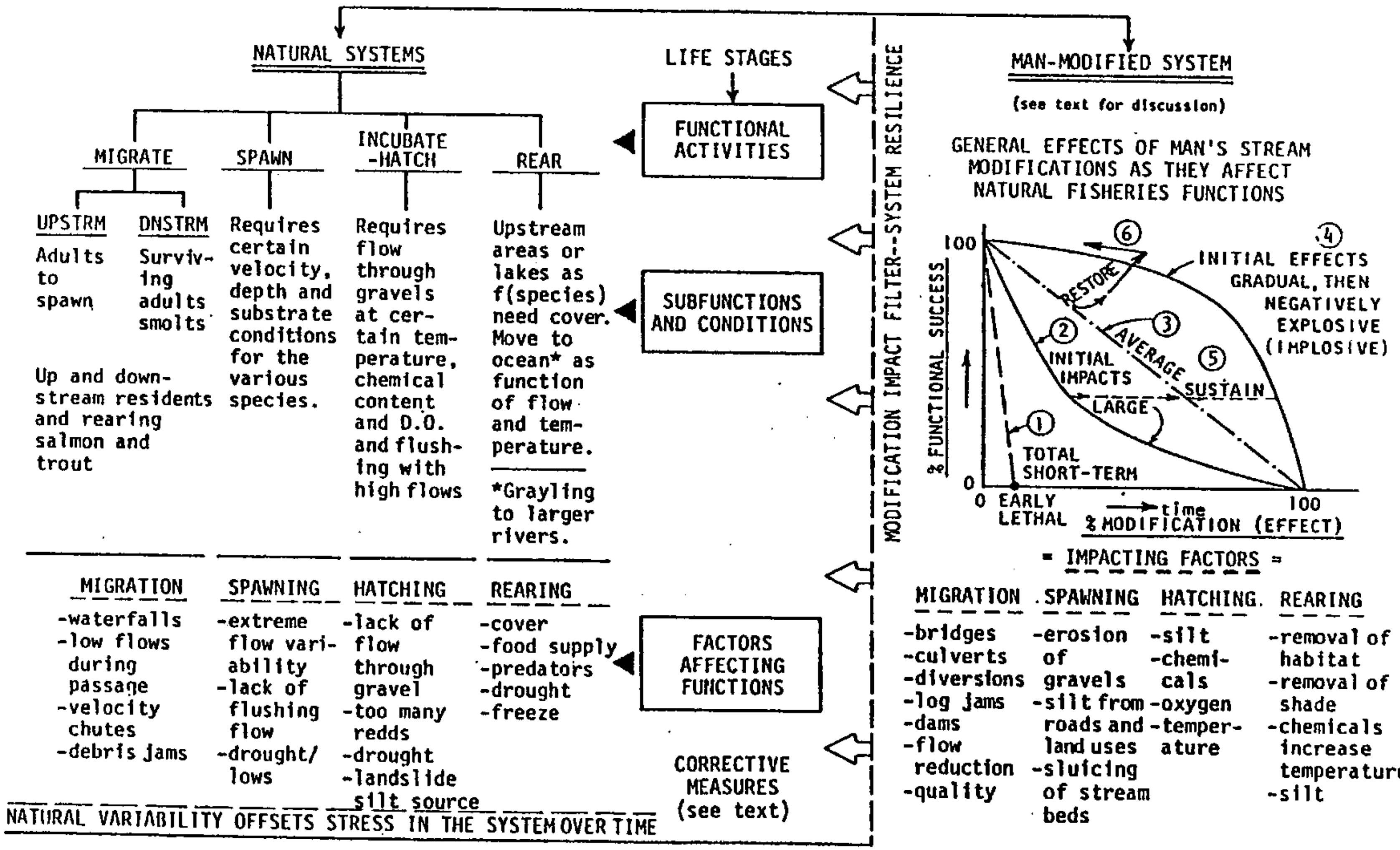


Figure VI-3. Fisheries functions in natural and man-modified stream systems (Orsborn 1983).

A slight modification to the system (Graph (1)) may cause the elimination of a total fish population. An example in this instance would be the installation of a poorly installed culvert which totally blocked migration. Clearcutting riparian vegetation on a tributary could cause a thermal block of the mainstream. Both would be short-term and could be lethal unless some of the species found a successful alternative spawning site. Of course, the other modifications depicted by lines (2), (3) and (4) can all be lethal in the long run if not corrected. And, all these impacts <u>can be either</u> initially large (2), or average degradations over time (the usual EIS function) (3) --or one which starts gradually and subtly and then develops into a negatively explosive function (4) (implosive--a rapid decrease in population). Methods of sampling natural functions sometimes erroneously define this sudden degradation as being a type (1), short-term function. In most non-lethal cases there is a possibility that the system can sustain a run of some size (5). It is possible for certain negative effects to be offset over time, and for a run to be restored to a pre-impact level of success (6). Restoration would not be possible for early lethal (1) conditions without reseeding the run. Our human ability to offset the effects of modification (damage to the life-stage system of the fish species in a natural stream system) is limited.

We know there are certain physical limitations on fish in natural (free, real)[1] and man-modified (controlled, artificial)[1] systems. We can assess these physiological limitations for most species, but the difficulty comes in applying these limitations at various points in a watershed-stream system throughout time and space from a series of uncoordinated projects or activities.

Further difficulty arises when trying to assess the impacts of land-use on a stream system in quantifiable terms. One need only to try to "sample" a natural component such as streamflow, and then try to extrapolate in both time and space, to realize the lack of precision and reproducibility in this exercise. But, if <u>reasonable ranges of expected values</u> can be established and verified for the natural physical, chemical, and biological conditions required to sustain a fisheries, then more realistic assessments of potential impacts can be made. Also, the monitoring and enforcement of administrative management policies and regulations could operate within the same ranges of conditions (Orsborn, 1983).

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[1]It is probably more correct to say "free" or "open" implying that the stream system is being driven and controlled by the hydrologic cycle; "controlled" in the man-modified sense means the hydrology of the stream is modified in time and/or space through man-made changes in the watershed-stream system.

Integration of Basin and Channel Characteristics Through Common Characteristic Streamflow Values

A logic process for regionally analyzing the natural and altered states of streams is shown in Figure VI-4 (Stypula 1986). It describes a procedure to analyze:

- channel characteristics in watersheds with similar climates and geologic surface deposits;
- similarities in the geometric characteristics and their ratios (such as W/D) within some natural deviation;
- channels which are controlled, such as with bedrock (not free to deform), are not included in the analyses except as a separate category with common bedrock;
- watershed disturbances are considered next; and
- the final comparison is between parameters which define the stream segment in either a natural or impacted transient state trending towards a new natural state over time.

There are linkages here between the hydraulic geometry of channels and their shear-to-shape relationship which was discussed in Appendix V.

$$W/D = P^2/A - \text{Variable} \qquad \text{(VI-1)}$$

We also know that on the Olympic Peninsula the regional hydraulic geometry equation for water surface width (W) as a function of average annual flow (QAA) is

$$W = 4.82\ (QAA)^{0.47} \qquad \text{(VI-2)}$$

with a variability of about $\pm$ 15% in Figure 42. Substituting the hydraulic geometry equation for top width, W, into the shear-shape relationship yields

$$4.82\ (QAA)^{0.47}/D = P^2/A - \text{Variable} \qquad \text{(VI-3)}$$

and for natural channels the variable equals [2 + 2 (D/W)].

Using this equation rearranged in the form

$$QAA = [(D/4.82)\ (P^2/A - \text{Var})]^{2.13} \qquad \text{(VI-4)}$$

integrates average annual flow with the channel geometric characteristics described in the shear-shape relationship.

Using a similar approach for Oregon midcoast basins, Orsborn and Stypula (1987) found that

$$W = 7.5\ (QAA)^{0.50} \qquad \text{(VI-5)}$$

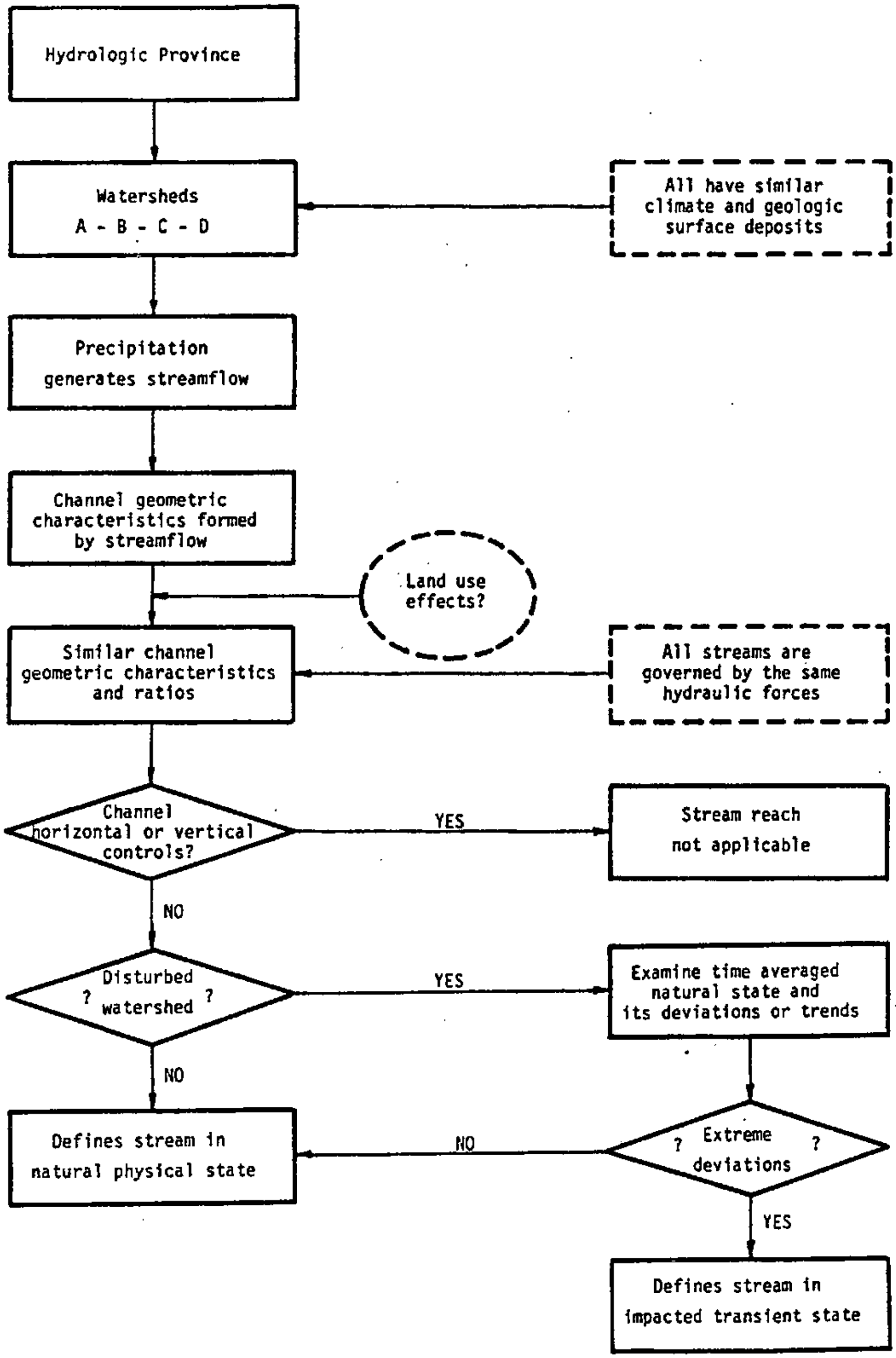


Figure VI-4. Flow chart of logic to determine the natural or transient state of a stream (Stypula 1986).

on a regional basis and

$$7.5\ (QAA)^{0.50}/D = P^2/A - Var \qquad \text{(VI-6)}$$

Using this equation the water top width (W), mean depth (D) and mean velocity (V) and average annual flow (QAA) could be estimated quite accurately. Three USGS gaging stations, not used in the regional model, were tested and the results are summarized in Table VI-1.

Returning to the general equation for average annual flow in terms of channel geometry on the Olympic Peninsula we have

$$QAA = [(D/4.8)\ (P^2/A_C - Var)]^{2.13} \qquad \text{(VI-4)}$$

We know also from the hydrologic modeling chapter that

$$QAA = 0.0032\ (\overline{P})^{1.6}\ (A_b) \qquad \text{(VI-7)}$$

where $(\overline{P})$ in this equation is the average annual precipitation in inches per year from the isohyetal chart, and (A_b) is the drainage area in square miles. The bar over $(\overline{P})$ and subscripts (b) and (c) in (A_b) and (A_c) are used to differentiate between precipitation, wetted perimeter, basin area and channel area. Equating these two relationships to each other yields

$$0.0032\ (\overline{P})^{1.6}\ (\overline{A}_b) = [(D/4.8)\ (P^2/A_c - Var)]^{2.13} \qquad \text{(VI-8)}$$

which demonstrates a linkage between the size of a stream channel at average annual flow in terms of basin precipitation and drainage area, and the adjusting response variables of:

- mean hydraulic depth, D;
- wetted perimeter squared (P^2) representing boundary resistance to flow;
- flow area (A_c, channel cross-section).

Recall also that on an average regional basis:

(1) from the basin energy model the basin area, $A_b = QAA/(CH^{0.5})$; (VI-9)

(2) channel area at average annual flow is $A_c = 1.07\ (QAA)^{0.86}$; (VI-10) and from these

(3) A_b/A_c reduces to: $1.07(C)\ (QAA)^{1.06}/(H)^{0.5}$ (VI-11)

Almost any combination of interactive relationships could be introduced into these combined basin, flow and channel equations by using a common flow (QAA in this case) as the integrating linkage.

A similar relationship for regional average, annual, one-day floods can be developed for the shear-shape relationship

Table VI-1. Measured and Estimated Values of Average Annual Flow, Width, Depth and Velocity for Deer, Fall and Flynn Creeks in Oregon Midcoast Region (Orsborn and Stypula 1987).

USGS Number (14-)	Gaging Station Name	Aver. Flow QAA m^3/S	Top Width (m)	Aver. Depth (m)	Average Velocity (m/s)
-306810	**DEER CREEK**	0.18			
	Estimate (1)[a]	0.19			
	Estimate (2)[b]	0.19			
	Actual sizes[c]		3.26	0.16	0.34
	Est. sizes[d]		3.20	0.17	0.34
-306300	**FALL CREEK**	4.67			
	Estimate (1)[a]	4.14			
	Estimate (2)[b]	4.60			
	Actual sizes[c]		15.16	0.46	0.67
	Est. sizes[d]		16.20	0.50	0.58
-306800	**FLYNN CREEK**	0.12			
	Estimate (1)[a]	0.18			
	Estimate (2)[b]	0.14			
	Actual sizes[c]		3.14	0.13	0.30
	Est. sizes[d]		2.60	0.14	0.32

[a]Assumes P = W + 2D rectangular.

[b]Assumes P = W + D in natural channels and P = W for Flynn Creek.

[c]Actual sizes based on hydraulic geometry at the USGS Stations.

[d]Estimated based on QAA of record. W/D ratios for Deer, Fall and Flynn Creeks are 20, 32 and 24, respectively.

$$W/D = (P^2/A_c - Var) \quad \text{(VI-1)}$$

and for regional average floods

$$W = 3.44\ (Q1F2)^{0.42} \quad \text{(VI-12)}$$

Combining these two equations for (W), and rearranging as we did for average annual flow

$$Q1F2 = [(D/3.44)\ (P^2/A_c - Var)]^{2.38} \quad \text{(VI-13)}$$

which is similar to Eq. (VI-4).

This equation could be used to predict changes in channel geometry due to an increase in average flood size. There is more deviation in the regional flood relationship than there was for average annual flow.

Integrating Flows to Fish Habitat

An important aspect of integrating the streamflow regime and fisheries life-stage activities requires that we compare natural and altered monthly and/or seasonal stream-flow characteristics against fish utilization of the stream. Part of the basic information required for this analysis is a periodicity chart such as the one shown in Figure VI-5 for the Skokomish-Dosewallips WRIA (WDOE 1985).

The other component needed for this analysis is the pre- and post-impact monthly streamflow records or estimated values. Monthly flows are not the only ones of importance to the fisheries, of course, but their averages and their variability provide important indices at the planning and management levels. The use of annual and monthly values was discussed in Appendix III on the hydrology of streamflow. Hydrologic modeling using regional ratios of the monthly maximum, mean and minimum flows to the long-term average daily flow is a very effective method for estimating monthly flows in ungaged areas.

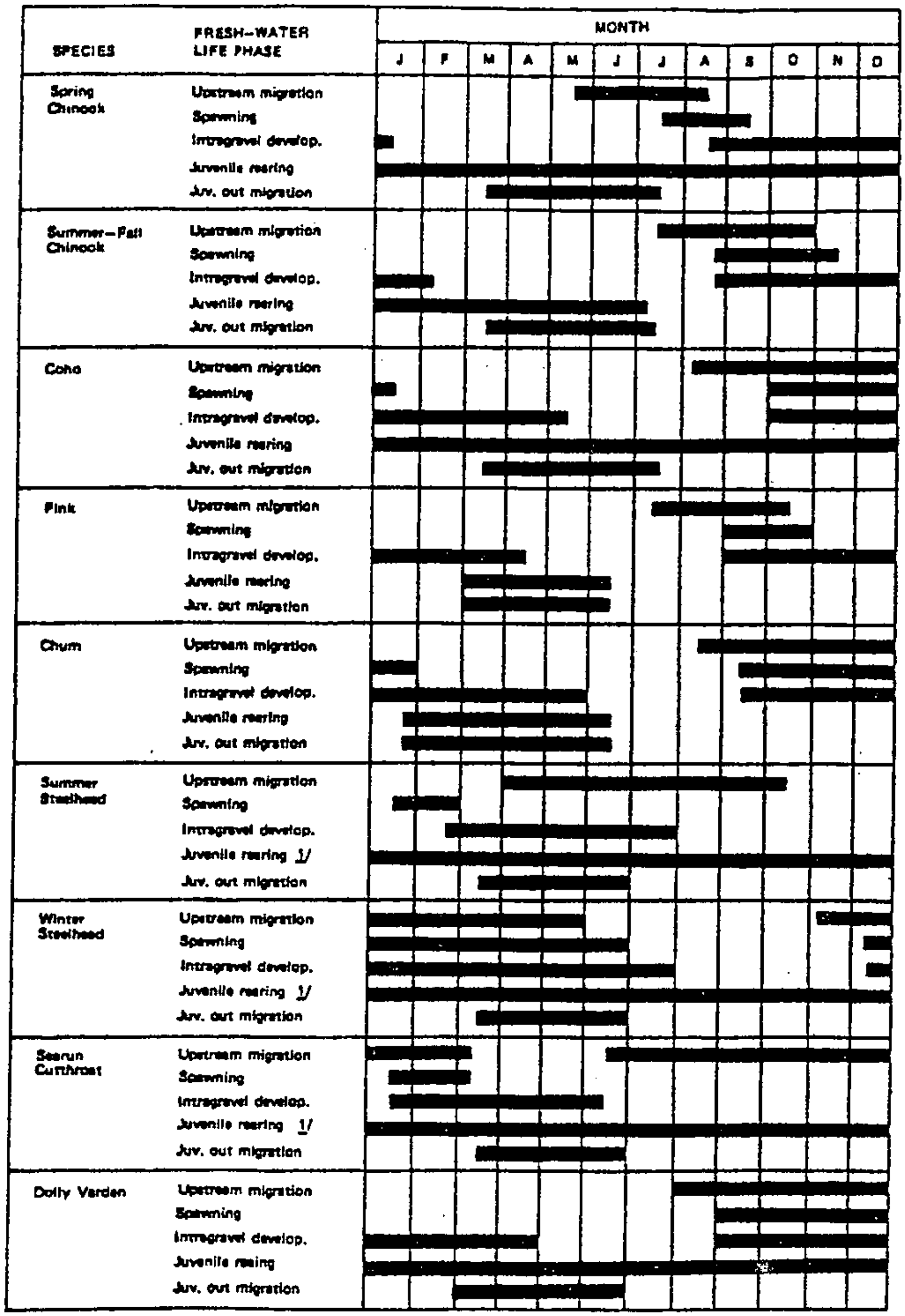
In the next section the combined interrelationships of flow, basin, channel and spawning habitat are integrated for a series of streams in western Washington.

