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THE INTEGRATION OF BASIN, STREAMFLOW AND CHANNEL CHARACTERISTICS FOR CHANNEL CONDITION ANALYSES

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A Note to the Readers of this Report

If you are a person who is interested in the basic concepts and the results of this study, but not the development of equations, we suggest that you bypass Part 3-Methods of Analysis from pages 3-1 through 3-70. The Summary of Part 3 is on pages 3-71 through 3-74, and should be read to fit with the rest of the report.

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1. INTRODUCTION

Problem Definition

With the recent listings of chinook salmon, bull trout, and other salmonids under the Endangered Species Act, the quality of streams and fish habitat has become a primary concern in the Pacific Northwest. In an effort to increase the survival of these listed salmonids, resource managers have accelerated extensive (and often expensive) programs to restore aquatic habitat degraded by various land use activities. Often these efforts take place without benefit of a template of stream channel conditions to target conditions the restoration plans attempt to emulate. Natural resource management agencies and regulators need some reliable means to evaluate the status and trends in the physical condition of stream channels and associated aquatic habitats. Given the dynamic nature of channel form, it can be difficult to distinguish natural variability in watershed processes from those changes associated with human activities. The purpose of this project was to evaluate the concept of "regional indices of channel morphology" for typical stream types found in Washington, and to determine if they can provide a useful diagnostic and predictive tool to help evaluate existing and potential channel characteristics.

The negative influence of various land use activities on the hydrology and geomorphology of streams have been extensively investigated and documented (Hammer, 1972; Leopold, 1973; Arnold et al, 1982; Booth, 1990). The transition of a watershed from a natural to an altered state includes removing vegetation, compacting soils, creating impervious surfaces, and altering natural drainage networks. These actions change fundamental watershed processes that control the rates and distribution of surface water runoff and sediment budgets. An early Northwest example of these detrimental conditions was the study completed on Big Beef Creek by Madej (1978). She was able to show how logging, impoundment and development changed the channel geometry, increased the sediment load, and contributed to the decline of the coho population of Big Beef Creek. This thesis is summarized as one of the case studies in Part 4.

When conducting stream studies of habitat assessment and other water resource investigations, it is desirable to determine the condition of the stream and the watershed factors controlling the characteristics of the stream. For example:

- Is the stream in a natural, stable condition (i.e. an appropriate geomorphic state, as best as we can define that state);
- If the stream is in an "unnatural" condition, how far removed is it from its natural condition; and

- What is the potential for returning the stream to its "natural" condition?

But what is natural? How can we "fix" (***determine the essential elements of***) a stream channel and fish habitat if we don't know what is broken? If a stream is "broken" (***disrupted by change***), what should it look like?

The objectives of this report are to:

1. discuss methods for measuring and assessing the condition (i.e. naturalness) of a stream reach;
2. summarize a systematic method for characterizing the existing state of a stream reach; and
3. provide examples of procedures and models for determining stream condition in terms of basin, channel characteristics and flow.

Channel Condition Studies

Channel condition studies, when coupled with stream hydrology, lead to the following applications: the design of bridges and culverts; channel capacities; flood plain inundation; instream flow analysis and usability of habitat; habitat modification; upstream fish passage during migration seasons; temperature effects; availability of rearing habitat in pools and side channels; diversions; flow reservations; water availability studies, habitat productivity; and water supply analysis .

Fundamentals

Part 2 of this report covers the following topics and forms the analytical basis of the study: the state of our current knowledge about stream width adjustment; an overview of basin, streamflow and channel characteristics; dimensional analyses of the basins and channels; channel hydraulic geometry; the influences of flow reductions on channel characteristics; regional relationships between basin and channel characteristics; and accounting for changes in channel geometry. We conclude Part 2 with recommended steps for utilizing channel indices as tools for protection and recovery of stream habitats.

Definitions

The term "state" is synonymous with "condition" and deals with existing conditions. The existing physical condition of a stream reach is compared to a baseline or reference set of conditions in other natural stream reaches. The compared conditions would include: flow regime and reach slope, which dictate channel pattern and hydraulic geometry. Taken together these measures define the site conditions in three dimensions, and show the results of the dynamic forces involved.

In order to communicate and visualize stream conditions, a form of classification is helpful. We have chosen to use the illustrations in Rosgen (1996) as that visualization tool. Although there are some analytical shortcomings in Rosgen design procedures, the classification system is very useful (Miller and Ritter 1996).

Mackin (1948) introduced the concept of the "graded stream" in which there is a long-term balance between erosion and deposition. More specifically: "A graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and the prevailing channel characteristics, just the velocity required for transportation of all of the load supplied from above".

Burkham (1981) looked at the uncertainties associated with changes in stream channel form and quoted Blench's (1957) "in-regime" theory :

> "...that average values of the quantities we appreciate as constituting regime do not show a definite trend over some interval---usually of the order of a score [*twenty*] or two of years . . . [*rivers in regime*] demonstrate themselves to us in the form of varying discharges, breadths, depths, velocities, meander patterns, sediment contents, and so forth, but their average behavior does not usually change greatly over small periods of historic time."

Note that Blench's use of "average" behavior is very similar to Mackin's definition of a graded stream. But, it seems that Mackin's emphasis that the slope is "delicately adjusted" by the flow regime is the most revealing component of both concepts, because slope represents the rate of expenditure of potential energy.

We are going to use dimensionless ratios in our analysis. The ratios of forces are referred to in fluid mechanics as dimensionless numbers. For example the Froude number is the ratio of inertia to gravity forces, or the ratio of the resistance to change to the gravity forces (change), or the ratio of the flow velocity to the velocity of a gravity (surface) wave in a channel. It is written as

$$N_F\,(\text{Chan}) = V/\,(gD)^{0.50} \qquad (1\text{-}1)$$

where V is the mean velocity, g is the acceleration due to gravity, and D is the mean depth of flow. All terms are in a consistent system of units. An important geomorphic use of the Froude number was developed for watersheds by Strahler (1958) where the relief, H, is used in place of the channel mean depth, D. The Froude number of the watershed is:

$$N_F \text{ (Shed)} = V / (gH)^{0.50} \tag{1-2}$$

This dimensionless ratio of forces will be used with Eq. (1-1) to relate basin to channel characteristics in Part 2 - Fundamentals.

In streams, and in all "open channel" flow conditions (the water surface is open to the atmosphere), the Froude number is used to design physical hydraulic models. For design conditions, such as bankfull flow, the Froude number in the model is made equal to the Froude number in the prototype, or

$$N_F \text{ Model} = N_F \text{ Prototype} \tag{1-3}$$

Streams in nature operate in the same manner as physical stream models, wherein little streams mimic big streams. As long as we use the appropriate dimensionless ratios, we can avoid scale effects when combining channel and basin characteristics, and in relating one stream to another.

One dimensionless ratio commonly used in habitat work is W/D, or the water surface width of the channel (W) divided by the mean hydraulic depth (D). The depth (D) is calculated by $D = A_c/W$, where A_c is the channel cross-sectional area at that flow. But, this in essence reduces all channels to equivalent rectangular shapes. It might be more descriptive to write W/D as

$$W/D = W/\left[D\left(D_{max}/D\right)\right], \quad \text{or} \quad W/D_{max} \tag{1-4}$$

Using D_{max} incorporates the shape of the channel. For example: for rectangular channels, $D = D_{max}$; and for triangular channels, $D_{max} = 2D$ or $D = 0.5\ D_{max}$. Also, triangular channel cross sections (such as those in bends), usually have a constant W/D over a range of flows. If W/D_{max} is used, a triangular section with the same flow area as the rectangular section, will have a W/D max that is half of the W/D for the rectangular section. Therefore the triangular cross-section provides greater depth habitat at reduced flows.

Methods of Analysis

To extend the fundamental relationships developed in Part 2, three regional stream channel databases have been selected in Washington State for comparison in Part 3: (1) the Olympic Peninsula; (2) some of the lowland streams north and east of Seattle; and (3) the mixed mountainous and agricultural region of Northeast Washington located east of the Columbia River, and north of Grand Coulee dam.

The Olympic Peninsula stream gage locations include basins having a diverse mixture of geology, with streams flowing through valleys ranging from bedrock, through boulders to sandy gravels. The lowland streams east of Puget Sound are less diverse in character than the Olympic streams and are experiencing urbanization to varying degrees. The northeast Washington streams included in the analysis have experienced diversions for irrigation and logging impacts, as have the other two regions. Precipitation varies on the basins used in the three regions from 40-200 in/yr on the Olympic Peninsula, to 37-66 in/yr in the Puget Lowlands, and to 18-30 in/yr in northeastern Washington.

In this paper, we do not attempt to account for land-use effects on stream channels in a detailed cause and effect manner for such a broad range of conditions. Rather, our objective is to determine **IF** relationships exist among channel, streamflow and basin characteristics, and **IF** those relationships can be of assistance in the investigation of those streams, for whatever purpose.

Applications- Case Studies

Examining channel characteristics on a regional basis should provide a means whereby a problem (such as degraded fish habitat) can be more effectively defined, and solutions designed and monitored. The smaller the region, and the more uniform the climate and geology, the better will be the analysis. The methods of analysis developed in Part 2 or 3 will be demonstrated in Part 4 to examine four case studies of habitat improvement on the Olympic Peninsula, restoration of a gold-dredged stream in Idaho, documentation of increased sediment load effects on a Kitsap Peninsula stream and the effects of dams and diversions on fish habitat and channel geometry in a North Olympic stream.

Summary and Conclusions

The results of the analyses as applied to the case studies are summarized, and compared with the project objectives. There will be no panaceas, but there should be a better understanding of the relationships between basins and their stream channels. The basins generate the channels that we have an affinity to degrade, and aggrade, in response to our development activities on a watershed, or in response to local, so-called channel "improvements".

As researchers, planners, designers and managers, we work on stream problems as if they were something new. These are definitely not new problems, but the problem-solvers are new, and some tend to reinvent the wheel. The fundamentals of problem definition tend to be set aside in favor of talking about solutions, issues and stakeholders. **These latter emphases are important, but there is nothing like good data and the application of fundamental principles to assist in problem definition and the comparison of alternatives.**

By focusing on apparent solutions before conducting a thorough and thoughtful analysis of the problem, we are doomed to treat the symptoms, and not the actual causes of the problem. Linking the problem analysis with an understanding of the fundamental watershed processes that control channel form is key to project success. In terms of restoring instream habitats that are critical for the recovery of native salmonids, one must also understand (or at least appreciate) and anticipate the functional relationship of channel condition to life history requirements.

A note about the method of allometric analysis:

> "(it is the) development of simple or multiple power-function equations that express the relative rates of change among the variables of a system. A principal geomorphic utility of the method is to show adjustment between two variables" (Osterkamp 1979).

These power relationships are used throughout this report. Allometric analysis is used to relate one variable in a fluvial-geomorphic system to another variable in that system.

We hope that the methods and examples described in this report will be of assistance to those persons engaged in stream projects, whatever their professional position.

> *"Today natural diversity still baffles us. Even the simplest natural communities escape our comprehension. We abstract and simplify them intellectually with energy flow charts or systems diagrams. When we understand the pictures and formulae, we delude ourselves into believing we understand reality." (Dasman 1973)*

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2. FUNDAMENTALS

One of our project objectives was to examine the feasibility of estimating channel top width and other channel characteristics from basin characteristics such as drainage area. This could be done empirically, but without doing a thorough analysis of the physical relationships between basin, streamflow and channel characteristics, the foundation and linkages would be missing.

State of Our Current Knowledge about Width Adjustment

A Task Committee (TC) of the American Society of Civil Engineers prepared the most comprehensive report on river width adjustment to date (ASCE 1998). In Part I the TC covered processes and mechanisms and in Part II the TC discussed modeling. The objectives of the TC efforts were to:

- "Review the current understanding of the fluvial processes and bank mechanics involved in river width adjustment
- Evaluate methods (including regime analysis, extremal hypothesis and rational, mechanistic approaches) for predicting equilibrium river width
- Assess our present capability to quantify and model width adjustment
- Identify current needs to advance both state-of-the-art research and the solution of real world problems faced by practicing engineers". ASCE (1998).

The ASCE/TC reports covered the following topics:

- geomorphic context of river width adjustment;
- the regime theory and the power law approach (including hydraulic geometry by Leopold and Maddock 1953);
- the extremal hypothesis approach which uses sediment transport and friction combined with stream power (or energy dissipation) to determine channel width;
- tractive force methods to obtain the geometry of stable channels;
- the near-bank fluvial processes and their interactions with bank materials;
- the formation of the cross-sectional channel shape;
- longitudinal changes in channel cross sections; and

- linking fluvial processes to channel-width adjustments through velocity, boundary shear stress, secondary flows and turbulence structure.

Under the heading of bank mechanics the TC addressed: bank erosion; reduced resistance to erosion; mass failure and bank stability; basal endpoint control; vegetative effects; seepage effects; and the advance of banks. The conclusion and recommendations of Part I - Processes and Mechanisms, are closely related, especially the conclusion that civil engineers be aware of the geomorphic aspects of width adjustment. Likewise, the first recommendation proposed that **stream reconnaissance procedures should be developed that emphasize the geomorphic context of width adjustments.** It is interesting to note that none of the work by Rosgen (1994) was cited in the two TC reports.

Part 2 of the ASCE/TC report covered modeling and included:

RAPID ASSESSMENT TECHNIQUES: Empirical Models of Channel Evolution; Channel Stability Diagram;

NUMERICAL WIDTH-ADJUSTMENT MODELS: Hydraulics and Hydrodynamics (including summaries of 12 models); Sediment Transport and Continuity: sediment (sand and gravel) is routed using the 12 models;

RIVER BANK MECHANICS: The types of bank processes and bank materials are accounted for in the 12 models. **None of the models accounts for the influences of riparian vegetation.**

TESTING AND APPLICATIONS: Tests with laboratory data; and field testing.

Procedure for Approaching Width-Adjustment

An eight-step procedure was outlined by the Task Committee:

1. Problem identification;
2. Reconnaissance and data collection;
3. Desk assessment of equilibrium conditions;
4. Application of empirical channel response or dynamic models;
5. Application of numerical models (if warranted);
6. Validate the model results against field data (if available);
7. Numerical models should be applied to existing conditions and to assess any known or anticipated future impacts; and
8. Selection of a solution (river management).

Considering these two comprehensive ASCE articles as a point of departure for our more general EPA study on "Channel Condition", there are some useful observations to be made:

1. although the ASCE/TC reports on width adjustment deal mainly with mechanics and mathematical models, the TC concluded that they can only make "tentative predictions of width adjustment,"
2. our empirical and fundamental models, derived from dimensional analysis of basin, flow and channel characteristics, can be expected to demonstrate both low and high degrees of variability in their predictive capabilities due to natural and data anomalies;
3. there is a lack of sufficient laboratory and field data for testing the TC width adjustment models (these models are data-intensive);
4. our simpler models based on parameters such as the expected width, depth, velocity, flow area and wetted perimeter, are less data-intensive and are gathered on a regular basis; and
5. we will be representing the "geofluvial" approach as described by the Task Committee (ASCE 1998) because of the analogous parameters considered in our basin, flow and channel models.

The eight-step procedure on page 2-2 for approaching channel width adjustment is not a new approach to problem solution, but it is sound, especially if Step 1 **includes problem definition.**

Overview of Basin, Streamflow and Channel Characteristic Models

The fundamental models have been organized along the lines of work done on the Colville Indian Reservation (Orsborn and Orsborn, 1997). The models were developed by relating drainage basin, streamflow and channel characteristics to each other and to themselves. The basin and channel characteristics are linked physically by streamflow. Changes on the basin cause changes in streamflow and responsive changes in channel characteristics. Streamflow data can be highly variable in a region due to priorities for gaging programs by resource agencies, natural variability in precipitation, geology, soils, elevation and uncommon periods of record. Superimposed on natural variability are changes in land use which cause changes in streamflow, debris and sediment loads, and thus channel geometry. Also, local impacts due to streamside road building, changes in riparian vegetation and cattle grazing will cause direct changes in the stream channel without any upstream changes in land use. Diversions and storage also exert influences on streamflow, and thus channel characteristics.

Natural variability causes wide swings in precipitation over a climatic-geographic region. Add to this natural variability the influences of diversions, storage, channel changes and measurement accuracy, and we are forced to model "average-condition" relationships, and their variability. Sometimes we have to remove data from the models for certain gaging stations due to their unusual influence on the models caused by geologic anomalies, or biases in the periods of record. Usually some of the station data are left out of models to test their accuracy. Actually, the variability of the model data points gives a good idea of how reliable the models are.

Building the models involves the measurement and use of basin, streamflow and channel characteristics (BC, QC and CC). The basic relationship says that one characteristic is related to (is a function of (f), or is dependent upon, or is related to) another set of characteristics. For example we know that basin area, A_b, catches precipitation and explains 80-90% of the variability in a large number of streamflow (QC) models. As an example of the logic:

- Flow characteristics are related to basin characteristics
- Q (Any flow, say Max, Peak Flood) = f(Basin Area, A_b)
- QC (characteristic flow) = f(BC, Basin characteristics)
- QPF Max = C $(A_b)^n$ (Power Equation) (one application)
- Dependent flow = f (Independent basin area), which in turn is a function of the maximum, basin-wide precipitation within the flow period of record.

Characteristic flows can be low, average or flood flows, extreme flows or monthly flows. This simple starting point does not cover all cases, of course. In the following diagram (matrix, Figure 2-1) one reads up along the vertical scale (1, 2 or 3) to select a dependent characteristic and then horizontally across a line to select an independent characteristic (1, 2 or 3) to relate to the dependent characteristic. A few of the possible combinations are listed in Table 2-1.

Figure 2-1. Matrix of Models of Combinations of Basin, Streamflow and Channel Characteristics (Orsborn and Orsborn 1997). BC = Basin Characteristics, QC = Flow Characteristics and CC = Channel Characteristics

	(3) CC	**3:1**	**3:2**	**3:3**
Dependent Variables	**(2) QC**	**2:1**	**2:2**	**2:3**
	(1) BC	**1:1**	**(na)**	**(na)**
	ORIGIN	**BC** (1)	**QC** (2)	**CC** (3)

Independent Variables

Table 2-1. Combinations of Basin, Streamflow and Channel Characteristics In Hydrologic and Hydraulic Geometry Models (REFER TO FIGURE 2-1) (Orsborn and Orsborn 1997).

Combination Numbers	Notes and Examples of Models Developed for CCT Study
(Start at lower left in Figure 2-1 and go up)	
1:1	Basin Characteristics (BC) related to BC. **Example**: Stream Length (LS) related to Basin Area (A_b): $LS = 1.2(A_b)^{1.0}$
2:1	Flow Characteristics (QC) related to BC. **Example**: Average Annual Flow (QAA), $QAA = 0.0025\ (P)^{1.64}\ A_b$, where P = Average Annual Precipitation, in/yr.
3:1	Channel Characteristics (CC) related to BC. **Example**: Water Surface Top Width, W, at a characteristic flow such as QAA, related to basin area (A_b): $W = C(A_b)^n$; $C = f(Q, \text{Chan. Type})$ **Regional Model**
(Move to bottom of center column and go up, Figure 2-1).	
1:2	(na) BC: QC; logically not physically correct for basin characteristics to be a function of (dependent on) flow characteristics. The inverse equations are covered by 2:1 above.
2:2	Flow to flow, QC: QC: models can be built either by : (1) Correlating the same types of flows at two sites such as peak flows; or by (2) using ratios of various statistical flows to the average annual flow such as: Q7L2/QAA, QPF2/QAA, etc. at long-term gages in a region.*
3:2	CC related to QC, **Channel to Flow Characteristics, the basis of Channel Hydraulic Geometry**; one of the models used to check channel geometry over time using changes in W, D, V Ac and P related to Q; regional models for common flows such as QAA.
(Move to bottom of last column on right and read up, Figure 2-1).	
1:3	(na) BC:CC, like 1:2 not physically logical because basin characteristics are not dependent on channel characteristics; conditions covered in 3:1, CC: BC.
2:3	Flow related to Channel Characteristics, QC = f (CC); this is hydraulic analysis of flow down a channel, $Q = A_c V$ where; A_c = cross-sectional flow area; V is the mean velocity over the flow area, A_c. This equation, Q = AV, is the standard basis for stream gaging and hydraulic geometry; when the energy equation is used with Q = AV at several cross-sections the water surface profile in a stream can be calculated for individual flows.
3:3	CC : CC, Channel to channel characteristics; W/D, channel shape factor used in fish habitat; W/D versus P^2 / A_c, where P is the wetted perimeter (contact length of water with the bed of the stream at a cross-section of the channel).

*Note: Q7L2 = 7-day average Low Flow, 2-yr. Recurrence Interval (RI)
QPF2 = Flow (Q), Peak (P), Flood (F), 2-yr RI
QAA = Flow (Q), average annual (long-term)

In 1970 the U. S. Geological Survey completed a nationally oriented study of determining streamflow characteristics from drainage-basin characteristics (Thomas and Benson 1970). The subtitle read, "A study of relations for estimating streamflow characteristics from drainage-basin characteristics in four hydrologically differing regions of the conterminous United States." The study included drainage basins in the: East (Potomac River), Central (subbasins of the Missouri River in Kansas, Nebraska, and Missouri); South (in Louisiana, Arkansas and Mississippi); and West (the Sacramento and San Joaquin River basins in the central valley of California).

The authors tried to select "virtually natural streamflow" for analysis. Because they used a multiple regression analysis they chose to use the longest periods of record rather than use a common base period. It is interesting to note the number of records and their length available in each region: East (41 of 18 years or more); Central (41 of 12-61 years); South (42 of 15-29 years and West (44 of 16 or more years). This thorough study used 71 streamflow indices and their statistical characteristics (e.g. standard deviation), and tested them against 30 meterologic and topographic characteristics of the basins, because they "control the amount of streamflow from the basin and the distribution of this flow in time" (Thomas and Benson 1970).

This report became the bible of USGS personnel who used it to evaluate the gaging station programs in the States. Although the basin characteristics were selected on the basis of hydrologic knowledge, their retention was primarily statistical. Basin area was the most common parameter in all regions to be found significantly related to all characteristic streamflows.

It is interesting to note some of the conclusions from this study:

1. "The interrelationships between the basin indices along with the inability to describe completely a drainage basin, ***makes tenuous any assertions about the physical effects of the basin characteristics on runoff;***
2. despite the inability of the relations to describe the fundamental causes of streamflow variation, ***the basin indices significant in the relations are numerical measures that are related to the flow variations;*** and
3. ***low-flow relations are unreliable in all study regions; they can provide only rough estimates of low-flow characteristics at ungaged sites."*** (Thomas and Benson 1970).

Perhaps part of the problem is that some of the basin characteristics selected for analysis are not physically compatible with the purpose for which they were chosen, and/or they have unknown interdependence with other characteristics. For example, "the index of forest cover (F) used in this analysis is the percentage of total drainable area shown as forested on the topographic maps." The maps were updated only once or twice in 15-20 years, and logging was changing the forested area much more rapidly than that in many basins. Mean basin elevation was selected to account for variations in precipitation, temperature, wind, vegetation and ruggedness. But, these factors are not physically true, because mean basin elevation (E) says that the outlet of the basin is at mean sea level. This is true for only those basins, which empty into the sea. Physically, the relief of the basin accounts for all the energy available to cause both surface and ground water to flow from the basin.

Dimensional Analysis of the Basin, Flow and Channel Characteristics

Analysis of the Basin

This analysis has been provided by Strahler (1958), who opened his article stating that geomorphic studies can be founded on sound geometrical and mechanical bases using dimensional analysis. Dimensional analysis is based on the dimensions in Newton's second law: $F = Ma = ML/T^2$, or the dimensions of force, mass, length and time. Details of dimensional analysis, dimensionless numbers and the Buckingham Pi theorem are available in many textbooks (Rouse, 1938).

Strahler's analysis focused primarily on drainage density (drainage length divided by basin area), and a ruggedness number (relief, H, times drainage density, D). He also considered the Reynolds Number of the basin, (the ratio of inertia to viscous forces), and the Froude Number of the basin Q^2/gH (the ratio of inertia to gravity forces). Relief (H) is used as the characteristic dimension, much like the Froude Number for open channel flow uses depth, D. The Q^2 term represents the **Froude Number squared, not the true Froude Number**.

Strahler used Q as a volume rate of flow per square foot of channel cross-section, which reduces to a velocity term (L/T). Also, Strahler considered relief (H) to be the maximum in the basin. If one uses the difference in elevation between the basin outlet and the highest contour within the basin, a much more consistent value of H results (Orsborn 1976). The acceleration due to gravity, g, is considered to be constant, and when regional models are built, g becomes a part of the coefficients.

The Froude Number of the basin offers us the best of Strahler's relationships for estimating streamflow in terms of basin characteristics.

Rewriting the Strahler basin Froude Number: $Q1/(gH)^{0.5}$ (2-1)

where: Q1 is the discharge generated from a watershed flowing through one square foot of river channel cross-section; a "unit" discharge with the dimensions of $L^3/T/L^2$ or L/T, a velocity term like V = Q/A; g is the acceleration due to gravity (32.2 ft/sec^2, L/T ^{2}); and H is the basin relief in feet (L).

For this ratio of inertia to gravity forces we have L/T on the top and bottom of Eq. (2-1), giving the dimensionless Froude Number.

Now, if we assume that the "unit" discharge in Eq. (2-1) comes from each square mile of watershed area, instead of flowing through each square foot of channel, and we multiply both top and bottom by A_b, we have not changed conditions, and

$$(Q1 / (gH)^{0.50})(A_b / A_b) = Q2 / ((gH)^{0.50} A_b) \tag{2-2}$$

We can also rearrange Eq. (2-2) and use Q(x) to denote any statistical flow of interest:

$$Q(x) = C (g)^{0.50} A_b (H)^{0.50} \tag{2-3}$$

where C is part of a total coefficient and (x) denotes some characteristic flood, average or low flow which must be regionally calibrated from USGS gage records. Combining the first coefficient, C and the $(g)^{0..50}$ gives C′ in

$$Q(x) = C' A_b (H)^{0.50} \tag{2-4}$$

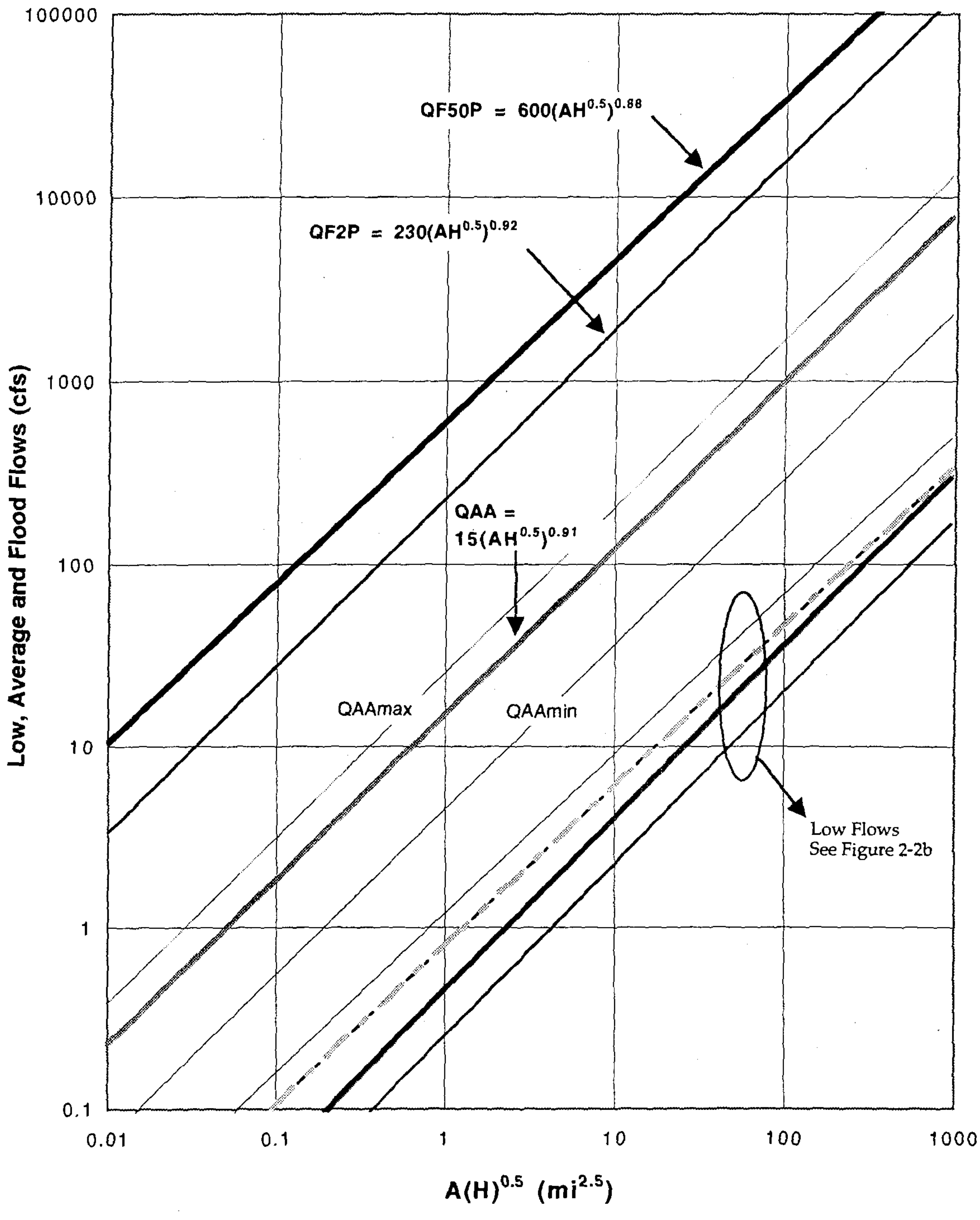
which is the form of the equation used to develop the relations in Figures 2-2a and 2-2b. These are the basic regional equations developed from Eq. 2-4 for characteristic low, average, and flood flows for the Siuslaw National Forest in the mid- and north-coast regions of Oregon (Orsborn 1981). The basins range in size from 0.3 to 667 sq. mi. and the relief ranges from 400 ft. to 2,400 ft.

In Figure 2-2, the graphs from top to bottom display, as a function of the "basin energy" terms A $(H)^{0.50}$:

- the 50-year, peak flood;
- the 2-year, peak flood;
- the range of maximum and minimum average annual flow that has occurred at gages in the region (range is $\pm$ 70% of QAA);
- the average annual flow (QAA); and
- the 7-day average low flows with 2- and 20-year recurrence intervals for the different groups of basins; the low flows become less the farther south their basins lie in the mid-coast region.

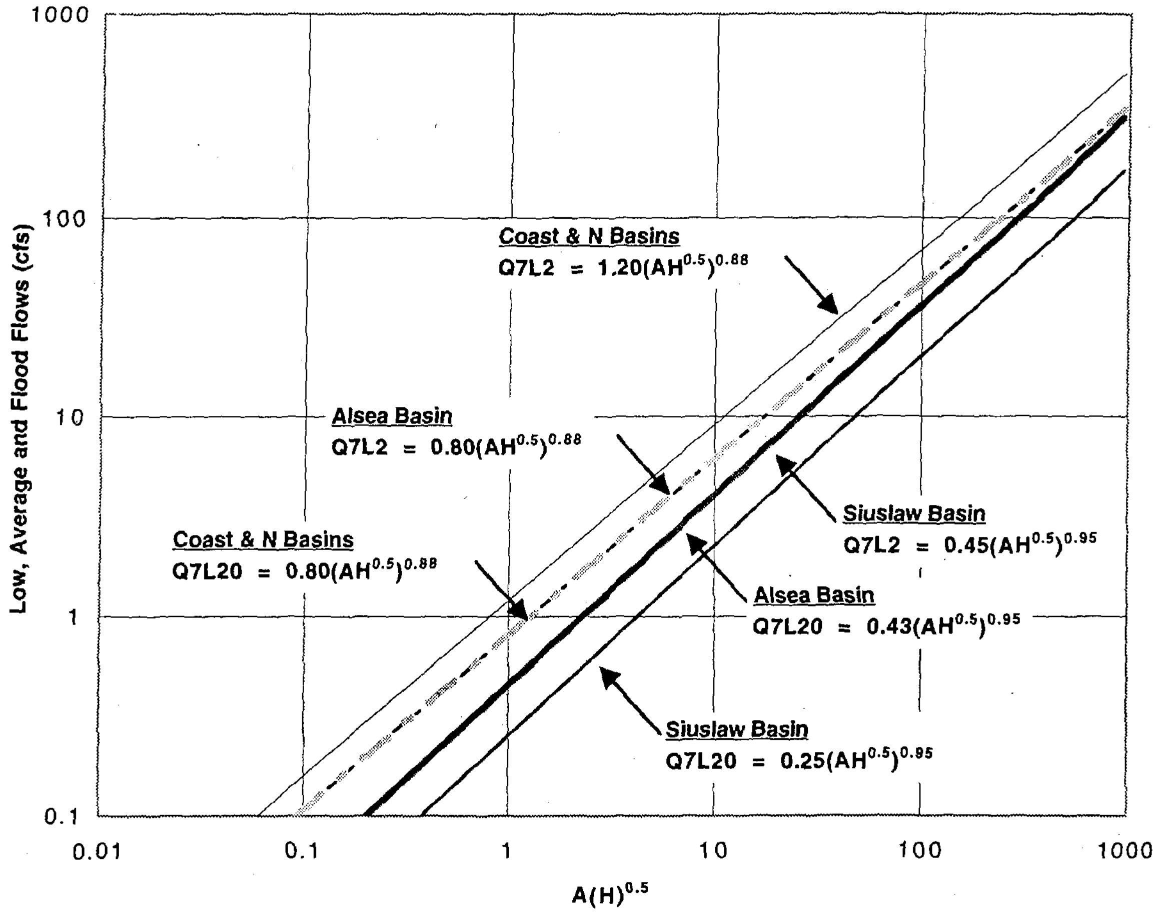
The original Figure 2-2 was drawn on 6 by 5-cycle log-log graph paper, and when reduced, the lines, data points, stream names, gage numbers and notes

Figure 2-2a. Siuslaw National Forest Basin Energy Models (Orsborn 1981)



Note: QAAmax = 1.7(QAA) and QAAmin = 0.3(QAA)

Figure 2-2b. Detail of Low Flows for Siuslaw National Forest Basin Energy Models (Orsborn 1981)



became too crowded to show clearly (Orsborn, 1981). Therefore, only the graphs have been shown for the characteristic flood, average and low flows.

It has been demonstrated that the same average relationships (coefficients and exponents) apply equally well to the coastal regions in Alaska and Washington (Orsborn 1983; Amerman and Orsborn 1987). In 1971, Yang related the potential energy to stream morphology through two laws governing stream systems: (1) the "ratio of average fall between any two different order streams in the same river basin is unity"; and (2) "a natural stream chooses its course of flow in such a manner that the rate of potential energy expenditure is a minimum" (Yang 1971). Using Horton's (1945) laws of stream order, average stream length and average stream slope, Yang was able to calculate longitudinal stream profiles. They agreed with observed data quite well, and define the average rate of energy expenditure of watersheds (H).

Analysis of the Channel

The channel can be analyzed in plan, profile and cross-section, the three views being physically interrelated. Plan, or pattern, provides the aerial view of geographic arrangement of the channel in straight, meandering or braided patterns, plus other less common patterns.