Total Basin System Integration

This section summarizes portions of the results of a study (Orsborn 1981) which examined the interrelationships among the four basin components as shown graphically in Figure IV-6:

- the streamflow which provides the maximum (optimum) spawning area is on the vertical scale (QMSA); and

on the horizontal scale is a combination of basin and streamflow characteristics including:



1/ Includes early or late downstream juvenile migration.

Figure VI-5. Timing of salmon and searun trout fresh water life phases in Skokomish-Dosewallips Water Resource Inventory Area (WDOE 1985).

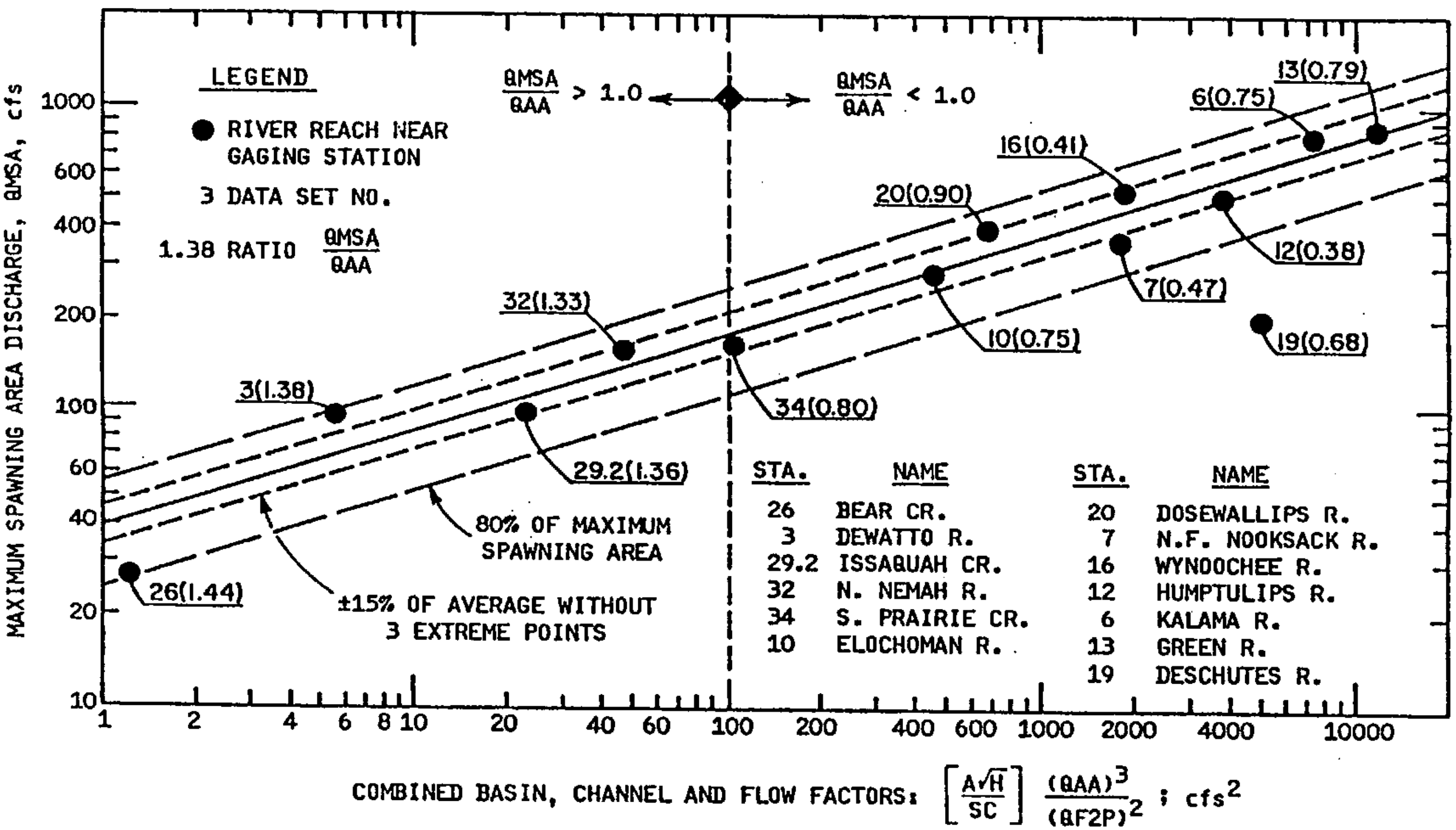


Figure VI-6. Steelhead optimum spawning discharge related to basin, channel and flow factors in northwest and southwest Washington streams (Orsborn 1981).

- the basin energy ($AH^{0.5}$);
- the slope of the channel in the basin which is approximately (H / main stream channel length above the site); and
- the ratio of $(QAA)^3 / (QF2P)^2$ which represents not only influential flow parameters, but is also a measure of the average low flow (Q7L2) based on the "1,2,3 Power" relationship.

The maximum spawning area and all the other data were derived from reports on studies conducted by the USGS for the Washington Department of Fisheries 15 to 20 years ago (example reference, Collings et al. 1974); the spawning flow data used in Figure VI-6 was for steelhead.

Considering describing some of the features depicted in Figure VI-6 one sees that:

(1) the streams cover a wide range of natural and impacted streams; some of the impacted ones are Bear Creek (26, urbanization) and Kalama (6, logging); some scatter is due to geologic variability;

(2) the discharge at which the maximum spawnable area occurs is a function of channel geometry, so QMSA really represents a specific point on the hydraulic geometry graphs; QMSA represents the most habitat available for a particular species in a particular reach of channel based on human interpretation of fisheries preferences for velocity and depth;

(3) the two outside, long-dashed lines represent flows which cover 80% of the available spawning area at QMSA based on the rating curve of spawning area (using velocity and depth criteria) as a function flow; only one data point falls outside these limits (19--Deschutes);

(4) the short dashed lines on either side of the solid line represent deviations of ± 15% from the average regression line; this band contains all but three of the stations (3-Dewatto which is a Hood Canal, low-lying, ground-water stream; and 19--Deschutes River and 26--Bear Creek);

(5) considering that the best stream gaging records are ± 5%, the graphs in Figure VI-6 represent a solid, integrating relationship between fisheries habitat, channel geometry, streamflow and basin characteristics.

Some in-depth studies to test these components separately would help to further define its applicability in other regions of the state; this application covers samples of Cascade, Puget Sound, Olympic, Coastal and Southwest Washington ecoregion streams; and

(6) an important characteristic number is defined when the combined terms on the X-scale are greater or less than 100; note that when the combined basin, channel and flow factors are less than 100,

then the ratio of QMSA/QAA is greater than 1.0 (1.33, 1.36, 1.38 and 1.44) for Dewatto, Issaquah, North Nemah and Bear; and conversely, streams with the X-scale combined terms greater than 100 all have a ratio of QMSA/QAA less than 1.0 (ranging from 0.38 for the Humptulips to 0.90 for the Dosewallips).

It certainly seems that the logic for these consistent relationships can be defined by indepth analysis of the sites, their channel and basin morphologies and the separate terms on the X-scale.

A basic approach to this type of analysis and for testing regional parameters in classification systems is discussed next. Then the results of this and previous appendices are incorporated in a discussion of the proposed AMC and alternative classification systems in Appendix VII.

Consideration of an Allometric Approach to Modeling Fluvial Morphology

There is a considerable amount of literature about the difficulties associated with monitoring changes in watersheds and stream channels over time (Heindl, AWRA "Watersheds in Transition" 1972; and the recent text by Schumm, Mosley and Weaver on "Fluvial Morphology" 1987). The text by Schumm et al. (1987) is an exceptional piece of model and prototype documentation of basin and stream channel morphology. **Some of their basic references should be reviewed for possible future synthesis into the monitoring of watershed impacts on channel morphology.**

For now emphasis is being placed on ALLOMETRIC ANALYSIS as a means for relating basin-channel-flow-habitat characteristics between and within ecoregions, zones or basins. Allometric implies variation in constitution without variation in form. The concept has been applied by other researchers, but Osterkamp (1979) thoroughly analyzed its utility.

The concept is that:

(1) simple, or multiple power-function equations, can be developed for flow-geomorphic relations;

(2) the fixed exponent is assumed to hold, based on dimensional analysis or process equations;

(3) this simulates holding the effects of other variables constant; and as conditions change at, between or among sites; then

(4) the evaluation of the coefficient(s) over time (t) or space(s) gives a measure of the change(s) at a site, or difference(s) between sites.

This principle was applied in the basin-energy ($AH^{0.5}$) relationships when they were used as hydrologic models and in developing the general average annual flow model ($QAA = 0.0032 (P)^{1.6} A$). In modeling low, average and flood flow relations using gages in a hydrologic province, the main variable is in the magnitude of the coefficient (C) in

$$(QX) = C[A(H)^{0.5}]^{n} \qquad \text{(VI-14)}$$

where QX denotes any type of characteristic flow. The exponent n, evaluated from flow records, shows very little deviation among regions or zones.

Osterkamp (1979) demonstrated channel and flow interrelationships which contain both hydraulic geometry equations and flow estimation equations based on channel characteristics. We can relate channel geometry and habitat features to basin characteristics based on the coefficients and exponents in the on-site hydraulic geometry equations as demonstrated in the previous section. The advantages of the allometric, invariant power function approach to modeling fluvial systems are:

(1) the method results in increased accuracy and sophistication of the adjustment between two variables for empirical studies;

(2) when employing multiple regression (or a similar curve-fitting technique), a specified exponent for an independent variable avoids error that would otherwise be inherent in the computation owing to non-linear effects by other independent variables;

(3) conflict caused by defining separate regional relations between two variables is eliminated;

(4) pre-established exponents, based on numerous data, provide a measure of safety when relating and extrapolating very limited data;

(5) invariant power functions provide a uniformity that permits the comparison of results within a study, or with other studies; and

(6) the method helps focus attention on geomorphic and hydrologic processes, whereas free, bivariant analysis ignores process.

These concepts have been applied in Appendix III on hydrologic modeling and in Appendix IV on relationships among basin characteristics. With further examination of channel cross sections, it seems that channels could be grouped (classified) on the basis of fixed (common) exponents for their hydraulic geometry equations (W,D,V = function of flow). This, in turn, would be related to the materials through which the channel is passing. These, and other possibilities such as dimensionless ratios, are examined in Appendix VII on classification methods.

APPENDIX VII.--APPLICATIONS OF HYDROLOGIC, BASIN AND CHANNEL CHARACTERISTICS TO CLASSIFICATION

APPENDIX VII. APPLICATIONS OF HYDROLOGIC, BASIN AND CHANNEL CHARACTERISTICS TO CLASSIFICATION

Introduction

> A classification system does not stand by itself in the stream evaluation analysis. Streams are difficult to understand when only the existing state is known; therefore, they must be placed in perspective as to where they have been and where they are going. Just knowing the present state doesn't provide much information in respect to the many states the stream can assume, nor does it allow the stream habitat to be properly classified. Once a stream habitat is classified, however, the remaining evaluation procedures are considerably simplified. A classification system must be developed as it is the main motor in the evaluation procedures. (Platts 1983)

We have laid the foundation of this study by quantifying physical interrelationships of hydrology, basins and stream channels for use in the AMC tasks of classification, monitoring and research.

Hydrologic Parameters

Streamflows govern fisheries habitat in both the upper and lower flow ranges. Floods can create or destroy habitat depending on the relative size and duration. Low flows, and whether they occur in the winter or summer, can exert another limiting factor. This is especially true if land use has altered the flow regime so that low flows are reduced, and an extended dry cycle occurs which causes passage, temperature and overcrowding problems. Therefore, if the hydrologic stability and variability can be defined for hydrologic/climatic provinces in Figure VII-1, then these can be used to classify basins according to their water supply characteristics. Some gages will appear to fit in provinces other than their original provinces.

Most of the streamflow parameters (indices) will be dimensionless ratios using the characteristic flows (statistical floods, average and low flows) and their various ratios in Table III-9 (repeated as Table VII-1). Table III-5 is repeated as Table VII-2 for the notation used with characteristic flows.

Numerous combinations of flow terms can be used to demonstrate different characteristics of the flow regime, recognizing the limited streamflow records which we have. Greater extremes can be expected in the future, but for now we have to work with available data. Examples of the combinations of characteristic flows, which are described in this section, are applied in the following section.

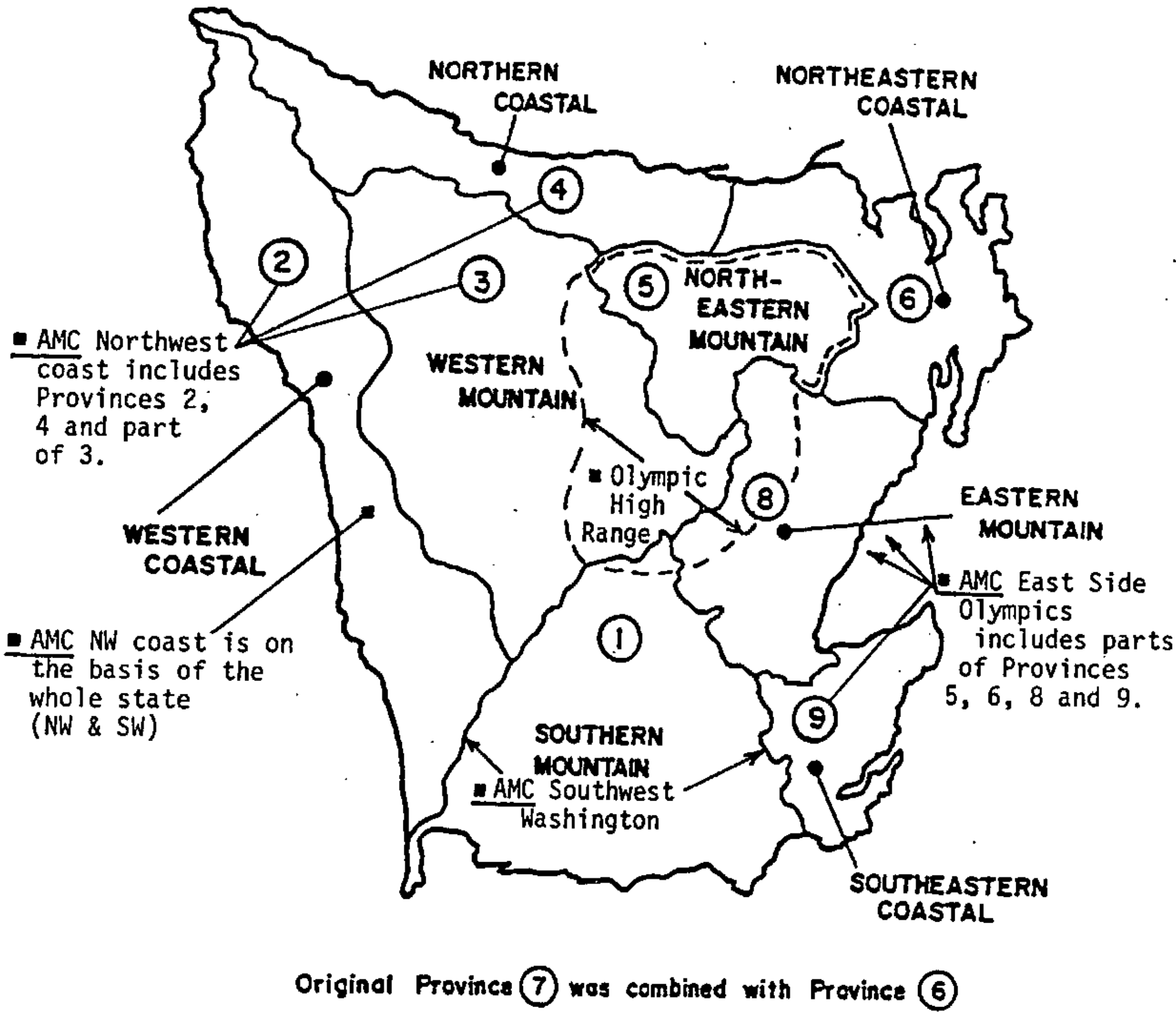


Figure VII-1. Hydrologic provinces and AMC ecoregions.

Table VII-1. Ratios of Characteristic Flows for Twenty Stream Gages on the Olympic Peninsula: Low, Average and Flood Flows for Period of Record at Each Station

Province/ Stream Gage Code	Station Name	USGS Gage No. 12-	Q7L2 / Q7L20	Q7L2 / Q30L2	Q7L20 / Q30L20	Q7L20 / QAA	Q7L2 / QAA	QAA / Q7L2	Q1F1.01 / QAA	Q1F2 / QAA	Q1F50 / QAA	Q1F50 / Q1F2	Q1F2 / Q7L2	Min QA / QA (%)	Max QA / QA (%)
1.1	Cloquallum River	032500	1.57	0.90	0.76	0.056	0.088	11.3	3.9	9.1	15.3	1.7	103.0	74.8	133.9
1.3	Satsop River	035000	1.21	0.91	0.93	0.098	0.120	8.4	4.4	9.1	19.4	2.1	76.6	59.5	144.2
1.5	Humptulips River	039000	1.55	0.88	0.89	0.071	0.110	9.1	4.5	10.0	18.2	1.8	91.1	64.9	140.5
2.1	Moclips River	039220	2.20E	0.80E	0.81E	0.012E	0.026E	38.7E	5.2E	12.8E	24.8E	1.9E	496.7E	62.9E	135.2E
2.3	Dickey River	043100	2.21E	0.79E	0.81E	0.010E	0.023E	43.6E	5.5E	13.8E	27.3E	2.0E	603.1E	61.9E	136.1E
2.4	Sooes River	043163	2.03E	0.80E	0.85E	0.016E	0.032E	31.0E	4.7E	11.0E	20.3E	1.8E	340.0E	64.9E	132.7E
3.1	N.F. Quinault River	039300	1.40	0.76	0.84	0.130	0.190	5.4	3.1	7.2	20.3	2.8	38.4	65.5	133.7
3.5	Hoh River	041000	1.52	0.78	0.76	0.200	0.300	3.3	3.3	6.4	13.6	2.1	21.4	68.8	127.0
3.7	Soleduck River	041500	1.36	0.82	0.87	0.093	0.130	7.9	4.4	9.7	22.1	2.3	76.2	57.8	134.0
4.1	Hoko River	043300	1.43	0.80	0.88	0.034	0.049	20.4	5.9	11.6	23.4	2.0	237.0	71.6	143.4
4.2	E. Twin River	043430	1.37	0.84	0.90	0.042	0.057	17.6	4.3	9.2	13.6	1.5	160.8	66.1	124.6
5.2	Dungeness River	048000	1.48	0.86	0.87	0.200	0.300	3.3	1.6	5.1	13.8	2.7	16.7	52.4	144.9
6.1	Siebert Creek	047500	1.30	0.93	0.87	0.120	0.150	6.6	2.2	14.6	73.9	5.1	95.8	40.9	210.5
6.2	Snow Creek	050500	1.47	0.81	0.83	0.094	0.140	7.4	3.6	9.3	29.5	3.2	68.6	55.5	138.9
6.3	Little Quilcene River	052000	1.52E	0.82E	0.84E	0.130E	0.190E	5.2E	2.6E	7.5E	23.4E	3.1E	38.8E	53.5E	146.1E
8.2	Duckabush River	054000	1.49	0.81	0.84	0.120	0.150	6.5	2.6	7.2	13.8	1.9	40.6	49.3	136.2
8.3	Hamma Hamma River	054500	1.50	0.85	0.89	0.110	0.160	6.1	2.8	7.1	14.8	2.1	42.9	70.9	126.1
8.8	S.F. Skokomish River	060500	1.31	0.89	0.92	0.093	0.120	8.2	4.3	9.7	21.1	2.2	79.6	57.9	142.2
9.1	Goldsborough Creek	076500	1.31	0.95	0.89	0.140	0.180	5.5	2.8	6.7	12.4	1.8	37.0	68.1	140.5
9.2	Kennedy Creek	078400	1.50	0.87	0.86	0.030	0.044	22.6	4.4	9.2	18.3	2.8	208.5	72.0	127.9

All characteristic flows based on longest period of record through 1979.

E Ratios made with estimated flows based on correlation with one or more gages

Table VII-2. Notation for Characteristic (Signature) Streamflow Abbreviations

QA	Average daily flow for a particular year (arithmetic mean)
QAA	Average annual flow (arithmetic mean) for period of record
Q1L	One-day average low flow for a particular year
MinQ1L	Minimum instantaneous low flow on a particular day
Q7L	Seven-day average low flow for a particular year
Q7L2	Seven-day average low flow with a two-year recurrence interval
Q7L20	Seven-day average low flow with a twenty-year recurrence interval
Q30L	Thirty-day average low flow for a particular year
Q30L2	Thirty-day average low flow with two-year recurrence interval
Q30L20	Thirty-day average low flow with twenty-year recurrence interval
QPF	Peak (instantaneous) flood flow for a particular year
QPF2	Peak flood flow with a two-year recurrence interval
QPF50	Peak flood flow with a fifty-year recurrence interval
Q1F	One-day average flood flow for a particular year
Q1F2	One-day average flood flow with two-year recurrence interval
Q1F50	One-day average flood flow with fifty-year recurrence interval
Q3F2	Three-day average flood with two-year recurrence interval
Q7F2	Seven-day average flood with two-year recurrence interval
Q3F50	Three-day flood with fifty-year recurrence interval
Q7F50	Seven-day flood with a fifty-year recurrence interval
MaxQPF	Maximum instantaneous peak flood of record
MaxQ1F	Maximum one-day average flood of record
QMA#	Monthly average flow for month # (# = 10-12, 1-9 in a water year
MaxQMA#	Maximum monthly average flow for month #
MinQMA#	Minimum monthly average flow for month #

All of these flows (flood, average, low) are for average daily flow values except for QPF, QPF2, and QPF50 which are instantaneous peak flow values. Daily averages are for sequential numbers of days.

Ratios of Characteristic Flows:

Flood Ratio: (Q1F50/Q1F2): one-day, average, fifty-year to two-year daily floods; ranges between 1.5 on East Twin (North) and 5.1 on Siebert Creek east of Port Angeles. Most values range between 1.7 and 2.8 for 17 of the 20 gages in Table VII-1.

Variability in Average Annual Flow: [QA(Max) - QA(Min)]/(QAA): maximum average annual flow minus minimum average annual flow divided by the average flow for the period of record. Discussed in more detail later.

Low Flow Ratio: (Q7L2/Q7L20) or the low flow frequency slope index to estimate the variability in low flow from year to year; values range between 1.21 (Satsop) and 1.57 (Cloquallum) for 17 of the 20 gages; the three coastal basins (Moclips, Dickey and Sooes) in Province 2 have low flow ratios greater than 2.0 implying a high degree of variability in low flow from year to year. Q7L2/Q7L20 = 2.0 means Q7L20 is equal to only 50% of Q7L2.

High to Average Flow Ratio: (Q1F2/QAA) indicates the relative sizes of average high flows to the long-term average daily flows; the larger the ratio the steeper the upper end of the duration curve will be; although five of these ratios in Table VII-1 are between 10.0-14.6 (Siebert Creek), the other fifteen are between 5.1 (Dungeness) and 9.7 (S.F. Skokomish).

Average to Low Flow Ratio: (QAA/Q7L2) describes the stability of the lower end of an average duration curve; larger numbers mean less stability from year to year during flow recessions. This ratio is discussed in more detail later under application of the hydrologic (streamflow) indices.

Unit Flow Values

Each characteristic flow is divided by the drainage area to yield "unit flows" in cfs per square mile (csm). Flood unit values can usually be applied to ungaged basins in a province with pretty good confidence. As was shown in the chapter on hydrology, average annual flow values can be fairly consistent for basins with similar amounts of average annual precipitation ($QAA = 0.0032\ P^{1.6}\ A$). Average annual flow will vary primarily as a function of elevation, because of the usual precipitation-elevation relationships. Low flows are most strongly influenced by soils, geology and glaciers. Therefore, low flow unit values can be highly variable even within the same hydrologic province. Applying unit low flow values to ungaged sites can be very misleading unless some low flow measurements are made on site, and are correlated with same-day flows at a long-term gage to check the unit low flow value.

Maximum Unit Flood: Max QPF/A; based on maximum peak flood of record; considerable variability due to storm patterns, uncommon periods of record, and the "instantaneous" nature of the peaks.

Average Daily Unit Flood: Q1F2/A; much more stable within provinces; average statistical flood.

Average Daily Unit Flow: QAA/A; related to average annual precipitation and drainage area as discussed in modeling chapter.

Average Daily Unit Low Flow: Q7L2/A; average statistical low flow; not much difference between 1-, 3- and 7-day average low flows.

Average Daily Unit Base Flow: Q7L20/A; measure of "base" or fairweather low flow from natural storage including glaciers.

Average Daily Unit Extended Low Flow: Q30L2/A; thirty-day average low flow can be used as a drouth index; the 30-day average flows are usually 10-30% larger than Q7L2 on the Peninsula. Some of these flow RATIOS and then UNIT VALUES are examined next.

Applications of Hydrologic Streamflow Indices

In order to identify gaging stations in the subsequent tables and graphs of hydrologic indices, Table III-10 is repeated as Table VII-3 giving code numbers, names, provinces and USGS gaging station numbers. Also the map in Figure III-16 is repeated as Figure VII-2 showing the hydrologic provinces, and the numbers and locations of the gages within each province. This information will be important in the subsequent discussion about streamflow indices for stream/province classification. Average annual precipitation will be used as a basin characteristic.

Ratios of Characteristic Flows

The ratios of characteristic flows, summarized in Table VII-1 and will be used extensively. Starting with the low flows, the decimal values of Q7L2/QAA are shown in Column 8. In Province 1 (Southern Mountain/AMC S.W. Washington in Figures VII-1 and -2) the average low flows run about 9-12% of the average annual flow and include the S.F. Skokomish at 12%. Provinces 2 and 4 (AMC N.W. Coast) have low indices of Q7L2/QAA equal to about 2 to 6%.

The more mountainous Provinces 3 and 5 reflect more precipitation, snow and glaciers at higher altitudes. Therefore, their low flows run about 19-30% of the average annual flow. The Soleduck River's basin lies to the north and has its origin in lower mountains than do the Hoh, Quinault and Dungeness. The Soleduck acts more like the streams on the East side of the Peninsula (East Side Olympics Ecoregion--AMC) in Provinces 5, 6, 8 and 9. The ratios of Q7L2/QAA in these provinces range from 13-18%.

This narrative about the ratio of the 7-day average, two-year low flow (Q7L2) to the average annual flow (QAA) for each of the 20 base gages on the Peninsula has been presented as an example of classification (grouping) on the basis of average low flow (Q7L2) characteristics (as a dimensionless function of the average amount of

Table VII-3. USGS Continuous Gaging Stations used in Olympic Peninsula Streamflow Models: Province/Stream Gage Code, Stream/Gage Name and USGS Gage Number

Province/Stream Gage Code	Gage Name	USGS Gage No. 12-
1.1	Cloquallum River at Elma, WA	032500
1.2	E.F. Satsop River near Elma, WA	034200
1.3	Satsop River near Satsop, WA	035000
1.4	Wyoochee River at Oxbow, near Aberdeen, WA	035500
1.5	Humptulips River near Humptulips, WA	039000
2.1	Moclips River at Moclips, WA	039220
2.2	Raft River below Rainy Creek near Queets, WA	039520
2.3	Dickey River near La Push, WA	043100
2.4	Sooes River below Miller Creek near Ozette, WA	043163
3.1	N.F. Quinault River near Amanda Park, WA	039300
3.2	Quinault River at Quinault Lake, WA	039500
3.3	Queets River near Clearwater, WA	040500
3.4	Clearwater River near Clearwater, WA	040000
3.5	Hoh River near Forks, WA	041000
3.6	Hoh River at U.S. Hwy 101 near Forks, WA	041200
3.7	Soleduck River near Fairholm, WA	041500
4.1	Hoko River near Sekiu, WA	043300
4.2	E. Twin River near Pysht, WA	043430
4.3	Lyre River at Piedmont, WA	044000
5.1	Elwha River at McDonald Bridge near Port Angeles, WA	045500
5.2	Dungeness River near Sequim, WA	048000
6.1	Siebert Creek near Port Angeles, WA	047500
6.2	Snow Creek near Maynard, WA	050500
6.3	Little Quilcene River near Quilcene, WA	052000
8.1	Dosewallips River near Brinnon, WA	053000
8.2	Duckabush River near Bronnon, WA	054000
8.3	Hamma Hamma River near Eldon, WA	054500
8.4	Jefferson Creek near Eldon, WA	054600
8.5	N.F. Skokomish River below Staircase Rapids near Hoodsport, WA	056500
8.6	Deer Meadow Creek near Hoodsport, WA	058000
8.7	S.F. Skokomish River near Potlatch, WA	060000
8.8	S.F. Skokomish River near Union, WA	060500
9.1	Goldsborough Creek near Shelton, WA	076500
9.2	Kennedy Creek near Kamilche, WA	078400

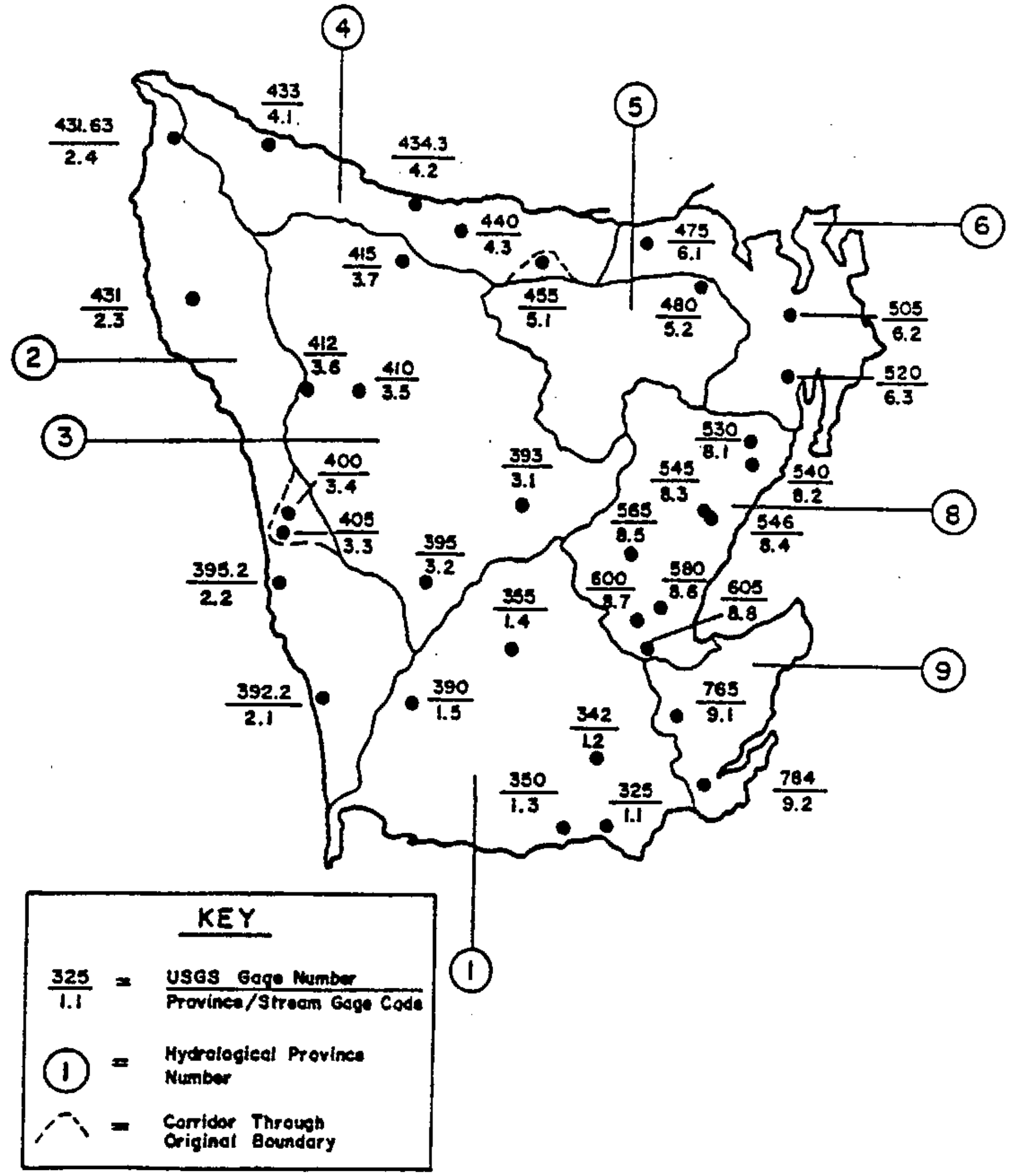


Figure VII-2. Continuous USGS stream gaging stations used in study: USGS gage number, and province/stream gage code (USGS gage no. has prefix of 12-.

stream flow leaving a basin, QAA). Ratios of flows will be examined to develop relationships which discriminate between hydrologic provinces.

The average annual flow is a measure of the net precipitation released by the basin as streamflow. For Q7L2/QAA the larger values indicated a more stable duration curve and generally better habitat conditions with more flow over longer time periods. Generally, streams with larger low to average flow ratios generally have lower ratios of floods to average annual flows, Q1F2/QAA.

Dimensionless Duration Curve

By following these procedural steps one can determine which gaging stations belong in a particular region using a "dimensionless" duration curve shown in Figure VII-3 (not all lines are shown to avoid congestion).

- For a set of gaging stations determine the values of Q1F2/Q7L2 and QAA/Q7L2; usually available from the USGS.
- Assume the floods are equaled or exceeded zero percent of the time and plot the values of Q1F2/Q7L2 on the Y-Scale at X = 0.
- For gages in each province (Figure VII-2), connect the highest and lowest values of Q1F2/Q7L2 with Q7L2/Q7L2 = 1.0 at 100% of the time. These straight lines are the dimensionless duration curves.
- Next, plot the values of QAA/Q7L2 on each line (or on the approximate line location if the graph is too congested).
- The plotting positions on the Y-Scale of the Q1F2/Q7L2 values differentiates and clusters the basins according to their high to low flow ratios.
- The resultant plotting positions of the QAA/Q7L2 values on the X-Scale (% time), and their consistencies by province, tells whether or not a gage belongs (should be classified) in that particular province.

Note for example in Figure VII-3 that the three gages in Province 2 all plot at about 42% of the time. In Province 1, the S.F. Skokomish (8.8) acts more like the Humptulips (1.5) and the Satsop (1.3) and should be regrouped in Province 1 hydrologically. These variations in basin and stream classifications will be consistently demonstrated throughout these examples of streamflow ratios.

Variability and Stability of Average Annual Streamflows on the Peninsula

The average annual flows for the twenty (20) Peninsula gaging stations in Table VII-4 have been analyzed in two dimensionless ratios.