One of the most comprehensive and current references for determining historical changes in streams was prepared by Smelser and Schmidt (1998). Although they limited their investigation to mountainous streams, they provided numerous examples of historical studies to evaluate geomorphic channel changes in different geologies. The stream types that Smelser and Schmidt studied included were B3, B4, C3, C4, F3, F4, G3 and G4 as organized and documented by Rosgen (1994, 1996).

Chitale (1970) used data from 35 rivers inside and 7 rivers outside India, whereas Ackers and Charlton (1970) studied the development of meanders in a laboratory flume using four median sand diameters of 0.15, 0.21-0.26, 0.45, 0.70 mm and all sizes mixed together.

Chitale (1970), and Ackers and Charlton (1970) focused on the meander length and both used dimensional analysis to develop their analytical parameters which included the **Froude Number** of the flow $F = V/(gD)^{0.50}$. F is a ratio of water velocity to the velocity of a gravity wave superimposed on the water surface, or the ratio of inertia to gravity forces in the channel flow.

Chitale (1970) used prototype data for streams ranging in discharge from 5000 to 1,500,000 cfs, and bed material mean sizes of 0.01 to 5.0 mm on very mild slopes. He tied the ratio of river length (LR) to the valley length (LV) to: m/D (mean grain size/average depth); S (the slope in ft per 10000 ft of channel length); and W/D (the water surface width to mean depth ratio). With respect to channel cross-sectional shape, the tortuosity ratio (LR/LV) varies as $(W/D)^{-0.66}$. So we can expect W/D to make a large change from 10 to 100 (10-fold increase) and only a small, average change in LR/LV of 17%. Channel width is variable through the meander, so using this water surface width in our cross-sectional analysis will not be as prudent as using the W/D ratio in a riffle or glide.

Stypula (1986) performed a dimensional analysis of channel cross-sectional and flow characteristics using mean hydraulic depth (D), the mass density (ρ) and the average velocity (V) as the repeating variables. Resulting dimensionless relationships included (D/W, D/P, D/R, D/k_h and V^2/gD), where: P is the wetted perimeter; R is the hydraulic radius (A/P); and k_h is a bed roughness height, and D/k_h is referred to as a relative smoothness.

The "shape" factor of W/D was used with D/P and D/R to develop a "Shear-Shape" relationship. The shear component was developed as follows:

$$[1/(D/P)]\ (D/R) = (P/D)\ (D/R) = P/R = P^2/A \qquad (2\text{-}5)$$

where the substitution of R = A/P has been made.

To develop a theoretical basis for the relationship of W/D versus P^2/A the two factors were calculated for rectangular channels by varying W/D between 0.01 and 1000 and calculating P^2/A. This yielded the equation for natural and artificial **rectangular** channels of

$$W/D = P^2/A - (4 + 4D/W) \qquad (2\text{-}6)$$

Next, **natural** channel data were used from numerous sources listed in Figure 2-3. Then more natural channels were added for sand channels in Central Washington and small eroded rills in the loess hills near Pullman, Washington. All the channels were combined by Orsborn and Stypula (1987) into one set of two curves in Figure 2-3. Natural (non-rectangular) channels follow the relationship

$$W/D = P^2/A - (2 + 2D/W) \qquad (2\text{-}7)$$

To combine the hydraulic geometry with the shear-shape equation one must merely substitute $W = a\,(Q^b)$ and $D = cQ^d$ into Eqs. (2-6) and (2-7), which yields

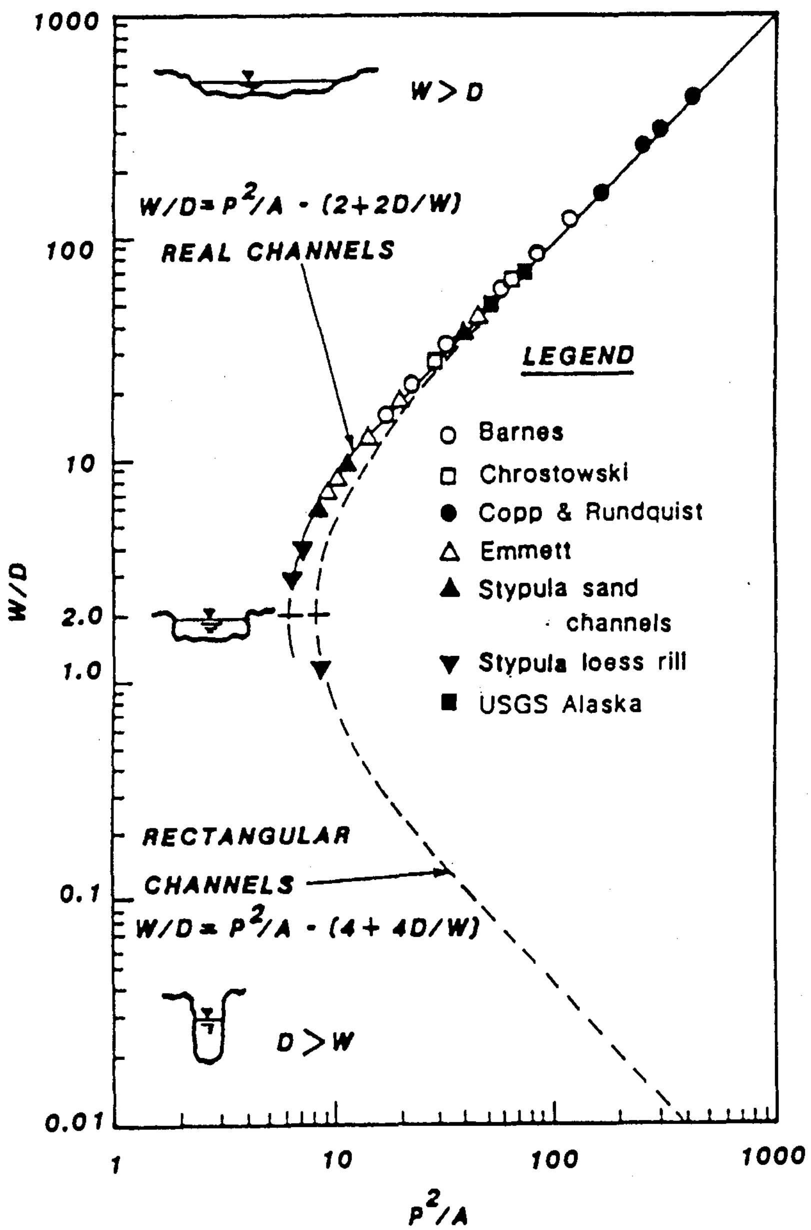
$$aQ^b/D = P^2/A - (2 + 2D/W) \qquad (2\text{-}7a)$$

for natural, non-rectangular channels, and

$$W/(cQ^d) = P^2/A - (4 + 4D/W) \qquad (2\text{-}6a)$$

for both natural and artificial rectangular channels where W is at, or nearly a constant. Notice that Manning's resistance coefficient does not appear in these

Figure 2-3. Shear-Shape Relationships for Natural and Rectangular Stream Channels (Orsborn and Stypula 1987)



open-channel flow equations. Their utility and reliability were examined by Orsborn and Stypula (1987, 2000) and an example of the results is shown in Table 2-2.

An analysis of W/D versus P^2/A was made for the Lower Elwha River on the Olympic Peninsula by Orsborn and Orsborn (1999a). This set of graphs in Figure 2-4 shows those from Figure 2-3 plus the straight-line relationships for very wide and very narrow channels. The left-hand scale has been changed to A/P^2 to show increasing numerical values on both scales. Also, Q is directly proportional to A, and inversely proportional to P. The Lower Elwha channel has become starved for gravel below the two dams (Figure 2-4) and now has a mean grain size of about 6-8 inches. Note that natural channels have a most efficient section when W/D is 1.5, (A/P^2 is a maximum), not 2.0 as it is for rectangular channels. The low flow measurements gave W/D values of 38 to 221 for the Lower Elwha River, all "wide, shallow channels" used in hydraulic calculations when R approaches D.

This leads us into a discussion of CC = f (QC) (from Figure 2-1 on page 2-4, relationship 3 : 2) where the channel cross-sectional characteristics (CC) are related to discharge (flow) characteristics (QC).

Table 2-2. Measured and Modeled Values of Average Annual Flow, Width, Depth and Velocity for Deer, Fall and Flynn Creeks in the Oregon Mid-coast Region (Orsborn and Stypula 1987).

USGS NUMBER	Gaging Station Name	Average Flow, Q_a (m^3s^{-1})	Top Width (m)	Average Depth (m)	Average Velocity (ms^{-1})
14306810	Deer Creek	0.18			
	Est. eq. (2-6a)[a]	0.19			
	Est. eq. (2-7a)[b]	0.19			
	Actual sizes[c]		3.26	0.16	0.34
	Est. sizes[d]		3.20	0.17	0.34
14306300	Fall Creek	4.67			
	Est. eq. (2-6a)[a]	4.14			
	Est. eq. (2-7a)[b]	4.60			
	Actual sizes[c]		15.16	0.46	0.67
	Est. sizes[d]		16.20	0.50	0.58
14306800	Flynn Creek	0.12			
	Est. eq. (2-6a)[a]	0.18			
	Est. eq. (2-7a)[b]	0.14			
	Actual sizes[c]		3.14	0.13	0.30
	Est. sizes[d]		2.60	0.14	0.32

NOTES:

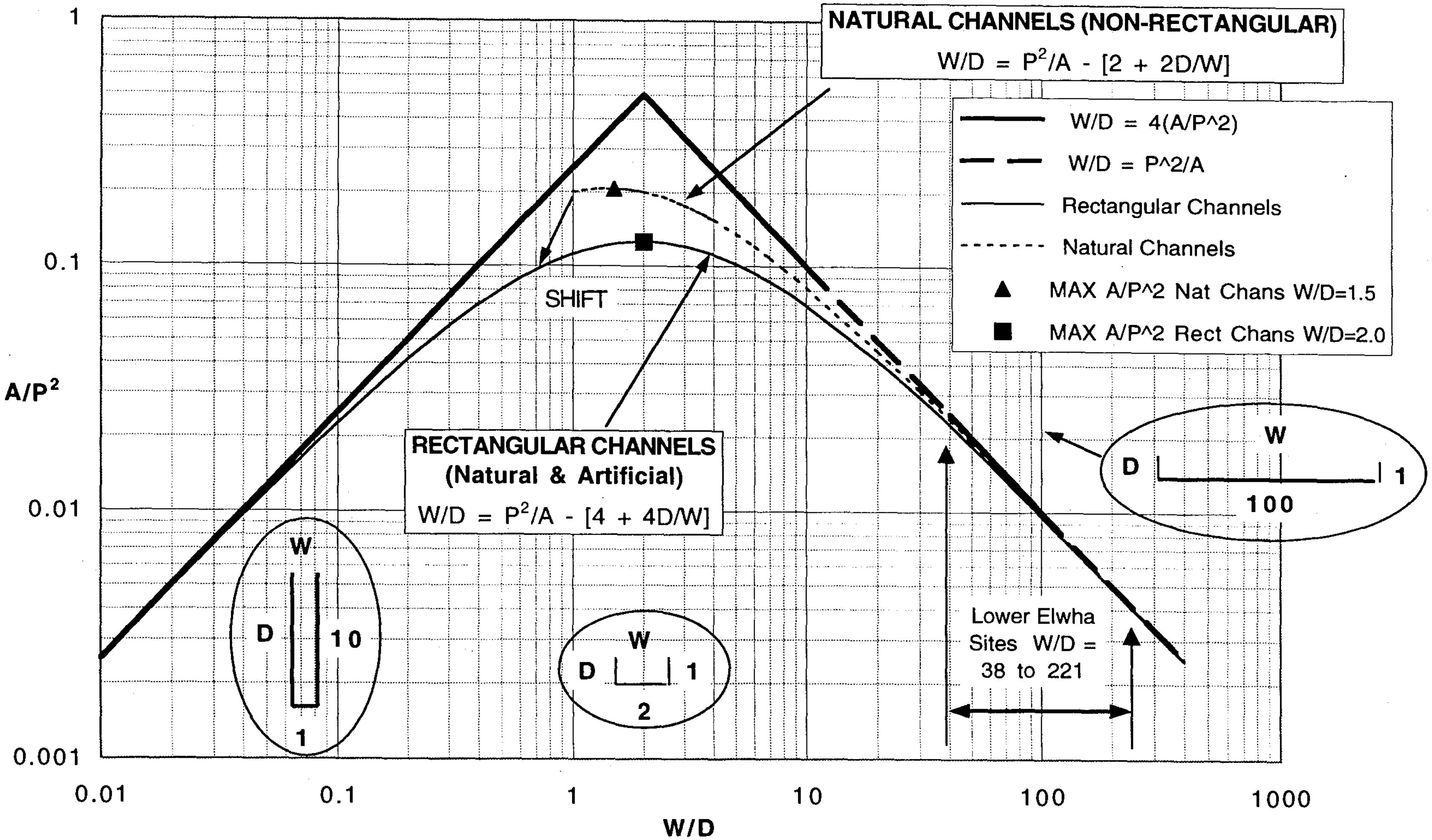
[a] Assumes P = W + 2D, rectangular section.

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

[c] Actual sizes are based on hydraulic geometry at the gaging stations.

[d] Estimated from equations for W, D and V based on Q_a of record at 10 Regional USGS gaging stations.

Figure 2-4. General Shear-Shape Relationships for Rectangular and Non-rectangular (natural) Channels (Orsborn and Orsborn 1999a)



Channel Hydraulic Geometry

The traditional analysis of hydraulic geometry is applied to streams based on the continuity equation: $Q = AV = WDV$, and $W = aQ^b$, $D = cQ^d$ and $V = eQ^f$ where: W is the water surface width; D is the mean depth; and V the mean velocity (Leopold and Maddock 1953). For ease of understanding we have not used Leopold's and Maddock's nomenclature for coefficients and exponents; we have used alphabetical continuity a-j, keeping W, D, V, A and P in the same sequence.

Chezy's and Manning's works showed that V is a function of the hydraulic radius (R) which is the flow area (A) divided by the wetted perimeter (P). Including these latter two factors in the suite of hydraulic geometry equations, we have $A = gQ^h$ and $\mathbf{P = iQ^j}$. **Wetted perimeter** accounts for two influences, the resistance to flow (shear), and **a measure of available habitat** for certain life-stages of fish.

Williams (1978) examined the at-a-station exponents in the hydraulic geometry equations for W, D, V, slope (energy gradient) and friction factor at 165 USGS gaging stations across the country. The cross-sections had ranges of exponents of: width (b) = 0.00 -0.82; depth (f) = 0.10 - 0.78; and velocity (m) = 0.03 - 0.81 (f and m are d and f in our report). The Williams' flows varied between 0.01 and 70,000 cfs, widths from 1.0 to 1900 ft, mean depths from 0.1 to 35.0 ft and median bed material sizes varied from 0.06 to 100 mm (0.0024 to about 4 inches).

Quoting from Williams (1978) to summarize the objectives and results of his study:

> "The original theory was intended to produce only the average hydraulic exponents for a group of cross sections in a similar type of geologic or hydraulic environment. The present test shows that the theory does indeed predict these average exponents, with a reasonable degree of accuracy.
>
> An attempt to forecast the exponents at any selected cross section was only moderately successful. **Empirical equations are more accurate than the minimum variance, Gauckler-Manning, or Chezy methods. Predictions of the exponent of width are most reliable, the exponent of depth fair, and the exponent of mean velocity poor."** (Williams 1978)

Also, in comparing measured and theoretical hydraulic exponents (b, f, and m, or b, d, and f in this report for W, D, and V), Williams (1978) stated:

> "A number of variables, as discussed earlier, might have some influence on the hydraulic exponents. **However, Langbein's papers suggest that most such factors cannot be taken into account individually in a minimum-variance analysis because their effects usually cannot be**

> **determined separately.** He believes that in spite of the interaction and net influence of such variables, there will result in nature a statistical array of exponent values in which certain values (the averages) are more common. These most common values of m, f, and b represent a central tendency, and the correct combination of variables is that for which the minimization of variances yields the most common exponents." (Williams 1978)

These general guidelines are for **regional channel geometry analysis**, or as originally described "in a downstream direction". This indicates increasing discharge (as a function of increasing drainage area), but it occurs at a decreasing rate due to decreasing precipitation at lower elevations. Regional hydraulic geometry analyses can be completed using gages from different basins. These analyses are used later in this report to connect channel characteristics to basin characteristics.

We will be using regional hydraulic geometry analyses based on average low, annual and flood flows at-each-station. **The channel cross-section is the "response variable" that can react to changes in watershed and streamflow characteristics**. Analyses of changes in channel hydraulic geometry for different periods of record will indicate changes in width, depth and velocity, wetted perimeter, bankfull flow, sediment size (or bed slope), or all of the above. Usually, even though width and depth may change, cross-sectional area will remain about the same for a particular streamflow.

One other comment about analyzing data to determine the hydraulic geometry at-a-station; Williams (1978) showed two examples, one for the Colorado River near Grand Canyon, Arizona and the other for Prairie Dog Fork of the Red River near Childress, Texas. The Colorado River showed a near-perfect plot of W, D, and V as a function of Q. Conversely, the Prairie Dog Fork showed a high degree of variability (width varied by up to 110 percent, with a mean of 24 percent). Lines were drawn parallel to the mean lines for W, D, and V to indicate they included 90 per cent of the data points (Williams 1978).

As an outgrowth of this data scatter problem, we analyzed the feasibility of using just three (and increasing numbers) of the W, D, V, A and Q data points. Class problems in river engineering and a recent analysis for the Colville Tribe showed that if you select W, D, V, and A data points at just three discharges (low, medium and high), the graphs and equations will all fall within the 90 percent lines. These are 95 percent lines (two standard deviations) if you conduct a statistical analysis of the data (Orsborn and Orsborn 1999b). The variability in coefficients and exponents as a function of the number of data points used in the at-a-station hydraulic geometry analysis is shown in Figures 2-5a and 2-5b. In the graphs the general coefficient C is used to represent the coefficients, while E is the exponent used in lieu of the exponents for W, A, D, and V, respectively.

Figure 2-5a. San Poil River in Northeastern Washington (SPR047). Number of Points Test for "C", used in the Power Relationships for Hydraulic Goemetry.

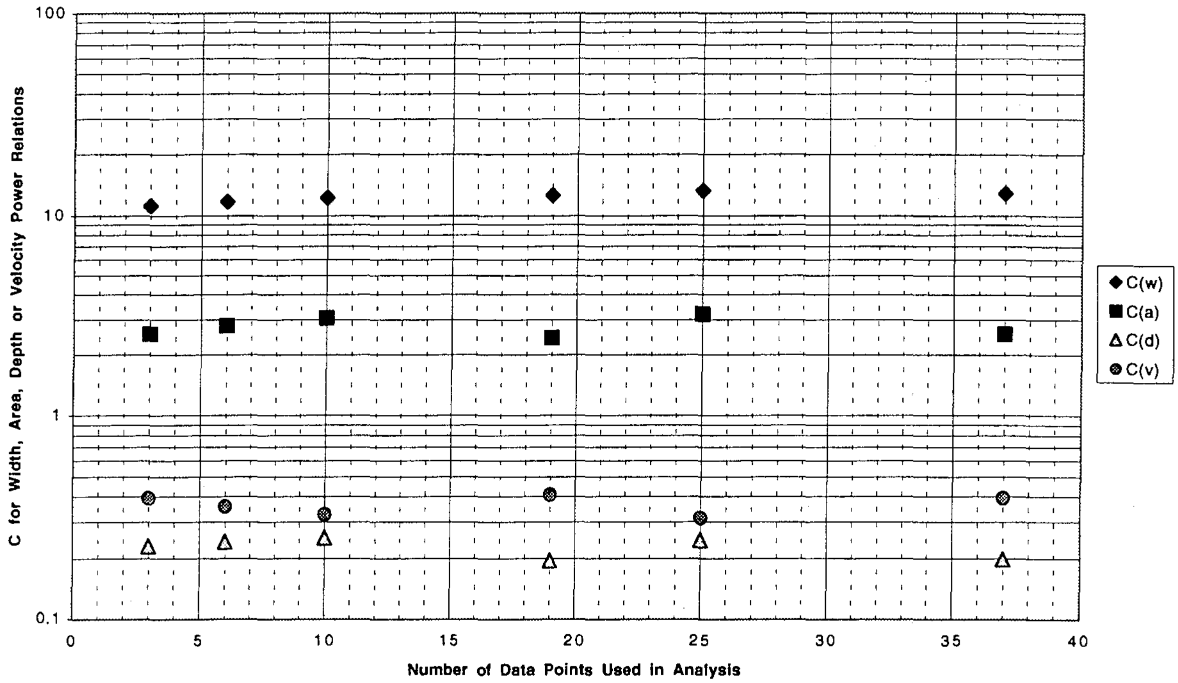
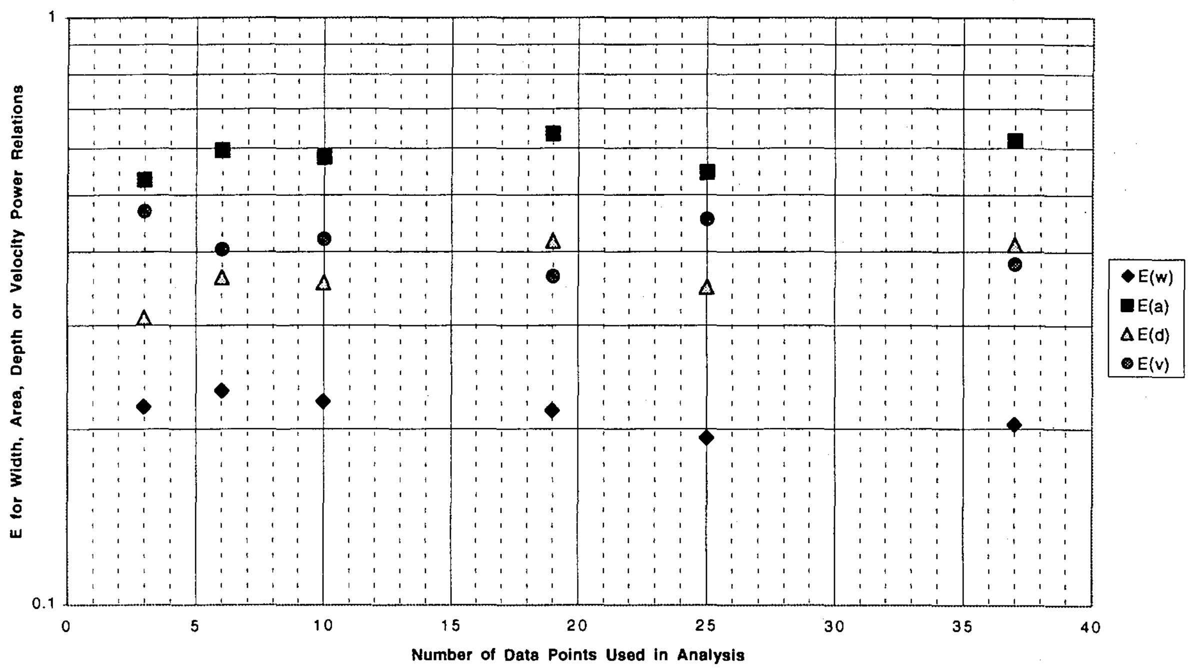


Figure 2-5b. San Poil River in Northeastern Washington (SPR047). Number of Points Test for "E", used in the Power Relationships for Hydraulic Goemetry.



A Severity Factor Analysis to Determine the Influence of Flow Reduction on Channel Characteristics

In 1976, Orsborn and Deane, while working on the physical aspects of instream flow needs, developed a method for evaluating the effects of flow reductions and other factors on habitat parameters. Called the Severity Factor (SF), the method allows an individual to select and evaluate any set of factors, as long as one chooses correct physical, quality or biological relationships. The method is based on channel geometry under initial flow conditions (Stage 1) compared with channel geometry under reduced flow conditions (Stage 2, 3, etc.). The initial flow condition can be any desired reference flow, bankfull, average annual, or the average low flow.

Our 1976 **example** used five sets of conditions involving:

- flow reduction (Q1/Q2);
- the volume of that reduction (Vol. 1/Vol. 2, flow x time);
- the change in width to depth ratio (W2 : D2/W1 : D1);
- the change in water surface width with respect to the flow area (W2 : A2) / (W1 : A1) to account for increased potential heating; and
- a depth ratio term raised to an exponent $(D1/D2)^{1.33}$ to account for the reduction in reaeration in pools based on the increase in reaeration as depth decreases in riffles where the measurements of channel geometry are made (Langbein and Durum 1967).

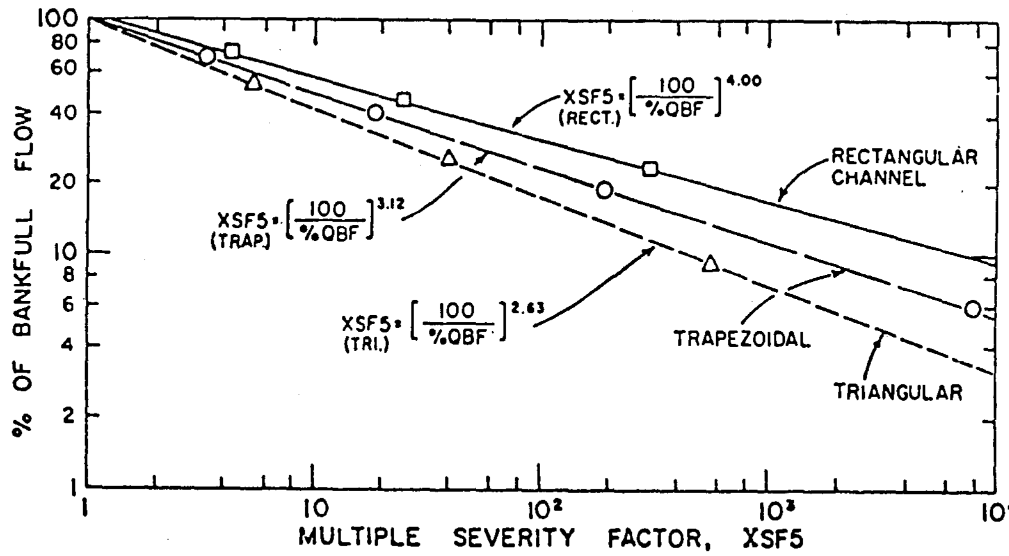
This set of five severity factors (SF5) was developed for linear-sided triangular, trapezoidal and rectangular channels. These results were compared with the real-stream data from Chrostowski (1972). All five terms were calculated for a series of 10 percent flow reductions below bankfull. The generated data for three shapes of channels are given in Table 2-3. Note that SF5 in the last two columns of Table 2-3 can take two forms, a summation (ΣSF5) or a multiple (XSF5), the latter form being more sensitive. The reader is referred to the original report for developmental details of the severity factor methodology (Orsborn and Deane 1976).

The five parametric ratios in each of the three shapes of channels were plotted separately as a percentage of the original bankfull flow. These were combined to produce the results of multiple XSF5 in Figure 2-6.

Table 2-3. Components of Severity Factor Analysis of Dimensionless Ratios for Triangular, Trapezoidal and Rectangular Channels. Data for Figure 2-6. (Orsborn and Deane 1976)

Stage	%QBF1	Q1:Q2	(Q1 + .1Q1) / (Q2 + .1Q1)	(W2 : D2) / (W1 : D1)	(W2 : A2) / (W1 : A1)	$[D1/D2]^{1.33}$	ΣSF5	XSF5
Triangular Section								
10	100	1.00	1.00	1.00	1.00	1.00	5.00	1.00
8	55	1.81	1.69	1.00	1.30	1.35	6.15	5.37
6	26	3.90	3.09	1.00	1.70	1.97	10.66	40.36
4	9	11.51	5.89	1.00	2.50	3.38	23.28	572.86
2	1	73.67	9.69	1.00	5.00	8.50	96.86	30339.15
0	---	---	---	---	---	---	---	---
Trapezoidal Section								
10	100	1.00	1.00	1.00	1.00	1.00	5.00	1.00
8	66	1.51	1.44	1.09	1.23	1.28	6.55	3.73
6	39	2.55	2.24	1.21	1.54	1.69	9.23	17.99
4	19	5.13	3.73	1.59	2.23	2.85	15.53	193.36
2	6	16.84	6.90	2.55	4.15	6.43	36.87	7906.61
0	---	---	---	---	---	---	---	---
Rectangular Section								
10	100	1.00	1.00	1.00	1.00	1.00	5.00	1.00
8	71	1.42	1.36	1.25	1.30	1.33	6.66	4.17
6	45	2.24	2.01	1.67	1.70	1.97	9.59	25.18
4	23	4.30	3.31	2.50	2.50	3.38	15.99	300.67
2	8	13.26	6.27	5.00	5.00	8.50	38.03	17667.29
0	---	---	---	---	---	---	---	---

Figure 2-6. Multiple Severity Factor (XSF5) for Flows Less than Bankfull for Triangular, Trapezoidal and Rectangular Idealized channels. Data In Table 2-3. (Orsborn and Deane 1976).



An example of natural channel geometry W/D ratios is shown in Figure 2-7 for nine of the channel sections measured by Chrostowski (1972). We found that some of the W/D ratios plotted versus %Q in the real channels were very close to "ideal" triangular, trapezoidal and rectangular channels.

CHANNEL SHAPE	STREAM NAME	EQS. FOR REAL CHANNELS	EQS. FOR IDEAL CHANNELS
Triangular	Rock#2 (f)*	$5.0 / (\%Q)^{0.35}$	$5.0 / (\%Q)^{0.35}$
Trapezoidal	L. Brush #1 (c)*	$8.0 / (\%Q)^{0.45}$	$10.0 / (\%Q)^{0.50}$
Rectangular	L. Brush #3 (a)*	$13.4 / (\%Q)^{0.56}$	$18.0 / (\%Q)^{0.60}$

*Figure letter in Figure 2-7. Eqs: (W/D) 2: (W/D) 1 = $C/(\%Q)^{m}$

These same kinds of relationships can be derived from at-a-station hydraulic geometry equations. For example, Wilmont Creek, on the Colville Indian Reservation in north central Washington, is triangular in shape at gaging site WIL028, and W/D is a constant (Orsborn and Orsborn 1999c, Figure 2-8). Plotting the cross-section in the traditional, distorted fashion is not as effective in portraying the true channel geometry as is plotting at an undistorted scale (Potyondy and Schmidt 1999).

Regional Relationships between Basin Characteristics (BC) and Channel Characteristics (CC) Using Flow Characteristics (QC)

Strahler (1958) developed a Froude Number of the basin, which Orsborn (1981) expanded into a regional streamflow equation

$$QX = C\ (A)\ (H)^{0.50} \qquad (2\text{-}8)$$

where QX = any characteristic regional flow such as QPF2, Q1F2, QAA or Q7L2 for a series of gaging stations. The regional coefficients have average values of 230, 15, and 1.2 for QPF2, QAA and Q7L2 from the mid-coast of Oregon to south central Alaska along the Pacific Coast.

Channel hydraulic geometry, either regional or at-a-station, gives us relationships between flow and channel geometry. For example, using one such relationship for water surface width at the average annual flow:

For the Dungeness River USGS Gage No. 12048000:

At-a-station: $$W = 59.5\ (Q)^{0.049} \qquad (2\text{-}9)$$

Regional Eq. : $$W = 4.82\ (QAA)^{0.47} \qquad (2\text{-}10)$$

For the Dungeness River, with QAA = 383 cfs, by Eq. (2-9), W = 80 ft, and by the regional Eq. (2-10), W = 79 ft. The low value of the width exponent (b = 0.049) indicates an essentially rectangular cross section.

If the regional Eq. 2-10 is rearranged

$$QAA = (0.21W)^{2.13}$$

or

$$QAA = 0.035\ (W)^{2.13} \qquad (2\text{-}11)$$

Figure 2-7. Channel Width to Depth Ratios as a Function of Discharge Reduction for Different Natural Channel Shapes. (Orsborn and Deane 1976). Data from Chrostowski (1972).