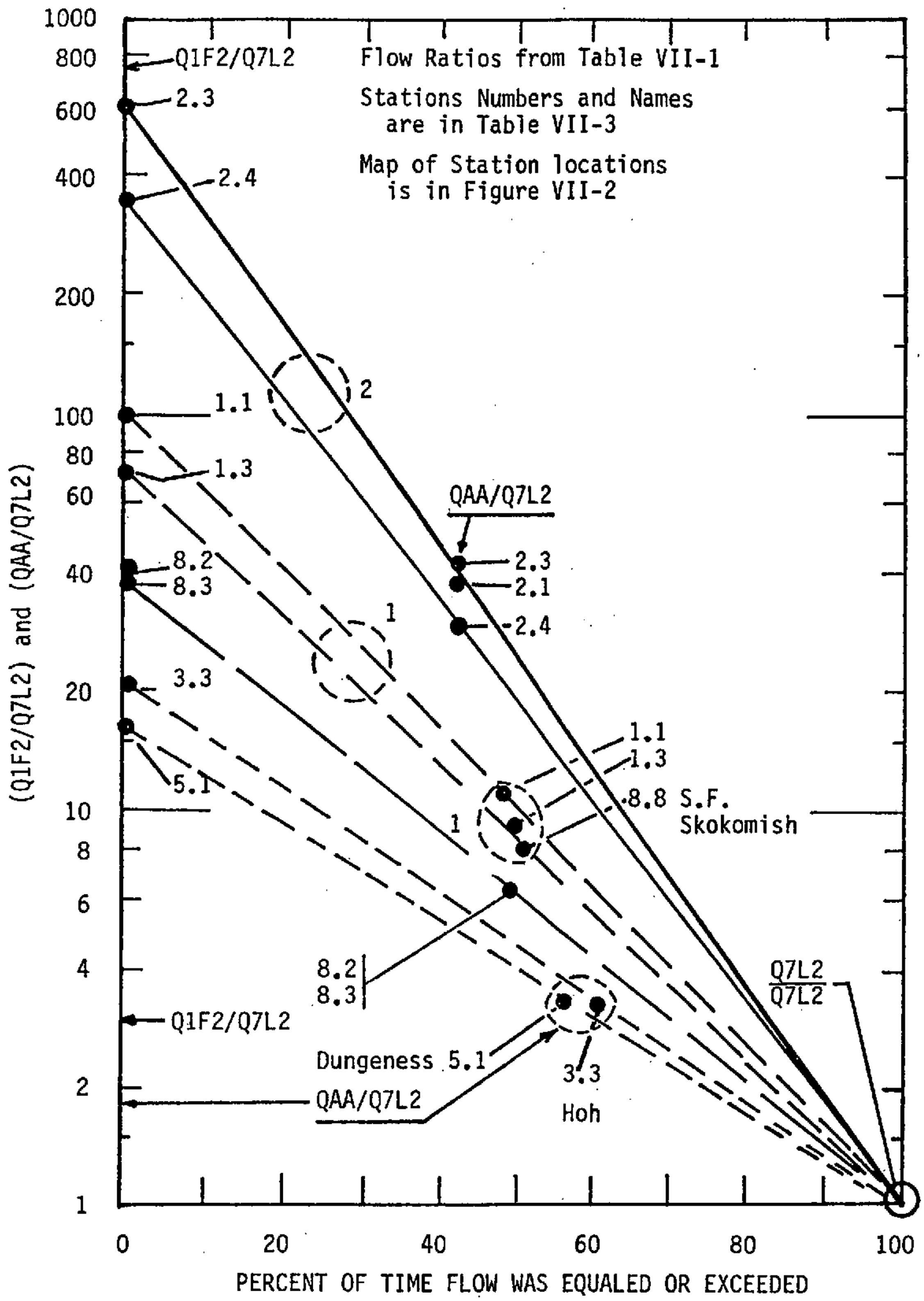


Figure VII-3. Dimensionless form of duration curves showing plotting points of Q1F2/Q7L2 and QAA/Q7L2 versus percent of time.

Table VII-4. Variability in Average Annual Flows for 20 Stream Gaging Stations on the Olympic Peninsula for the Period of Record at Each Gage Through 1979. Calculated from Data in Table III-7.

Station No.	Station Name	$\left[\frac{\text{QA Max} - \text{QA Min}}{\text{QAA}}\right]$*	$\left[\frac{\text{QA Max}}{\text{QA Min}}\right]$
1.1	Cloquallum	0.59	1.79
1.3	Satsop	0.85	2.42
1.5	Humptulips	0.76	2.16
2.1	Moclips	0.72	2.14
2.3	Dickey	0.74	2.19
2.4	Sooes	0.68	2.04
3.1	N.F. Quinault	0.68	2.04
3.5	Hoh	0.58	1.84
3.7	Soleduck	0.76	2.32
4.1	Hoko	0.72	2.00
4.2	Twin	0.58	1.88
5.2	Dungeness	0.93	2.77
6.1	Siebert	1.71	5.14
6.2	Snow	0.82	2.44
6.3	L. Quilcene	0.92	2.73
8.2	Duckabush	0.87	2.76
8.2	Hamma Hamma	0.55	1.77
8.8	S.F. Skokomish	0.84	2.45
9.1	Goldsborough	0.72	2.06
9.2	Kennedy	0.51	1.66

*QAMax and QAMin are the largest and smallest (wettest and driest) average annual flows recorded during the period of record at each gage. ΔQA = "the change" in flow, or difference between two values taken over a common time period.

- the differences between the highest and lowest average annual flows (QAMax - QA Min), or (ΔQA), divided by the average annual flow (QAA); and

- the ratio of QAMax divided by QAMin.

The first ratio deals with the maximum variability that can be expected to occur as a decimal value of the long-term average, and is a measure of the stability of QAA and thus the average annual precipitation (QAA = C(P·A) in a province). Smaller numbers in Table VII-4 indicate less variability in average annual flows. A value of 1.0 would indicate a 100% possible variation in average flow from year to year. For example, (150 - 50)/100, or (300 - 100)/200 or (60 - 20)/40 would all have ratios of 1.0. In Table VII-4 the ΔQ/QAA values for the S.F. Skokomish is similar to the Humptulips (0.84 vs. 0.76). But the most stable stream is Kennedy Creek (9.2, Ratio - 0.52) and the most unstable is Siebert Creek (6.1, Ratio 1.71).

Another measure of average flow stability and variability is QAMax/QAMin in the last column of Table VII-4. As ΔQA/QAA increases so does QAMax/QAMin, but there is some variability (± 5%) between and within provinces as shown in Figure VII-4. Part of the variability is most likely due to:

(1) a lack of long, common periods of record; and

(2) a skewed distribution of annual flows about the mean, as discussed about monthly flows in the hydrology Appendix III.

The equation in Figure VII-4 says

$$QAMax/QAMin = 3\ (\Delta QA/QAA)^{0.93} \qquad \text{(VII-1)}$$

on the average with a variability of about ± 5%. Siebert Creek has the largest percentage difference between high and low average annual flows at 5.14 (514%), Kennedy has the smallest (1.66) indicating more consistent precipitation from year to year in the low headwaters (400 ft. msl).

Ratios of Average Floods to Average Low Flows, and Their Relationships to the Ratios of Average Annual to Average Low Flows

One would expect these two ratios (Q1F2/Q7L2 and QAA/Q7L2) to correlate well within provinces because Q7L2 is in both ratios (common denominator). But, as shown in Figure VII-5, the relationship changes when QAA/Q7L2 ≈ 8.0 and Q1F2/Q7L2 ≈ 75. The upper dashed line is an envelope which includes all the data points. The equations of the graphs are for QAA/Q7L2 > 8

$$(Q1F2/Q7L2) = 6\ (QAA/Q7L2)^{1.22} \qquad \text{(VII-2)}$$

and for QAA/Q7L2 < 8

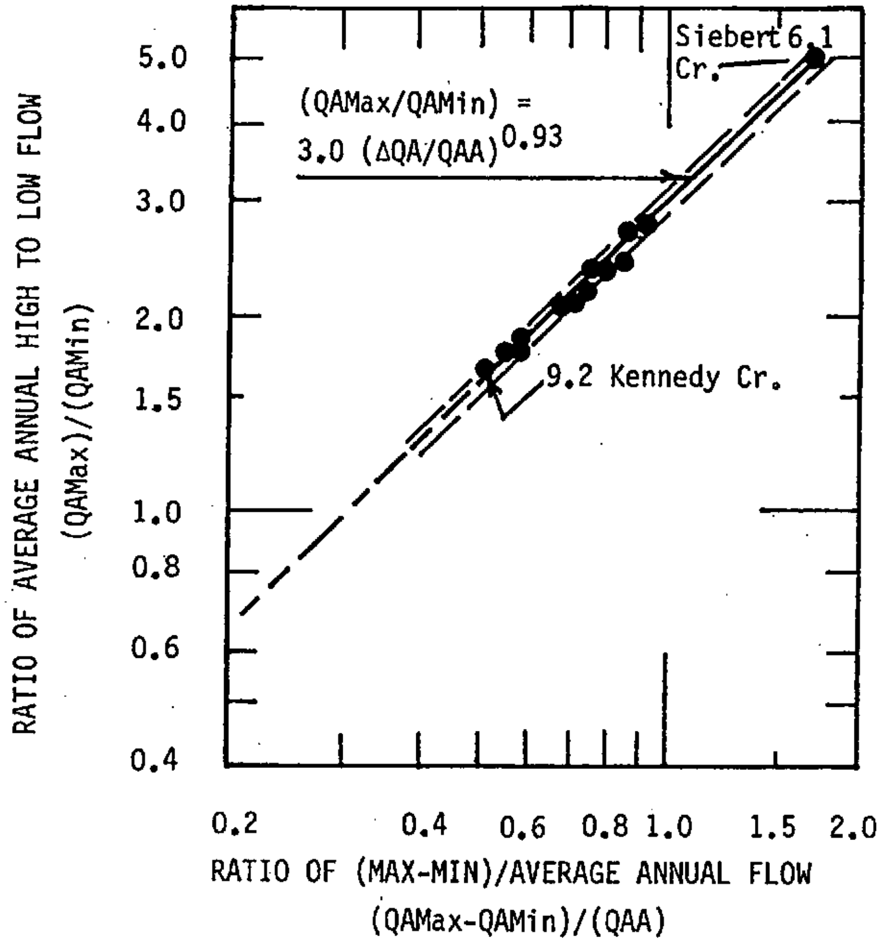


Figure VII-4. Relationship between the ratio of maximum to minimum average annual flow, and the maximum difference in average annual flows divided by the long-term average for Olympic Peninsula streams. Data from Table III-7.

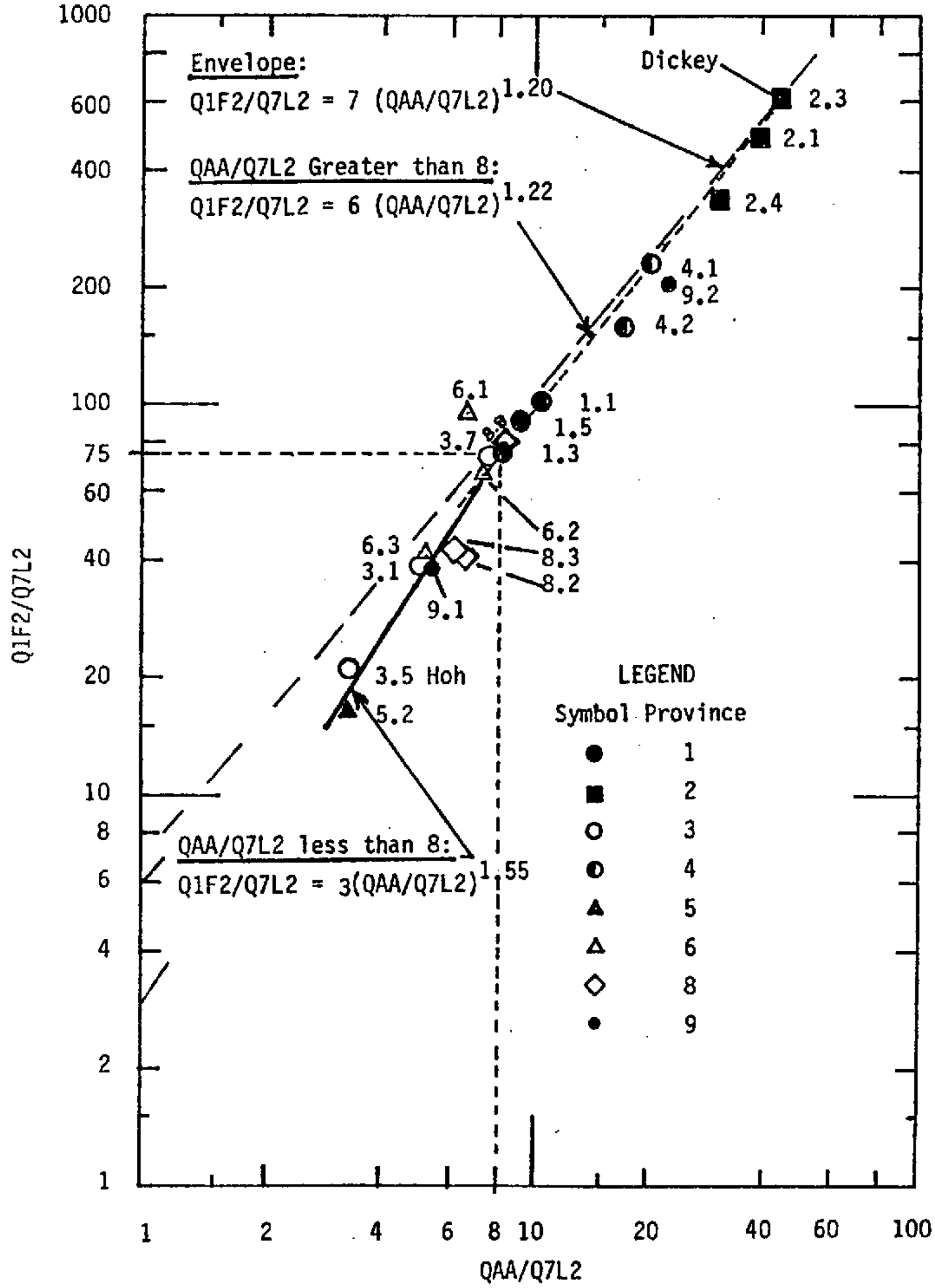


Figure VII-5. Ratios of average floods to average low flows related to ratios of average annual flows to average low flows for Olympic Peninsula stream gages. Data are from Table VII-1. See Table VII-3 for station code, and Figure VII-2 for locations.

$$(Q1F2/Q7L2) = 3\ (QAA/Q7L2)^{1.55} \qquad \text{(VII-3)}$$

In the upper right of the graph the AMC Northwest Coast basins (Provinces 2 and 4) are dominant with East Twin River (4.2) and Kennedy Creek (9.2) not conforming. Similarly, in the lower left of the graph stations 9.1--Goldsborough (near Kennedy Creek), 8.2--Duckabush and 8.3--Hamma Hamma are not conforming with the average (line) of the other data points.

The Hoh (3.5) and Dungeness (5.2) both start high in the Olympics on the west and east sides of the Elwha River, respectively. The low Q1F2/Q7L2 and QAA/Q7L2 indicate large low flows from glaciers for the Hoh, and relatively small floods for the Dungeness as we will see in the section on unit flow values (cfs/sq. mi. or csm). The above equations can be used to estimate the third characteristic flow if the other two are known or have been modeled.

Ratios of Average Annual Flows to 2-Year and 20-Year Low Flows

For flow ratios relating average annual to low flows, QAA/Q7L2 is plotted in Figure VII-6 versus QAA/Q7L20, the 7-day average, 20-year, "fair weather" base flow. Once again the stations in the Northwest Ecoregion (Provinces 2 and 4) have the highest ratios as they did for floods (lowest low flows). Also, the Hoh (3.5) and Dungeness (5.2) have the lowest QAA/Q7L2 ratios.

The relationships make a break at about QAA/Q7L2 = 20 and QAA/Q7L20 = 30. The upper part of the graph indicates that the 20-year low ratio is increasing more rapidly than the 2-year low flow ratio. In the lower graph an average line would indicate that the flow ratios are changing at the same rate (the exponent which is the slope of the line, would be 1.0, an average of 0.94 and 1.05).

These equations can be used as models for estimating Q7L2 and Q7L20 from QAA, as well as for classifying streams according to their low flows and their relative capability to support a fishery during low flows.

Flow Unit Values

Values of characteristic flows divided by their drainage areas (cfs/sq. mi, or csm) can be useful for both classifying groups and for modeling average annual, larger monthly flows and flood flows. Low flow unit values are useful for indexing overall geologic and/or glacial effects on the low flow supply, but should be field verified if used as models to estimate low flows at ungaged sites.

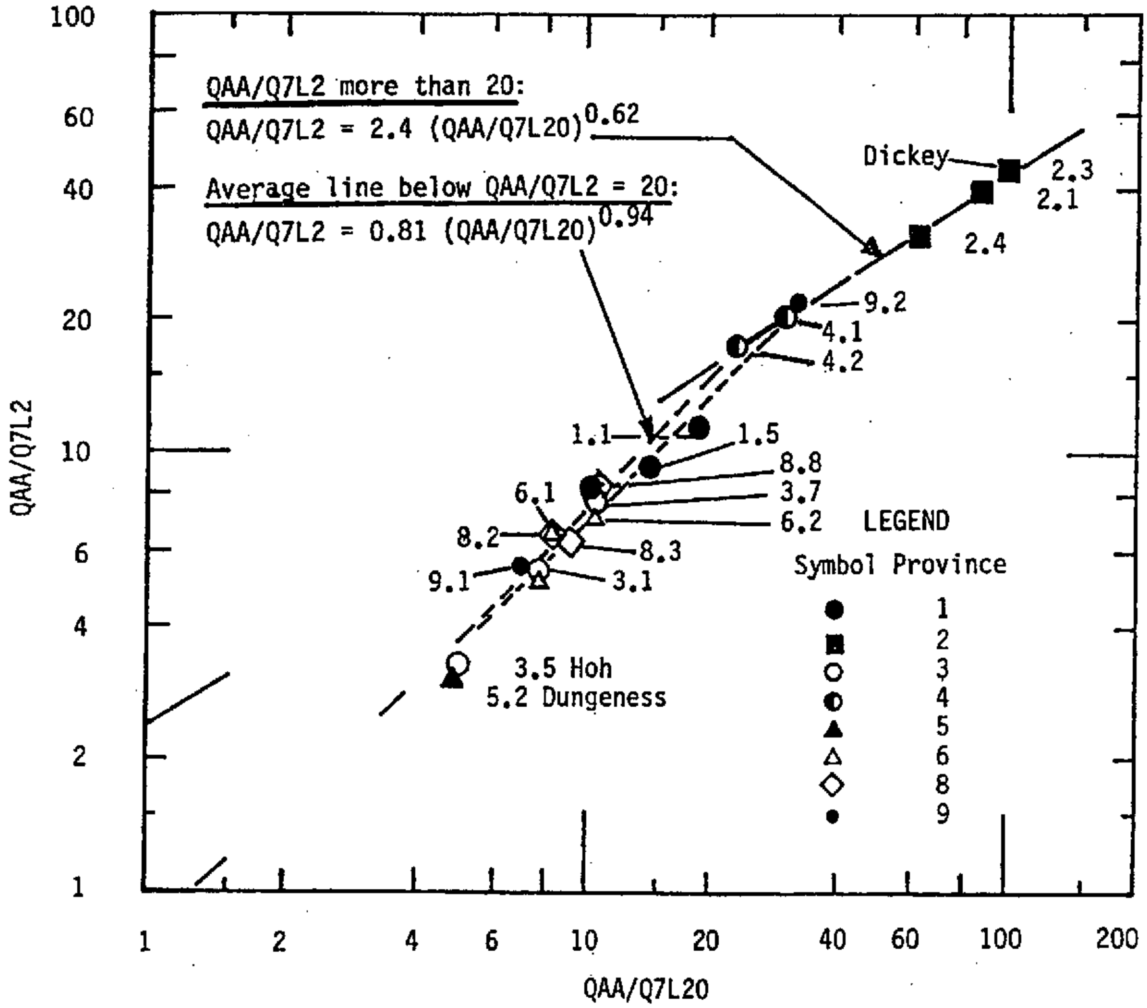


Figure VII-6. Relationship between ratios of average annual flow to 2-year and to 20-year low flow for gaging stations on the Olympic Peninsula. Data are from Table VII-1. See Table VII-3 for station codes and Figure VII-2 for locations.

Unit Maximum Flood Flows of Record

The highest instantaneous (peak) floods of record are listed for 28 Peninsula gaging stations in Table VII-5. There are some obvious similarities in events that occurred at the same time. Instantaneous flows resulting from highly variable storm conditions do not make as useful a set of indices as do flows averaged over longer periods of time.

Unit Daily Average Floods, Annual and Low Flows

The unit values for the 2-year daily flood (Q1F2), the average annual flow (QAA) and the 7-day average low flow (Q7L2) are shown in Table VII-6. There is reduction in the variability in average floods compared with peak values. Average annual flow values are much more consistent, but grouping some stations together based on location within regions can be misleading (e.g., Province 4, Northwest Coast, Hoko (4.1) and East Twin (4.2) are consistently different in unit flow values).

The low unit flows display both consistency and variability within their assigned provinces. The S.F. Skokomish (8.8) fits in Province 8 with respect to its low flow (geology), but relates better to the Humptulips (1.5) with respect to floods and average annual flows.

Flow ratios are demonstrated again in Figure VII-7, but in this instance unit flow values are used. By plotting QF/(QA·QL) (unit values of the characteristic flows) versus QL the calculated values tend to fall mostly in a band between the two lines designated "Region 1" and "Region 2" (these "regions" are not geographically defined like the AMC ecoregions, only by their mathematical relationship in Figure VII-7). This unit flow relationship among flood, average and low flows is similar to the 1:2:3 power relationship. All of the gaging stations (basins) fit on, near or between the two lines except for Goldsborough (9.1) and Dungeness (5.2) which lie at the NE and SE extremities of the Peninsula. Their positions depend primarily on the unusual relative sizes of their floods and low flows.

Note the consistency of the basins which have their origins near the center of the Olympic mountains (Olympic High Range Ecozone) and have a unit low flow value greater than 1.0 (Humptulips, S.F. Skokomish, Dosewallips, Hamma Hamma, N.F. Quinault and Hoh). All the stations on the east side of the Peninsula (except S.F. Skokomish) tend to follow the lower line. Northern, western and southern stations relate the upper line with few exceptions (2.4 Sooes and 4.2 E. Twin). Part of this inconsistency is due to uncommon periods of record and variability in basin geology.

Basin Parameters and Indices for Classification

Numerous relationships between basin characteristics were discussed in Appendix IV. In this section we will examine those characteristics singly and in combination for use as indices to classify basins above

Table VII-5. Unit Values of Peak Flow of Record (csm) for 28 Gaging Stations on the Olympic Peninsula. Data from Table III-13.

Province Gage Code No.	Station Name	Unit Peak Flood (csm)	Month/Year of Event
1.1	Cloquallum	94	12/59
1.3	Satsop	156	1/35
1.5	Humptulips	254	1/35
2.1	Moclips	122	12/75
2.2	Raft	226	12/75
2.3	Dickey	200	1/68
2.4	Sooes	102	11/77
3.1	N.F. Quinault	362	11/77
3.3	Queets	293	1/35
3.4	Clearwater	267	11/55
3.5	Hoh (208 sq. mi.)	186	1/61
3.6	Hoh (253 sq. mi.)	182	11/49
4.1	Hoko	275	12/72
4.2	East Twin	87	11/62
5.1	Elwha	112	11/49
5.2	Dungeness	44	11/49
6.1	Siebert	104	11/55
6.2	Snow	65	1/59
8.1	Dosewallips	140	11/49
8.2	Duckabush	135	11/49
8.3	Hamma Hamma	117	1/68
8.4	Jefferson	146	12/66
8.5	N.F. Skokomish	472	11/34
8.6	Deer Meadow	247	1/61
8.8	S.F. Skokomish	283	1/35
9.1	Goldsborough	36	1/68
9.2	Kennedy	79	12/77

Table VII-6. Unit Values of Characteristic Average Floods (Q1F2), Average Annual (QAA) and Average Low Flows (Q7L2) for 20 Gaging Stations on the Olympic Peninsula. Data for Flows from Table III-7; for Drainage Area from Table III-12.

Province/ Gage Code No.	Station Names	Drainage Area (sq. mi.)	Unit Average Values --(all values in csm)-- FLOOD[1]	ANNUAL[2]	LOW[3]
1.1	Cloquallum	65	38	4.2	0.37
1.3	Satsop	299	61	6.7	0.80
1.5	Humptulips	130	103	10.3	1.13
2.1	Moclips	35	78	6.0	0.16
2.3	Dickey	86	88	6.4	0.15
2.4	Sooes	32	71	6.5	0.20
3.1	N.F. Quinault	74	84	11.6	2.18
3.5	Hoh	208	63	9.8	2.93
3.7	Soleduck	84	72	7.4	0.94
4.1	Hoko	51	93	8.0	0.39
4.2	E. Twin	14	42	4.6	0.26
5.2	Dungeness	156	12	2.4	0.73
6.1	Siebert	16	16	1.1	0.16
6.2	Snow	11	14	1.5	0.18
6.3	L. Quilcene	20	18	2.4	0.47
8.2	Duckabush	66	45	6.3	1.10
8.3	Hamma Hamma	51	50	7.1	1.18
8.8	S.F. Skokomish	76	93	9.6	1.17
9.1	Goldsborough	39	20	3.0	0.54
9.2	Kennedy	17	33	3.6	0.16

[1]Q1F2: 2-year, 1-day average flood flow.
[2]QAA: average annual flow, or average daily flow.
[3]Q7L2: 2-year, 7-day average low flow.

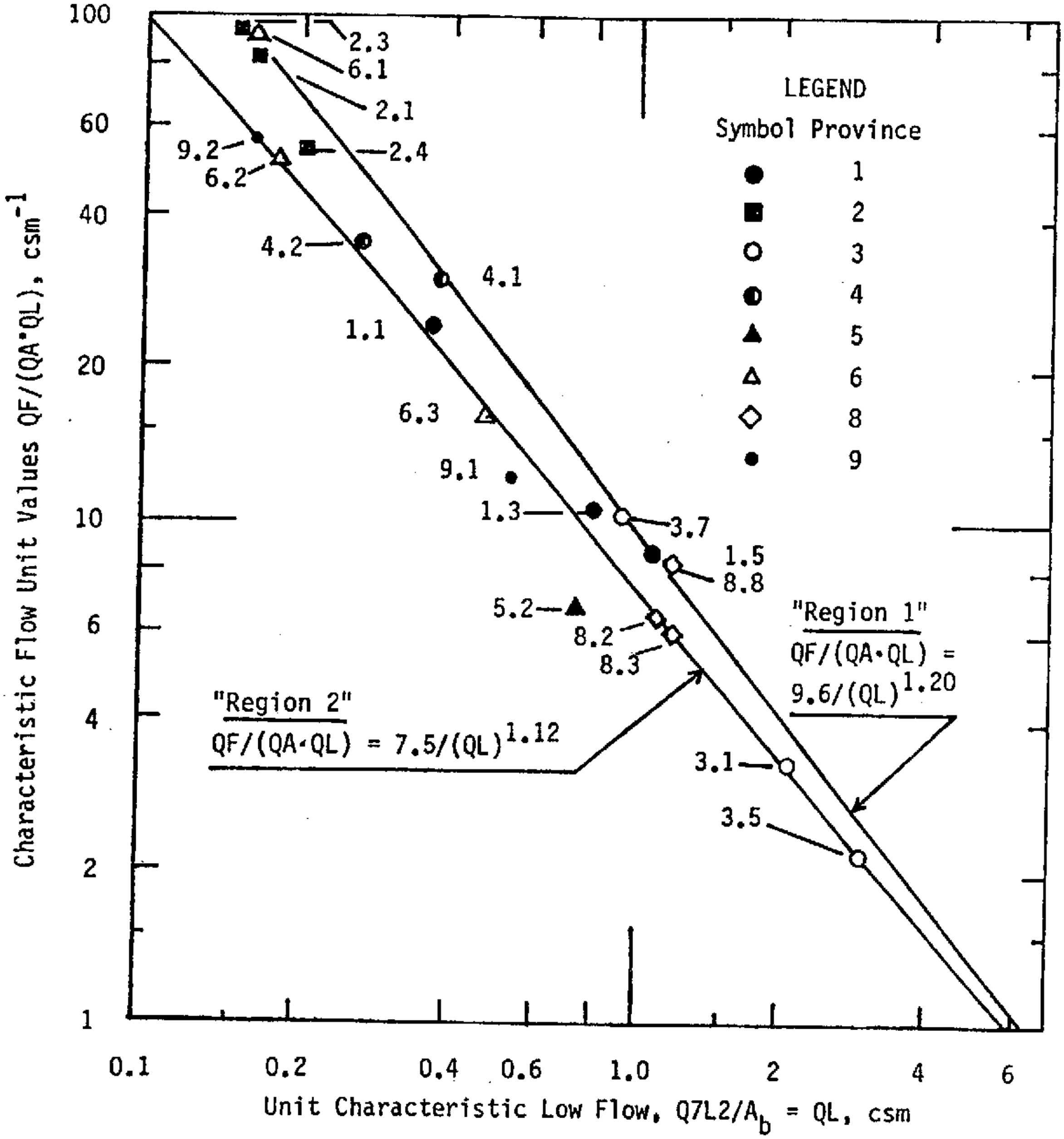


Figure VII-7. Combined unit flows as a function of unit low flows for gaging stations on the Olympic Peninsula. Data are from Table VII-6. See Table VII-3 for station codes and Figure VII-2 for station locations.

stream segments. In Appendices III and VI on hydrologic modeling and integration of basin, streamflow and channel characteristics, respectively, we have seen some of their mathematical linkages.

Stream Order

This index, if methodically applied, can be useful for comparing characteristics within and between basins (Hughes and Omernik 1981). The definition and consistent use of the term stream order and its measurement or assignment of order can be plagued with uncertainty (Omernik 1977). Stream analysis from maps can give widely divergent results depending on map scale, the map/photo interpreter and when the map was made.

Stream order was used in the Olympic Peninsula analysis on a sample basis in the South Fork Skokomish (Figure IV-4). Stream density (LST/A) was shown to be a constant in the basin regardless of stream order. Stream order should be maintained as a basin index in the AMC classification system, and should use blue lines on the largest scale USGS maps for the analysis.

Stream and Drainage Density

This parameter (LST/A or LD/A), depending on whether one uses blue-line stream length, or total drainage length, can be a strong tool in both analysis and classification if consistently applied according to standards. Low flows, as will be demonstrated later, correlate well with stream density, and floods correlate well with the total drainage density. The only example of stream density used on the Olympic Peninsula was on the S.F. Skokomish, but it has been shown to be a reasonable index for soils, geology, groundwater and low flows (Orsborn 1976). Stream density would be a good index for testing by AMC in conjunction with stream order in its stream-basin classification system.

Combinations of Basin Input, Stream Length and Relief

This combination of terms can be written as the ratio of

$$(P \cdot A)/(LT \cdot H^2) \qquad \text{(VII-4)}$$

where (P·A) represents the average annual input to the basin, (LT) is the total stream length (delivery system) and (H) is the basin relief which has been squared to make the ratio dimensionless except for the year term in P, but it can be considered a long-term average. Stream length was not analyzed for the whole Peninsula, so an example for southwestern Washington streams is presented in Figure VII-8. The relationship includes basins in the Deschutes, Cowlitz and Lewis River basins and

$$P \cdot A/LT \cdot H^2 = 45/(H)^{2.5} \qquad \text{(VII-5)}$$

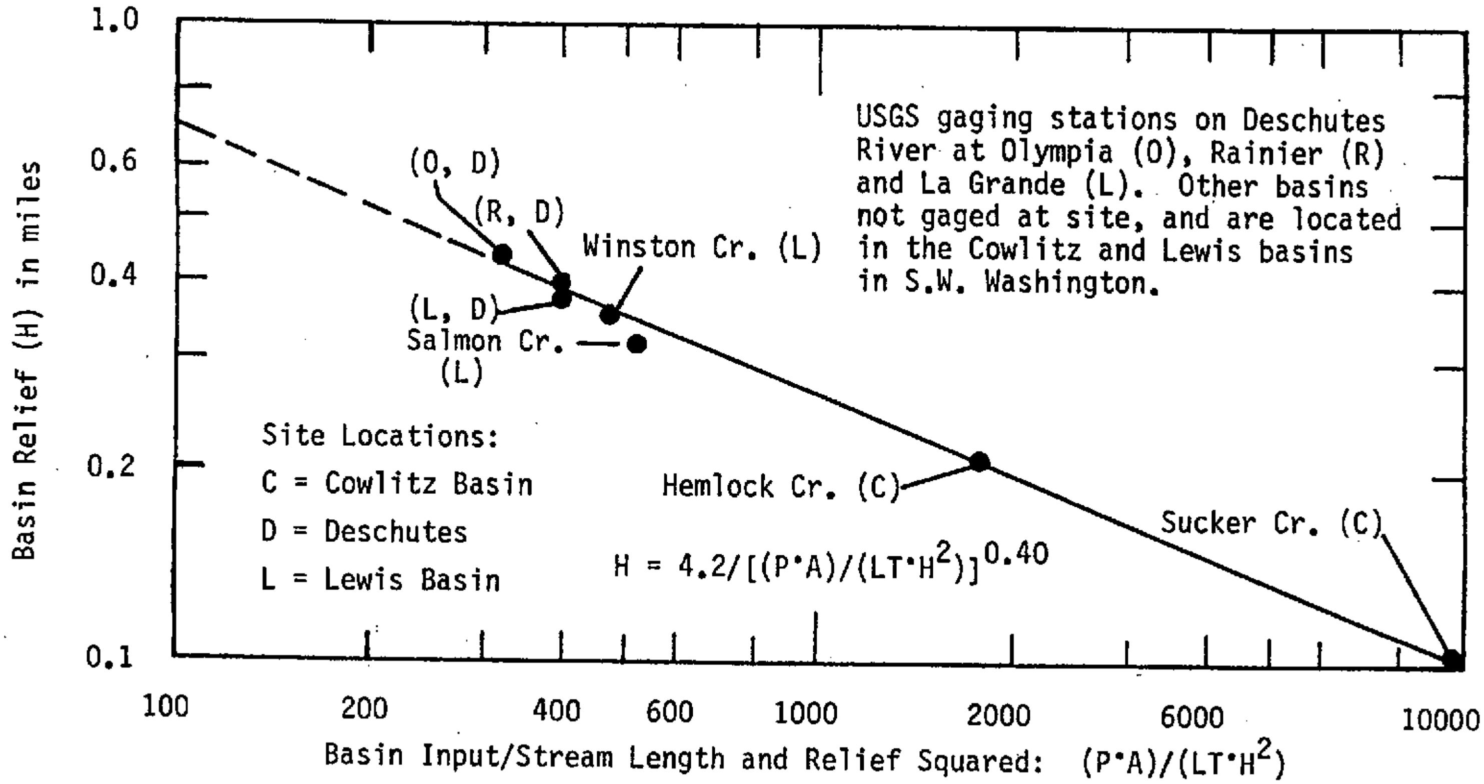


Figure VII-8. Relationship between basin relief (H), average input to the basins (P·A) and total stream length (LT) for basins in the Deschutes, Cowlitz and Lewis River basins in southwest Washington.

If this relationship is rearranged to solve for P, then

$$P = 45\ LT \cdot H^2/A(H)^{2.5} \qquad \text{(VII-6)}$$

which reduces to

$$P = 45\ (LT)/A(H)^{0.5} \qquad \text{(VII-7)}$$

which shows stream density (LT/A) and/or basin energy ($AH^{0.5}$) on the right side. This basin energy relationship was derived from this analysis of field data, not from fundamental principles. The coefficient of 45 is calibrated for the basins used from Southwest Washington. The stream length in the Deschutes basin was already shown to be a variable defined by

$$LT = 5.6\ (A)^{0.6} \qquad \text{(VII-8)}$$

This is displayed in Figure VII-9. If this is substituted into Eq. VII-7, then

$$P = 250/[(A)^{0.4}\ (H)^{0.5}] \qquad \text{(VII-9)}$$

for the Deschutes basin and others with similar stream densities.

Total stream length (LT) can be related to both drainage area (A) and average annual precipitation (P) as shown in Figure VII-9 on the upper graph.

Basin Input (P A) Related to Basin Energy (A $H^{0.5}$)

The basin parameters for the basins of the 20 gaging stations on the Olympic Peninsula are listed in Table VII-7. The last two columns list average basin precipitation on the basin (P·A = INPUT in sq. mi.-in./year) and basin energy ($AH^{0.5}$) has gravity (g) built into it, so its units are cfs. Therefore, the dimensions in both input and basin energy are L^3/T.