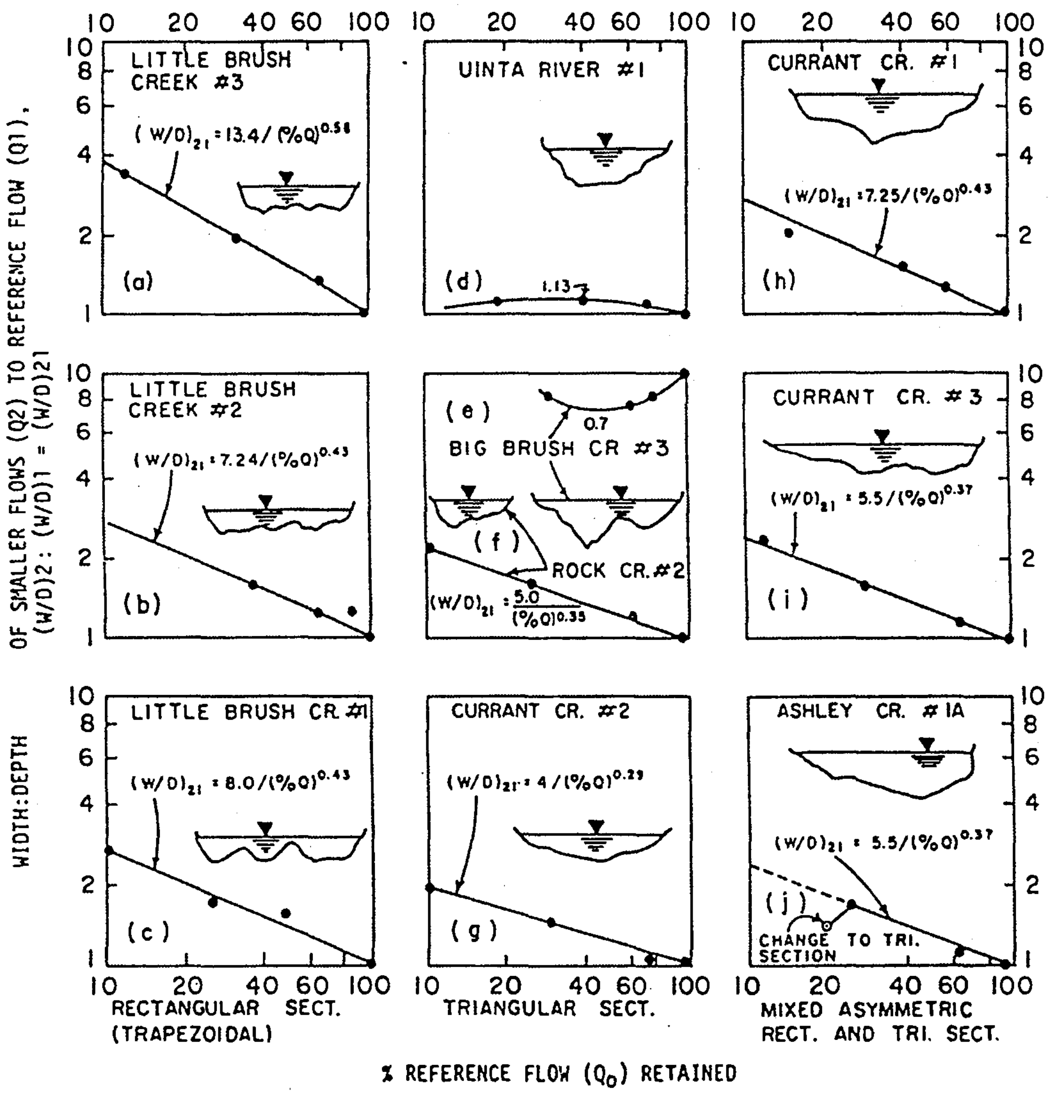
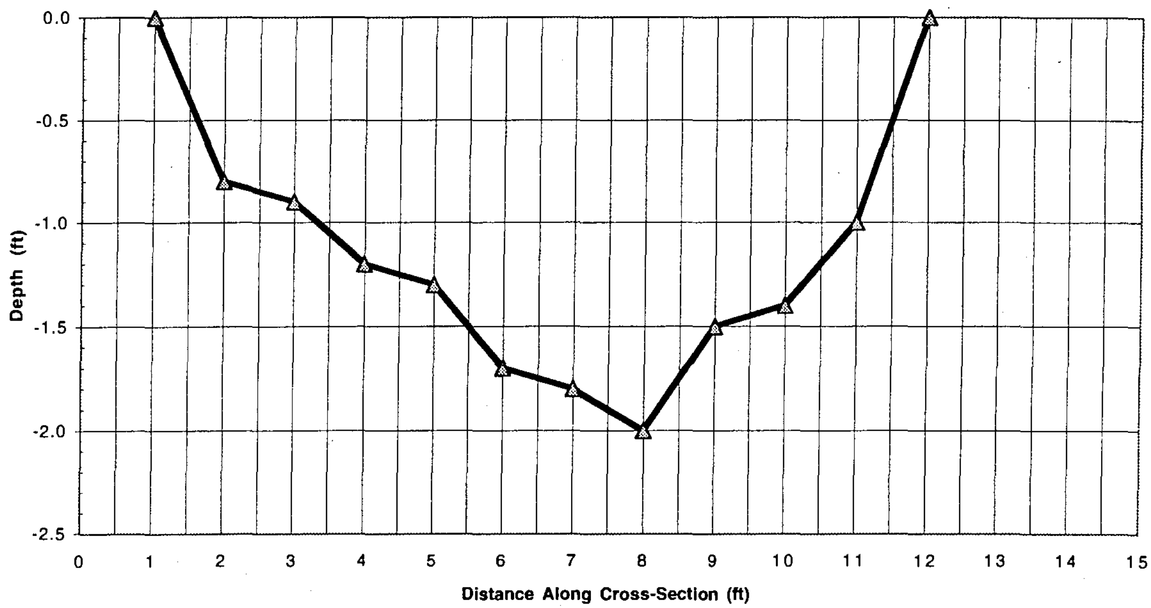


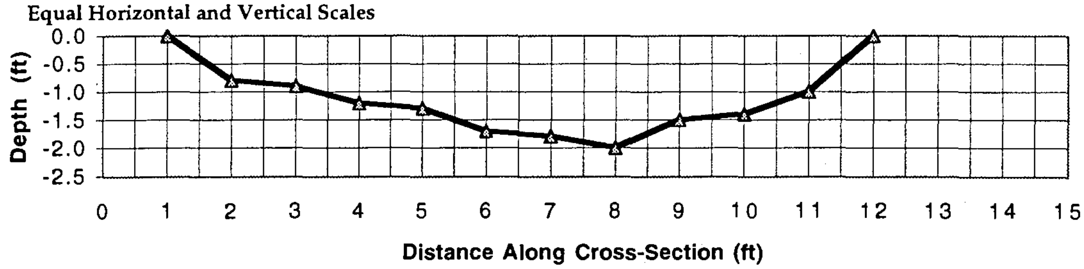
Figure 2-8. Cross-Sections for CCT Priority Low Flow Study Sites, Wilmont Creek WIL028

(Orsborn and Orsborn 1999c)

Exaggerated Vertical Scale



Equal Horizontal and Vertical Scales



Now we have equations for QAA in terms of basin characteristics (BC, Eq. 2-8 and in Figure 2-2a) and channel characteristics (CC, Eq. 2-11). Setting these two equations equal to each other:

$$QAA = 15\ [A\ (H)^{0.50}]^{0.91} = 0.035\ (W)^{2.13} \qquad (2\text{-}12)$$

and reducing to find W (or D, V, A and P by other equations)

$$W = (428\ (A)^{0.91}\ (H)^{0.50})^{0.47}$$

or

$$\mathbf{W\ (at\ QAA) = 17.2\ (A)^{0.43}\ (H)^{0.22}} \qquad (2\text{-}13)$$

This equation is good only for stations (or ungaged watersheds) which have the coefficient of 15 in Eq. 2-8. The coefficients range from 20 to 1.7 across the Olympic Peninsula. Inserting average annual precipitation (P) into Eq. 2-8 gives

$$QAA = 0.0193\ (PBE)^{1.14} \qquad (2\text{-}14)$$

where BE is the basin energy ($AH^{0.50}$), and Eq. 2-14 is an average line for the Olympic Peninsula gages. Combining Eq. 2-14 with Eq. 2-11 yields

$$QAA = 0.035\ (W)^{2.13} = 0.0193\ (PA(H)^{0.50})^{1.14}$$

Reducing these equalities gives

$$\mathbf{W\ (at\ QAA) = 0.75\ (P)^{0.54}\ (A)^{0.54}\ (H)^{0.27}} \qquad (2\text{-}15)$$

Also, the equation developed by Amerman and Orsborn (1987) for QAA on the Olympic Peninsula states

$$QAA = 0.0032\ (P)^{1.60}\ A_b \qquad (2\text{-}16)$$

where P is the average annual precipitation (inches per year) and A is the watershed area (square miles). Although this equation was developed for USGS gages on the Olympic Peninsula, similar equations have been developed for other regions of Washington, Oregon, Idaho and Alaska. For example, in northeastern Washington,

$$QAA = 0.0025\ (P)^{1.64}\ A_b \qquad (2\text{-}17)$$

The exponent of 1.60 - 1.64 on P allows for changes in QAA as a function of changes in P.

Now, if we write Eq. (2-16) equal to Eq. (2-11) for regional channel width, then

$$QAA = 0.0032\ (P)^{1.60}\ A_b = 0.035\ (W)^{2.13}$$

and $$W = [0.088\ (P)^{1.60} A_b]^{0.47}$$

and $$\mathbf{W\ (at\ QAA) = 0.32\ (P)^{0.75} A_b^{\ 0.47}} \qquad (2\text{-}18)$$

Rounding the area exponent 0.47 to 0.50 makes about a 6% difference for an area of 10 sq. mi. and 14% difference at A = 100 sq. mi. This is a simpler expression to use than Eq. 2-15 to estimate W at QAA. Similar expressions can be developed for the other channel characteristics of D, V, A and P (wetted perimeter). **But the USGS summary form 9-207 only provides Q, W, D, V and A. To find the wetted perimeter (P), one must obtain form 9-275 that covers the field measurements of the discharges used to verify the calibration curve for the station.**

These other expressions for channel dimensions related to basin characteristics at three characteristic flows (Q1F2, QAA and Q7L2), are developed in Part 3 for three regions in Washington.

The USGS considers gage records as excellent if 95% of the calibration measurements are within about 5% of the true value. The grading goes to good (10%), fair (15%) and poor for records greater than 15% from true. The variability of the flow measurements over time would be a function of land-use changes, gaging station channel changes, the stability and amount of precipitation from year to year and whether or not the streamflow was influenced by upstream storage or diversions.

Accounting for Changes in Channel Geometry

To account for the "condition of a channel" (poor or good) one must consider a number of scales, or indexes, of evaluation:

- a channel may be "in balance" with its water and debris load, and still not fit a cross-sectional template for the region due to geologic or human geometric constraints;
- the main stream channel may be underfit due to excessive diversions of flow out of the watershed, and the accumulation of sediment in the mainstem from unaffected tributary sediment flows;
- the channel may be over- or under-sized due to a modified flow regime caused by either a natural extended increase or decrease in flow, or a regulated flow regime, or both; and

- an historical mass wasting may have been deposited in a stream valley, and the stream is now downcutting (as a function of the existing flow regime).

It appears that we need a systematic method of analysis that may involve each of the following steps, but to a varying degree:

- review of historical records of flow;
- a method of classification to put some geomorphic boundaries on the site being investigated, and to help in the visualization of the site;
- a simple hydrologic analysis to estimate the characteristic flows at a site (average low, average annual and average flood) Q7L2, QAA and Q1F2, and major changes in these characteristic flows and in precipitation over time;
- an abbreviated analysis of the channel hydraulic geometry of the site to provide relationships of geometric characteristic (W, D, V, A and P) as a function of discharge;
- regional channel hydraulic geometry models for comparison with the present site geometry;
- an integrating analysis of how the W/D ratio, and other geometric dimensionless ratios, change as a function of streamflow reduction; a type of severity factor analysis which ties flow to geometric characteristics which serve as analogs to water quantity and quality parameters; and
- an evaluation of the history of major land-use and water-use changes on the watershed.

The steps listed above will be explored in Part 3 - Methods of Analysis. We will be analyzing slices of data about stream conditions, but a series of slices taken over time should provide a more comprehensive evaluation of stream condition and/or trends.

An Example for Evaluating Effects of Land Use Change on Channel Geometry

As a final example of a descriptive model let us put some numbers on the problem of land use change and estimate some effects of a clear-cut on downstream channel size. We can use the rational equation

$$Q_p = CIA_b \tag{2–19}$$

Where Q_p is the peak flood (cfs) generated from a basin area (A_b) in acres, the rainfall intensity (I) is in inches per hour and the coefficient (C) depends on the type of land use and cover. Let us assume that the entire basin is uniformly timbered and C = 0.10; and for the logged area (in the first couple of years after logging), C = 0.8. For I = 2 in./hr on saturated ground, most of the rain is available for runoff. The peak flow (Q_p) is in units of either acre-in/hr or cfs, because 1 acre–in/hr = 1 cfs. Under natural, pre-logging conditions, A_b = 20 sq. mi. (12800 acres), I = 2 in/hr, and C = 0.10. Therefore, Q = 0.10 (2) (12800) = 2560 cfs, or 128 cfs per sq. mi. which is common for the Olympic Peninsula. The overall basin and subbasins are shown in Figure 2-9, and the basin characteristics are in Table 2-4.

Figure 2-9. Sketch of Example Basin with 5% (1 sq. mi.) clear-cut. (not to scale).

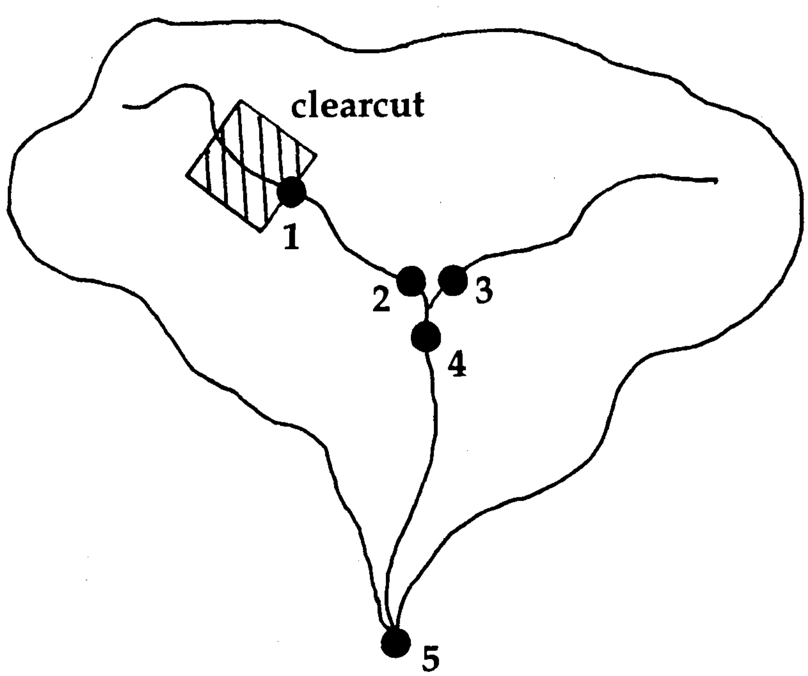


Table 2-4. Basin Characteristics and Peak Flows for Figure 2-9 under Pre-Logging Conditions.

Point No.	Area (A_b) (sq. mi.)	Area (A_b) (acres)	Natural Q_p at Pt (cfs)
1	4	2560	512
2	8	5120	1024
3	4	2560	512
4	12	7680	1536
5	20	12800	2560

After logging 1.0 sq. mi. (640 acres), C = 0.8 on that area and the flows would adjust about as shown in Table 2-5.

Table 2-5. Comparison of Pre- and Post-Logging Peak Flows at the Check Points*

Point No.	Natural Q_p at Pt. (cfs)	Post-Log Q_p at Pt. (cfs)	Increase in Flow at Pt. (cfs)	Percent Change (%)
1	512	1408	896	175
2	1024	1920	896	88
3	512	512	0	0
4	1536	2432	896	58
5	2560	3456	896	35

*The flood flows are not strictly additive because of storage in the channel.

At the lower end of the logging the channel (assuming near bankfull conditions for Q_p) must now be subjected to 1408 cfs instead of the natural condition flow of 512 cfs, an increase of 175 %. Using the regional Olympic Peninsula equation for Q1F2, the natural channel width would be about $W = 3.44\ (Q1F2)^{0.42}$, where Q1F2 = 0.73 (QPF2) (Amerman and Orsborn 1987)

If we assume our calculated peak flood is the average QPF2, then

$$W = 3.44\ (0.73\ QPF2)^{0.42} \qquad \text{(Eq. 2-20)}$$

The natural and logged channel potential widths would be as shown in Table 2–6.

Table 2–6. Natural and Post-Logging Channel Widths for Estimated Average Daily Flood Conditions

Point No.	Natural Q1F2 (cfs)	Natural Width, W (ft)	Post-Log Q1F2 (cfs)	Post-Log Width, W (ft)	% Change in W (%)
1	375	41	1028	63	54
2	750	55	1400	72	31
3	375	41	375	41	0
4	1125	66	1775	80	21
5	1875	82	2522	92	12

Based on the following assumptions, we have estimated the percent change in channel width due to logging one sq. mile out of a 20 sq. mi. watershed on the Olympic Peninsula:

1. Logging was equally distributed on both sides of this first-order perennial stream;

2. Changes in runoff due to changes in land use were estimated by changing the runoff coefficient (C) in the rational equation ($Q = CIA_b$) for the logged area from 0.1 to 0.8 after logging; and

3. The channels were formed in bank and bed materials that were freely deformible.

The results of this example have demonstrated that for an increase in flood runoff due to a land use change, we can expect the following:

1. Most of the channel widening will have the potential to take place in the reach between Points 1 and 2;

2. There is a potential for about a 50 percent increase in channel width in this reach;

3. Sediment deposited in the lower, flatter reaches will cause the channel to widen and become shallower, but the cross-sectional area will stay about the same. (e.g. S. F. Skokomish River in Amerman and Orsborn (1987) and in Figure 3-9 on p. 3-15);

4. Although the percent increase in the potential channel width decreases as the flow moves downstream (54 to 12%), most of the channel change will probably take place in the downstream, flatter reaches; and

5. Regional channel geometry equations are useful in conducting analyses of historical and current channel sizes.

We could have used the same kind of analogy for an urbanizing area. The runoff coefficient, C, would have increased to about 0.90, and the floods would have increased. But in this case, there would be less infiltration, and the low flows would tend to decrease. For the logging operation the low flows may have actually increased due to reduced transpiration by trees.

"The December 1964 flood on Coffee Creek (a small high-gradient mountain stream in Trinity County, California) was of rare frequency and unprecedented in historic time. Erosion and deposition during the flood were catastrophic and significantly changed the character of the valley." ..... *"Within the valley, the preflood channel was commonly filled, and new channels formed at entirely different locations." (Stewart and LaMarche 1967)*

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3. METHODS OF ANALYSIS

Introduction

In the evaluation of "channel condition" there are various levels of evaluation that can be conducted, but all levels need a frame of reference, a benchmark, a template, a basis of comparison. For the condition of a stream we need a comparative reach of stream that is natural. Better yet, we need a series of natural reaches from which more comprehensive regional models can be developed. Although USGS gaging stations provide the best and most complete flow and geometry data, some of the data has been distorted by either nature or humans, or both. And, USGS sites are selected for their stability.

In Part 2, a series of example models were developed that related channel characteristic (CC) width (W) to basin characteristics (BC) at average annual flow (QAA). In Part 3, this analysis will be expanded to include: (1) the channel cross-sectional dimensions (W, D, A_c and P); (2) at the three characteristic flows (Q1F2, QAA and Q7L2); and (3) for three regions in Washington State: the Olympic Peninsula (Amerman and Orsborn 1987); a region north, and east of Lake Washington (Johnson and Orsborn 1997; Moscrip and Montgomery 1997); and a region in northeastern Washington (Orsborn and Orsborn 1997, 1999).

General Analytical Methods

In each region we use the following steps:

(1) develop a table of USGS gaging stations with their gage numbers, basin characteristics, and their combined parameters (basin input, PA; basin energy (BE) = A (H) $^{0.50}$; and P·BE); (the reliefs (H) were not measured in the Puget Lowland region, because they were not needed for that project);

(2) prepare a table of the width, depth, area and wetted perimeter (where available) for each gage site at the three characteristic flows (Q1F2, QAA and Q7L2);

(3) plot the regional hydraulic geometry graphs of channel characteristics as a function of each characteristic flow; this step is preceded by development of the at-a-station hydraulic geometry equations for each USGS gage site;

(4) develop and select the best regional models of characteristic flows related to basin characteristics;

(5) equate the regional hydraulic geometry models to the best basin model for each of the characteristic flows, and for each channel geometric property (W, D, A_c and P); (note that velocity is not included because it is not a geometric characteristic of the channel);

(6) check for the applicability of empirical relations between channel dimensions in the field and basin characteristics;

(7) check to see if the channel dimensions can be estimated within reasonable limits by developing regional models of channel dimensions as a function of basin characteristics; and

(8) compare measured versus modeled channel dimensions; and

(9) decide on the project design approach.

Examples of using these nine steps towards evaluating channel conditions are presented next for three regions in Washington State.

OLYMPIC PENINSULA REGION

The information to develop the analyses for the Olympic Peninsula gages is given in:

Table 3-1. Basin characteristics for gaging stations;

Table 3-2. Calculated values of at-a-station hydraulic geometry for three characteristic flows at USGS gaging stations;

Table 3-3. Channel properties at Q1F2, QAA and Q7L2 for USGS Gaging Stations including W/D values;

Figure 3-1. Regional hydraulic geometry at Q1F2;

Figure 3-2. Regional hydraulic geometry at QAA;

Figure 3-3. Regional hydraulic geometry at Q7L2;

Figure 3-4. Regional hydraulic geometry: cross-sectional area versus Q7L2, QAA and Q1F2; and

Figure 3-5. USGS stream gaging stations on the Olympic Peninsula.

In the interest of brevity the basin, flow and channel characteristics are not included in such detail for the Puget Lowland and Northeast Washington regions. Only summary data, graphical relationships and regional equations that were developed from the databases are presented.

Empirical relationships between channel and basin characteristics are examined first, followed by the combination of basin characteristics with hydraulic geometry, examples of which were developed in Part 2.

Table 3-1. Basin Characteristics for Gaging Stations on the Olympic Peninsula

Province/ Stream Gage Code	Station Name	USGS Gage No.	Basin Relief, H (mi)	Drainage Area, Ab (sq. mi.)	Average Annual Precip., P (in/yr)	COMBINED PARAMETERS: Basin Input (PA) (sq. mi-in/yr)	COMBINED PARAMETERS: Basin Energy $(A)(H)^{0.5}$ $(mi)^{2.5}$	COMBINED PARAMETERS: P•BE $(in/yr)(mi)^{2.5}$
1.3	Satsop River	12035000	0.47	299.0	128	38272	205.0	26238
1.5	Humptulips River	12039000	0.58	130.0	155	20150	99.0	15346
3.1	N.F. Quinault River	12039300	0.64	74.1	200	14820	59.3	11856
3.5	Hoh River	12041000	0.79	208.0	167	34736	184.9	30874
3.7	Soleduck River	12041500	0.59	83.8	99	8296	64.4	6372
4.1	Hoko River	12043300	0.22	51.2	124	6349	24.0	2978
4.2	East Twin River	12043430	0.22	14.0	90	1260	6.6	591
5.2	Dungeness River	12048000	0.84	156.0	62	9672	143.0	8865
6.1	Siebert Creek	12047500	0.33	15.5	41	636	8.9	365
6.2	Snow Creek	12050500	0.60	11.2	43	482	8.7	373
6.3	L. Quilcene River	12052000	0.88	19.6	51	1000	18.4	938
8.2	Duckabush River	12054000	0.90	66.5	113	7515	63.1	7129
8.3	Hamma Hamma River	12054500	0.66	51.3	110	5643	41.7	4584
8.8	S.F. Skokomish River	12060500	0.63	76.3	153	11674	60.6	9266
9.1	Goldsborough Creek	12076500	0.030	39.3	84	3301	6.8	572
9.2	Kennedy Creek	12078400	0.055	17.4	59	1027	4.1	241

Table 3-2. Calculated Values of At-a-Station Hydraulic Geometry for Three Characteristic Flows at USGS Gaging Stations on the Olympic Peninsula.

Province/ Stream Gage Code	Station Name	USGS Gage No.	Q7L2 (cfs)	QAA (cfs)	Q1F2 (cfs)	W @ Q7L2 (ft)	D @ Q7L2 (ft)	V @ Q7L2 (fps)	A @ Q7L2 (ft^2)	W @ QAA (ft)	D @ QAA (ft)	V @ QAA (fps)	A @ QAA (ft^2)	W @ Q1F2 (ft)	D @ Q1F2 (ft)	V @ Q1F2 (fps)	A @ Q1F2 (ft^2)
1.3	Satsop River	12035000	238.7	2035.0	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	12039000	146.7	1337.0	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
3.1	N.F. Quinault River	12039300	161.1	887.0	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	12041000	610.0	2028.0	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	12041500	79.3	621.0	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	12043300	19.5	408.0	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	East Twin River	12043430	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	12048000	113.6	393.0	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	12047500	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	12050500	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	L. Quilcene River	12052000	9.4	48.6	365	19.9	0.62	0.75	12.3	25.9	0.97	1.92	25.1	35.7	1.67	6.06	59.6
8.2	Duckabush River	12054000	73.4	422.0	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	12054500	59.9	364.0	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	12060500	88.8	741.0	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	12076500	20.6	116.0	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	12078400	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

Notes:
Water surface width (W)
Mean hydraulic depth (D)
Mean velocity (V)
Cross-sectional area (Ac) = (WxD)

Table 3-3. Channel Properties at Q1F2 (Average Flood), QAA (Average Annual Flow) and Q7L2 (Average Low Flow) for Olympic Peninsula USGS Gaging Stations, including W/D values.

Province/ Stream Gage Code	Station Name	USGS Gage No.	W @ Q1F2 (ft)	W @ QAA (ft)	W @ Q7L2 (ft)	D @ Q1F2 (ft)	D @ QAA (ft)	D @ Q7L2 (ft)	W/D @ Q1F2 (--)	W/D @ QAA (--)	W/D @ Q7L2 (--)
1.3	Satsop River	12035000	300	252	212.6	4.6	2.3	1.20	65.2	109.6	177.2
1.5	Humptulips River	12039000	220	187	160.1	8.0	2.7	0.96	27.5	69.3	166.8
3.1	N.F. Quinault River	12039300	165	133	110.2	6.2	3.6	2.17	26.6	36.9	50.8
3.5	Hoh River	12041000	173	129	106.4	6.6	3.6	2.48	26.2	35.8	42.9
3.7	Soleduck River	12041500	91	85	80.1	8.3	3.7	1.82	11.0	23.0	44.0
4.1	Hoko River	12043300	148	93	52.2	4.8	1.9	0.63	30.8	48.9	82.9
4.2	East Twin River	12043430	62	33	14.8	1.6	1.0	0.55	38.8	33.0	26.9
5.2	Dungeness River	12048000	87	80	75.4	3.7	2.1	1.31	23.5	38.1	57.6
6.1	Siebert Creek	12047500	28	18	12.8	1.4	0.8	0.48	20.0	22.5	26.7
6.2	Snow Creek	12050500	22	22	15.4	1.2	0.6	0.36	18.3	36.7	42.8
6.3	L. Quilcene River	12052000	36	26	19.9	1.7	1.0	0.62	21.2	26.0	32.1
8.2	Duckabush River	12054000	82	73	65.4	5.0	2.1	1.01	16.4	34.8	64.8
8.3	Hamma Hamma River	12054500	99	88	79.2	3.6	1.7	0.83	27.5	51.8	95.4
8.8	S.F. Skokomish River	12060500	273	213	168.7	2.5	1.6	1.00	109.2	133.1	168.7
9.1	Goldsborough Creek	12076500	44	38	33.5	3.5	1.6	0.80	12.6	23.8	41.9
9.2	Kennedy Creek	12078400	56	29	11.4	2.3	1.0	0.35	24.3	29.0	32.6

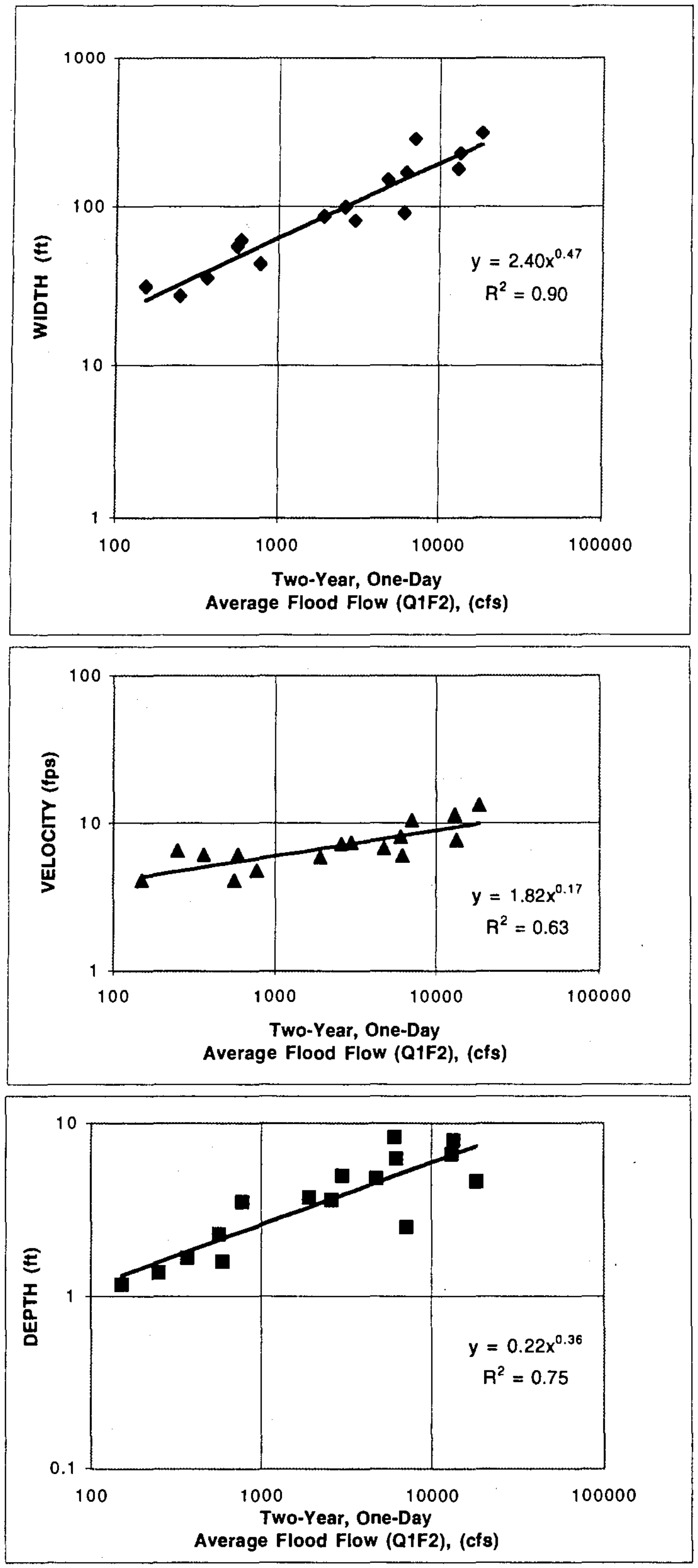


Figure 3-1. Regional Hydraulic Geometry: Width, Velocity and Depth Versus the Two-Year, One-Day Average Flood Flows for Olympic Peninsula Streams.

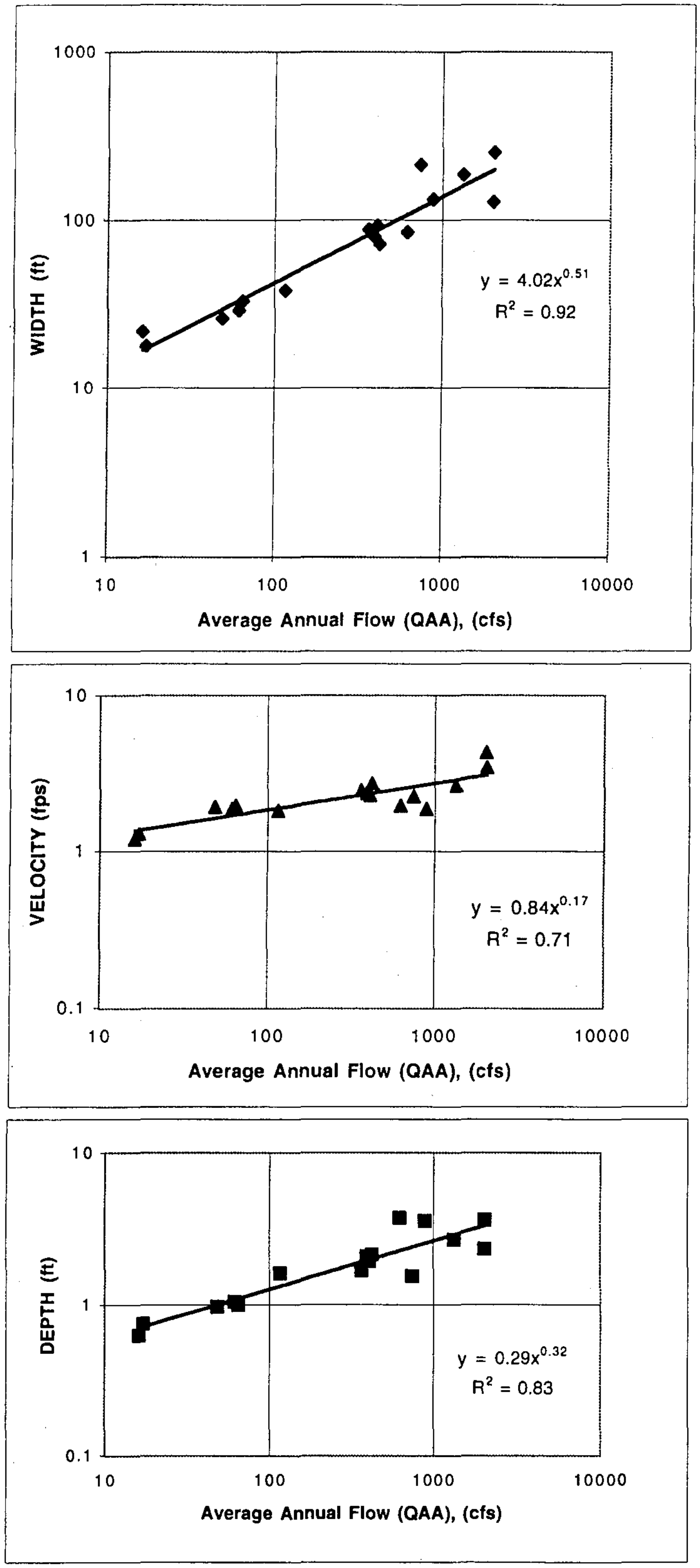


Figure 3-2. Regional Hydraulic Geometry: Width, Velocity and Depth Versus Average Annual Flows for Olympic Peninsula Streams.

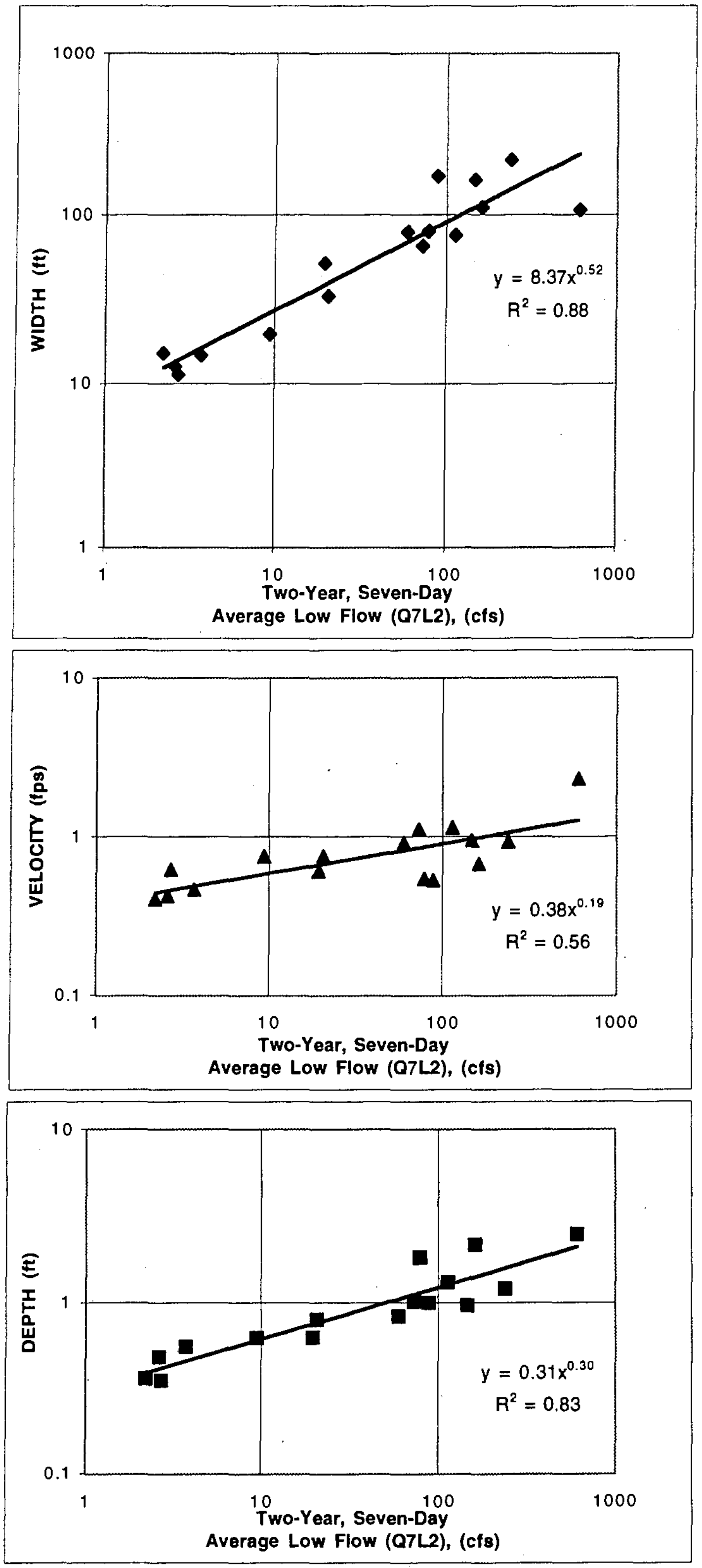


Figure 3-3. Regional Hydraulic Geometry: Width, Velocity and Depth Versus the Two-Year, Seven-Day Average Low Flows for Olympic Peninsula Streams.