The values for these two factors have been plotted in Figure VII-10. The relationships for each of the four graphs from top to bottom are:

$$\text{INPUT} = C\ (\text{ENERGY})^{1.0} \qquad \text{(VII-10)}$$

$$(P \cdot A) = 460\ A(H)^{0.5}$$
$$(P \cdot A) = 270\ A(H)^{0.5}$$
$$(P \cdot A) = 210\ A(H)^{0.5}$$
$$(P \cdot A) = 65\ A(H)^{0.5}$$

Also, for the Soleduck (3.7), Duckabush (8.2) and Hamma Hamma (8.3) no line was drawn so as to avoid crowding, but their relationship is

$$P \cdot A = 130\ A(H)^{0.5} \qquad \text{(VII-11)}$$

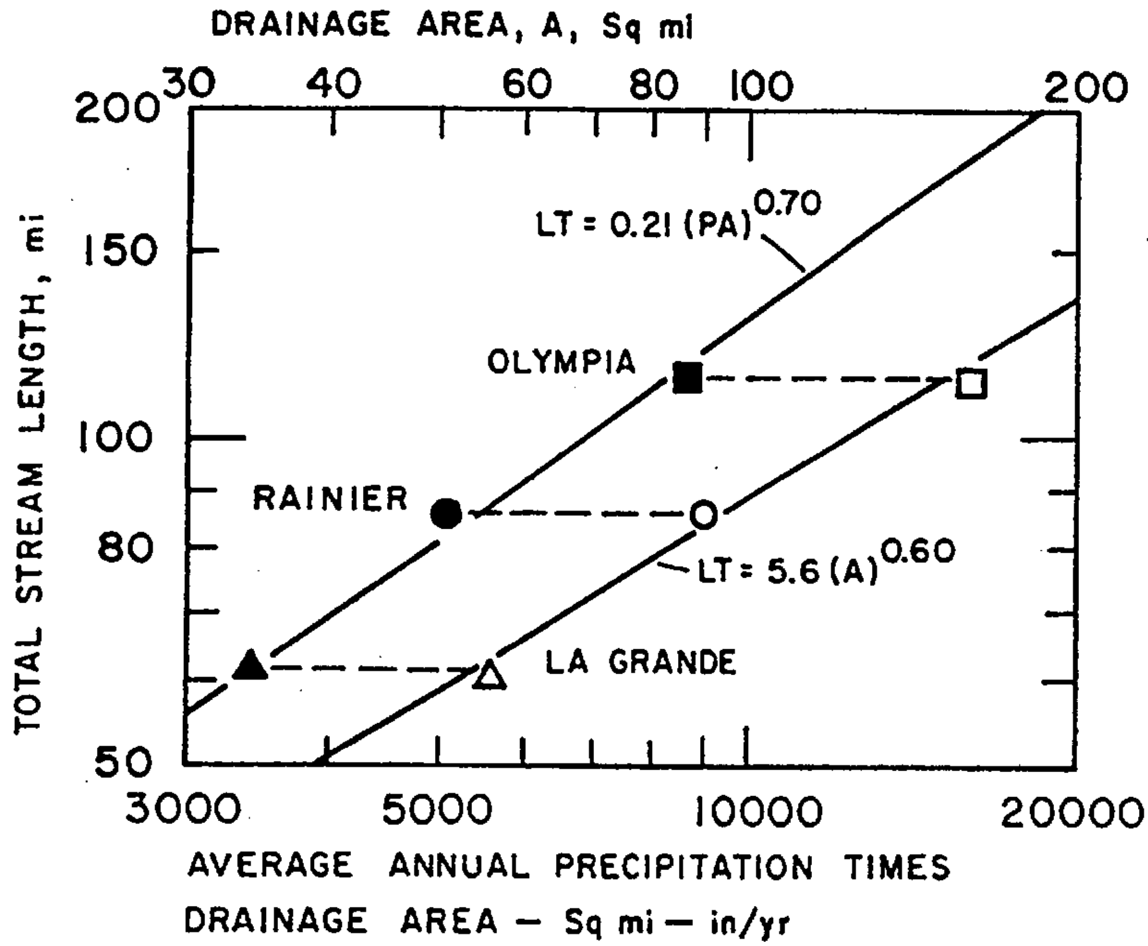


Figure VII-9. Relationships of total stream length to drainage area and annual precipitation in the Deschutes River basin of Washington (Orsborn 1976).

Table VII-7. Basin Characteristics for the Twenty USGS Base Gaging Stations on the Olympic Peninsula.

Province/ Stream Gage Code	Station Name	USGS Gage No. 12-	Gage Elev. (ft)	Headwater Elev. (ft)	Basin Relief, H (ft)	Basin Relief, H (mi)	Drainage Area, A (sq. mi)	Average Annual Precip., P (in/yr)	COMBINED PARAMETERS Basin Input (PA) (sq.mi-in/yr)	COMBINED PARAMETERS Basin Energy $(A)(H)^{0.5}$ $(mi)^{2.5}$
1.1	Cloquallum River	032500	20	800	780	0.15	64.9	72	4673	25.1
1.3	Satsop River	035000	30	2500	2470	0.47	299.0	128	38272	205.0
1.5	Humptulips River	039000	120	3200	3080	0.58	130.0	155	20150	99.0
2.1	Moclips River	039220	25	500	475	0.09	35.0	120	4200	10.5
2.3	Dickey River	043100	50	1000	950	0.18	86.3	95	8199	36.6
2.4	Sooes River	043163	70	800	730	0.14	32.0	116	3712	11.5
3.1	N.F. Quinault River	039300	620	4000	3380	0.64	74.1	200	14820	59.3
3.5	Hoh River	041000	320	4500	4180	0.79	208.0	167	34736	184.9
3.7	Soleduck River	041500	1060	4160	3100	0.59	83.8	99	8296	64.4
4.1	Hoko River	043300	50	1200	1150	0.22	51.2	124	6349	24.0
4.2	East Twin River	043430	10	1200	1190	0.22	14.0	90	1260	6.6
5.2	Dungeness River	048000	570	5000	4430	0.84	156.0	62	9672	143.0
6.1	Siebert Creek	047500	280	2000	1720	0.33	15.5	41	636	8.9
6.2	Snow Creek	050500	220	3400	3180	0.60	11.2	43	482	8.7
6.3	L. Quilcene River	052000	90	3600	3510	0.66	19.6	51	1000	15.9
8.2	Duckabush River	054000	240	5000	4760	0.90	66.5	113	7514	63.1
8.3	Hamma Hamma River	054500	510	4000	3490	0.66	51.3	110	5643	41.7
8.8	S.F. Skokomish River	060500	100	3400	3300	0.63	76.3	153	11674	60.6
9.1	Goldsborough Creek	076500	200	360	160	(0.030)	39.3	84	3301	6.8
9.2	Kennedy Creek	078400	110	400	290	(0.055)	17.4	59	1027	4.1

*All characteristics except headwater elevation are from USGS Annual Gaging Station Records, and Williams et al. (1985).

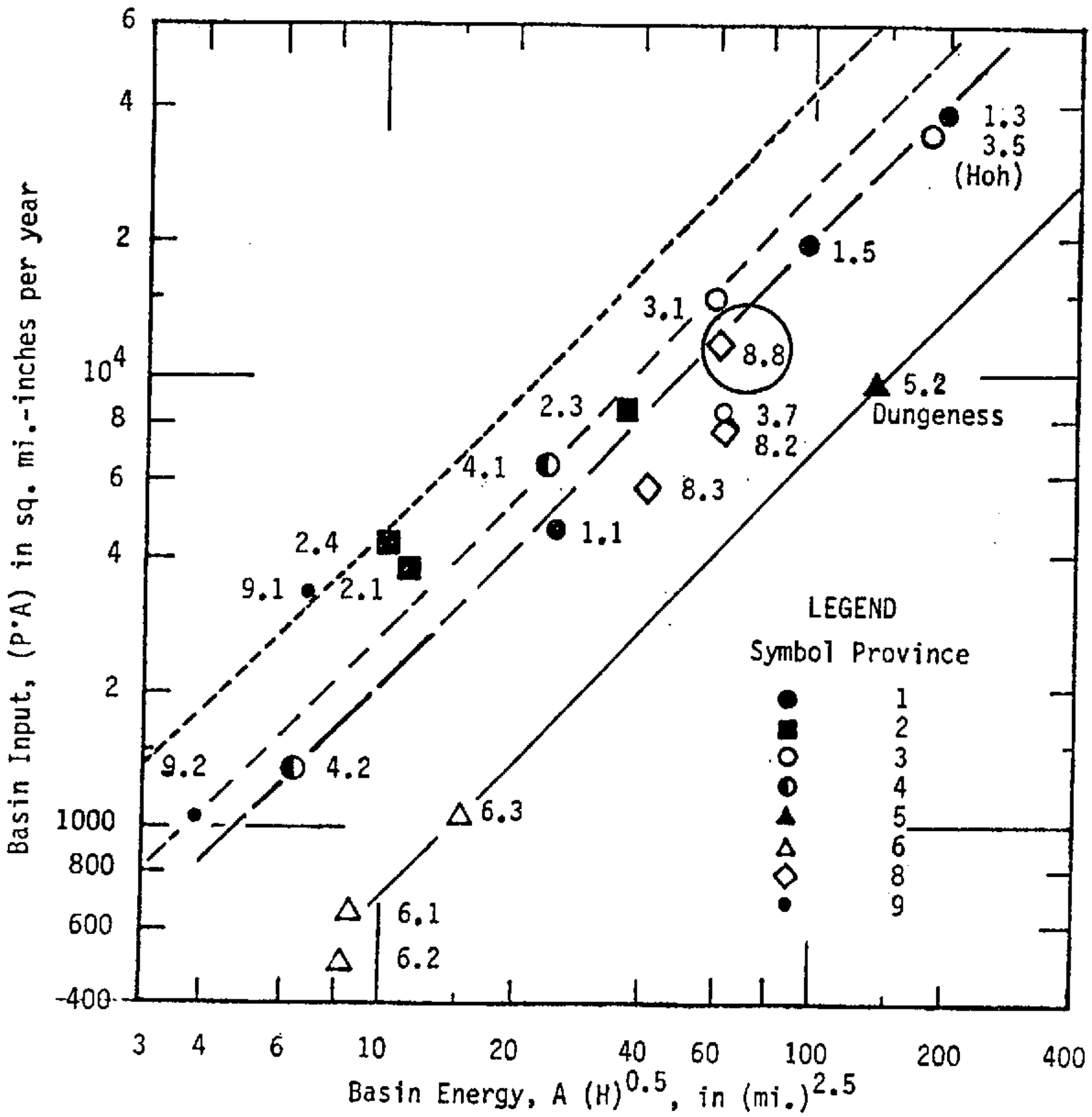


Figure VII-10. Basin input from average annual precipitation related to basin energy for USGS stream gaging stations on the Olympic Peninsula. Data are from Table VII-7. See Table VII-3 for station codes and Figure VII-2 for locations.

for these mountainous eastern and northwestern basins. These equations can be reduced to $P = C(H)^{0.5}$, but only if lower limits of elevation and precipitations were applied.

The coefficients in each equation (C = 460, 270, 210, 130 and 65) are no doubt a function of precipitation, but no solution was developed at this time. As we saw in the chapter on streamflow modeling, the average annual flow

$$QAA = C(A) \qquad \text{(VII-12)}$$

with a series of (C) values.

And, when (C) was evaluated in terms of (P) then

$$QAA = 0.0032(P)^{1.6} A_b \qquad \text{(VII-13)}$$

Rearranging this for A gives

$$A_b = QAA/(0.0032\ (P)^{1.6}) \qquad \text{(VII-14)}$$

and substituting this into the left side of any of the five "regional" equations like Eq. (VII-11) yields

$$(QAA)(P) = C\ (0.0032\ (P)^{1.6})\ (A_b)\ (H)^{0.5} \qquad \text{(VII-15)}$$

Transferring (P) to the right side and basin energy $A(H)^{0.5}$ to the left side combines average annual streamflow with basin energy to describe basin average annual precipitation such that

$$(QAA)/[A_b\ (H)^{0.5}] = C[0.0032\ (P)^{0.6}] \qquad \text{(VII-16)}$$

Even though the general relationship for solving for the coefficient (C) has not been developed, it is obvious from the above equation that for basins in the provinces where C = 460, 270, 210, 130 and 65 that

$$\frac{\textbf{AVERAGE ANNUAL FLOW}}{\textbf{BASIN ENERGY}} = \textbf{FUNCTION OF AVERAGE ANNUAL PRECIPITATION}$$

Various streamflow and basin indices for use in classifying regions, zones and basins have been developed. In the next section several channel characteristics will be developed into classification indices to show how they relate to channel response variables (and fish habitat parameters).

Additional basin parametric relationships were developed in Appendix IV for Lebar Creek in the South Fork Skokomish basin as an example basin. These relationships demonstrated that:

- characteristic streamflows, such as average annual flow, could be determined from the length of perennial stream in a basin;

- basin characteristics, such as perennial stream length (LS, LST) are strongly correlated with basin area (A), basin average precipitation (PA) and basin energy $(A)(H)^{0.50}$;
- the relationship between basin relief (H) and $(PA)/[LS(H)^2]$ is consistent between Lebar Creek and basins in Southwestern Washington (Figures VII-8, page VII-22); and
- the Lebar Creek basin analysis showed that when the average basin precipitation (PA) is related to basin energy $(A)(H)^{0.50}$ the equation is the same as for the South Fork Skokomish River (Eq. VII-10 on page VII-23 and circled data point in Figure VII-10 on page VII-26)

$$(PA) = 210\ A(H)^{0.50} \qquad \text{(VII-10)}$$

Channel Parameters as Classification Indices

As demonstrated in Appendix V on channel characteristics, the use of hydraulic geometry values of width, depth, velocity and area at particular flows (QAA or Q1F2) gives regional Hydraulic geometry equations. For the average annual flow:

$$W = 4.82\ (QAA)^{0.47} \qquad \text{(VII-17)}$$

$$D = 0.26\ (QAA)^{0.35} \qquad \text{(VII-18)}$$

$$V = 0.80\ (QAA)^{0.18} \qquad \text{(VII-19)}$$

$$A_c = 1.07\ (QAA)^{0.86} \qquad \text{(VII-20)}$$

and for average flood flows

$$W = 3.44\ (Q1F2)^{0.42} \qquad \text{(VII-21)}$$

$$D = 0.13\ (Q1F2)^{0.44} \qquad \text{(VII-22)}$$

$$V = 2.24\ (Q1F2)^{0.14} \qquad \text{(VII-23)}$$

$$A_c = 0.55\ (Q1F2)^{0.83} \qquad \text{(VII-24)}$$

These equations describe how channels and velocity increase in size as drainage areas increase and are displayed in Figures V-6, -7 and -8 on pages V-14, -15 and -16.

The data points used to develop these graphs and equations are for streams covering the entire Olympic Peninsula and represent wide ranges in geology and precipitation which govern flow and channel relationships. Constructing these relationships for smaller regions and channel with similar geology would reduce the variability.

methods of channel classifications. These are described by Eqs. VII-17 through VII-20. Low flow and flood flow geometry relations have more variability, but they can both be related to average annual flow relations. Also, by examining Eqs. VII-21 through VII-24 one can see that depth at flood flow increases more rapidly than width at the average flow. As a result W/D values at most stations decrease when the flow increases from QAA to Q1F2.

To develop a dimensionless relationship which can be used in the shear-shape relationship, streampower and sediment transport from Appendix V, divide Eq. VII-18 into Eq. VII-17 which gives

$$W/D = [4.82\ (QAA)^{0.47}/0.26\ (QAA)^{0.35}] \qquad \text{(VII-25)}$$

which reduces to

$$W/D = 18.5\ (QAA)^{0.12} \qquad \text{(VII-26)}$$

which means that width changes more rapidly in a downstream direction than does depth (exponents 0.47 versus 0.35) at average annual flow.

Substituting the average equation (C = 10) for QAA as a function of basin energy gives

$$W/D = 18.5\ [10A(H)^{0.50}]^{0.12} \qquad \text{(VII-27)}$$

which reduces to

$$W/D = 24\ (A)^{0.12}(H)^{0.06} \qquad \text{(VII-28)}$$

Holding this equation in reserve a more direct approach is taken using **the data in Table VII-8.** Beginning with water surface width related to basin area, then to basin energy, the variability is reduced to two lines for W/D versus basin energy.

- **Figure VII-11**: Channel width (W) at average annual flow is plotted as a function of basin drainage area (A_b). There is only a trend in all the data, with clusters for some subregions (subregions 2, 6 and 8). Station 8.8, the South Fork Skokomish River, demonstrates its typical over-width, due probably to heavy logging in the basin, and a subsequent sediment imbalance, aggradation and widening. A similar plot of mean depth (not included) demonstrated an expected response, with the South Fork Skokomish having a mean depth shallower than would be expected.

- **Figure VII-12**: By relating channel width at average annual flow to basin energy $(A)(H)^{0.50}$, the scatter from Figure VII-11 is reduced. All the data points except 8.2 (Duckabush) and 8.8 (S.F. Skokomish) group themselves along three parallel lines with the equations of

Table VII-8. Channel and Basin Properties at Average Annual Flow for Olympic Peninsula USGS Gaging Stations

Station Code No.	Stream Name	Water Surface Width, W (ft)	Mean Water Depth, D (ft)	W/D (-)	Basin Area, A_b (sq. Mi)	Basin Relief, H (mi)	Basin Energy $A(H)^{0.50}$ $(mi)^{2.50}$
1.3	Satsop	252	2.3	108	299	0.47	205
1.5	Humptulips	187	2.7	69	130	0.58	99
2.1	Moclips	57	1.4	41	35	0.09	11
2.3	Dickey	81	2.5	32	86	0.18	37
2.4	Sooes	70	1.9	37	32	0.14	12
3.1	N.F. Quinault	133	3.6	37	74	0.64	59
4.1	Hoko	93	1.9	48	51	0.22	24
4.2	E. Twin	33	1.0	33	14	0.22	7
5.2	Dungeness	80	2.1	39	156	0.84	143
6.1	Siebert	18	0.8	24	16	0.33	9
6.2	Snow	22	0.6	34	11	0.60	9
6.3	L. Quilcene	26	1.0	27	20	0.66	16
8.2	Duckabush	73	2.1	34	66	0.90	63
8.3	Hamma Hamma	88	1.7	53	51	0.66	42
8.8	S.F. Skokomish	213	1.6	137	76	0.63	61
9.1	Goldsborough	38	1.6	24	39	0.03	7
9.2	Kennedy	29	1.0	28	17	0.06	4

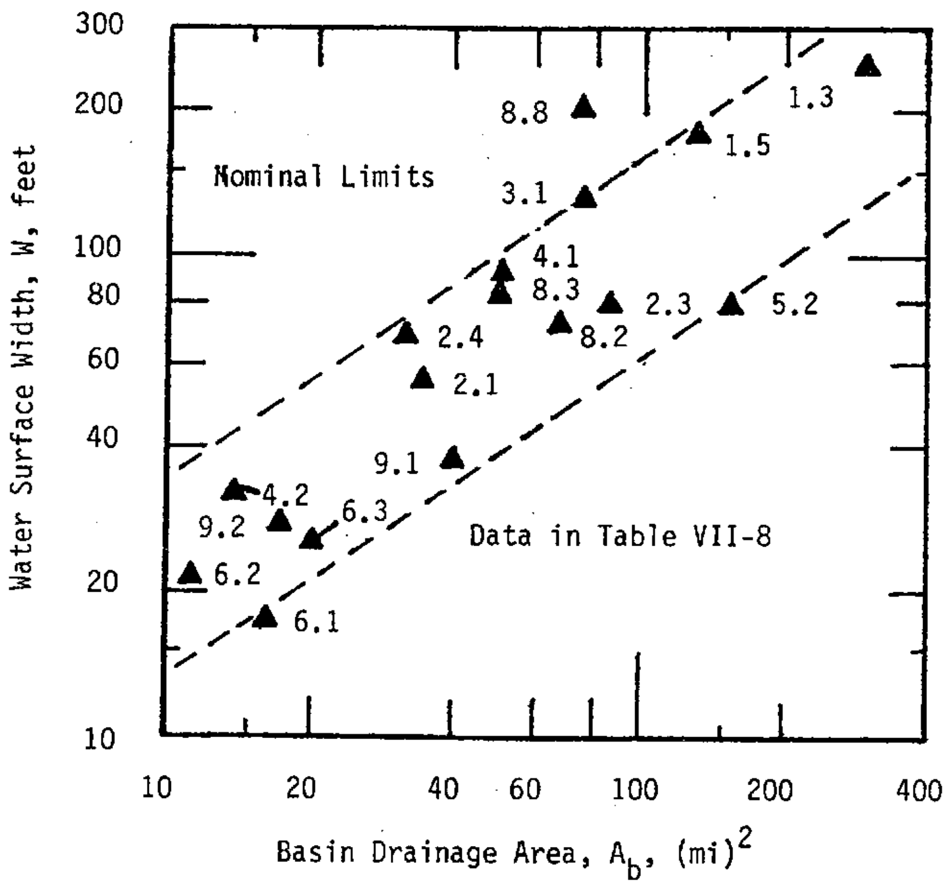


Figure VII-11. Water surface width at average annual flow related to basin drainage area for USGS gaging stations on the Olympic Peninsula.

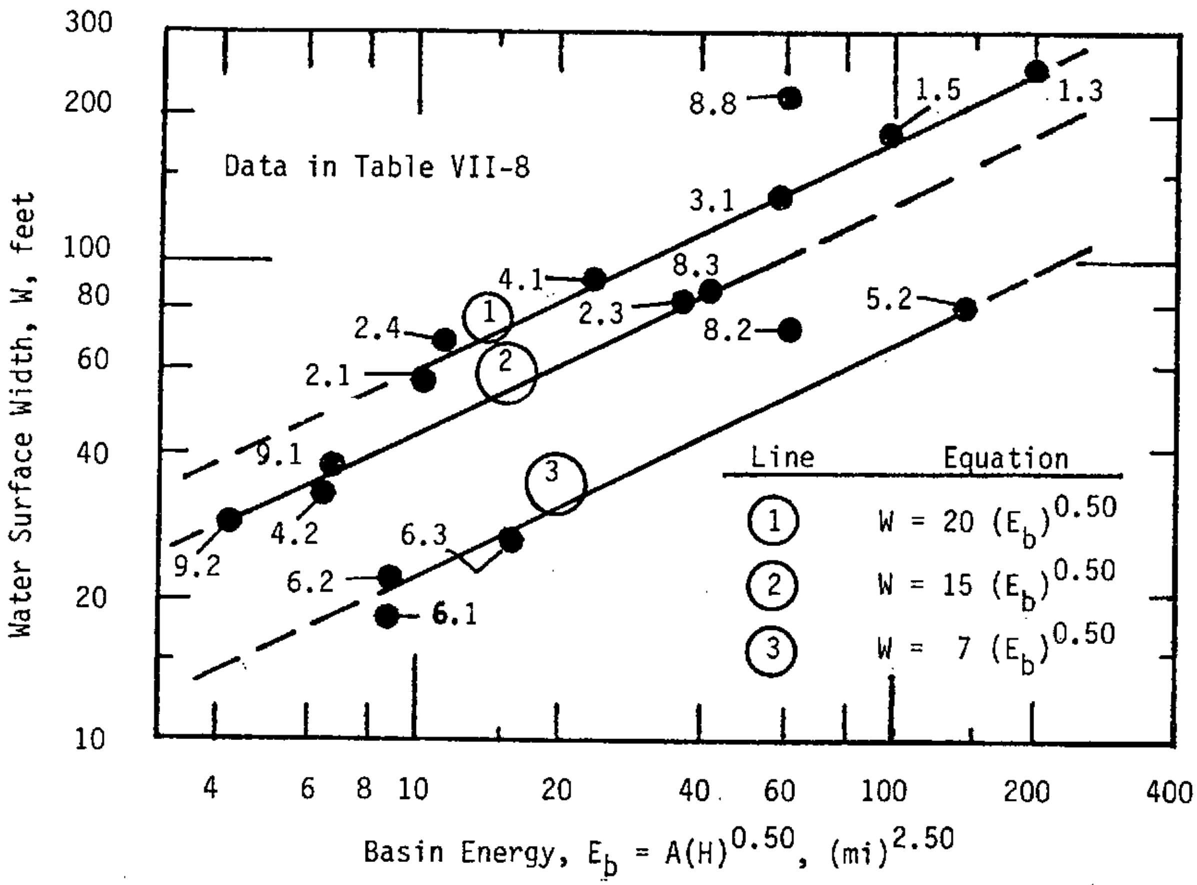


Figure VII-12. Water surface width at average annual flow related to basin energy for USGS gaging stations on the Olympic Peninsula.

Line (1): $W = 20\ (E_b)^{0.50}$ (VII-29)

Line (2): $W = 15\ (E_b)^{0.50}$ (VII-30)

Line (3): $W = 7\ (E_b)^{0.50}$ (VII-31)

where E_b is the basin energy terms, $A(H)^{0.50}$.

If the coefficients (20, 15 and 7) could be related to another variable, then the three equations could be solved simultaneously. Several parameters and ratios of flows were tried, but no solution was found. The coefficients are no doubt related to precipitation, because the northeast rain shadow basins (5.2, 6.1, 6.2 and 6.3) form the lowest line (Line 3). Also, most of the middle line (Line 2) basins have intermediate amounts of precipitation. But, when average annual precipitation (P) was multiplied times basin energy [$A(H)^{0.50}$] the relationships in the above equations held their relative positions. The coefficients changed, but the exponents remained constant at one half.

There are certainly local channel characteristics which influence the width. For example, the Dickey Creek gage (2.3) is located just downstream of a bridge with abutments which confine the width. The substrate is composed of 2- to 3-ft boulders. These two factors would constrain the width and depth relationship.

Another factor to consider in channel classification is that the land use history above these USGS gages has not been evaluated. Tests of changes in hydraulic geometry over the history of the gages have not been made. The most recent channel calibration data was used. This is one aspect of the monitoring program which could be very fruitful--an assessment of how USGS calibration records in certain regions have changed in two classes of basins:

(1) natural, or relatively undisturbed basins; and

(2) heavily impacted basins for which the land-use history can be quantified as to the types, locations and sizes of changes. This second evaluation would require good documentation of land use changes, cumulative precipitation (mass diagram), flow and channel changes.

- **Figure VII-13**: The step-by-step solution to W/D as a function of basin energy yields a set of two relationships

Upper Line: $W/D = 18\ (E_b)^{0.30}$ (VII-32)

Lower Line: $W/D = 18\ (E_b)^{0.17}$ (VII-33)

This relationship sets all the gaging station W/D ratios at average annual flow into two groups except for Station 8.8 (S.F. Skokomish). Stations 3.1 (N.F. Quinault) and 8.3 (Hamma Hamma) are a little away from the relationships, but generally fit them. Also, the Satsop River gage (1.3) indicates that the channel may be too wide or aggraded.

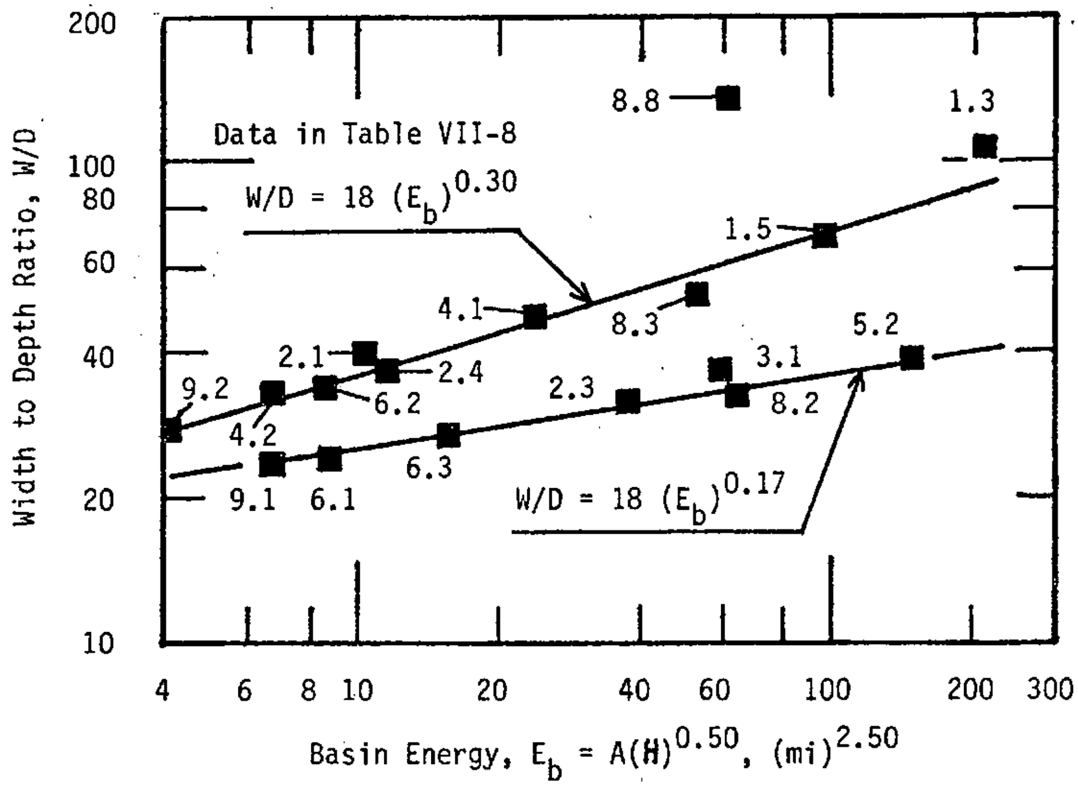


Figure VII-13. Width to depth ratio at average annual flow related to basin energy for USGS gaging stations on the Olympic Peninsula.

Notice the similarity of these two equations to Eq. VII-28. In this case, it is the exponents which are some function of another variable because the coefficient (18) is a constant.

If Eq. VII-33 is reduced after inserting area and relief to the half power, then

$$W/D = 18(A)^{0.17}(H)^{0.08} \qquad \text{(VII-34)}$$

which is very similar to Eq. VII-28 which was derived from the regional hydraulic geometry relation. Eq. VII-34 applies to most of the basins on the east side of the Peninsula.

The two relationships in Figure VII-13 (Eqs. VII-32 and -33) and the three groupings in Figure VII-12, along with the regional hydraulic geometry equations, are certainly adequate to demonstrate that classifying channels on the basis of their geometries, and basin energy, is a reasonable approach to evaluate channel response. When precipitation was added to the W/D versus basin energy relationships in Figure VII-13, the two graphs came closer to each other but there was no improvement in the relationships.

The results of these various classification systems are summarized in the next section.

Summary of Classification Systems Developed on the Bases of Streamflow, Basin and Channel Characteristics

Methods for grouping basins, streams and segments (sites) on the basis of hydrologic, basin and channel indices have been demonstrated for a sample of USGS gaging stations. Limitations on the analysis include:

(1) the land use history of the basins above the gages was not known;

(2) the most recent stream transect data for gage calibration was used to quantify the hydraulic geometry;

(3) the variability in the hydraulic geometry over time at the USGS gage was not evaluated; and

(4) the gages do not have common periods of record.

But, the results of the channel physical characteristics analysis, given the unknowns, demonstrated consistent relationships for most gages. The analyses also demonstrated that channels which are out of balance (e.g., 8.8 South Fork Skokomish) do not fit the relationships.

Hydrologic Classification Based on Streamflow

- **Table VII-1 (page VII-3):** The ratios of characteristic flows can be grouped by ranges of values which "regionalizes" the gage sites.

Some of the implications of the ratios to the variability of the flow regime as discussed on page VII-5.

- **Figure VII-3 (page VII-10):** Demonstrates how subregions can be defined using a "dimensionless duration curve." The average flood and average annual flow are normalized to the average low flow. The plotting points of QAA/Q7L2 on the straight gage lines demonstrate the consistency with which flows at gage sites fit the relationships. The larger ratios of QAA/Q7L2 indicate less stability in the flow regime.

- **Table VII-4 (page VII-11) and Figure VII-4 (page VII-13):** The variability in the year-to-year average annual flow is a quick classification tool. The average annual flow over periods of years is quite stable and easy to estimate accurately for ungaged sites. Some of the variability in these relationships is tied to the fact that the gages do not have common periods of record. But, Siebert Creek (6.1) obviously has the most variability in average flow, and Kennedy Creek has the least.

- **Figure VII-5 (page VII-14):** This graph is another way of visualizing the relationships which were displayed in the dimensionless duration curve (page VII-10) using the same flow ratios. As floods are reduced and low flows increase (due to glacial flows for gages 3.1, 3.5, 5.2, 8.2 and 8.3), or just due to better infiltration characteristics (6.3 and 9.1) there is a break in the relationship. The west coastal basins (2.1, 2.3, 2.4) show the highest variability on the average, between average floods and average annual flows, and between average annual flows and average low flows (defined in Figure III-13, page III-30); this dimensionless relationship shows how much variability there is among the highest, average and lowest annual daily flows.

- **Figure VII-6 (page VII-16):** This graph demonstrates the variability in the average 2-year low flow, and the 20-year low flow, as functions of the average annual flow. Both consistencies and inconsistencies can be seen for the gages within the hydrologic provinces. Province 2 gages consistently have the highest flow ratios and the glacially fed basins have the lowest values (less variability from year to year). But, Goldsborough (9.1) and Kennedy (9.2) show the high degree of intra-province variability which they consistently display in the southeast part of the Peninsula.

- **Figure VII-7 (page VII-20); and Table VII-6 (page VII-19):** Unit flow values per square mile of basin area have advantages and disadvantages for classification:

  (1) Floods values can be used quite confidently, unless there is a significant amount of valley storage which controls the values at some gages in a province;

  (2) Average annual unit flows decrease as basins becomes larger and precipitation decreases with elevation; and

(3) Unit low flow values are indicative of the geology, groundwater and/or glacial supply during the low flow period. Unit values of average low flow ($Q7L2/A_b$) are called a "low flow index" with 1.0 csm being taken as a reference or index.

In Figure VII-7, the Peninsula gages tend to fall into two general "Regions," with some basins tending to be anomalies, such as the Dungeness (5.2). Relatively speaking it is a mixed basin with part of its watershed in the high Olympic Mountains, and the rest lies in the rain shadow. Once again, the South Fork Skokomish (8.8) acts more like the Humptulips (1.5) than it does the other Province 8 basins (Duckabush, 8.2 and Hamma Hamma, 8.3). This may be partly due to its location "on the SE Corner" of the Olympic Range, and it may be due to increased flooding due to heavy logging activity. It may be a natural or an artificial relationship, because the average precipitation on the South Fork basin is about 150 inches per year, versus 113 and 110 for the Duckabush and Hamma Hamma basins. Precipitation is about 155 inches per year on the Humptulips basin.

Classification Using Basin Parameters

- **$(PA)/(LT \cdot H^2)$** represents several factors, but it is a ratio of the average annual water input to a basin, divided by the length of the delivery system (stream channels) above the site, and the basin relief (potential energy). A/LT = 1/SD or stream density. This combination of terms is consistently related to relief in southern Washington basins and in Lebar Creek, a second-order subbasin of the South Fork Skokomish (Figure VII-8, page VII-22; and Figure IV-9 on page IV-26 for Lebar Creek.

- **Stream order** was not demonstrated except for Lebar Creek, because it is merely a numerical index and not part of a set of quantifiable, physical relations which can be synthesized. As mentioned on page VII-21, the definition of stream density must be consistent stream order and drainage order are useful tools for descriptive classification work if properly applied. We may be able to explore their more effective use as part of future watershed quantification work.

- **Figure VII-9 (page VII-24)**: demonstrated relationships between cumulative stream length (LST) and drainage area, and (LST) as a function of basin input (PA). These were developed also for Lebar Creek and its subbasins in Appendix IV.

- **Figure VII-10 (page VII-26)**: relates basin input (PA) to basin energy $(A)(H)^{0.50}$ above the stream segment. The Olympic Peninsula basins form a series of about five groups with the plotting positions of streams from different geographic provinces being mixed, except for the NE "rain shadow" (Dungeness, Siebert, Snow and Little Quilcene). These basins usually diverge from those on the rest of the Peninsula when precipitation influences the classification parameter. Lebar Creek's analysis of this same set of terms showed it to have the same coefficient in the equation (VII-10, page VII-28) as for its parent basin Station 8.8--South Fork Skokomish.

Classification Using Channel Characteristics

Methods demonstrated include:

- **Regional hydraulic geometry** for width, depth, velocity and flow area for two characteristic flows, QAA and Q1F2;

- **Width to depth ratio from hydraulic geometry** was developed by dividing the two regional equations for average annual flow which led to $W/D = 18.5\ (QAA)^{0.12}$ (Eq. VII-26). Although it was not demonstrated, this could be substituted into the shear-shape and bed shear equations as shown by example in Appendix V on channel characteristics. It would be accurate only for those gage sites lying near the average equation for all the Peninsula gages. More localized relationships should be developed for the monitoring program baseline stations.

- **Width to depth ratio** was developed in an alternative three-step logic process using **basin energy**:

  (1) **Figure VII-11 on page VII-31**: water surface width (W) at average flow was plotted versus drainage area, and demonstrated a deviation from the mean of about 50 percent for all the Peninsula gaging sites used. Some sites were not used because of the known presence of bedrock.

  (2) **Figure VII-12 on page VII-32**: adding basin relief (H) to basin area (A) caused the width (W) values to be organized into three dominant groups. Several trials were run to determine a functional relationship between the three coefficients and another parameter, but none could be found at this time.

  (3) **Figure VII-13 on page VII-34**: The third step in this development classified the W/D ratios at average annual flow for almost all of the Peninsula gages into two groups. There were a couple of "exceptional" stations such as for the South Fork Skokomish River. Whereas the W/D ratio would be expected to be about 62 for a basin energy of 61, the actual gage calibration value is more than double at W/D = 137. Excess sediment load from logging activities have caused the stream to widen and become shallower (aggrade).

The physical connections among the basin morphology, hydrology and channel morphology have been demonstrated. Characteristics of each component have been used to group streams based on relationships among their basin, streamflow and channel parameters.

The final two appendices summarize the results of the expert workshop on classification (Flaherty 1989), and provide comments on the monitoring program.