Figure 3-4. Regional Hydraulic Geometry: Cross-Sectional Area Versus Q7L2, QAA and Q1F2.

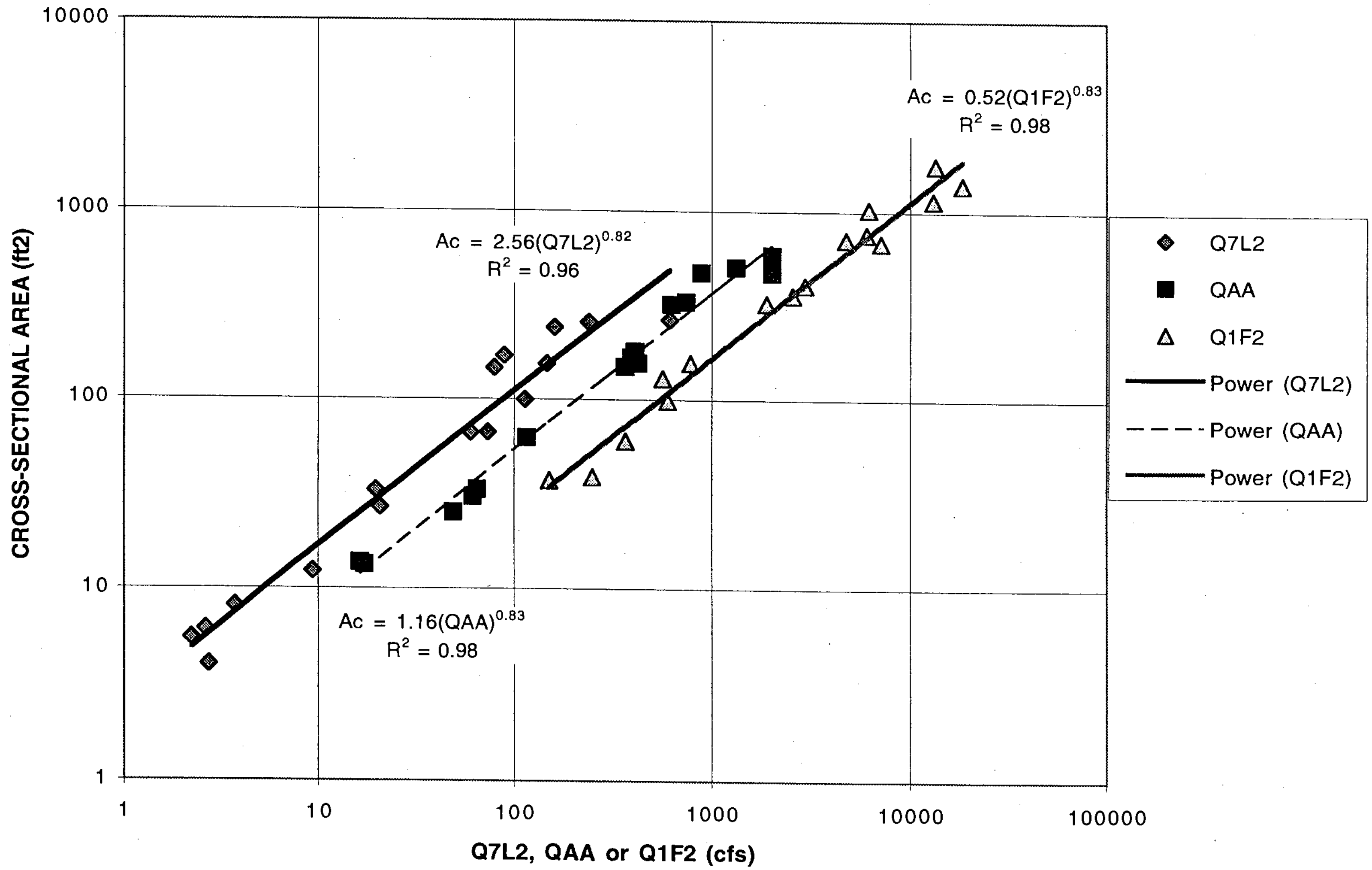
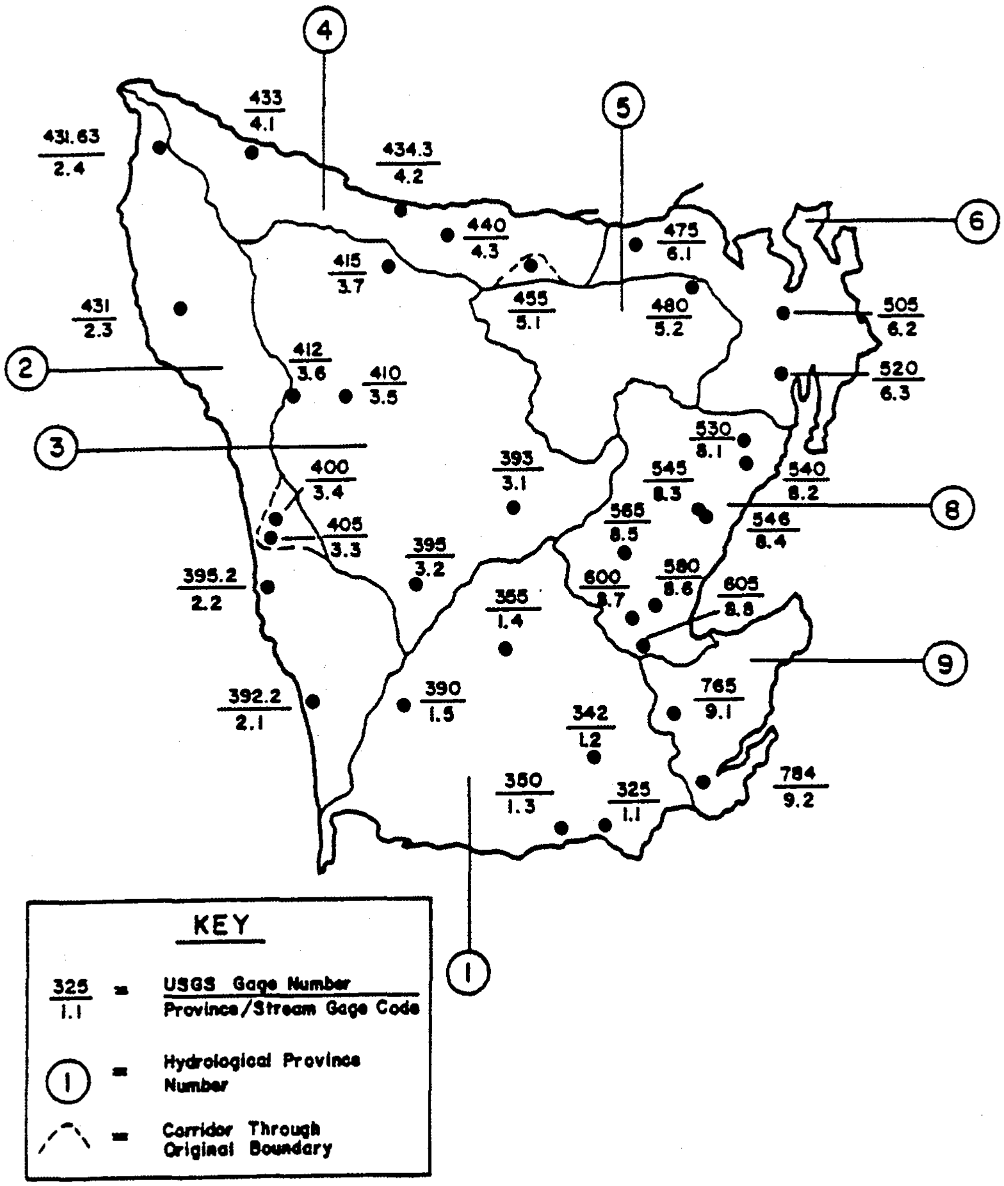


Figure 3-5. USGS Stream Gaging Stations on the Olympic Peninsula. Stations used in hydraulic geometry analysis are listed in Table 3-1. USGS Gage Number, and Province/Stream Gage Code (USGS Gage No. has prefix of 12-) (Amerman and Orsborn 1987).



Width, Depth and Channel Area at Q1F2

Width, depth and channel area data from Table 3-2 for 16 USGS gaging stations have been plotted in Figures 3-6, 3-7 and 3-8 versus the average annual amount of water entering the basins (PA_b). Other graphs of these channel characteristics were plotted against just basin area (A_b). Figure 3-9 is an example of W vs. A_b, at Q7L2, which was one of the better graphs of W vs. A_b. The data points were too widely scattered to be of use. Therefore, PA_b was chosen as the common independent variables for comparison of W, D and A_c at Q1F2, QAA and Q7L2.

Figure 3-6. Channel Characteristics versus PA_b for Olympic Peninsula Streams at Q1F2.

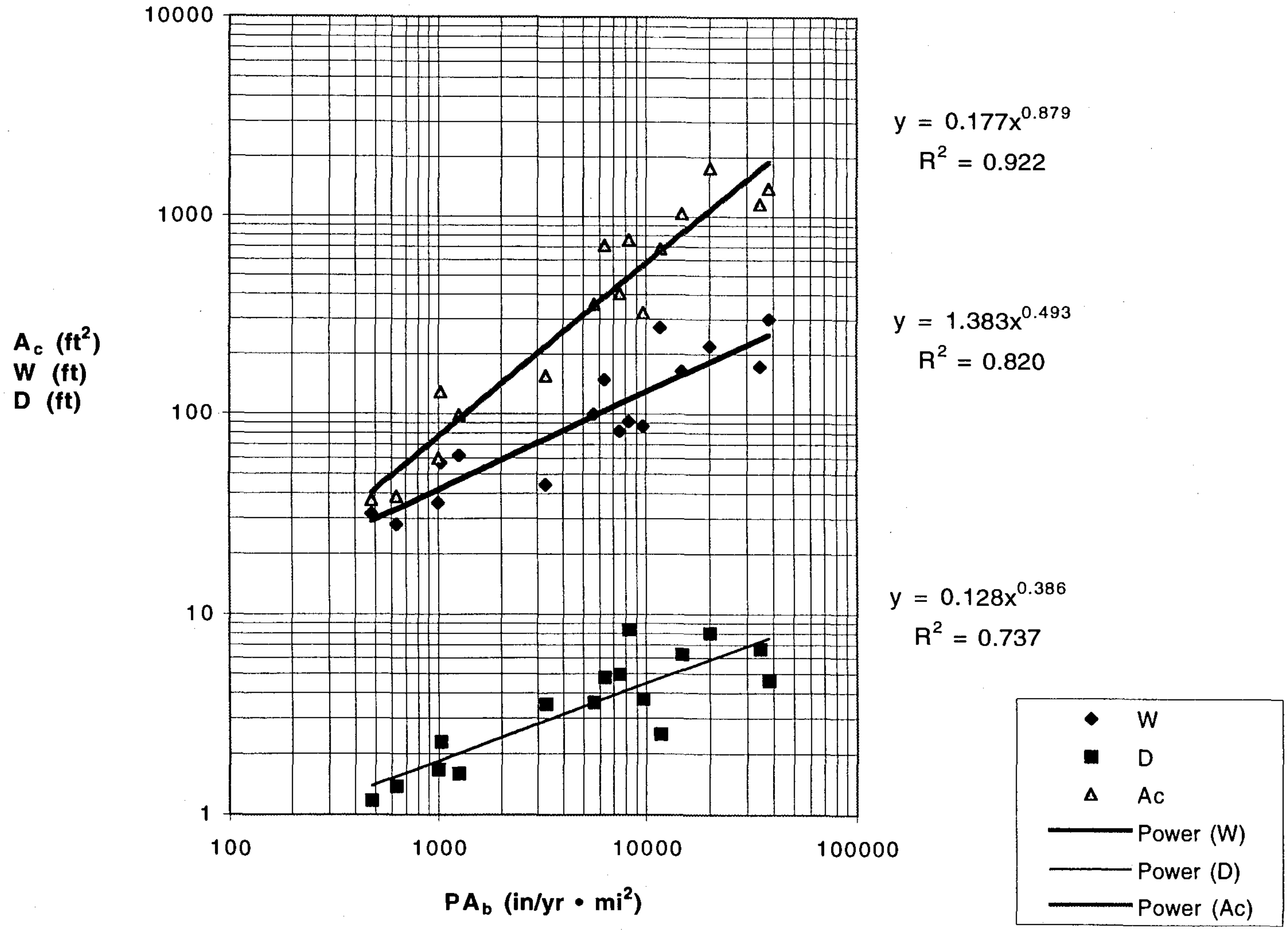


Figure 3-7. Channel Characteristics versus PA_b for Olympic Peninsula Streams at QAA.

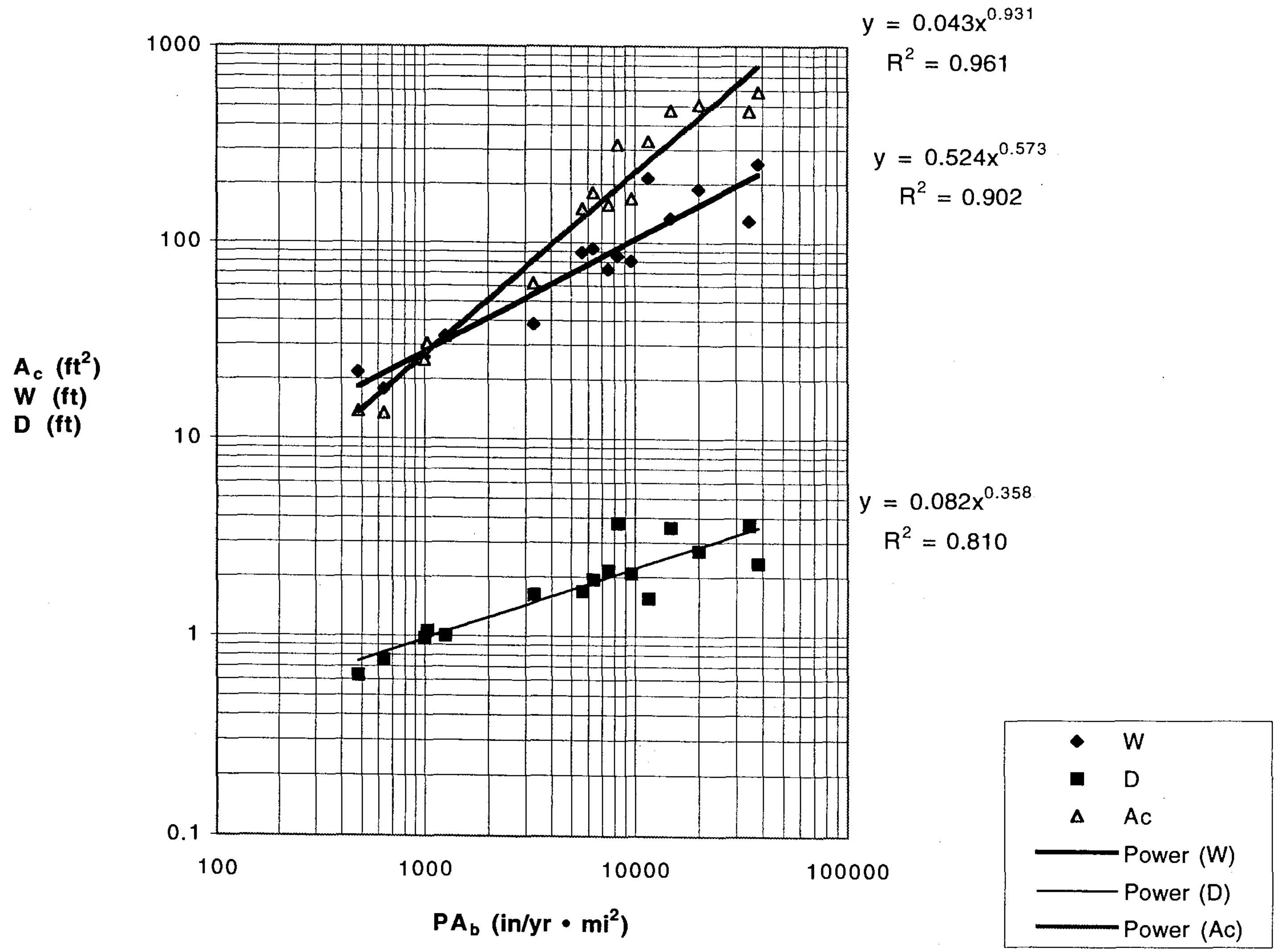


Figure 3-8. Channel Characteristics versus PA_b for Olympic Peninsula Streams at Q7L2.

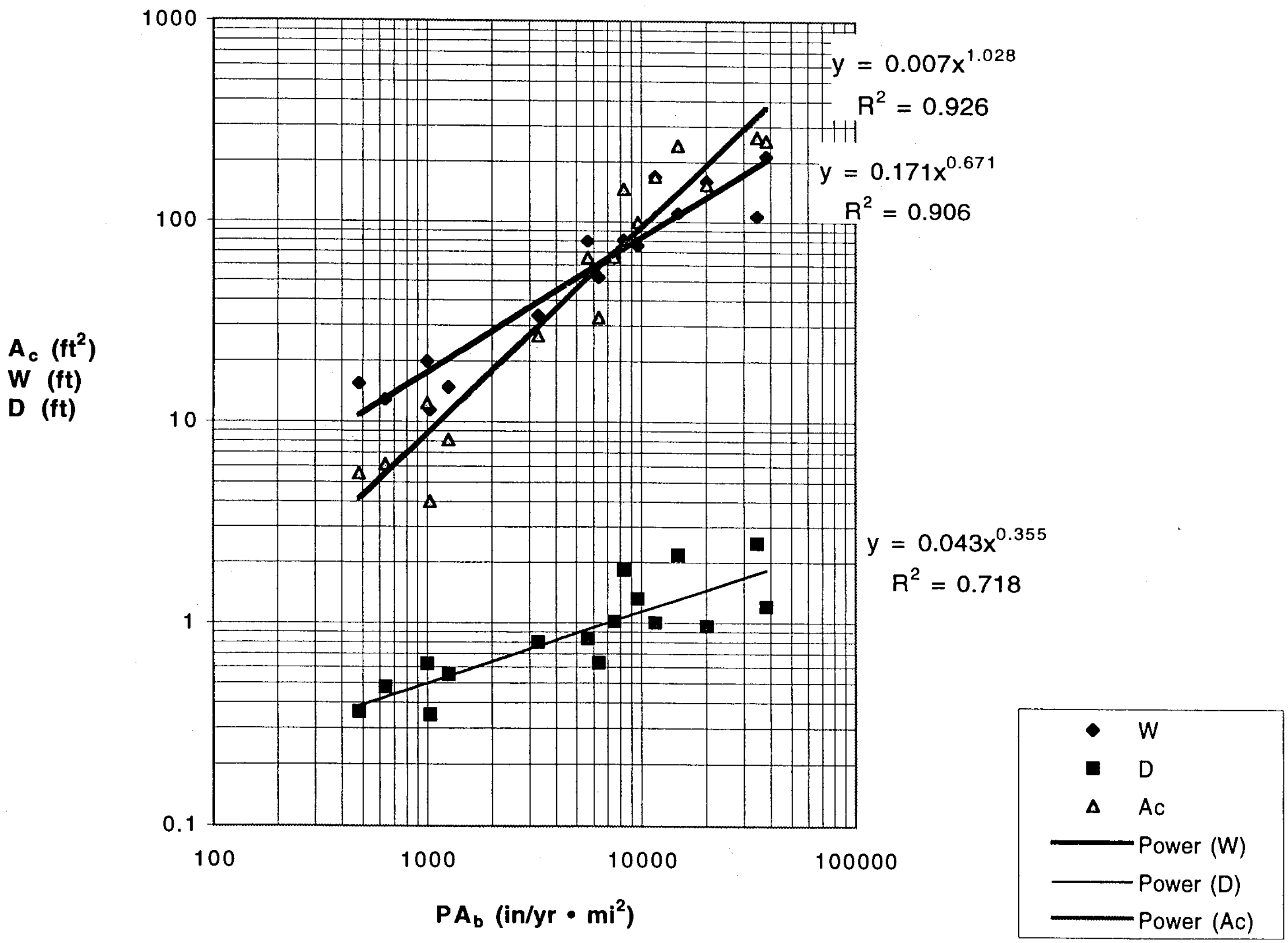
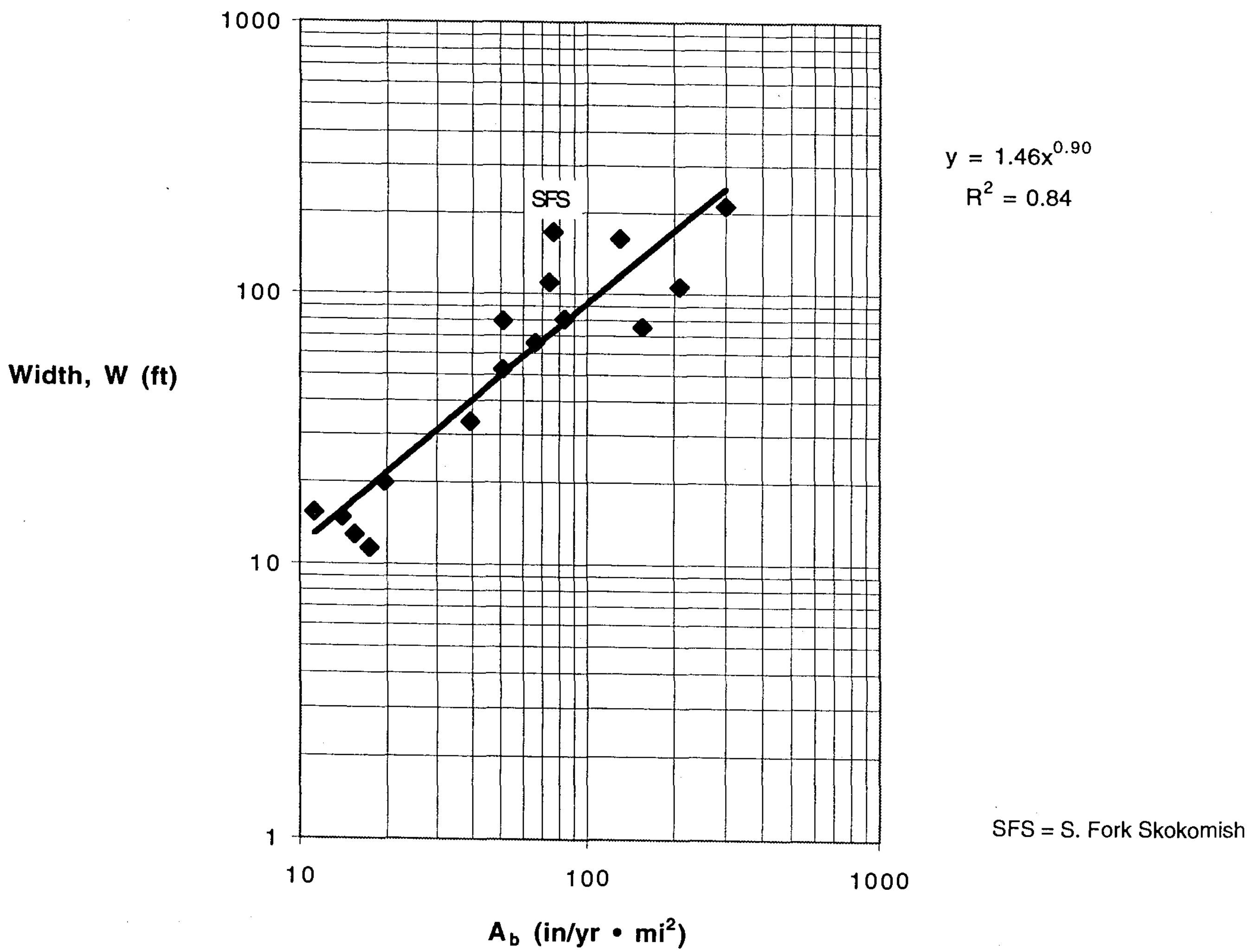


Figure 3-9. Channel Width versus A_b for Olympic Peninsula Streams at Q7L2.



Combined Relationships of Channel and Basin Characteristics for the Olympic Peninsula

In this section, channel geometric characteristics of W, D and A_c developed in the regional hydraulic geometry analyses (Figures 3-1, 3-2, 3-3 and 3-4), are combined with equations for Q1F2, QAA and Q7L2 as a function of basin characteristics.

FLOOD FLOWS

The **regional hydraulic geometry** equations for W, D, and A_c at Q1F2 are:

$$W = 2.40\ (Q1F2)^{0.47} \qquad (3\text{-}1)$$

$$D = 0.22\ (Q1F2)^{0.36} \qquad (3\text{-}2)$$

$$A_c = 0.52\ (Q1F2)^{0.83} \qquad (3\text{-}3)$$

For the mean daily flood as a function of basin characteristics we developed two relationships:

In Figure 3-10:

$$Q1F2 = 2.89\ (A_b)^{1.74} \qquad (3\text{-}4)$$

That is a relationship in which the dimensions are not the same on both sides of Eq. 3-4..

In Figure 3-11:

$$Q1F2 = 0.27\ (PA_b)^{1.05} \qquad (3\text{-}5)$$

in which the dimensions on both sides of the equation are the same (L^3 / T) (assuming the 1.05 exponent is really 1.00).

Setting Eq. 3-5 equal to Eqs. 3-1, 3-2, and 3-3 for W, D, and A_c gives for the average daily flood (Q1F2) for these 16 Olympic Peninsula streams:

Width:	$\mathbf{W = 1.30\ (PA)^{0.50}}$	**(3-6)**
Depth:	$\mathbf{D = 0.14\ (PA)^{0.38}}$	**(3-7)**
Area:	$\mathbf{A_c = 0.18\ (PA)^{0.87}}$	**(3-8)**

The values of W, D and A_c estimated by Eqs. 3-6, 3-7 and 3-8 are listed in Table 3-4, with the values calculated from the at-a station hydraulic (transferred from Table 3-2). The combined hydraulic geometry - basin characteristic values of W, D and A_c are compared with the estimated values in Figure 3-12.

Figure 3-10. Q1F2 versus A_b for Olympic Peninsula Streams.

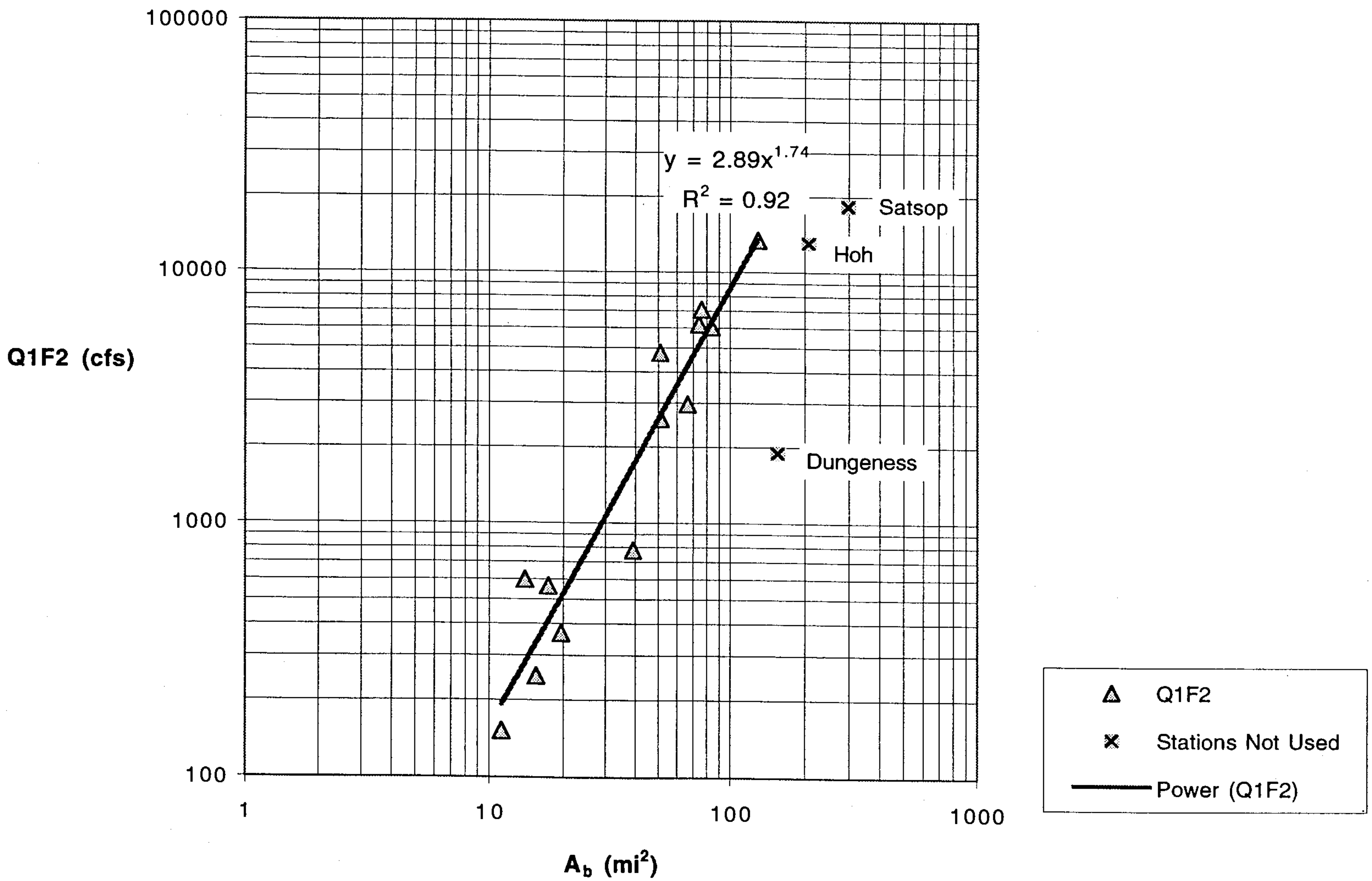


Figure 3-11. Q1F2 versus PA_b for Olympic Peninsula Streams.