APPENDIX VIII.--SUMMARY OF EXPERT WORKSHOP COMMENTARY ON EVALUATING STREAMS AND FOREST PRACTICES

APPENDIX VIII.
SUMMARY OF EXPERT WORKSHOP COMMENTARY ON EVALUATING STREAMS AND FOREST PRACTICES

Introduction

The expert workshop was designed to sharpen the AMC focus on classification systems, and how these systems can be used to assist in all phases of the TFW program. The workshop was held on May 24-26, 1989, and has been extensively reported in detail by Flaherty (June 23, 1989). The essences of the expert comments as they apply to the AMC program are summarized in this appendix. Topics identified for clarification and/or expansion are discussed in more detail in various chapters of this report on the physical aspects of classification, stream channel and basin characterisics.

The overall goal of the workshop was to assist in the development of a "research and monitoring program that can be used effectively in forest management decision-making regarding streams and fish habitat." The specific purpose of the workshop was to use the experts to develop the program with a sound consideration of geomorphic and biologic systems (Executive Summary, Flaherty 1989). A guiding criterion for the experts was that the AMC monitoring program needed to focus on response variables--stream conditions that are likely to respond to varying (new) levels of sediment, changed hydrologic regimes or in-channel structures (debris jams--JFO).

Comments made by the experts during the workshop which appear to have application to the AMC classification system are summarized in the remainder of this appendix. Some of the ideas are incorporated into the classification systems analysis in the report. The experts were asked to bring examples of their most recent articles and reports with them for use by the PI. <u>None did</u>. Therefore, appropriate articles from the literature and agency reports have been selected to fill this information gap. Also, copies of reports, proposals and planning documents were requested from TFW Committees by the PI, but none were been received.

One obvious void in the workshop was the lack of familiarity with the TFW program on the part of the experts, although the experts did receive a copy of the AMC planning document prior to the workshop. The topics on which the workshop was focused are summarized in alphabetical order in Table VIII-1 on the next page.

Table VIII-1. AMC Expert Workshop Topic Focus

- **Biological**
  - communities
  - response impacts
- **Classification**
  - cause of differences
  - mappable units
  - other classification systems
  - observable differences
  - response variables
  - scale effects
  - stratification of types
- **Climate**
- **Fisheries**
  - relation of watershed factors, etc. to fish
- **Impacts**
  - cause and effect
- **Interrelationships**
  - landscape:stream type
- **Managers and Regulators**
  - checklists
  - best practices
  - knowledge gaps
  - risk assessment
  - useful tools
- **Monitoring**
  - biological response
  - cumulative effects
  - environmental changes
  - knowledge gaps
  - management practices
  - natural variability
  - responses
  - risk determination
- **Sediment**
  - impacts on spawning, etc.
  - size distribution
  - types
- **Streams**
  - differences in types
  - geohydraulic zones
  - location and expected inputs
  - orders
  - reading streams
  - responses
  - types
- **Watershed Factors**
  - geology
  - hillslope processes
  - landscape patterns
  - models (conceptual, etc.)
  - sizing

Note the similarities between this list and the components in Table 3 and its summary which were developed independently.

Comments and Questions Applicable to the AMC Classification System as Developed by the Workshop Participants

(1) The final, applied version must be useful for land managers and regulators.

(2) There needs to be a "good" (STRONG, RATIONAL) tie between forest actions and biological reactions.

(3) Forest managers need flexible criteria.

(4) Does the AMC want a big, comprehensive model for the entire T/F/W program? (Answer: as a long-range goal, it is possible, KS. Implement things that work, and combine later in a more comprehensive form).

(5) State matters as simply as possible.

(6) Resources must be available to develop and drive the system.

(7) Some information will be useful in some contexts, and not in others.

(8) Are simple models possible when dealing with such complex (physical) systems?

(9) Specialists can handle the more complicated parts of the "process" modeling if needed.

(10) How much detail is needed?
   (a) Rosgen: focus needs to be on:
      - combination of cumulative effects
      - modeling
      - changes in the ENERGY SUPPLY OF THE WATERSHED as a function of STREAM TYPE
      - responses to the changes (different and unique to each stream type)
      - detailed monitoring of the unique stream types to show changes in:
         - particle size distribution/substrate composition
         - velocity distributions
         - hydraulic geometry relationships
         - width to depth ratios
         - channel factors which affect fish (habitat)
      - persons collecting data need to develop a rigor to build the parametric data base.

(11) How much perfection is required in (of) the model(s)? Adaptive management calls for development, testing and refinement of the models over time (Somers). This will be closely tied to the "information system, or data base."

(12) How will the model(s) account for noise, natural variabilities real impacts (Lisle)?

(13) The highly variable natural conditions may be what we need to measure and understand (Beschta) (upper and lower boundaries of risk for managers--JFO).

(14) Regarding classification Dietrich commented:
- the fish may not need our classification system (but managers of fish will--JFO).
- biologists should provide a fish perspective to develop criteria of importance (to the fish).
- maps can provide only certain levels of information.
- site visitations are more expensive, but may be where the true answers lie.
- specialists should do specialists' work (and generalists should integrate the specialists' work--JFO)
- persons with reasonable levels of training and access to new research developments should be making the "primary observations" (followed by more routine observation procedures --JFO).

(15) Comments in response by Platts:
- you must deal with the real world.
- decision-making is an art.
- there is no "science" to it.
- science must be converted to art for the decision-maker or it (the method) fails (always).
- classification is a valuable tool.
- if classification is done right it will tell you:
  - where you are coming from,
  - where you are and,
  - where you are going--under different scenarios.
- these are the tools you need for the manager.
- a photographic history, coupled with what the law states, gives the manager an immediate picture of the objective and why. Then they are open to suggestions.

(16) Some people questioned the need for (value of) classification (Dietrich). Where is evidence about rivers which says we predicted this and this is what happened?

(17) (Platts' response) Time does not allow this luxury (of 25 years of data). Decision makers need to be brought along--now. 100% accuracy is not as important as being accurate 51% of the time--but even 51% is better than what we have.

(18) (Rosgen concurred) A gap exists between understanding of the physical processes and the decision-making process. Risk is involved when replacing the physical process with a set of criteria. Process knowledge must be converted to managerial decision-making information.

Page	Paragraph	Comments
16	Task 2(c)	Expand the "data base" through interagency cooperation, and regional modeling of basins, streamflow and channel geometry. See recommendations in front of report. Modeling will tell you when to stop measuring, better than will statistical methods.

The general plan for continuing the AMC program seems reasonable, but don't place all your trust in fish as a measure of effectiveness. The stream segment characteristics you can restore to some degree through management practices and habitat restoration. But, you have no control over all the other environmental factors which regulate anadromous fish life cycles. You can change only the potential habitat.

- Recent, low level, air photographs of all monitored basins should be part of the data base.

- In the AMC monitoring program, cognizance of other data bases, such as the PNW Environmental Database for Washington will be helpful. WDOW (Lea Knutson, NED Coordinator) is a participant. The subproject on Washington Rivers Information System may be especially useful to the AMC.

"No one believes a hypothesis except its originator, but everyone believes an experiment except the experimenter." (Source Unknown)

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(19) How accurate is the classification system going to be (how much confidence can be built into it)?

(20) How important are specifics such as riparian vegetation and soils? (and how they are managed as part of the stream system--JFO).

(21) If we can capture the variabilities in vegetation (in the description of the valley or watershed) then we can focus on a higher level of model (Curry).

(22) What is the minimum amount of information we need to capture variability and build INTERPRETIVE MODELS (Curry)?

(23) What are the benefits of classifying at the stream level? (Benda)
- need to understand the ecosystem level for fish as they move.
- need a sense of how the system (basin-wide) works.
- need an understanding of how disturbances (from roads for example) translate across the basin system.
- reinforced by Rosgen as the very reason for using stream segments within the watershed as the basic classification unit.

(24) We don't understand how the river basins west of the Cascades work (Benda).
- sediment (composition) changes over time in a transient watershed.
- based on the results of model building we may find the segment is "too tight."
- the segment may be the level to look at environmental change.
- we may need to scale up to a broader landscape level.
- classification can (be used to) do certain things, but it may not be useful for routing sediment.

(25) (Rosgen) Comments of some relations between classification systems, measured relationships, extrapolation and data availability.
- it is not necessary to have long periods of river watching.
- data can be extrapolated between and among streams of similar character.
- an amazing amount of data exists, but little is being used
- much of the data is based on physical processes and the effects of changes in supply for a particular stream type.

(26) The basin-wide approach to evaluating disturbances to streams (managed and unmanaged) was advocated (Benda).

(27) Detailed classification systems based on processes can be distilled into indexes, ratings, pictures and codes. Communication at the appropriate level is critical.

(28) Whatever classification system is used it must be applied to "the entire basin" (Platts). Until you integrate stream types you can't manage a fish population which requires the entire basin (the "entire basin" needs of the fish requires definition--JFO).

(29) Because the life histories of fish are tied to different stream types at different life stages, basin geomorphology may be the only way to effectively classify "the system." (Cederholm, Sullivan).

(30) Fish are complex (to humans) but fish do exactly what they are supposed to do (Platts).

(31) Classification is a valuable forecasting tool (Platts):
- it tells the managers about risk.
- it tells them which streams (types) will not recover in our lifetime.
- more chances can be taken if the risks are lower.
- classification has to predict tradeoffs.
- classification puts the risk on the shoulders of the managers.

(32) Which comes first, classification or sampling? (Platts' and Rosgen's responses):
- inventories provide ground truth for classification systems.
- you have to measure and account for ANOMALIES.
- field work provides specifics for types established in the office.
- local influences can be evaluated only in the field.

(33) Can classification schemes and models forecast the movement of sediment through a basin's streams?
- how can you describe the effects of a 30-acre clearcut on a third-order channel (Dietrich)?
- classification sets up the procedures for the model to route the sediment (Platts).
- classify the watershed.
  - □ determine sediment from each class of land.
  - □ transport model routes the sediment (doubted by Dietrich).

(34) Models will not answer all questions but will allow for better evaluation of the managerial alternatives (Platts).

(35) Rosgen's Stream Typing System:
- in describing the "setting" of a stream consider the soils, valley geometry, landforms, climate and the ratio of bankfull width to floodplain width.
- watersheds contain stream segments with different characteristics which are dependent on valley slope, confinement, soils, vegetation--the ecosystem.
- sometimes "restorations" require undoing, and a lot of time to analyze (what was originally in place before the restoration).
- vegetation is critical to the morphology and sediment transport capacity of many stream types.
- width is related to meander length and discharge and these relationships vary by stream type.
- you must evaluate the natural energy balance in a given <u>system</u> (?--JFO--which <u>system</u>?) so that the <u>system</u> (<u>segment</u>, reach?--JFO) is not knocked out of balance.

- the delineating criteria for stream (segment) classification are:
  - sinuosity
  - gradient
  - W:D ratio
  - bank and bed soils
  - landform
  - particle size (substrate)
- "segments" of streams for classification should be equal to 20-30 widths in length. Actual lengths of sample reaches should be based on professional judgment (and geological horizontal and vertical controls--JFO).
- vegetative conversions affect bank stability and groundwater utilization along the banks.
- the flatter the gradient, the more sensitive is the stream to changes in sediment load, responses in gradient changes and W:D ratio.
- meander (stream--JFO) patterns can be subdivided into about eight subtypes; meander patterns can be either free to deform or geologically controlled--JFO.
- know the land-use history of the watershed and the evolutional direction of the stream segment (what pattern is it tending towards?)
- channel geometry and flow are interrelated through hydraulic geometry and can be quantified. Stream order (an index, not a quantitative measure--JFO) does not relate to (stream channel) morphology, so that is why bankfull width was selected as a size parameter (in Rosgen's method).

(36) Benda interpreted that Rosgen's philosophy implies keeping streams in their present condition:
- the underlying philosophy is that stability is good;
- ecologically the streams may not want to be stable;
- are we trying to homogenize the landscape by not wanting sedimentation and erosion because they are messy and look bad?
- perhaps (in certain situations) erosion might be the key to extreme variability (and habitat diversity--JFO).
- you might want to assess what variability means (to energy dissipation, habitat and stability--JFO), and what regulates the variability, natural flow, soil and vegetation conditions, or watershed and riparian artificial (man-made) impacts.

(37) Rosgen's responses:
- we are not seeking homogeneity.
- we are dealing with acceleration (in rates of erosion or sedimentation and resulting channel changes--JFO).
- our goal is to warn managers about the risk (associated with channel instabilities--JFO).

(38) The basis of measurement is whether the "practices" are affecting the fish population (Light):
- we want to maintain productivitiy.
- populations take nosedives on their own.
- we should try to prevent impacts which increase the frequency of nosedives.

(39) Niche diversity is critical (Platts):
- some streams will never come back to support fisheries (at the same level) after being logged.
- niche diversity has been lost.
- a large storm (3000-5000 year frequency) is needed to restore niche diversity.
- coastal streams with good P:R ratios are now going intermittent in the summer (because they are overloaded with cobble-gravel sediment--Cederholm).
- summer rearing areas are gone.

Many of these workshop comments, opinions, experiences and obervations have been discussed, expanded and incorporated into the body of this report.

APPENDIX IX.--COMMENTS ON DEVELOPMENT OF THE MONITORING PROGRAM

APPENDIX IX. COMMENTS ON DEVELOPMENT OF THE MONITORING PROGRAM

There has been regular contact and interaction between the Monitoring Program Coordinator and the Principal Investigator on this project even prior to its initiation in the spring of 1989. Discussions of field procedures, handbook contents, data management and all other aspects of the project were held. Drafts of handbooks, planning documents, memoranda and reports were reviewed, and feedback was provided.

The monitoring program must be the focal point of all other AMC tasks, because it will be the proving (or disproving) ground for the entire effort. Resources should be sufficient to establish a data base which can be integrated with other data bases, and with models from this project and other projects, so that the monitoring project can be accelerated. Delays, or a lack of adequate support for the monitoring project, will only delay the development of adequate decision tools for land managers, resulting in additional losses of land, timber, water, wildlife and fisheries resources.

The balance of these remarks are keyed to the recent AMSC planning document for the stream survey project.[1]

Page	Paragraph	Comments
1	4	The AMSC Extensive Stream Survey Project cooperator component may be able to provide examples for, and assistance to, the new state water planning program (DOE).
3	Fig. 2	The components of the basin, streamflow and channel classification aspects of this project could be superimposed on this type of a diagram.
4	Fig. 3	Are there objectives for element B? Are they the same as for A?
6	2	In all aspects of the program "factors" should be defined as to whether or not they are independent or dependent variables (inputs or outputs, respectively). For example, with respect to a stream segment, the factors listed are not all INPUT

[1]AMSC. 1990. Extensive Stream Survey Project Study Plan. Washington State Timber, Fish and Wildlife Program, June 26.

Page	Paragraph	Comments
		factors (independent variables)--the bed material is dependent. LOD is tied to channel type and size (e.g., bedrock channels maintain little if any LOD; LOD has less influence as the channel W/D increases and sinuosity (free or controlled by bedrock outcrops) decreases. Vegetation is dependent on elevation, soils, slope and precipitation, which is also elevation dependent.
6	4	Hypothesis 1: true, as long as the stream boundaries are deformable over the time period of our short records (not bedrock).
7	Table	Last flow item: Peak flows are not as important to sediment transport and channel changes as are 1-, 3- or 7-day average floods; long-term mean floods move more materials; abrupt flow changes (extreme floods) cause more dramatic changes.
7	1 (after table)	You may not need to measure all the inputs, but you better estimate the hydrologic regime at the monitoring sites, and correlate your limited streamflow records with a long-term gage. Are you going to "confirm" or "test" your beliefs?
7	2	Valley conditions do help define channel features, but the inputs come primarily from the upstream basin. Valley and channel variations are due to local geologic controls, vertical and horizontal, which govern gradient, and in turn stream power, etc. The local variables in a channel include:

valley slope	bank material
channel slope	bank vegetation
discharge	width:depth ratio
meander wave length	mean depth
sinuosity	velocity
meander width	friction
channel width	sediment rate
power/length	bedform
power/flow area	LOD

If changes in input (P or Q) are not monitored (even if only at other undisturbed sites) how will you know whether the change was due to natural and artificial causes? There should be at least one regional precipitation monitoring gage.

Page	Paragraph	Comments
7	(-)	Hypothesis 2: Are you assuming the same load is applied to different segments? Are you quantifying your extrapolations?
8	1	What is being reduced in natural variability? Is it being reduced or explained, or quantified or ... ?
8	2	The differences across the state are primarily due to the differences in the hydrologic regimes and the geology of the basins and channels.
8	(-)	Hypothesis 3: consider which of these factors are fixed, which are transients, which regulate others and how all will be "measured" (directly or indirectly)?
8	3	You need to consider the "states of nature" (S), their probabilities of occurrence (p), a set of alternative (A) conditions on the basins (mixes of land management practices) and build these into a management decision "value" matrix as sketched below. Choices will be governed by decision strategies such as maximizing benefits or minimizing impacts.

	POSSIBLE STATES OF NATURE			
MANAGEMENT ALTERNATIVES	S_1	S_2	S_3	S_4
1				
2				
3				
4				
Probabilities of States	p_1	p_2	p_3	p_4
Altered Probabilities	p_{11}	p_{22}	p_{33}	p_{44}

Page	Paragraph	Comments
		Depending on the management alternatives, the probability of the natural states might change (e.g., a 50-year flood [pl = 0.02] might become a 2-year flood [p = 0.50]), and have a 50% chance of occurring in any year instead of a 2% chance without the management change.
		This type of a decision matrix can be applied also to the monitoring sites in terms of either their natural or altered conditions. The decision matrix could be a focal point for many aspects of data acquisition, prediction models, or stream responses and they would lead to a management decision matrices.
		When dealing with so many overlapping and interdependent factors (like a Venn diagram), organizing the factors into probabilistic matrices will structure the decision-making process, and conclusions about resource status.
10	(-)	Hypothesis 4. Do the obstructions block flow and/or fish passage? What is the emphasis for obstructions?
10	1	In steep channels with large bed materials, and depending on the hydrologic regime and the stability of the sediment source, you may see no reduction in channel width. This will be a function of channel/valley type. Downstream, flatter (3rd-5th order) streams will show more immediate responses than steeper 1st- and 2nd-order streams.
11	3	(1) Particle size--see Shirazi and Seim (1979) for evaluating incubation success as a function of modified grain diameter (page 118 in preliminary draft report for this project, July 1989).
11	4	Surely not all the variables and methods are subject to revision (makes one nervous if this is true).
12	4	How will changes in watershed land use be evaluated in terms of watershed characteristics? For example, installing streets (or storm sewers) can be thought of as increasing the runoff coefficient and the drainage density. Watersheds can be typed based on their relationships among basin, streamflow and channel characteristics.