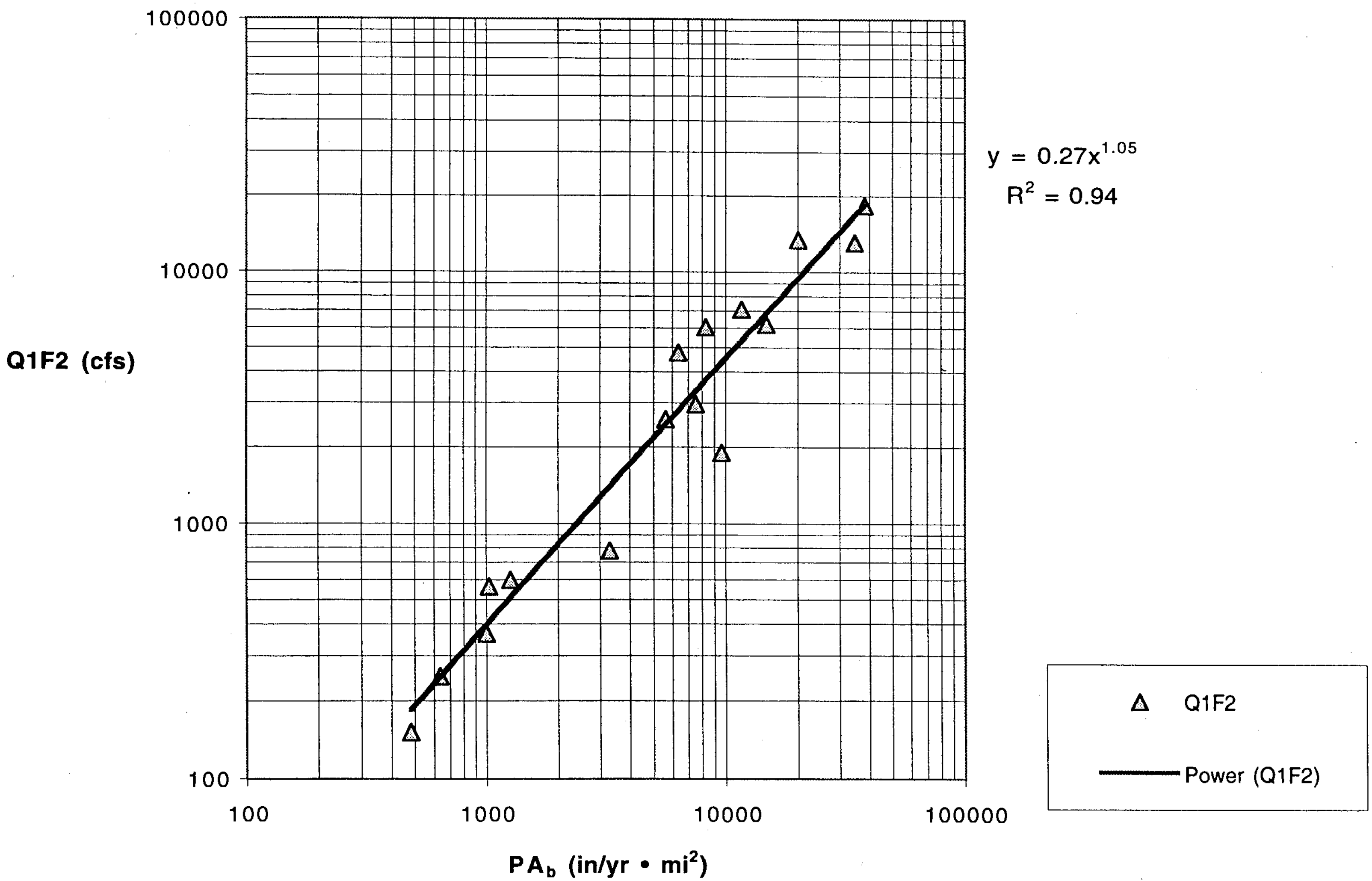
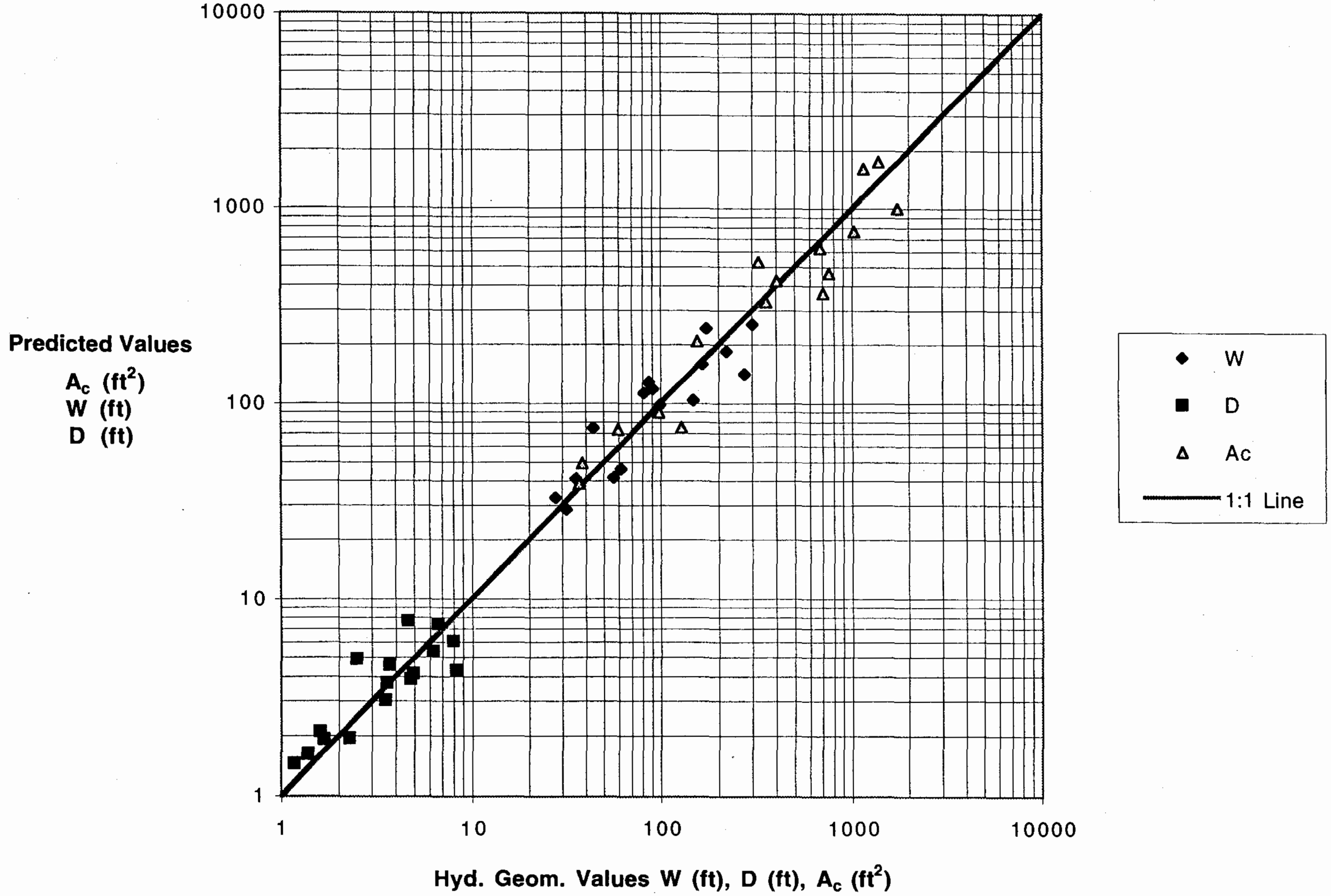


Table 3-4. Channel Width, Depth, and Area Comparison at Q1F2 for Olympic Peninsula Streams

					$W = C(PA)^E$		$D = C(PA)^E$		$A_c = C(PA)^E$	
					C:	1.3	C:	0.14	C:	0.18
					E:	0.5	E:	0.38	E:	0.87
					Table 3-2 Hyd. Geom.	Equation 3-6 Estimated	Table 3-2 Hyd. Geom.	Equation 3-7 Estimated	Table 3-2 Hyd. Geom.	Equation 3-8 Estimated
Province/ Stream Gage Code	Station Name	USGS Gage No.	Q1F2 (cfs)	Basin Input (PA_b) (sq. mi-in/yr)	W @ Q1F2 (ft)	W Pred (ft)	D @ Q1F2 (ft)	D Pred (ft)	A @ Q1F2 (ft^2)	A Pred (ft)
1.3	Satsop River	12035000	18307	38272	301	254	4.61	7.72	1387	1747
1.5	Humptulips River	12039000	13393	20150	220	185	7.99	6.05	1755	1000
3.1	N.F. Quinault River	12039300	6182	14820	165	158	6.25	5.38	1029	765
3.5	Hoh River	12041000	13053	34736	174	242	6.62	7.44	1150	1606
3.7	Soleduck River	12041500	6021	8296	91	118	8.29	4.32	756	462
4.1	Hoko River	12043300	4739	6349	148	104	4.79	3.90	710	366
4.2	East Twin River	12043430	595	1260	62	46	1.59	2.11	98	90
5.2	Dungeness River	12048000	1903	9672	87	128	3.73	4.58	324	528
6.1	Siebert Creek	12047500	249	636	28	33	1.38	1.63	38	49
6.2	Snow Creek	12050500	151	482	32	29	1.17	1.46	37	39
6.3	L. Quilcene River	12052000	365	1000	36	41	1.67	1.93	60	73
8.2	Duckabush River	12054000	2965	7515	82	113	4.95	4.16	404	424
8.3	Hamma Hamma River	12054500	2576	5643	99	98	3.59	3.73	357	330
8.8	S.F. Skokomish River	12060500	7083	11674	273	140	2.50	4.92	683	622
9.1	Goldsborough Creek	12076500	778	3301	44	75	3.52	3.04	155	207
9.2	Kennedy Creek	12078400	563	1027	56	42	2.28	1.95	129	75

Figure 3-12. Q1F2 Predictions versus USGS Values for Width, Depth and Channel Area for Olympic Peninsula Streams



AVERAGE ANNUAL FLOWS

Example equations for channel width at average annual flows were developed in Part 2. Equation 2-18 is

$$\mathbf{W\ (at\ QAA) = 0.32\ (P)^{0.75}\ (A_b)^{0.47}} \qquad (2\text{-}18,\ \mathbf{3\text{-}9})$$

For depth we combine the regional hydraulic geometry equations from Figure 3-2 with the Olympic Peninsula average annual flow equation (Eq. 2-16) so that

$$D = 0.29\ (QAA)^{0.32} \quad \text{and}$$

$$QAA = 0.0032\ (P)^{1.60}\ A_b \qquad (2\text{-}16,\ \mathbf{3\text{-}10})$$

which reduces to

$$D = 0.29\ (0.0032\ (P)^{1.60}\ A_b)^{0.32}$$

or

$$\mathbf{D = 0.046\ (P)^{0.51}\ (A_b)^{0.32}} \qquad \mathbf{(3\text{-}11)}$$

For channel area, A_c, using the regional geometry equation from Figure 3-4 at QAA, in combination with Eq. 3-10, yields

$$A_c = 1.16\ (QAA)^{0.83} \qquad \text{(From Figure 3-4)}$$

$$QAA = 0.0032\ (P)^{1.60} A_b \qquad \text{(substitute above)} \qquad (3\text{-}10)$$

and

$$\mathbf{A_c = 0.0098\ (P)^{1.33}\ (A_b)^{0.83}} \qquad \mathbf{(3\text{-}12)}$$

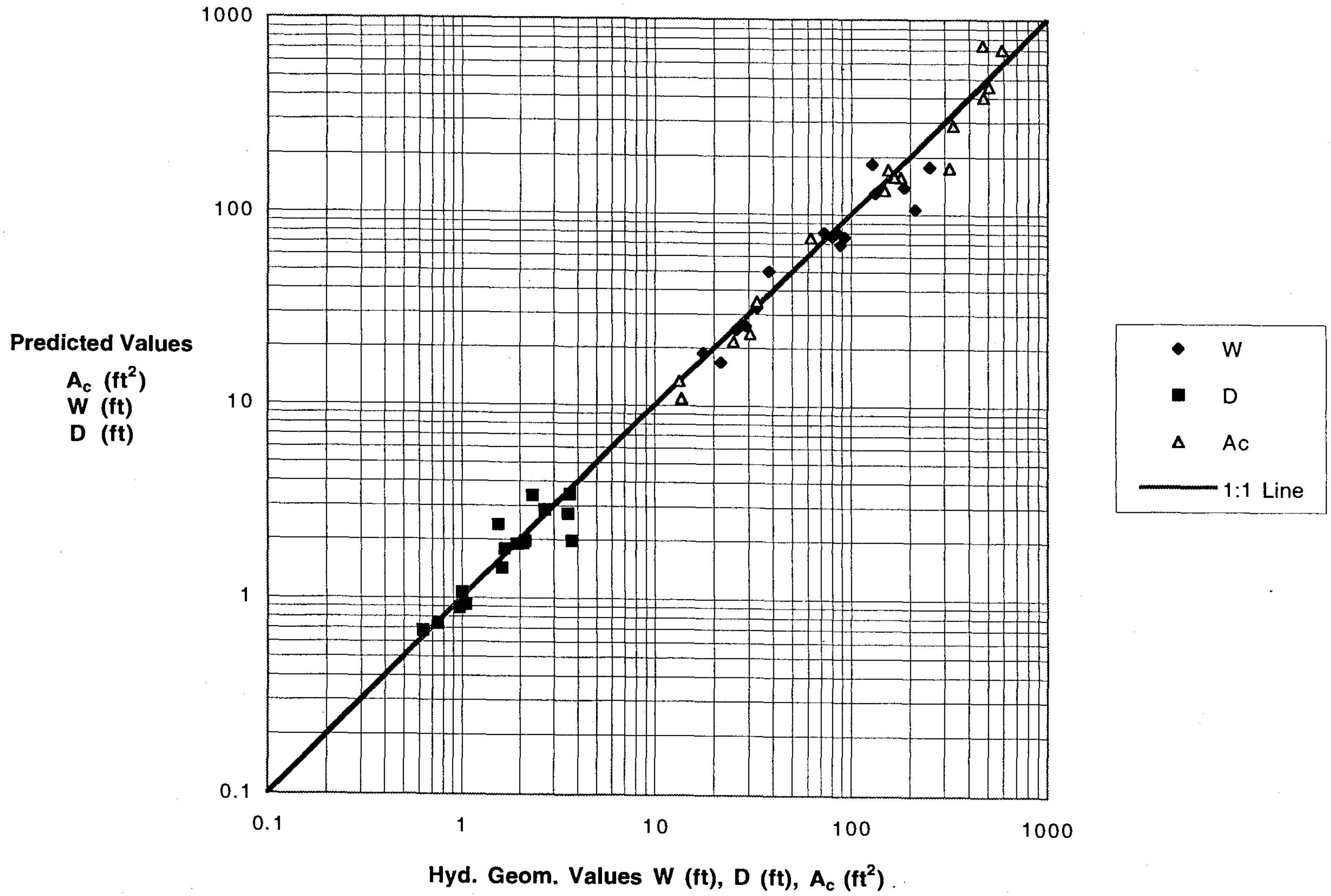
For comparison, the hydraulic geometry at-a-station values of W, D and A_c at QAA and the estimated values from Eqs. 3-9, 3-11 and 3-12, are listed in Table 3-5 and plotted in Figure 3-13.

Table 3-5. Channel Width, Depth, and Area Comparison at QAA for Olympic Peninsula Streams

	$W = C(P)^{E1}(A_b)^{E2}$	$D = C(P)^{E1}(A_b)^{E2}$	$A = C(P)^{E1}(A_b)^{E2}$
C:	0.32	0.046	0.0098
E1:	0.75	0.51	1.33
E2:	0.47	0.32	0.83

Province/ Stream Gage Code	Station Name	USGS Gage No.	QAA (cfs)	Average Annual Precip., P (in/yr)	Drainage Area, Ab (sq. mi.)	Table 3-2 Hyd. Geom. W @ QAA (ft)	Equation 3-9 Estimated W Pred (ft)	Table 3-2 Hyd. Geom. D @ QAA (ft)	Equation 3-11 Estimated D Pred (ft)	Table 3-2 Hyd. Geom. A @ QAA (ft^2)	Equation 3-12 Estimated A Pred (ft)
1.3	Satsop River	12035000	2035.0	128	299.0	252.3	177.5	2.33	3.39	587.8	705.7
1.5	Humptulips River	12039000	1337.0	155	130.0	186.9	138.5	2.70	2.86	504.6	456.0
3.1	N.F. Quinault River	12039300	887.0	200	74.1	133.0	128.7	3.56	2.72	473.5	401.4
3.5	Hoh River	12041000	2028.0	167	208.0	128.9	182.7	3.65	3.45	470.5	743.8
3.7	Soleduck River	12041500	621.0	99	83.8	85.2	80.5	3.74	1.98	318.6	174.5
4.1	Hoko River	12043300	408.0	124	51.2	93.0	75.6	1.93	1.89	179.5	156.4
4.2	East Twin River	12043430	64.7	90	14.0	33.1	32.3	1.00	1.06	33.1	34.8
5.2	Dungeness River	12048000	393.0	62	156.0	80.2	75.9	2.08	1.90	166.8	156.8
6.1	Siebert Creek	12047500	17.1	41	15.5	17.7	18.8	0.75	0.73	13.3	13.3
6.2	Snow Creek	12050500	16.2	43	11.2	21.7	16.7	0.63	0.68	13.7	10.8
6.3	L. Quilcene River	12052000	48.6	51	19.6	25.9	24.7	0.97	0.89	25.1	21.6
8.2	Duckabush River	12054000	422.0	113	66.5	72.6	79.7	2.14	1.96	155.4	171.7
8.3	Hamma Hamma River	12054500	364.0	110	51.3	88.3	69.2	1.68	1.78	148.3	133.6
8.8	S.F. Skokomish River	12060500	741.0	153	76.3	213.1	106.8	1.55	2.40	330.3	288.0
9.1	Goldsborough Creek	12076500	116.0	84	39.3	38.2	49.9	1.62	1.43	61.9	74.8
9.2	Kennedy Creek	12078400	61.3	59	17.4	29.0	26.1	1.05	0.92	30.4	23.8

Figure 3-13. QAA Predictions versus USGS Values for Width, Depth and Channel Area for Olympic Peninsula Streams



7-DAY AVERAGE LOW FLOWS

As shown in Figure 3-14, with data from Tables 3-1 and 3-2:

$$Q7L2 = 0.0067\,(PBE)^{1.06} \qquad (3\text{-}13)$$

and from Figures 3-3 and 3-4

$$W = 8.37\,(Q7L2)^{0.52} \qquad (3\text{-}14)$$

$$D = 0.31\,(Q7L2)^{0.30} \qquad (3\text{-}15)$$

$$A_c = 2.56\,(Q7L2)^{0.82} \qquad (3\text{-}16)$$

Substituting Eq. 3-13 for Q7L2 in the three equations just above yields

$$W = 8.37\,(0.0067\,(PBE)^{1.06})^{0.52}$$

or

$$W = 0.62\,(PBE)^{0.55} \qquad (3\text{-}17)$$

where PBE is average annual precipitation (**P**) multiplied by **B**asin **E**nergy = $A_b\,(H)^{0.50}$.

Substituting these terms into Eq. 3-17 gives

$$\mathbf{W = 0.62\,(P)^{0.55}\,(A_b)^{0.55}\,(H)^{0.29}} \qquad \mathbf{(3\text{-}18)}$$

The depth equation becomes

$$D = 0.31\,(0.0067\,(PBE)^{1.06})^{0.30}$$

or

$$\mathbf{D = 0.069\,(P)^{0.32}\,(A_b)^{0.32}\,(H)^{0.16}} \qquad \mathbf{(3\text{-}19)}$$

For the channel area (A_c) Eq. 3-16 combines with Eq. 3-13 to give

$$A_c = 2.56\,(0.0067\,(PBE)^{1.06})^{0.82}$$

or

$$\mathbf{A_c = 0.042\,(P)^{0.87}\,(A_b)^{0.87}\,(H)^{0.46}} \qquad \mathbf{(3\text{-}20)}$$

The calculated and estimated values of W, D and A_c for Q7L2 are listed in Table 3-6 and plotted in Figure 3-15.

Figure 3-14. Q7L2 versus PBE for Olympic Peninsula Streams.

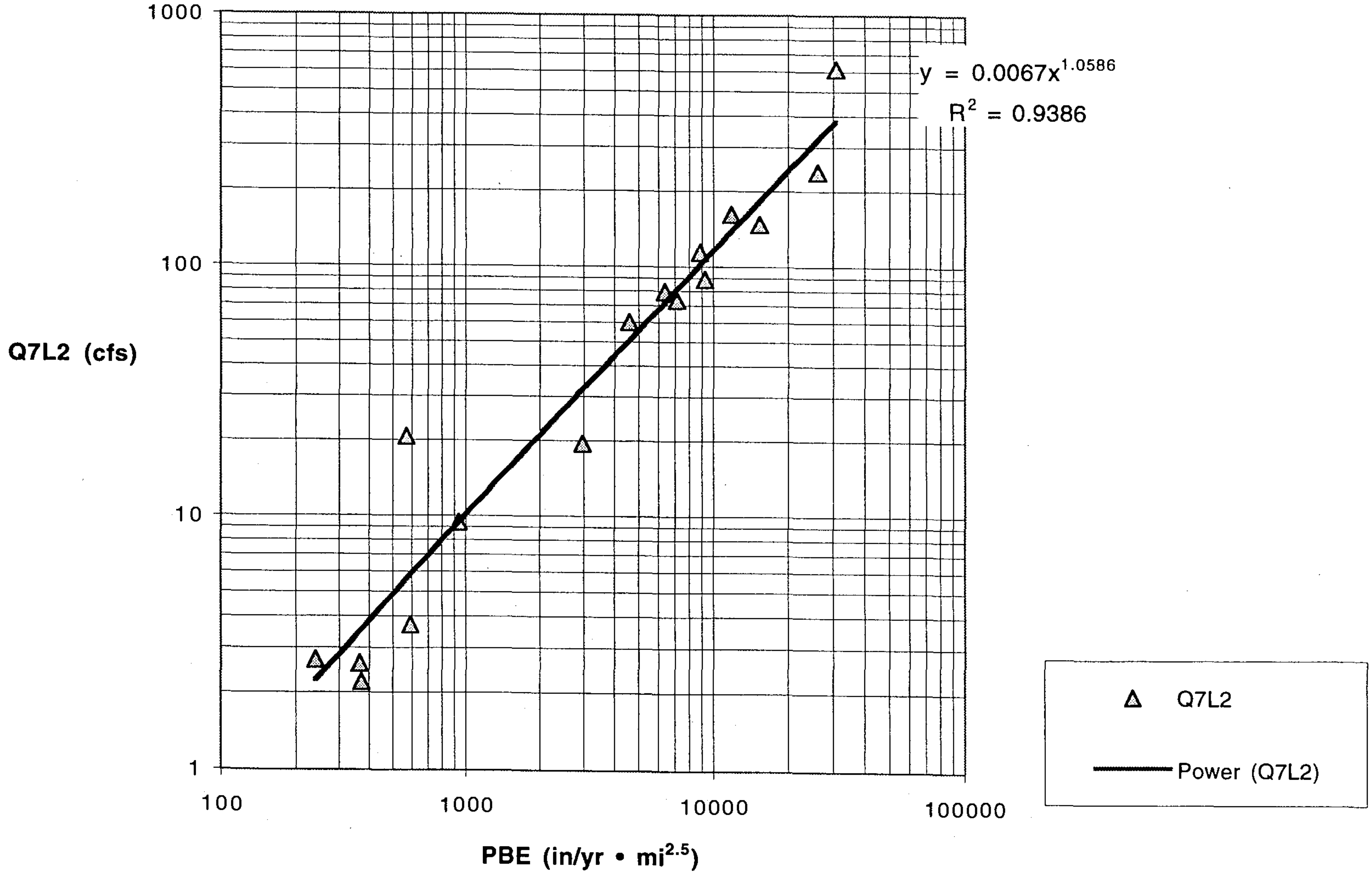
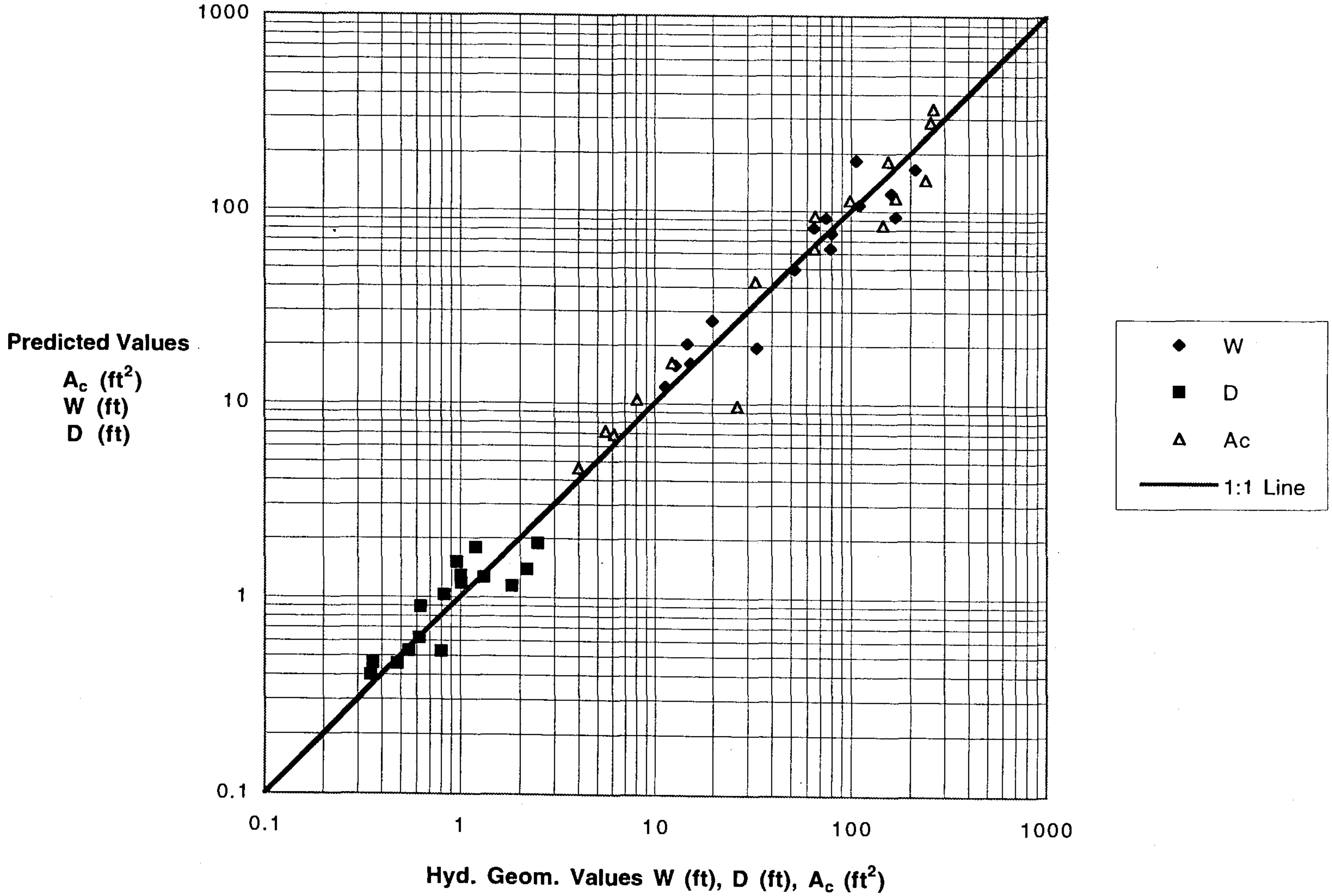


Table 3-6. Channel Width, Depth, and Area Comparison at Q7L2 for Olympic Peninsula Streams

	$W = C(PA)^{E1}(H)^{E2}$	$D = C(PA)^{E1}(H)^{E2}$	$A = C(PA)^{E1}(H)^{E2}$
C:	0.62	0.069	0.042
E1:	0.55	0.32	0.87
E2:	0.29	0.16	0.46

Province/ Stream Gage Code	Station Name	USGS Gage No.	Q7L2 (cfs)	Basin Input (PA) (sq. mi-in/yr)	Basin Relief, H (mi)	Table 3-2 Hyd. Geom. W @ Q7L2 (ft)	Equation 3-18 Estimated W Pred (ft)	Table 3-2 Hyd. Geom. D @ Q7L2 (ft)	Equation 3-19 Estimated D Pred (ft)	Table 3-2 Hyd. Geom. A @ Q7L2 (ft^2)	Equation 3-20 Estimated A Pred (ft)
1.3	Satsop River	12035000	238.7	38272	0.47	212.6	165	1.20	1.79	255.1	288
1.5	Humptulips River	12039000	146.7	20150	0.58	160.1	123	0.96	1.51	153.7	182
3.1	N.F. Quinault River	12039300	161.1	14820	0.64	110.2	107	2.17	1.39	239.1	145
3.5	Hoh River	12041000	610.0	34736	0.79	106.4	182	2.48	1.89	263.9	336
3.7	Soleduck River	12041500	79.3	8296	0.59	80.1	76	1.82	1.14	145.8	85
4.1	Hoko River	12043300	19.5	6349	0.22	52.2	49	0.63	0.89	32.9	43
4.2	East Twin River	12043430	3.7	1260	0.22	14.8	20	0.55	0.53	8.1	10
5.2	Dungeness River	12048000	113.6	9672	0.84	75.4	92	1.31	1.27	98.8	114
6.1	Siebert Creek	12047500	2.6	636	0.33	12.8	16	0.48	0.46	6.1	7
6.2	Snow Creek	12050500	2.2	482	0.60	15.4	16	0.36	0.46	5.5	7
6.3	L. Quilcene River	12052000	9.4	1000	0.88	19.9	27	0.62	0.62	12.3	16
8.2	Duckabush River	12054000	73.4	7515	0.90	65.4	81	1.01	1.18	66.1	94
8.3	Hamma Hamma River	12054500	59.9	5643	0.66	79.2	64	0.83	1.02	65.7	64
8.8	S.F. Skokomish River	12060500	88.8	11674	0.63	168.7	94	1.00	1.28	168.7	117
9.1	Goldsborough Creek	12076500	20.6	3301	0.030	33.5	19	0.80	0.53	26.8	10
9.2	Kennedy Creek	12078400	2.7	1027	0.055	11.4	12	0.35	0.40	4.0	5

Figure 3-15. Q7L2 Predictions versus USGS Hydraulic Geometry Values for Width, Depth and Channel Area for Olympic Peninsula Streams



Discussion of Olympic Peninsula Empirical and Combined Relationships of Channel, Flow and Basin Characteristics

Figures 3-6, 3-7, 3-8 and 3-9: (Data in Tables 3-1 and 3-2) The values of A_c, W, and D are plotted against PA_b (the average annual amount of precipitation entering the basins) in the first three figures for the three characteristic flows. For an example of simpler graphs, the W at Q7L2 is plotted against just A_b in Figure 3-9. It compares with W versus PA_b in Figure 3-8:

Figure 3-9: $W = 1.46\,(A_b)^{0.90}$; $R^2 = 0.84$

Figure 3-8: $W = 0.17\,(PA_b)^{0.67}$; $R^2 = 0.91$

The graph in Figure 3-8 improves the correlation by adding (P) and spreads the data along the PA_b axis.

The Olympic Peninsula gages represent a wide range of stream hydrology and geomorphology, and variable periods of record (Amerman and Orsborn 1987). Average annual precipitation (P) ranges from 40 to 200 inches per year on the USGS-gaged basins, and the accuracy of these values is limited by the low number of precipitation gages and snow courses (Williams et al 1985a, 1985b, and Williams and Pearson 1985).

Many of the stream gages on the Olympic Peninsula are situated in bedrock or large boulder cross-sections. The large rock and bedrock conditions, for example, exist at the Soleduck, Dungeness, Duckabush and Hoh gages, all of which plot below the width graph in Figure 3-6.

Also, some readily deformible gaging station cross-sections exist, such as the S. F. Skokomish, which has a width of 273 ft at Q1F2 (farthest point from the W vs. PA line in Figure 3-6). As a result of the excess sediment caused by logging the depth D has reduced to 1.0 ft (in Figure 3-8 for Q7L2). The low flow width has increased to 168 ft from a pre-logging width of about 90 ft.

Therefore, even though the Olympic Peninsula gages display quite a bit of variation as a function of (PA_b) in Figures 3-6, 3-7 and 3-8, knowledge of the geomorphology of gage sites assists in examining their plotting positions with respect to the average equations. Note the plotting position of the S.F. Skokomish in Figure 3-9 (W vs. A_b).

Comparing COMBINED equations and the EMPIRICAL relations for Q1F2:

At Q1F2

COMBINED	Eq. No.	EMPIRICAL	Fig. No.
Width: $W = 1.30\ (PA)^{0.50}$	3-6	$W = 1.38\ (PA)^{0.49}$	3-6
Depth: $D = 0.14\ (PA)^{0.38}$	3-7	$D = 0.13\ (PA)^{0.39}$	3-6
Area: $A_c = 0.18\ (PA)^{0.87}$	3-8	$A_c = 0.18\ (PA)^{0.88}$	3-6

These equations are all very similar because Q1F2 was equal to $0.27(PA_b)^{1.05}$ from Fig. 3-11, and this equation of $0.27\ (PA_b)^{1.05}$ was substituted into the hydraulic geometry equations. The comparison of the values of W, D and A_c at Q1F2 are given in Table 3-4 the last six columns, and in Figure 3-12. Some values of W and A_c are quite close, but depth, as Williams (1978, Part 2) discussed, "the exponent of depth (in hydraulic geometry) (is) fair." One would expect the W, D and A_c values at Q1F2 to display quite a bit of scatter over such a large hydrologically diverse region with highly variable geology and variable periods of record.

For average annual flow (QAA) the COMBINED and EMPIRICAL relations are:

At QAA

COMBINED	Eq. No.	EMPIRICAL	Fig. No.
$W = 0.32\ (P)^{0.75}\ A_b^{\ 0.47}$	3-9	$W = 0.52\ (PA)^{0.57}$	3-12
$D = 0.046\ (P)^{0.51}\ (A_b)^{0.32}$	3-11	$D = 0.08\ (PA)^{0.36}$	3-12
$A_c = 0.0098\ (P)^{1.33}\ (A_b)^{0.83}$	3-12	$A_c = 0.04\ (PA)^{1.93}$	3-12

For QAA, the combined equations account for the variation in runoff as a function of $(P)^{1.60}$, whereas for Q1F2 (and for Q7L2) the equations do not account for this. But for low flow $Q7L2 = 0.067\ (PBE)^{1.06}$, which says the low flow is a function (almost to the first power) of average annual precipitation (P), the drainage area of the basin (A_b) and the relief $(H)^{0.50}$. The area and relief $(AH^{0.50})$ were developed early in Part 3, Methods of Analysis, and as part of the Froude No. of the watershed (Eq. 1-2 and Eq. 2-4).

Comparing the COMBINED and EMPIRICAL EQUATIONS FOR Q7L2:

At Q7L2

COMBINED	Eq. No.	EMPIRICAL	Fig. No.
$W = 0.62\ (P)^{0.55} (A_b)^{0.55} (H)^{0.29}$	3-18	$W = 0.17\ (PA)^{0.55}$	3-8
$D = 0.069\ (P)^{0.32} (A_b)^{0.32} (H)^{0.16}$	3-19	$D = 0.04\ (PA)^{0.32}$	3-8
$A_c = 0.042\ (P)^{0.87} (A_b)^{0.87} (H)^{0.46}$	3-20	$A_c = 0.01\ (PA)^{0.87}$	3-8

The influence of the geology at the gaging sites on the estimating capability of the combined equations has been discussed. A comparison of common periods of record and site visits to all the gages not mentioned might improve our reasoning. But, the combined equations do improve our estimates of channel characteristics, even in this diverse region of about 8000 sq. mi.

The COMBINED equations are compared with the hydraulic geometry values of W, D, and A_c at Q7L2 in Table 3-6 and Figure 3-15.

PUGET LOWLAND REGION

Database and Empirical Relationships

There is no doubt that the streams in this region are responding to the urbanization of their watersheds (Moscrip and Montgomery 1997). These authors examined the influences of urbanization on: increases in flood flows (during a period of gradual decline in annual precipitation), and the attendant decrease in fish production, probably due to the increase in floods, and the more frequent and deeper scour of spawning beds.

Johnson and Orsborn (1997) used the following USGS-gaged streams for their preliminary design of the restoration of a natural, meandering channel in North Creek at the new University of Washington campus in Bothell: Quilceda, Woods, North, Swamp, Mercer, Griffin and two sites on Issaquah Creek. Mercer and Swamp Creeks, plus four others, were used by Moscrip and Montgomery (1997).

Most of the basin, channel and streamflow data for the eight Puget Lowland gages used in the North Creek restoration design are in Table 3-7. Data for Table 3-7 came from the USGS records for the gages (Form 9-207 and Williams, Pearson and Wilson 1985b). The data were arranged in common periods of record so that any changes in channel dimensions could be noted. For a preliminary regional analysis, channel area (A_c) was plotted as a function of basin area (A_b) for average daily floods (Q1F2) in Figure 3-16. The letters denote the stream name from Table 3-7, with IU denoting the Issaquah Creek upstream gage, and ID the downstream gage. There seemed to be a fairly good relationship among the upper data points, but Upper Issaquah, Griffin and North Creek fell well below the upper line.

This is made more obvious in Figure 3-17 where the graph has been drawn using only the upper five data points, and R^2 has increased from 0.70 to 0.97. This relationship, with three undersized cross-sectional channel areas, was found to hold true at the average annual flow (QAA) in Figure 3-18. This was still true when channel area (A_c) was plotted as a function of PA_b, the average annual basin inputs in Figure 3-19.

Now the question became, are the undersized channels narrow and deep, or shallow and wide, or a mixture? Next, the depth at Q1F2 was plotted versus basin area in Figure 3-20. Now Quilceda Creek appears as a deep channel (which may mean it is incised), but North, Griffin and Issaquah (U) are still below the main graph. In Figure 3-21, the width at Q1F2 was plotted against basin area, and shows Quilceda Creek has a narrower width to go with its greater depth to give an average area at Q1F2.

Table 3-7. Basic Streamflow, Channel and Basin Data for the Puget Lowland Region

Station	Q1F2	QAA	Q1F2/QAA Ratio	Q7L2	Ab	P	P*A	Years	Q1F2 W	Q1F2 D	Q1F2 W/D	Q1F2 Ac	QAA W	QAA D	QAA W/D	QAA Ac	Ac Ratio
Units:	*cfs*	*cfs*		*cfs*	*sq mi*	*in/yr*	*smi/y*		*ft*	*ft*		*ft*ft*	*ft*	*ft*		*ft*ft*	
Mercer	164.7	21.9	7.5	5.2	12	43	516	55-58	31	2.3	13.5	71.0	18	0.9	20.0	16.6	4.3
								68-71	27	2.9	9.3	75.1	15	1.3	11.5	18.7	4.0
								87-90	21	2.2	9.5	47.6	17	1.0	17.0	17.7	2.7
Issaquah-U	493.0	69.7	7.1	14.9	27	66	1782	55-58	54	1.5	36.0	85.0	33	0.9	36.7	28.4	3.0
Issaquah-D	1103.6	143.9	7.7	27.7	55	53	2915	68-71	47	4.0	11.8	180.1	43	1.4	30.7	57.5	3.1
								87-90	47	4.3	10.9	196.4	36	1.6	22.5	55.5	3.5
North Cr	255.8	36.4	7.0	6.3	25	38	950	55-58	20	2.3	8.7	47.0	18	1.0	18.0	19.2	2.4
								68-71	25	2.4	10.4	62.3	21	1.0	21.0	22.2	2.8
Swamp Cr	290.7	33.8	8.6	4.0	23	39	897	87-90	40	2.8	14.3	103.9	27	1.1	24.5	29.8	3.5
Woods Cr	1075.7	154.5	7.0	18.7	56	48	2688	55-58	47	3.7	12.7	165.6	42	1.5	28.0	61.6	2.7
								68-71	44	3.7	11.9	157.6	37	1.5	24.7	54.2	2.9
Griffin Cr	336.1	40.3	8.3	3.2	17	53	901	55-58	35	1.5	23.3	53.4	23	0.8	28.8	18.9	2.8
Quilceda Cr	144.2	25.6	5.6	4.1	15	37	555	55-58	20	3.7	5.4	73.7	16	1.2	13.3	20.1	3.7

Nomenclature:

Q1F2	one-day average flood flow with 2-yr recurrence interval (RI)	**P**	average annual precipitation on basin
QAA	average annual flow for period of record (POR)	**PA**	average inflow to basin (sq mi-in/yr)
Q7L2	7-day average low flow, 2-yr RI	**W**	channel water surface width
Ab	basin area	**D**	mean flow depth, Ac/W
		Ac	cross-sectional flow area of channel

Figure 3-16. NORTH CREEK REGIONAL ANALYSIS: Channel area at Q1F2 vs. Basin Area (All Points)

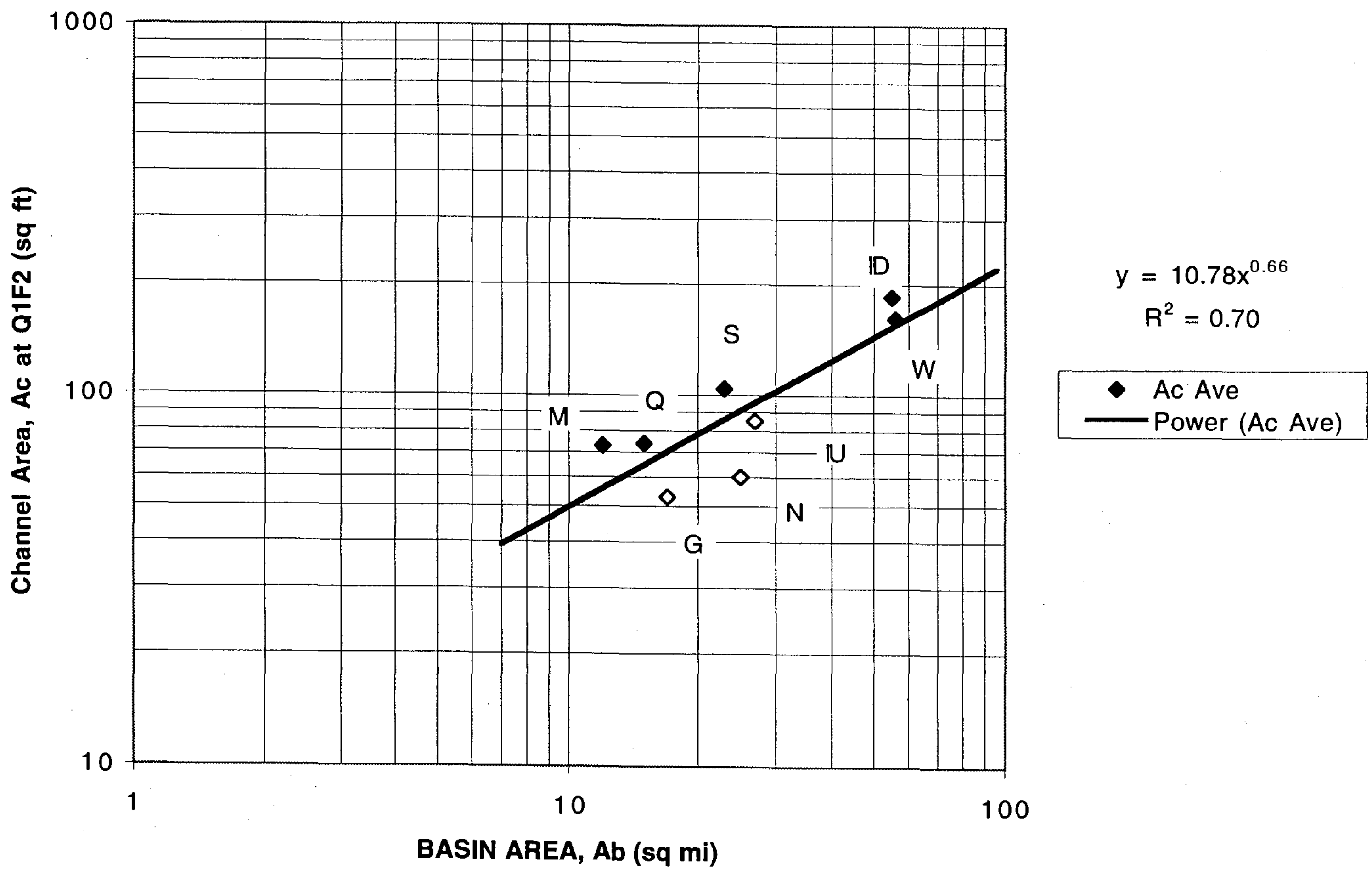


Figure 3-17. NORTH CREEK REGIONAL ANALYSIS:
Channel area at Q1F2 vs. Basin Area (Selected Points)

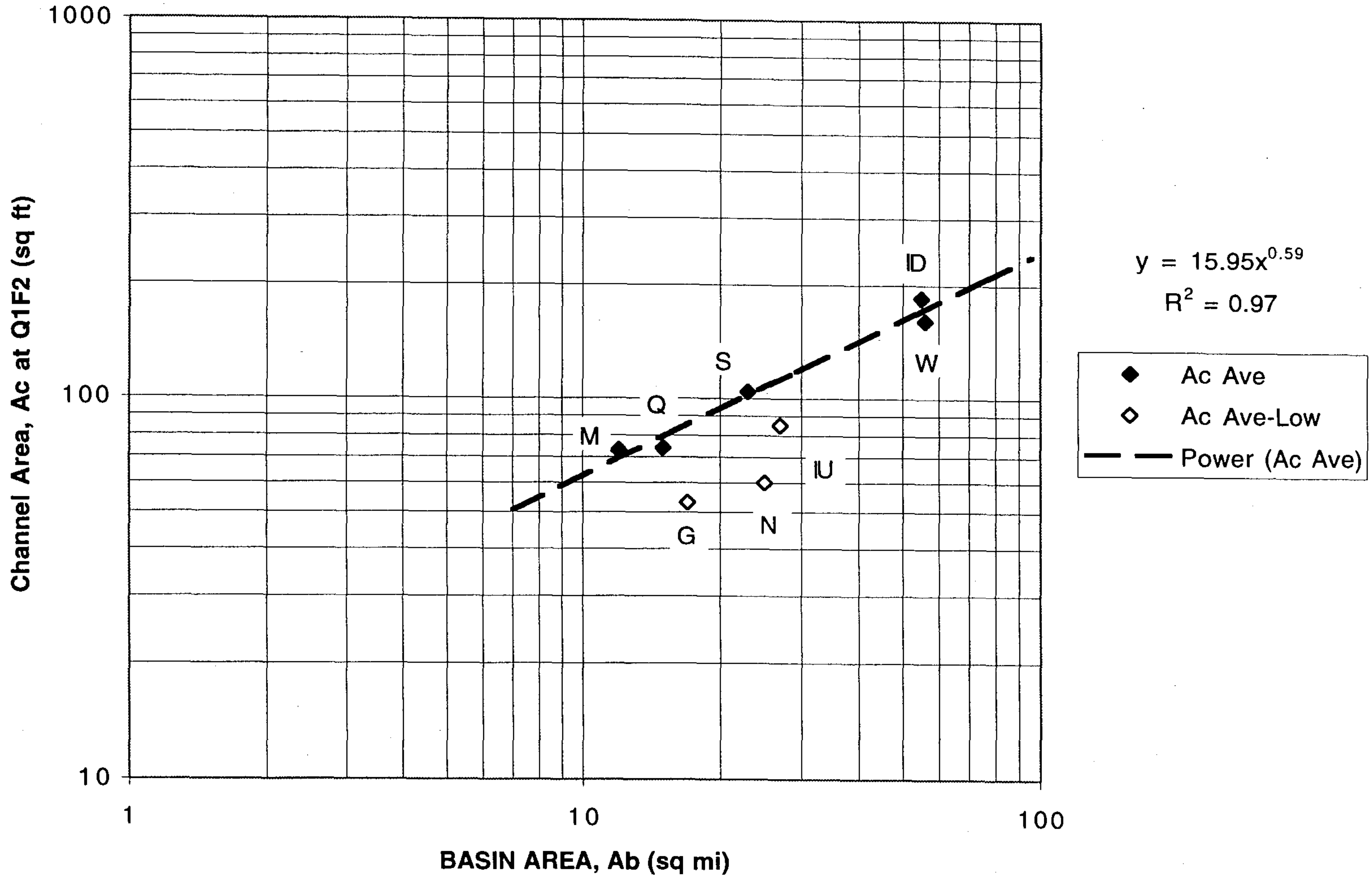


Figure 3-18. NORTH CREEK REGIONAL ANALYSIS: Channel area at QAA vs. Basin Area (Selected Points)

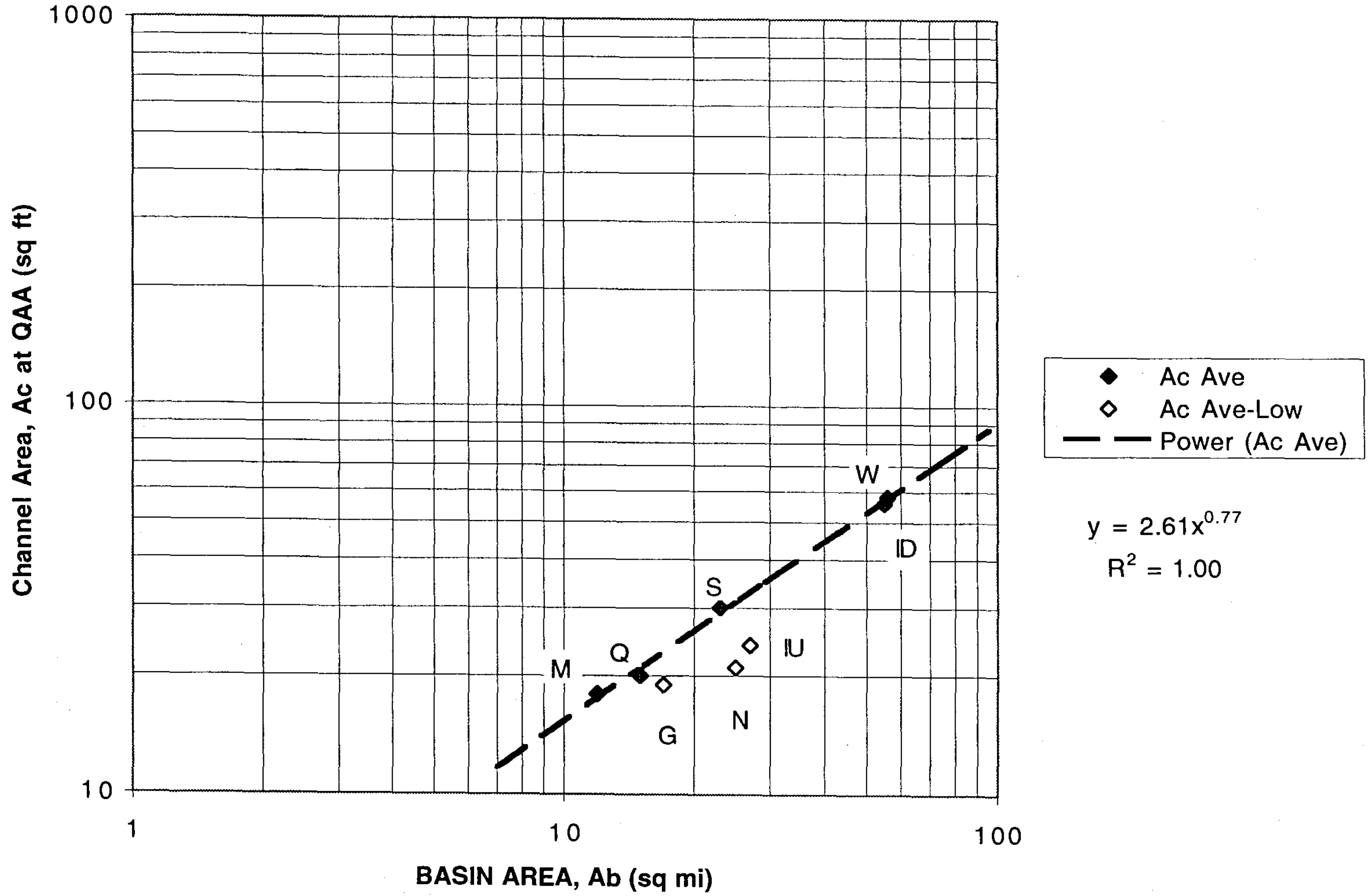


Figure 3-19. North Creek Regional Analysis, Channel Area at QAA for P*A

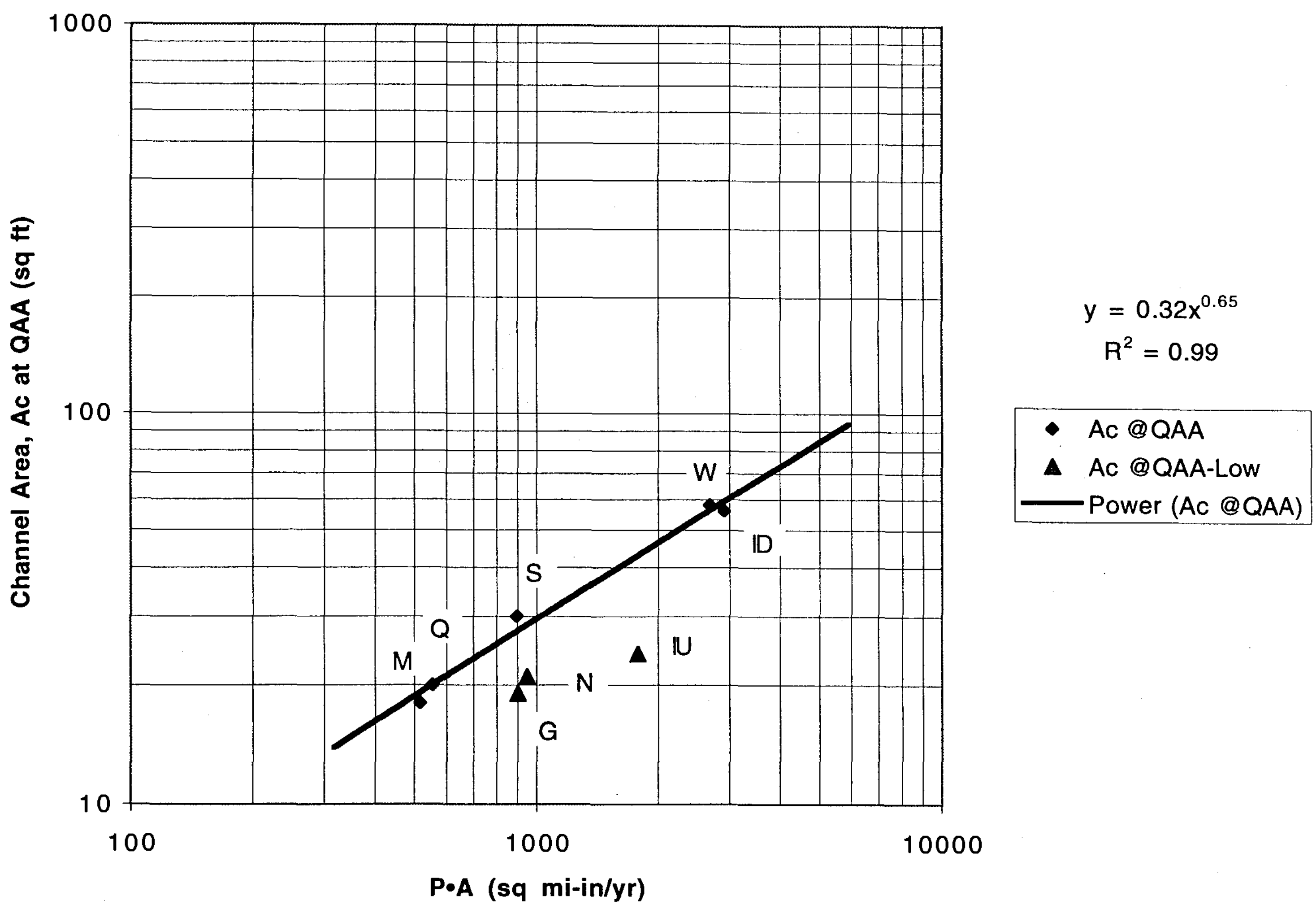


Figure 3-20: North Creek Regional Analysis of Depth at Q1F2.

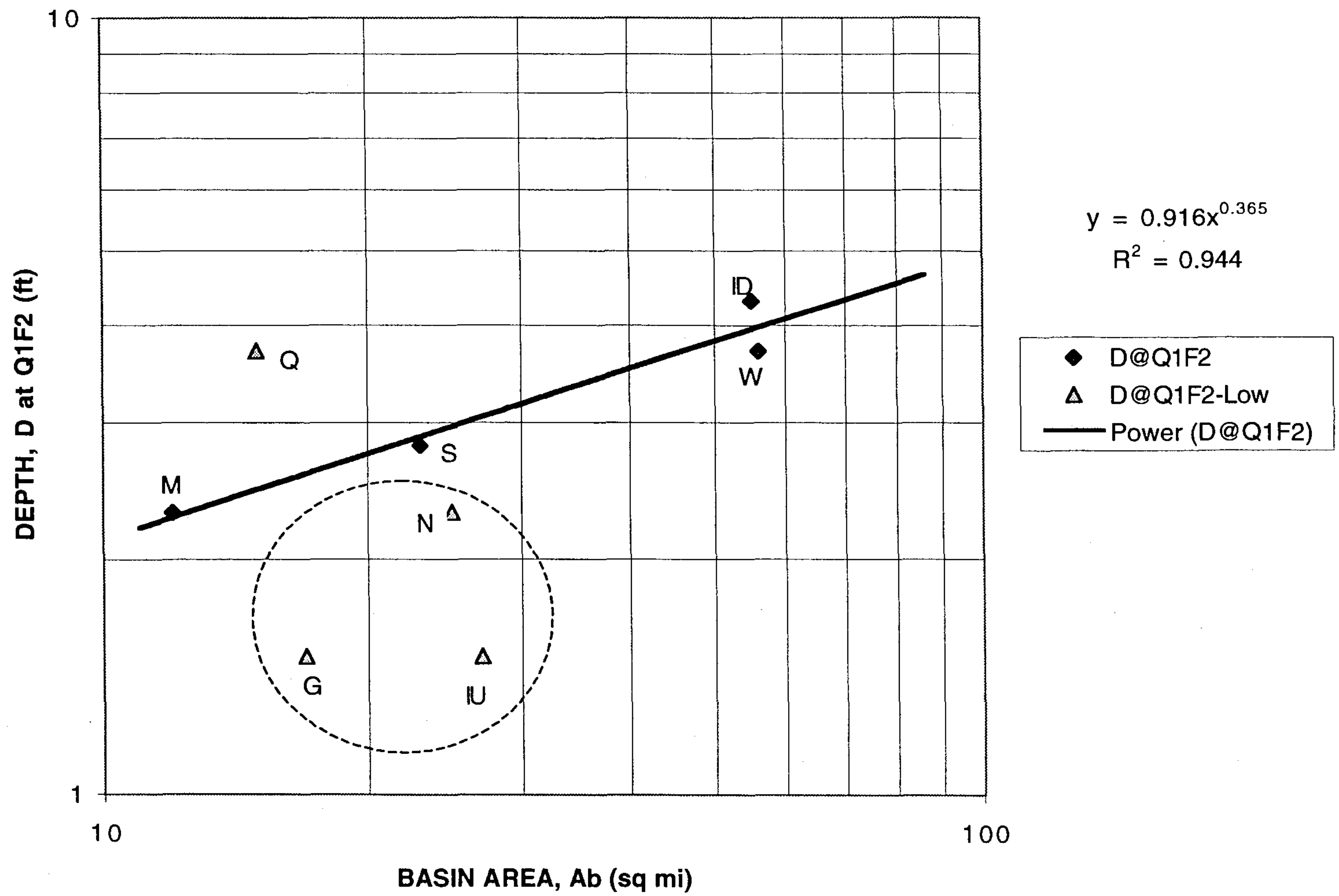
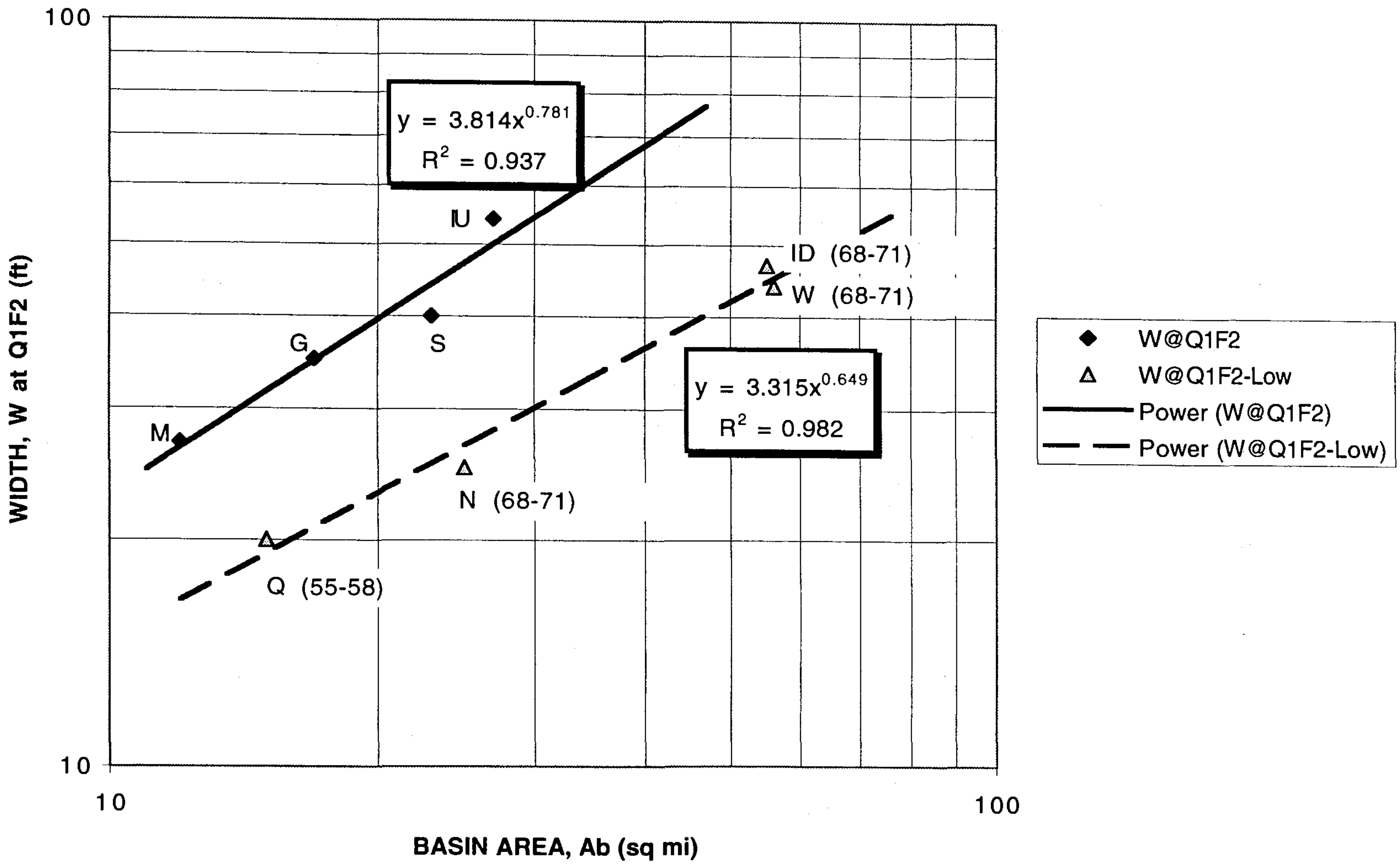


Figure 3-21: North Creek Regional Analysis of Channel Width at Bankfull Flow (Q1F2)



But Issaquah (U) and Griffin Creeks in Figure 3-21 show wider channels at Q1F2 whereas North Creek still shows as narrow. A field inspection of these three sites showed the North Creek upstream channel is riprapped with parallel vertical walls. The gaging station is located just upstream of a 90-degree bend as the creek turns and goes through a constricting bridge. Several hundred feet downstream of the bridge would be a better place to measure unrestricted channel characteristics. It was interesting to note that at the next street crossing upstream on North Creek, the stream channel had been rerouted in the same manner, parallel to the street, to make room for a new mall parking lot. The new channel was laden with large rock and LWD, and it turned 90° to go through a new bridge.

Issaquah (U) and Griffin Creeks were also checked and Issaquah (U) was confined in an almost rectangular channel (riprapped) just upstream of a bridge. The channel top does widen just before it reaches bankfull conditions. The Griffin Creek gage was located just downstream of a Tolt River pipeline trestle with it's numerous columns, and had unstable sediment deposits in multiple channels downstream of the trestle in several low bank channels.

Regional Hydraulic Geometry

Using the width, depth and area data in Table 3-7, plus the data for channel sizes at Q7L2, regional models of hydraulic geometry were developed.

For the mean daily flood, Q1F2:

$$W = 4.95\ (Q1F2)^{0.33} \qquad (3\text{-}21)$$

$$D = 0.98\ (Q1F2)^{0.20} \qquad (3\text{-}22)$$

$$A_c = 4.85\ (Q1F2)^{0.53} \qquad (3\text{-}23)$$

It was found that the average floods at each station (except North Creek) fit the model in Figure 3-22, which says

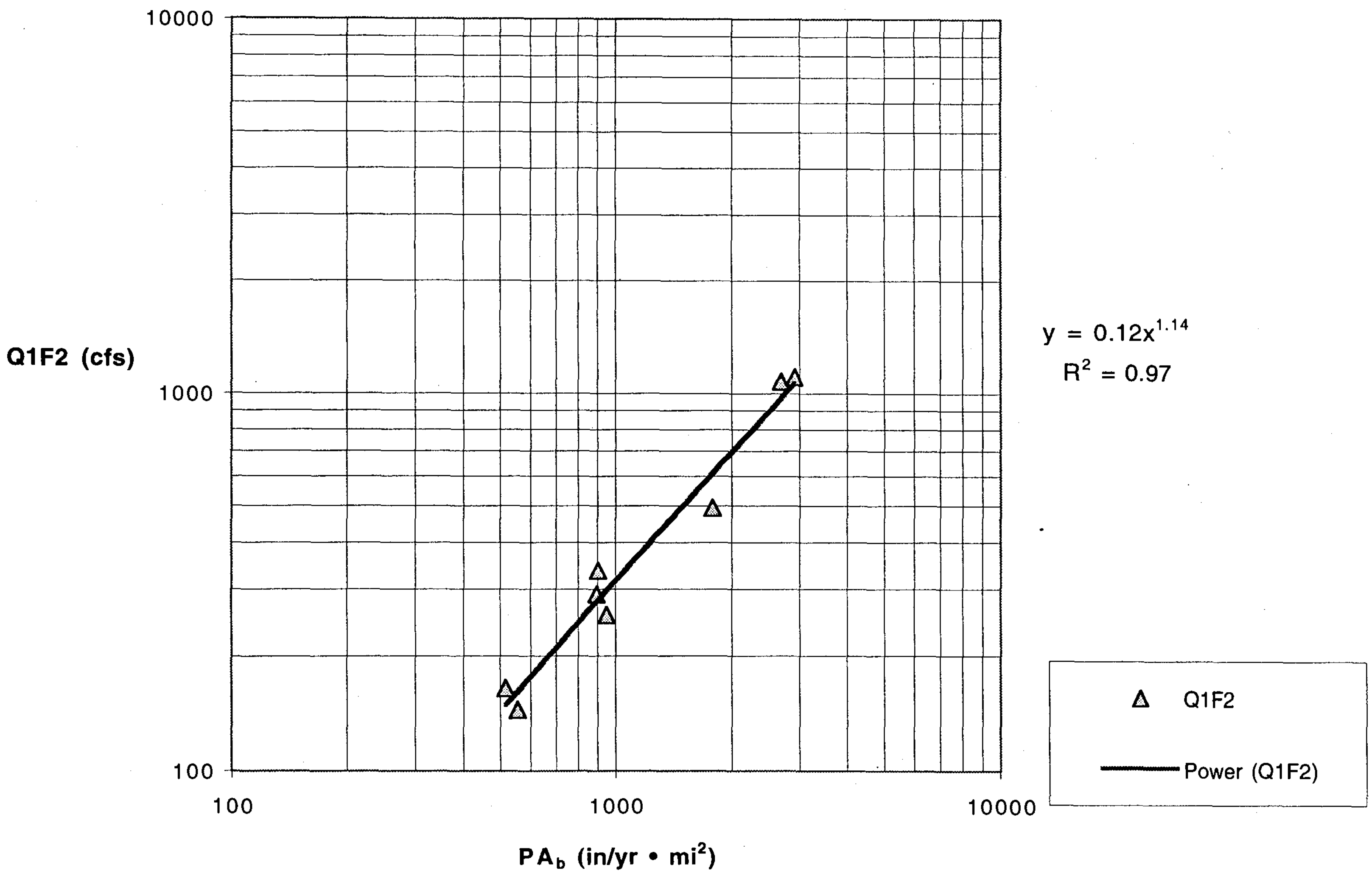
$$Q1F2 = 0.12\ (PA)^{1.14} \qquad (3\text{-}24)$$

Substituting Eq. 3-24 into Eqs. 3-21, 3-22 and 3-23 we find that width equals

$$W = 4.95\ \left(0.12\ (PA_b)^{1.14}\right)^{0.33}$$

which reduces (similarly for depth and area)

Figure 3-22. Q1F2 versus PA_b for Eight Puget Lowland USGS Gages for their Periods of Record (Data from Table 3-7).



for Q1F2 in this sample of Puget Lowland streams :

Width:	$W = 2.46\ (PA)^{0.38}$	**(3-25)**
Depth:	$D = 0.64\ (PA)^{0.23}$	**(3-26)**
Area:	$A_c = 1.58\ (PA)^{0.60}$	**(3-27)**

The values of W, D and A_c at Q1F2 calculated by Eqs. 3-25, 3-26 and 3-27, and the values determined by at-a-station hydraulic geometries, are listed in Table 3-8 and plotted against each other in Figure 3-23.

Once again floods show the most variability in depth, width and area in Figure 3-23. Most of the data points lie close to the line, but for Griffin, North and Upper Issaquah show the largest departures. This was probably due in large part to the confinement of the channels.

For average annual flow, QAA:

The regional average hydraulic geometry equations are:

$$W = 4.39\ (QAA)^{0.44} \qquad (3\text{-}28)$$

$$D = 0.59\ (QAA)^{0.17} \qquad (3\text{-}29)$$

$$A_c = 2.77\ (QAA)^{0.60} \qquad (3\text{-}30)$$

The regional equation for QAA, as a function of basin characteristics, was developed for the eight USGS gages in Table 3-7, and is similar to the Olympic Peninsula equation (Eq. 3-10) where $QAA = 0.0032\ (P)^{1.62} A_b$, which allows for variations in runoff as a function of precipitation.

For the Puget Lowland streams

$$QAA = 0.0040\ (P)^{162} A_b \qquad (3\text{-}31)$$

Inserting Eq. 3-31 for QAA into Eqs. 3-28, 3-29 and 3-30 gives

$$W = 4.39\ (0.0040\ (P)^{1.62}\ A_b)^{0.44}$$

which reduces to (along with the depth and area relationships)

for QAA in this sample of Puget Lowland streams:

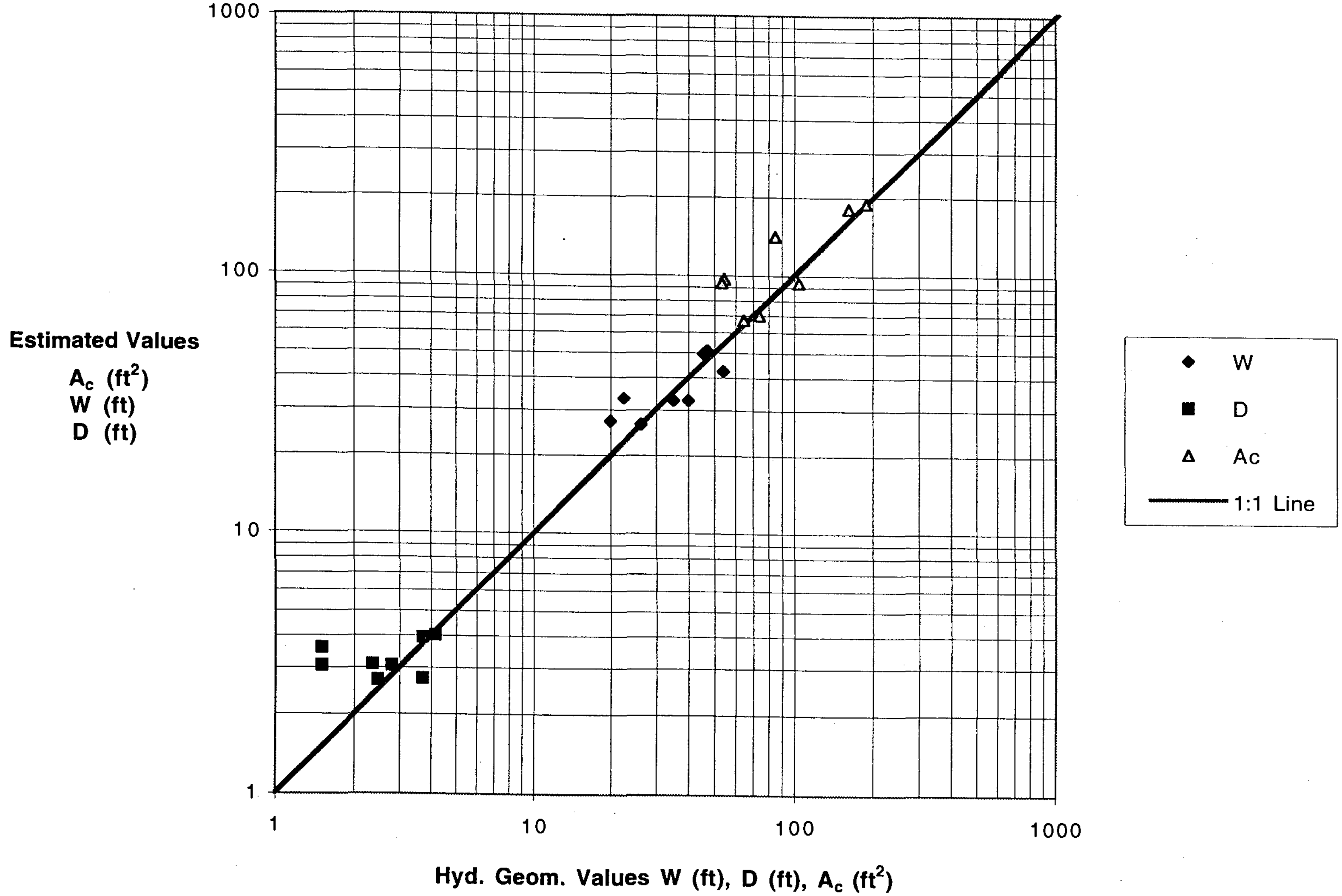
Width	$W = 0.39\ (P)^{0.71}\ (A_b)^{0.44}$	**(3-32)**
Depth:	$D = 0.23\ (P)^{0.28}\ (A_b)^{0.17}$	**(3-33)**
Area:	$A_c = 0.10\ (P)^{0.97}\ (A_b)^{0.60}$	**(3-34)**

Table 3-8. Channel Width, Depth, and Area Comparison at Q1F2 for Puget Lowlands

	$W = C(PA)^E$	$D = C(PA)^E$	$A_c = C(PA)^E$
C:	2.46	0.64	1.58
E:	0.38	0.23	0.60

Station Name	USGS Gage No.	Q1F2 (cfs)	Basin Input (PA_b) (sq. mi-in/yr)	Table 3-7 Hyd. Geom. W @ Q1F2 (ft)	Equation 3-25 Estimated W Est (ft)	Table 3-7 Hyd. Geom. D @ Q1F2 (ft)	Equation 3-26 Estimated D Est (ft)	Table 3-7 Hyd. Geom. A @ Q1F2 (ft^2)	Equation 3-27 Estimated A Est (ft)
Mercer		165	516	26.3	26.4	2.47	2.69	65	67
Issaquah-U		493	1782	54.0	42.3	1.50	3.58	85	141
Issaquah-D		1104	2915	47.0	51.0	4.15	4.01	188	189
North Cr		256	950	22.5	33.3	2.35	3.10	55	97
Swamp Cr		291	897	40.0	32.6	2.80	3.06	104	93
Woods Cr		1076	2688	45.5	49.4	3.70	3.94	162	180
Griffin Cr		336	901	35.0	32.6	1.50	3.06	53	94
Quilceda Cr		144	555	20.0	27.1	3.70	2.74	74	70

Figure 3-23. Channel Width, Depth and Area Estimations versus Hydraulic Geometry Values at Q1F2 for Puget Lowland Streams



The W, D and A_c values calculated by Eqs. 3-32, 3-33 and 3-34 and those determined from hydraulic geometry are in Table 3-9. They are also plotted in Figure 3-24.

As usual, channel relationships at QAA tend to have less scatter than at floods or low flows. The combined relationships in Figure 3-24 (as developed from Eqs. 3-32, 3-33 and 3-34 above), are much better than the empirical relationships in Figures 3-18 and 3-19.

For the 7-day average low flow, Q7L2, the regional hydraulic geometry is:

$$W = 6.46\ (Q7L2)^{0.51} \tag{3-35}$$

$$D = 0.36\ (Q7L2)^{0.16} \tag{3-36}$$

$$A_c = 2.33\ (Q7L2)^{0.67} \tag{3-37}$$

Using the data in Table 3-7 for Q7L2 and (PA), the following equation was graphed in Figure 3-25,

$$Q7L2 = 0.0033\ (PA_b)^{1.10} \tag{3-38}$$

which is very similar to the flood equation (3-24) of $Q1F2 = 0.12\ (PA)^{1..14}$

Substituting Eq. 3-38 into Eqs. 3-35, 3-36, and 3-37 yields,

for Q7L2 in this sample of Puget Lowland Streams:

Width:	$\mathbf{W = 0.35\ (PA)^{0.56}}$	**(3-39)**
Depth:	$\mathbf{D = 0.14\ (PA)^{0.18}}$	**(3-40)**
Area:	$\mathbf{A_c = 0.051\ (PA)^{0.74}}$	**(3-41)**

The comparison of predicted and measured values of W, D, and A_c at Q7L2 for Puget Lowland streams is shown in Table 3-10 and Figure 3-26.

Surprisingly, the combined low flow equations give some of the best results. Only some estimated areas are large or small, and the depth values are exceptionally close (see Table 3-10 in Columns 7 and 8).

Table 3-9. Channel Width, Depth, and Area Comparison at QAA for the Puget Lowlands

	$W = C(P)^{E1}(A_b)^{E2}$		$D = C(P)^{E1}(A_b)^{E2}$		$A = C(P)^{E1}(A_b)^{E2}$
C:	0.39	C:	0.23	C:	0.10
E1:	0.71	E1:	0.28	E1:	0.97
E2:	0.44	E2:	0.17	E2:	0.60

Station Name	USGS Gage No.	QAA (cfs)	Average Annual Precip., P (in/yr)	Drainage Area, Ab (sq. mi.)	Table 3-7 Hyd. Geom. W @ QAA (ft)	Equation 3-32 Estimated W Est (ft)	Table 3-7 Hyd. Geom. D @ QAA (ft)	Equation 3-33 Estimated D Est (ft)	Table 3-7 Hyd. Geom. A @ QAA (ft^2)	Equation 3-34 Estimated A Est (ft)
Mercer		21.9	43	12.0	16.7	16.8	1.07	1.01	17.7	17.1
Issaquah-U		69.7	66	27.0	33.0	32.6	0.90	1.30	28.4	42.1
Issaquah-D		143.9	53	55.0	39.5	38.1	1.50	1.38	56.5	52.1
North Cr		36.4	38	25.0	19.5	21.3	1.00	1.10	20.7	23.5
Swamp Cr		33.8	39	23.0	27.0	20.9	1.10	1.09	29.8	22.9
Woods Cr		154.5	48	56.0	39.5	35.8	1.50	1.35	57.9	47.8
Griffin Cr		40.3	53	17.0	23.0	22.7	0.80	1.13	18.9	25.8
Quilceda Cr		25.6	37	15.0	16.0	16.7	1.20	1.00	20.1	16.9

Figure 3-24. Channel Width, Depth and Area Estimations versus Hydraulic Geometry Values at QAA for Puget Lowland Streams

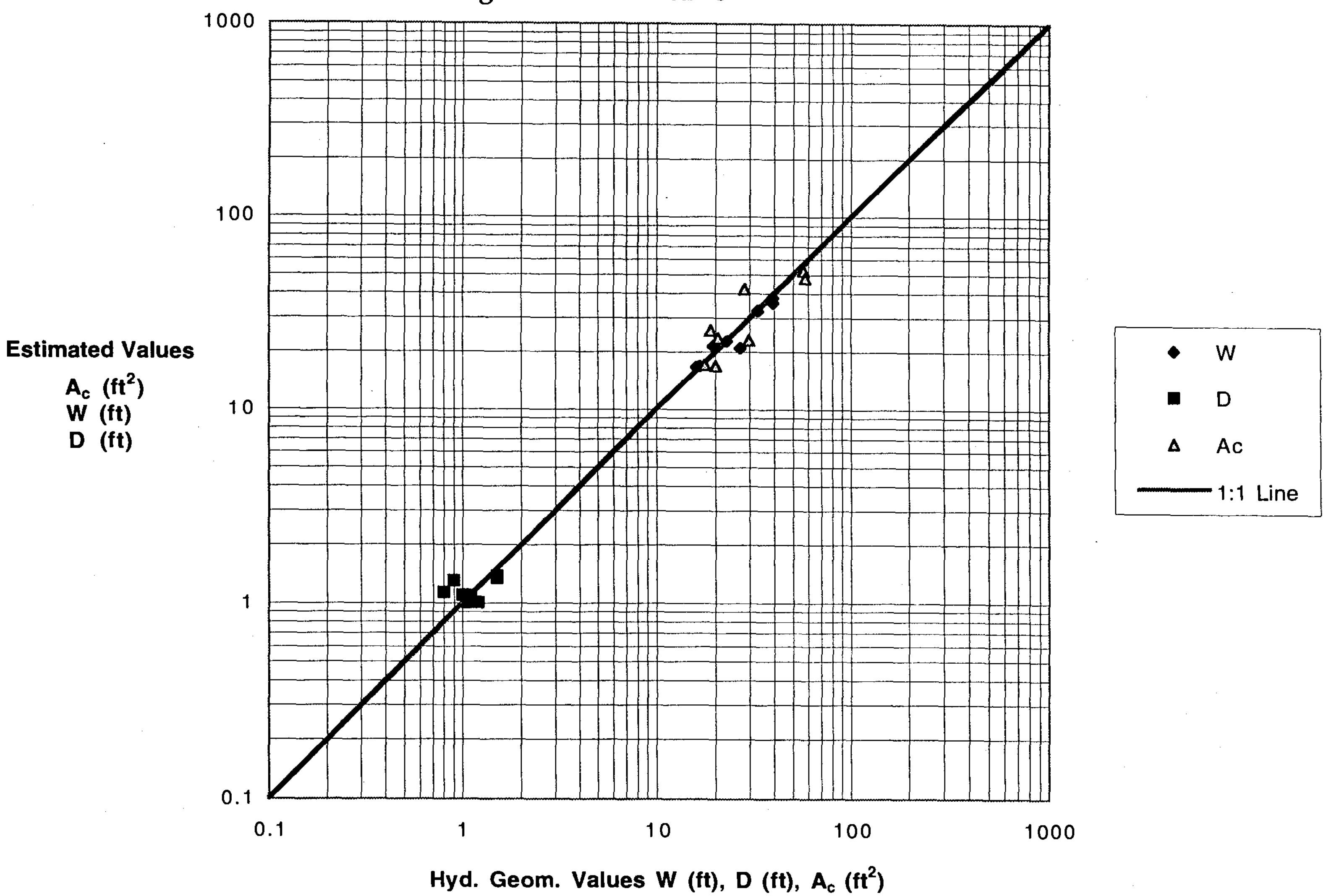


Figure 3-25. Q7L2 versus PBE for Eight Puget Lowland USGS Stations for Their Periods of Record (Data from Table 3-7).

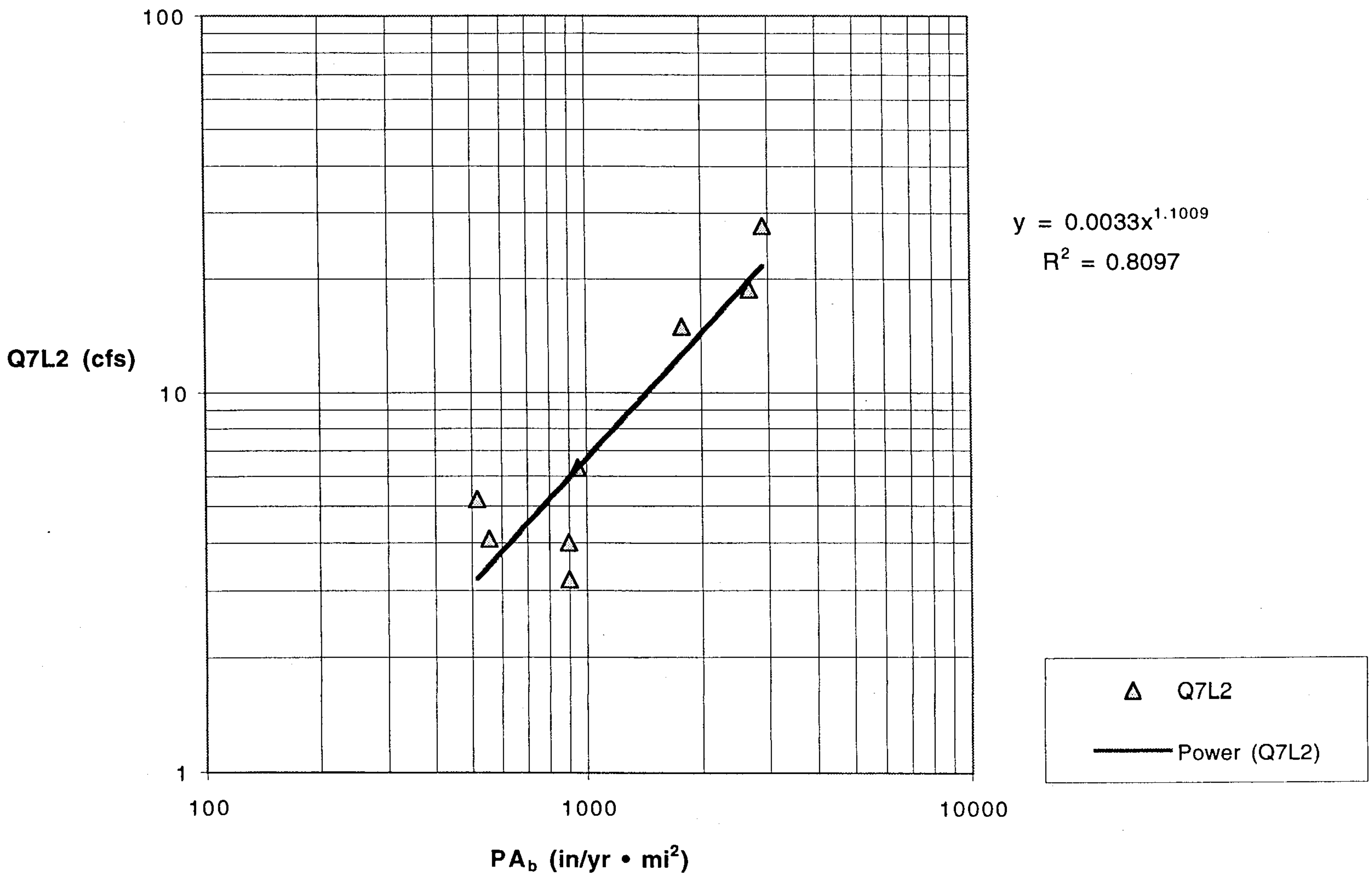
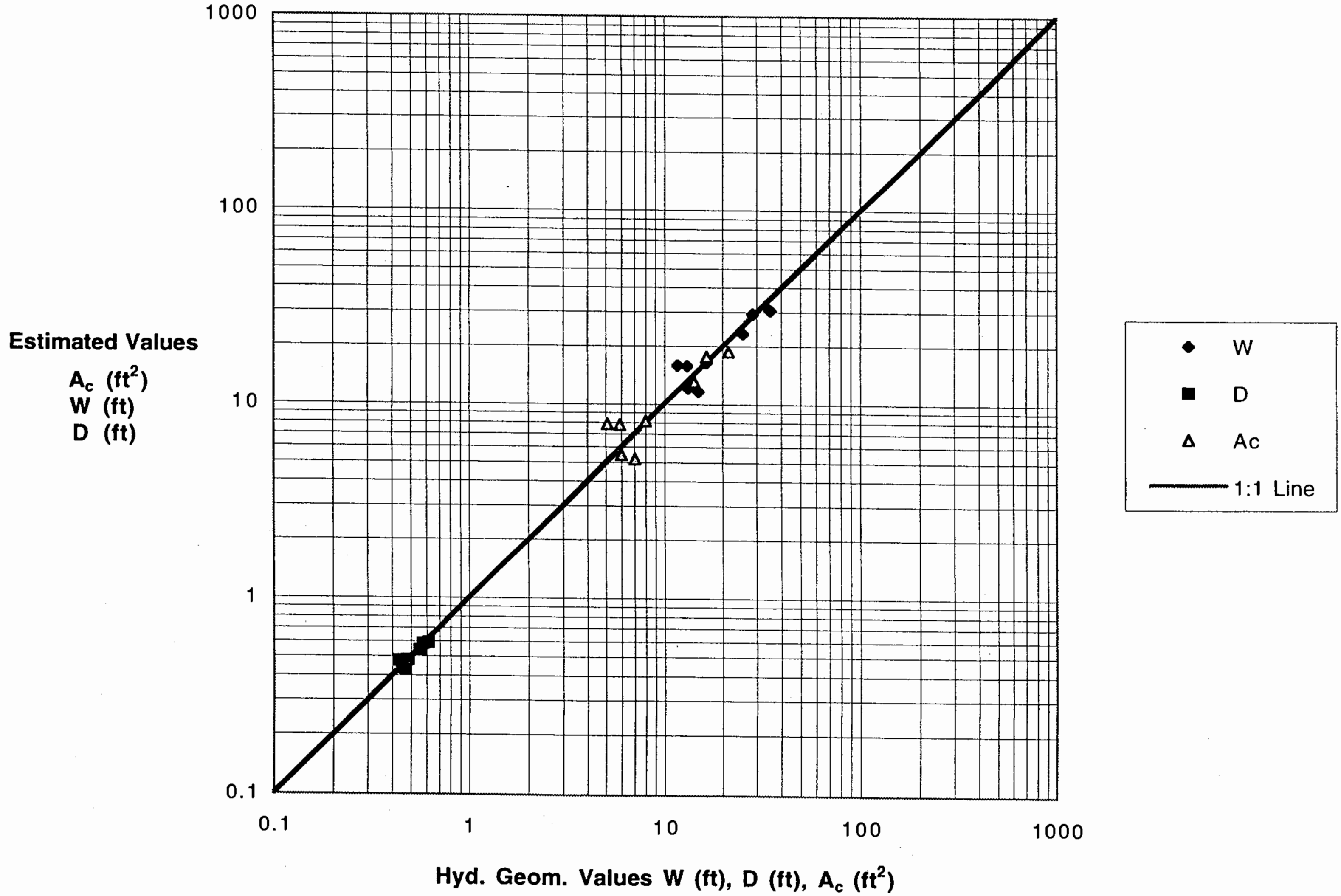


Table 3-10. Channel Width, Depth, and Area Comparison at Q7L2 for the Puget Lowlands

	W = $C(PA)^E$	D = $C(PA)^E$	$A_c = C(PA)^E$
C:	0.35	0.14	0.051
E:	0.56	0.18	0.74

Station Name	USGS Gage No.	Q7L2 (cfs)	Basin Input (PA_b) (sq. mi-in/yr)	Table 3-7 Hyd. Geom. W @ Q7L2 (ft)	Equation 3-39 Estimated W Est (ft)	Table 3-7 Hyd. Geom. D @ Q7L2 (ft)	Equation 3-40 Estimated D Est (ft)	Table 3-7 Hyd. Geom. A @ Q7L2 (ft^2)	Equation 3-41 Estimated A Est (ft)
Mercer		5.2	516	15.0	11.6	0.47	0.43	7.0	5.2
Issaquah-U		14.9	1782	25.6	23.2	0.55	0.54	14.2	13.0
Issaquah-D		27.7	2915	35.1	30.5	0.61	0.59	21.6	18.7
North Cr		6.3	950	16.5	16.3	0.48	0.48	8.0	8.1
Swamp Cr		4.0	897	13.1	15.8	0.45	0.48	5.9	7.8
Woods Cr		18.7	2688	28.8	29.1	0.58	0.58	16.6	17.6
Griffin Cr		3.2	901	11.7	15.8	0.43	0.48	5.1	7.8
Quilceda Cr		4.1	555	13.3	12.0	0.45	0.44	6.0	5.5

Figure 3-26. Channel Width, Depth and Area Estimations versus Hydraulic Geometry Values at Q7L2 for Puget Lowland Streams



NORTHEASTERN WASHINGTON REGIONAL STREAMS

Database and Empirical Relationships

The database for the streams used to develop regional models for the analysis of the hydrology and stream channels on the Colville Indian Reservation were reported initially in Orsborn and Orsborn (1997). The regional models for average floods and low flows were developed further in a later report by Orsborn and Orsborn (1999).

As was shown in Figure 2-1, flow characteristics (QC) are related to basin characteristics (BC); and flow characteristics (QC) are related also to channel characteristics (CC) through the analysis of channel hydraulic geometry. By setting the equations for Q1F2, QAA and Q7L2, in terms of BC and CC, equal to each other for each characteristic flow, combined solutions, as have been done for the Olympic Peninsula and Puget Lowland Regions, were developed.

But, in some regions, channel dimensions demonstrate strong empirical relationships, such as were seen for the Puget Lowland Region for channel are (A_c) related to basin area (A_b). Some of the empirical relationships for the Northeastern Washington Region will be examined next.

Width and Channel Area at QAA

The relationships of channel width (W) and channel area (A_c) to basin area (A_b) were explored at QAA to determine if this type of analysis should be pursued with Q7L2 and Q1F2. These extreme flows usually have poorer relationships to BC's than does QAA.

The data for the QAA test is given in Table 3-11. Water surface channel width (W) and channel cross-sectional area (A_c) are plotted against basin area (A_b) in Figure 3-27. Note that the regional USGS gage basins range in size from 36 (Deer) to 2200 (Kettle) square miles.

In Figure 3-28, the channel characteristics are plotted against basin energy ($BE = A\,(H)^{0.50}$) at QAA. The plotting points for the larger basins are improved, but some of the smaller basins still do not fit the relationships, especially Haller Creek. It and Sheep Creek have not been examined in the field, but they display channel areas (A_c) that are too small. Perhaps Haller Creek is cutting through deposition. We found this to be true for Hall Creek in the Northeast part of the CCT Reservation. But, none of the USGS records for stations on the Reservation were of long enough duration for use in this analysis.

Table 3-11. USGS Stations, Basin Area, Basin Energy, and Channel Width (W) and Area (Ac) for Developing CC:BC Preliminary Models at Average Annual Flow (QAA) in NE Washington.

Station Name	Area Ab (sq. mi.)	Basin Energy $BE = A_b(H)^{0.50}$ $(mi.)^{2.50}$	Channel Characteristics at QAA Width W (ft)	Area A_c (sq. ft.)
Kettle	2200	1691	180.1	488.8
Sheep	48	28	11.3	7.7
Deer	36	27	12.0	9.5
L. Pend. O.	132	96	25.3	35.0
Haller	37	25	7.0	4.1
Mill	83	59	25.5	27.4
Hangman	689	441	62.5	145.0

Figure 3-27. W and A_c versus A_b at QAA in NE Washington

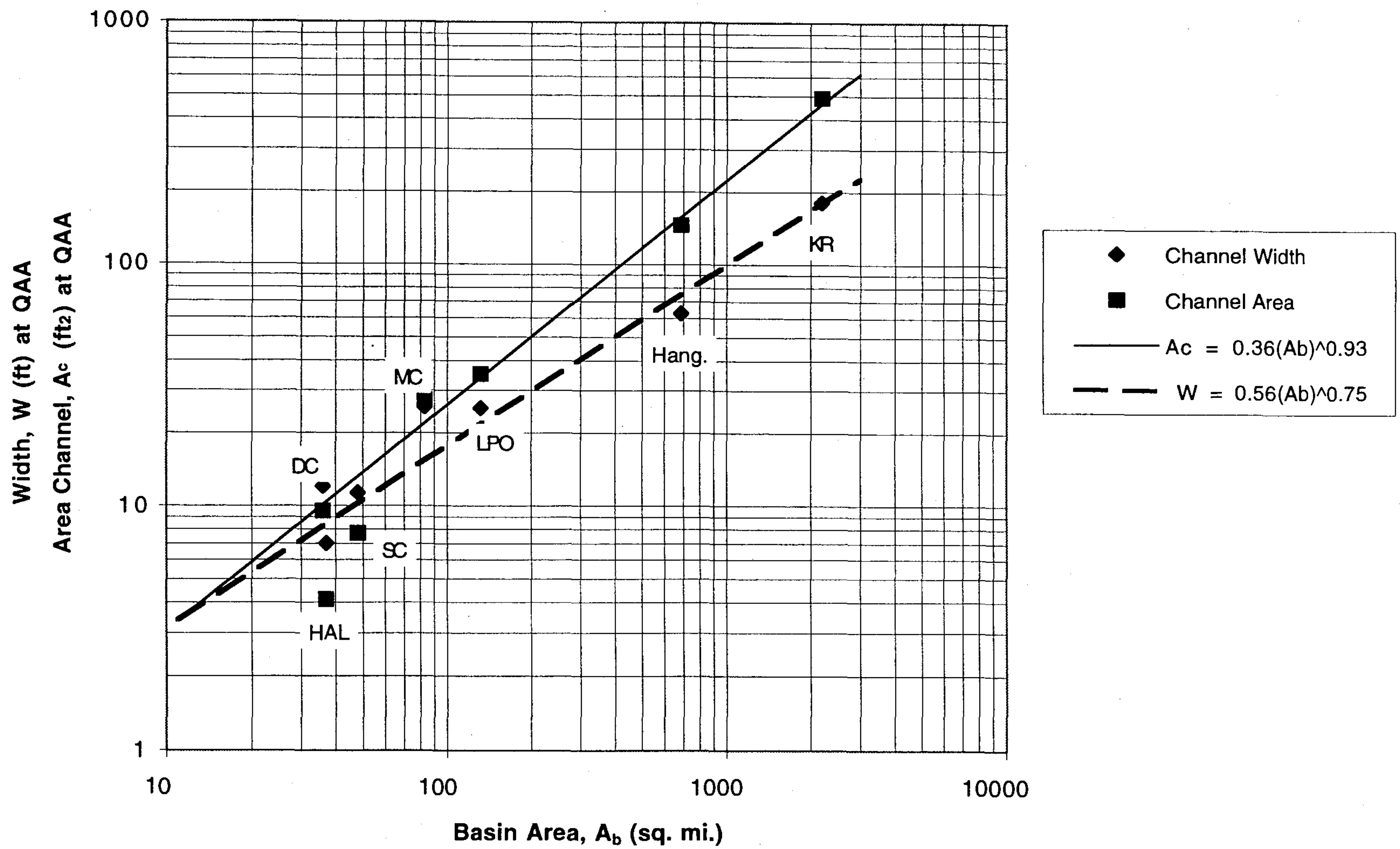
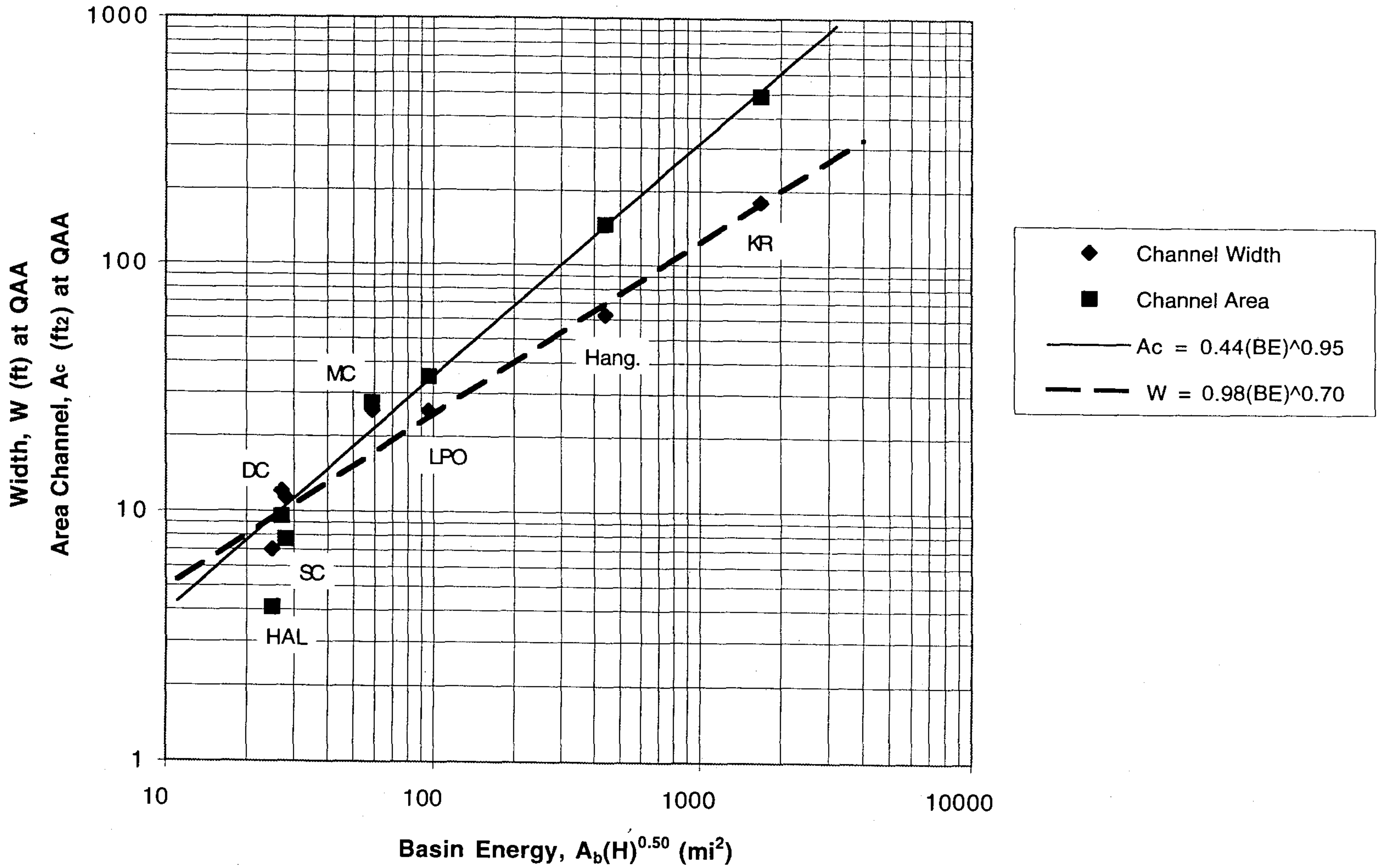


Figure 3-28. W and A_c versus Basin Energy at QAA in NE Washington



Combined Relationships of Channel and Basin Characteristics in Northeastern Washington

The at-a-station equations for the hydraulic geometry analyses are summarized in Table 3-12. The characteristic flows for the seven gages are listed in Table 3-13. The regional models for W, D, V, and (A_c) are graphed and listed in Figures 3-29, 3-30 and 3-31 for Q1F2, QAA and Q7L2, respectively.

The regional hydraulic geometry equations are:

FOR AVERAGE DAILY FLOOD FLOWS (Q1F2):

$$W = 1.67\ (Q1F2)^{0.53} \qquad (3\text{-}42)$$

$$D = 0.28\ (Q1F2)^{0.34} \qquad (3\text{-}43)$$

$$A_c = 0.47\ (Q1F2)^{0.87} \qquad (3\text{-}44)$$

FOR AVERAGE ANNUAL FLOWS (QAA):

$$W = 2.27\ (QAA)^{0.60} \qquad (3\text{-}45)$$

$$D = 0.34\ (QAA)^{0.31} \qquad (3\text{-}46)$$

$$A_c = 0.76\ (QAA)^{0.91} \qquad (3\text{-}47)$$

FOR 7-DAY AVERAGE LOW FLOWS (Q7L2):

$$W = 4.00\ (Q7L2)^{0.69} \qquad (3\text{-}48)$$

$$D = 0.35\ (Q7L2)^{0.29} \qquad (3\text{-}49)$$

$$A_c = 1.40\ (Q7L2)^{0.98} \qquad (3\text{-}50)$$

The models for the characteristic flows related to basin characteristics are presented next.

Table 3-12. AT-A-STATION CHANNEL GEOMETRY SUMMARY: USGS REGIONAL STATIONS, NORTHEASTERN WASHINGTON

Constant and exponent from power relation y = C(Q)^{exp} where y = W, D, V or Ac

			Width, W		Depth, D		Mean Velocity, V		Area Channel, Ac		Check	
											Product	*Sum*
Station No.	**Station Name**	**WY**	**C**	**exp**	**C**	**exp**	**C**	**exp**	**C**	**exp**	C(W*D*V)	expΣ(W,D,V)
12401500	Kettle R nr Ferry	1993-95	49.017	0.178	0.142	0.404	0.143	0.418	6.940	0.582	0.995	1.000
12407500	Sheep Creek	1970-73	10.849	0.015	0.309	0.320	0.297	0.667	3.350	0.335	0.996	1.002
12407520	Deer Creek	1970-72	6.100	0.234	0.460	0.189	0.358	0.576	2.809	0.422	1.005	0.999
12408300	L Pend Orielle	1973-75	11.867	0.186	0.541	0.233	0.157	0.581	6.421	0.418	1.008	1.000
12408420	Haller Creek	1968-77	3.465	0.352	0.277	0.376	1.041	0.272	0.961	0.728	0.999	1.000
12408500	Mill Creek	1977-80	18.554	0.083	0.295	0.336	0.182	0.584	5.465	0.419	0.996	1.003
12424000	Hangman Creek	1994-96	14.601	0.267	0.471	0.294	0.146	0.439	6.870	0.560	1.004	1.000

Table 3-13. CHARACTERISTIC FLOWS, FOR NE WASHINGTON USGS GAGES

USGS STATION No. (12--)	USGS STATION Name	Q7L2 (cfs)	QAA (cfs)	Q1F2 (cfs)
401500	Kettle	120.0	1496	11560
407500	Sheep	7.2	12	37
407520	Deer	3.6	18	105
408300	L. Pend O.	14.0	58	289
408420	Haller	0.6	7	37
408500	Mill	8.5	47	286
424000	Hangman	10.1	250	5710

Figure 3-29. Regional Models of Width, Depth, Velocity and Channel Area Related to Q1F2 at USGS Stations in NE Washington.

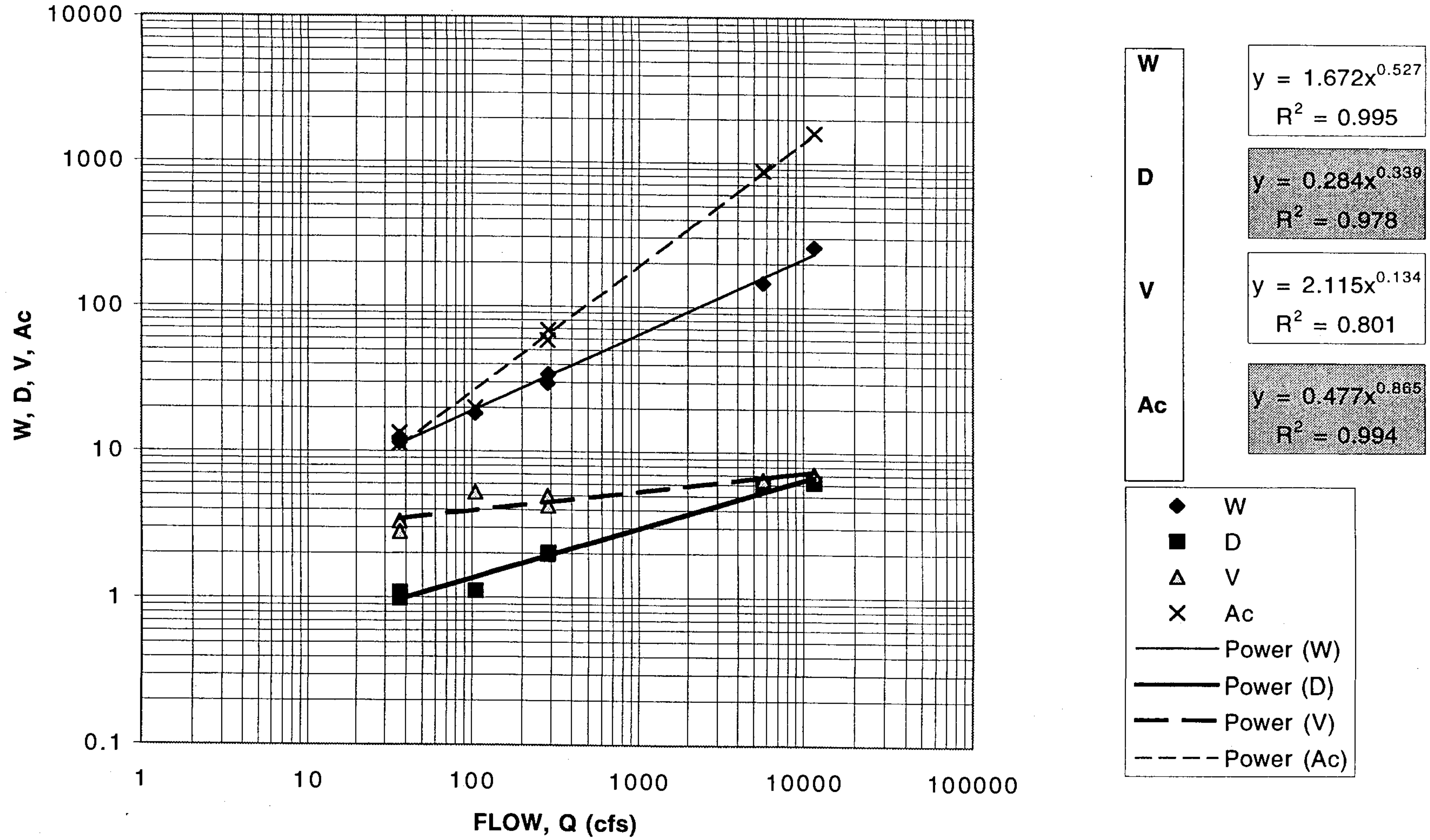


Figure 3-30. Regional Models of Width, Depth, Velocity and Channel Area Related to QAA at USGS Stations in NE Washington.

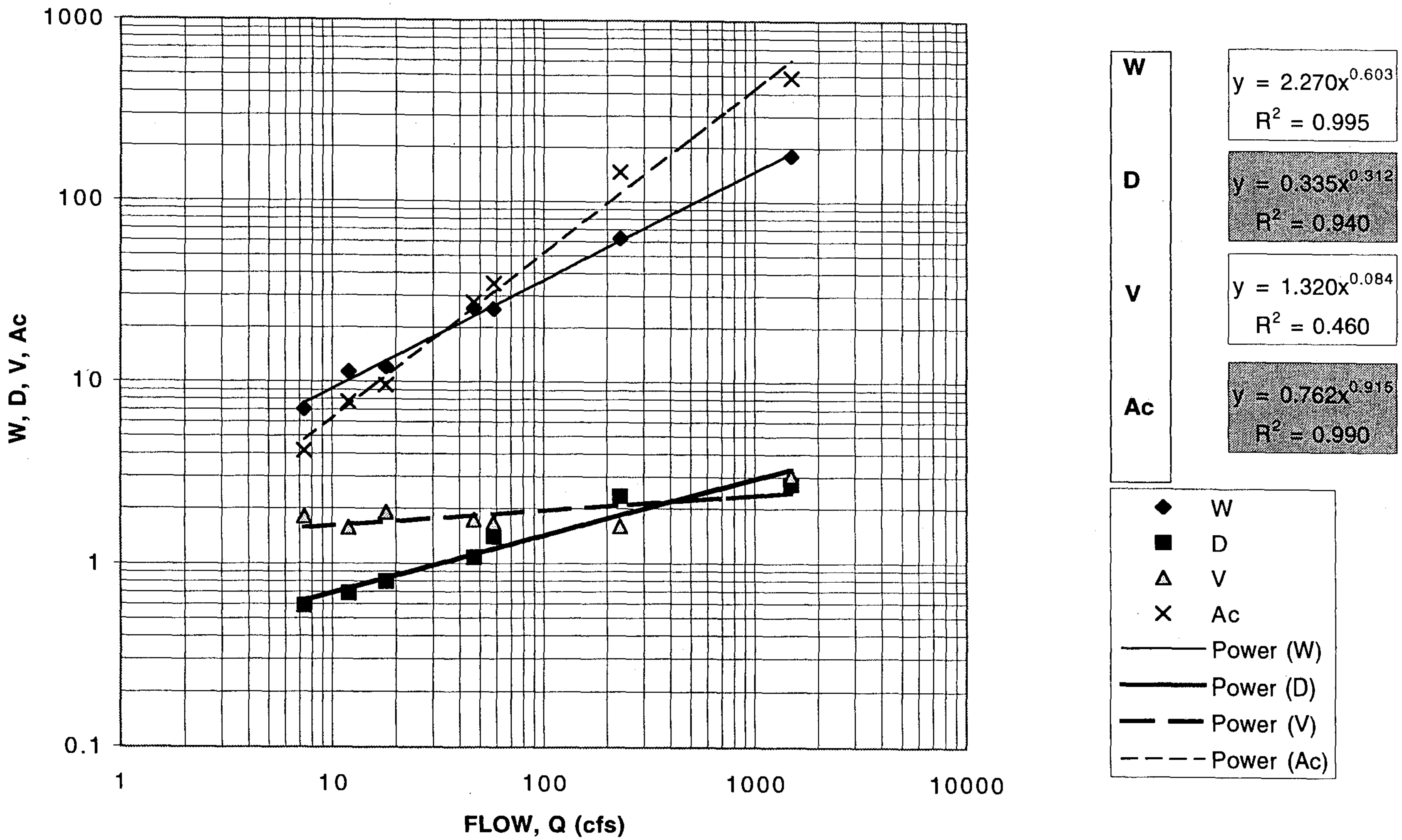
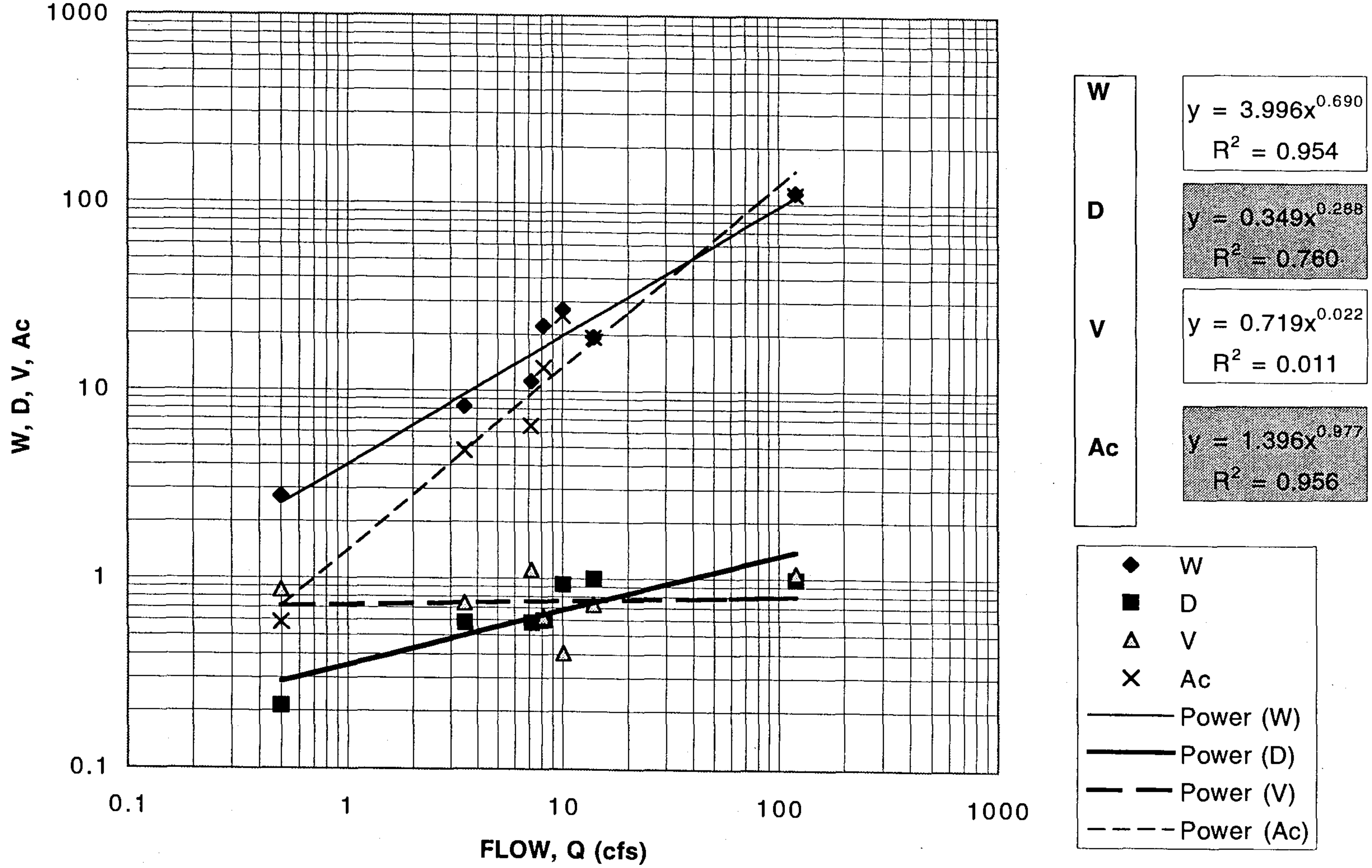


Figure 3-31. Regional Models of Width, Depth, Velocity and Channel Area Related to Q7L2 at USGS Stations in NE Washington.



FOR AVERAGE FLOOD FLOWS:

The regional equation of average flood flows as a function of basin energy ($BE = A\ (H)^{0.50}$) was developed for the CCT low flow report (Orsborn and Orsborn 1999). The data is in Table 3-14 and the graphical relation is in Figure 3-32.

The equation for average flood flow is

$$Q1F2 = 1.87\ (BE)^{1.15} \qquad \text{from Figure 3-32}$$

In terms of its basic elements

$$Q1F2 = 1.87\ (A_b)^{1.15} (H)^{0.58} \tag{3-51}$$

This equation is substituted into Eqs. 3-42, 3-43, and 3-44 for QIF2.

For Q1F2 at these six stations in Northeastern Washington:

Width:	$W = 2.33\ (A)^{0.61}\ (H)^{0.30}$	**(3-52)**
Depth:	$D = 0.35\ (A)^{0.39}\ (H)^{0.20}$	**(3-53)**
Area:	$A_c = 0.83\ (A)^{1.00}\ (H)^{0.50}$	**(3-54)**

The values of W, D and A_c at QIF2 for the hydraulic geometry and from the above three equations are summarized in Table 3-15 and compared graphically in Figure 3-33.

FOR AVERAGE ANNUAL FLOWS

The regional model for QAA was developed by Orsborn and Orsborn (1997) along the lines of those for the Olympic Peninsula and Puget Lowlands equations.

$$QAA = 0.0025\ (P)^{1.64}\ (A_b) \tag{3-55}$$

Next it is substituted into Eqs. 3-45, 3-46 and 3-47 to yield W, D and A_c at QAA in terms of basin characteristics.

For QAA in Northeastern Washington:

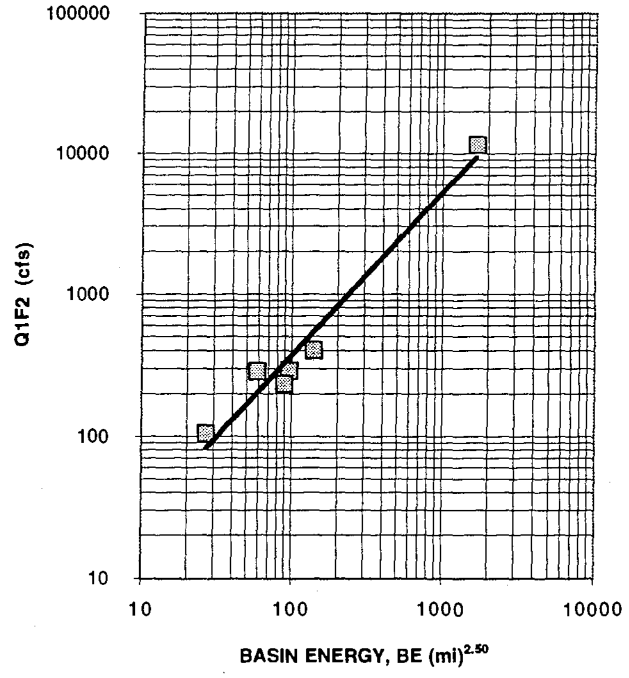
Width	$W = 0.062\ (P)^{0.98}\ (A_b)^{0.60}$	**(3-56)**
Depth:	$D = 0.053\ (P)^{0.50}\ (A_b)^{0.31}$	**(3-57)**
Area:	$A_c = 0.0032\ (P)^{1.49}\ (A_b)^{0.91}$	**(3-58)**

The values of W, D and A_c are compared in Table 3-16 and in Figure 3-34.

Table 3-14.
Data From Table 3-9, BASIN CHARACTERISTICS (Orsborn & Orsborn, 1997)

End POR	STATION No. (12--)	STATION Name	Basin Area Ab (sq. mi.)	Upper Elev. (ft.)	Lower Elev. (ft.)	Basin Relief H (mi.)	Basin Energy $A(H)^{0.50}$ $(mi.)^{2.50}$	QAA (cfs)	Q1F2 (cfs)
Current	401500	Kettle	2220	4920	1837	0.58	1691	1496	11560
1972	407520	Deer	36	4920	1970	0.56	27	18	105
1975	408300	L. Pend O.	132	4760	1983	0.53	96	58	289
1986	408500	Mill	83	4590	1950	0.50	59	47	286
1973	409500	Hall (Res)	160	5410	1420	0.76	139	73	402
1929	437500	Nespelem (Res)	122	4600	1790	0.53	89	45	234

Figure 3-32. Q1F2 as a function of Basin Energy for Selected USGS Stations in NE Washington.



$$Q1F2 = 1.87(BE)^{1.15}$$
$$R^2 = 0.97$$

Table 3-15. Channel Width, Depth and Area Comparison at Q1F2 for NE Washington

	$W = C(A_b)^{E1}(H)^{E2}$	$D = C(A_b)^{E1}(H)^{E2}$	$A_c = C(A_b)^{E1}(H)^{E2}$
C:	2.33	0.35	0.83
E1:	0.61	0.39	1.00
E2:	0.30	0.20	0.50

					Hyd. Geom.	Equation 3-52 Estimated	Hyd. Geom.	Equation 3-53 Estimated	Hyd. Geom.	Equation 3-54 Estimated
Station Name	**USGS Gage No.**	**Q1F2** (cfs)	**Drainage Area, Ab** (sq. mi.)	**Relief, H** (mi.)	**W @ Q1F2** (ft)	**W Est** (ft)	**D @ Q1F2** (ft)	**D Est** (ft)	**A @ Q1F2** (ft^2)	**A Est** (ft)
Kettle	12401500	11560	2220	0.58	231.4	217.6	6.77	6.34	1559	1403.3
Sheep	12407500	37	48	0.34	11.2	17.9	0.97	1.28	10.8	23.2
Deer	12407520	105	36	0.56	19.4	17.4	1.38	1.26	26.7	22.4
L. Pend O.	12408300	289	132	0.53	33.1	37.9	1.94	2.07	64.1	79.8
Haller	12408420	37	37	0.44	11.2	16.5	0.97	1.21	10.8	20.4
Mill	12408500	286	83	0.50	32.9	28.0	1.93	1.71	63.6	48.7
Hangman	12424000	5710	689	0.41	159.6	96.1	5.33	3.75	847	366.2

Figure 3-33. Channel Width, Depth and Area Estimations versus Hydraulic Geometry Values at Q1F2 for NE Washington

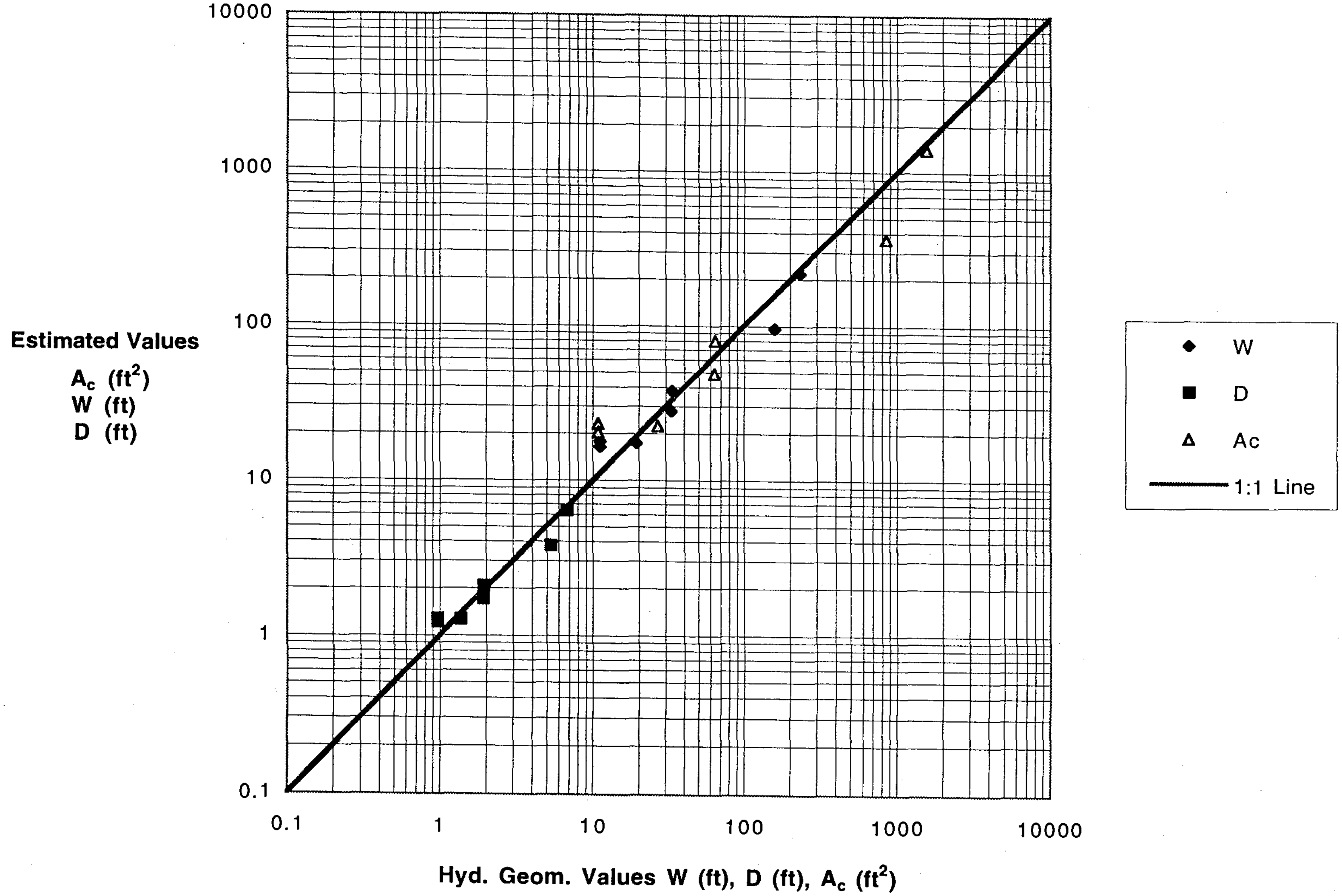
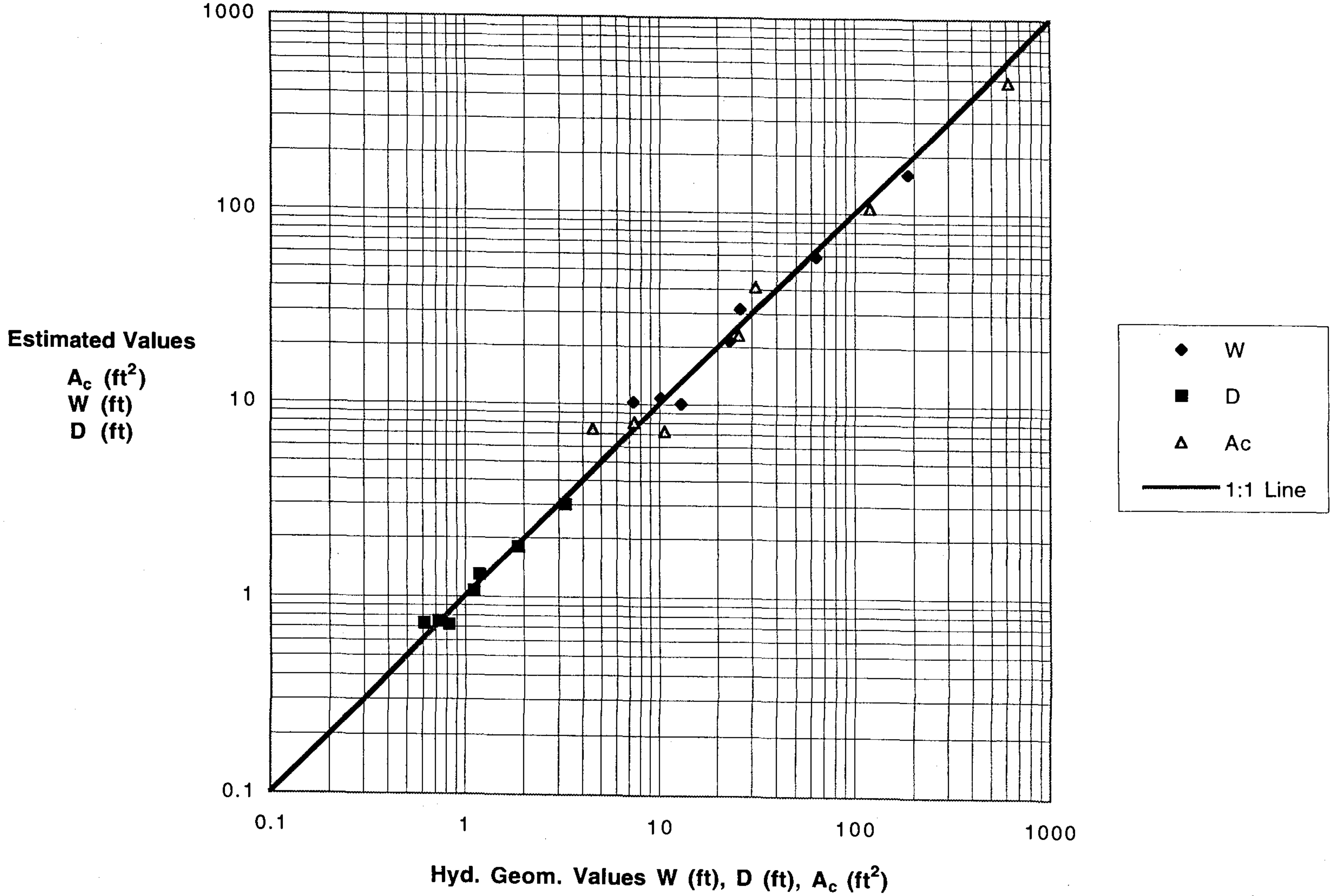


Table 3-16. Channel Width, Depth and Area Comparison at QAA for for NE Washington

	$W = C(P)^{E1}(A_b)^{E2}$		$D = C(P)^{E1}(A_b)^{E2}$		$A = C(P)^{E1}(A_b)^{E2}$
C:	0.062	C:	0.053	C:	0.0032
E1:	0.98	E1:	0.5	E1:	1.49
E2:	0.6	E2:	0.31	E2:	0.91

Station Name	USGS Gage No.	QAA (cfs)	Average Annual Precip., P (in/yr)	Drainage Area, Ab (sq. mi.)	Hyd. Geom. W @ QAA (ft)	Equation 3-56 Estimated W Est (ft)	Hyd. Geom. D @ QAA (ft)	Equation 3-57 Estimated D Est (ft)	Hyd. Geom. A @ QAA (ft^2)	Equation 3-58 Estimated A Est (ft)
Kettle	12401500	1496.0	27	2220	186.4	159.6	3.28	3.00	612.4	482.0
Sheep	12407500	12.0	18	48	10.2	10.7	0.73	0.75	7.4	8.0
Deer	12407520	18.0	20	36	13.0	10.0	0.83	0.72	10.7	7.2
L. Pend O.	12408300	58.0	29	132	26.3	31.5	1.19	1.30	31.3	41.1
Haller	12408420	7.0	20	37	7.3	10.2	0.61	0.73	4.5	7.4
Mill	12408500	47.0	26	83	23.1	21.4	1.11	1.06	25.8	22.9
Hangman	12424000	250.0	20	689	63.4	58.9	1.88	1.80	119.1	106.3

Figure 3-34. Channel Width, Depth and Area Estimations versus Hydraulic Geometry Values at QAA for NE Washington



FOR 7-DAY AVERAGE LOW FLOWS

In the report on the low flow program for the CCT Reservation, Orsborn and Orsborn (1999) separated the annual Q7L2 values in the USGS records (Williams et al 1985) into winter and fall events using Internet records for the Kettle River, Deer Creek, Little Pend Oreille River and Mill Creek (Table 3-17).

The regional equations for these four USGS stations, shown in Figure 3-35, are:

For fall: $Q7L2 = 0.021\,(PBE)^{0.83}$ (3-59)

For winter: $Q7L2 = 0.051\,(PBE)^{0.73}$ (3-60)

Using just the fall Eq. 3-59 for low flows and substituting this equation Eqs. 3-48, 3-49 and 3-50, gives the following combined equations:

For Q7L2 in the fall in NE Washington::

$$W = 0.28\,(P)^{0.57}\,(A_b)^{0.57}\,(H)^{0.29} \quad \textbf{(3-61)}$$

$$D = 0.11\,(P)^{0.24}\,(A_b)^{0.24}\,(H)^{0.12} \quad \textbf{(3-62)}$$

$$A_c = 0.032\,(P)^{0.81}\,(A_b)^{0.81}\,(H)^{0.41} \quad \textbf{(3-63)}$$

The Q7L2 estimated values of W, D and A_c, and those from the regional hydraulic geometry equations, are in Table 3-18 and are compared graphically in Figure 3-36.

Discussion of NE Washington Results

The NE Washington region, considering the range in basin size, had fairly good empirical relations between channel and basin characteristics, except for a few of the gaging stations (Figures 3-27 and 3-28). These inconsistencies for Hangman, Haller and Sheep Creeks are repeated in the combined relationships shown in Figure 3-32 (Q1F2), Figure 3-34 (QAA) and Figure 3-36 (Q7L2).

The Hangman Creek channel size has been strongly affected by heavy flooding form its watershed (shallow bedrock and agricultural land). It has extremely low flows due to poor groundwater supply and over-appropriated water rights. Sheep Creek and Haller Creek are the only other sites, which do not "fit" the relationships at Q7L2 (Figure 3-36).

TABLE 3-17. SUMMARY OF CHARACTERISTIC SEASONAL Q7L2 LOW FLOWS
(Orsborn & Orsborn, 1999)

	USGS Gage:	Kettle R	Deer Creek	LPOR	Mill Creek
	USGS No:	12401500	12407520	12408300	12408500
	POR (WY):	(1929-97)	(1960-72)	(1959-75)	(1941-86)
	BE:	1691	27	96	59
	PBE:	45648	540	2784	1534
Q1L2	Fall	157.5	4.0	14.0	9.3
	Winter	100.0	4.6	14.0	9.0
Q7L2	Fall	162.4	4.1	14.1	9.5
	Winter	130.9	5.4	15.0	10.2
Q7L10	Fall	83.4	1.7*	9.9	5.2
	Winter	70.0	4.6	10.4	6.3
Q7L20	Fall	77.0	Extr 1.2*	Extr 8.6	5.1
	Winter	57.9	Extr 4.3	Extr 9.0	5.6
Q30L2	Fall	189.2	4.4	15.4	10.7
	Winter	169.9	6.4	19.3	12.1
Q60L2	Fall	213.3	5.0	16.3	11.4
	Winter	186.5	6.8	21.1	13.4

Notes: Extr = Extrapolated graphically from Q7L2 and Q7L10, cannot be calculated from data; period of record too short.
* Unusually low values compared to other gages; maybe due to diversions.
BE = Basin Energy; PBE = Annual Precipitation times Basin Energy
These seasonal low flows were calculated from USGS daily flow records on the Internet for each POR.

Figure 3-35. Q7L2 versus Annual Preciptiation times Basin Energy (PBE) for Four Northeast Washington USGS Gages

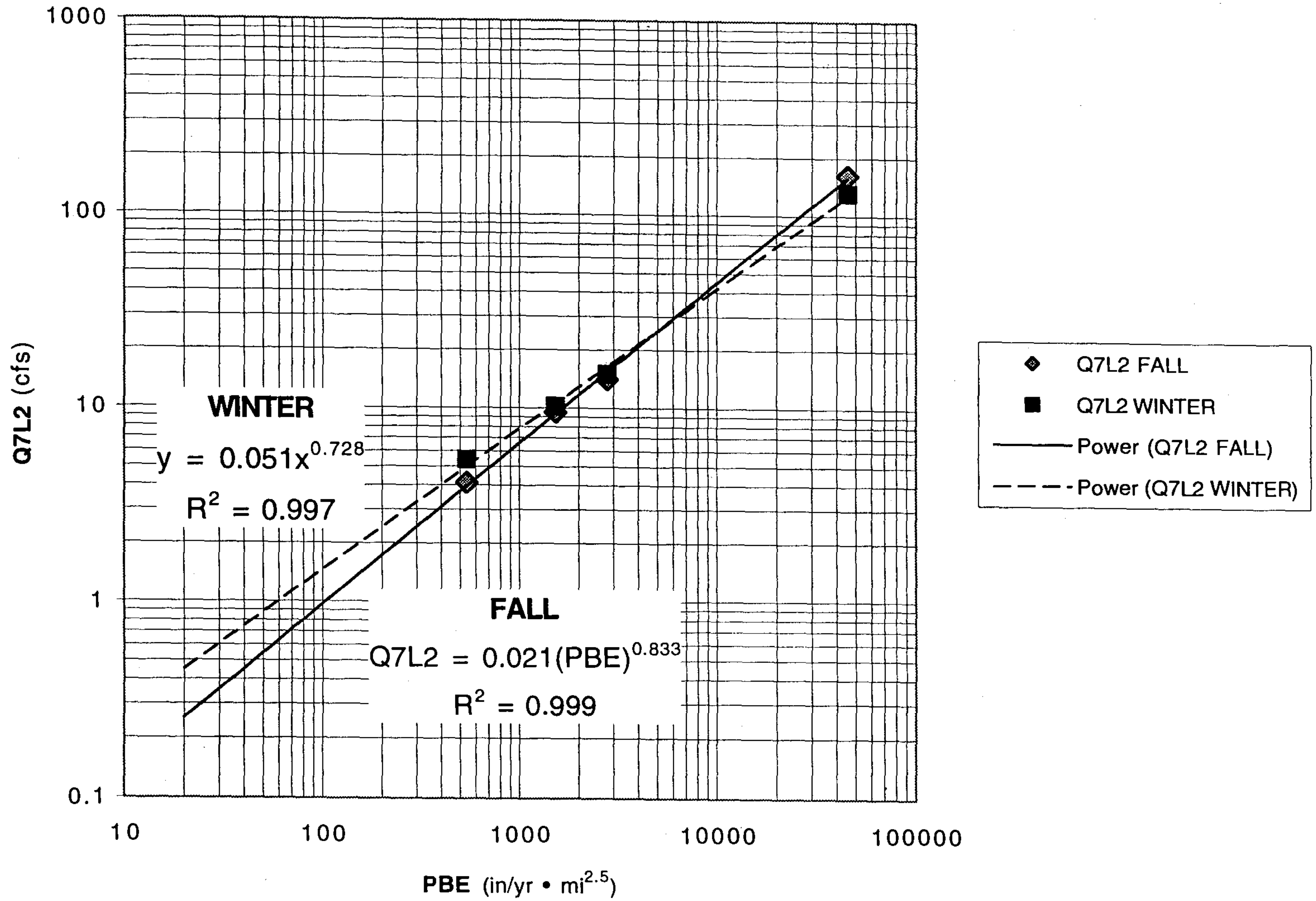
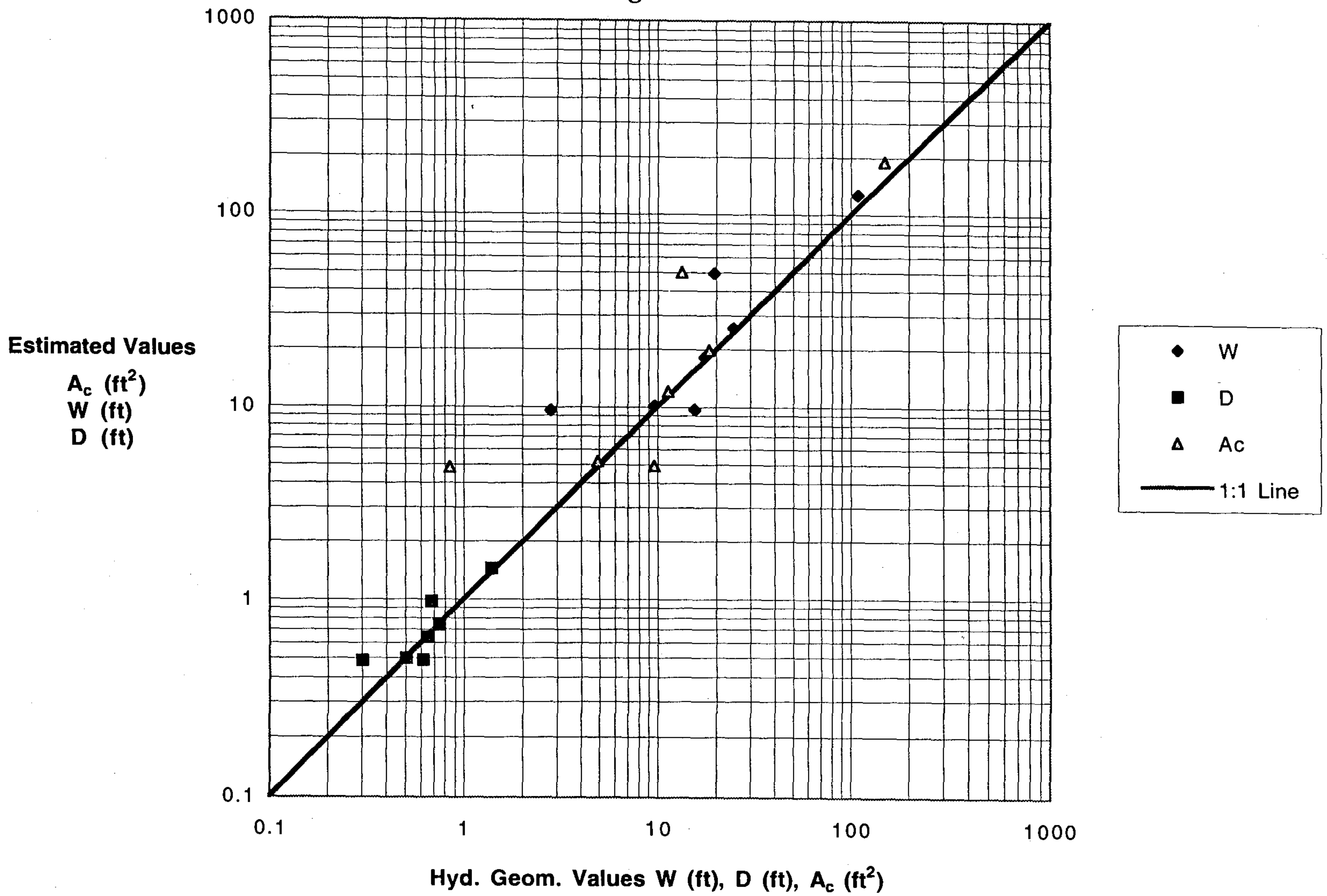


Table 3-18. Channel Width, Depth and Area Comparison at Q7L2 for for NE Washington

	$W = C(P*A_b)^{E1}(H)^{E2}$	$D = C(P*A_b)^{E1}(H)^{E2}$	$A = C(P*A_b)^{E1}(H)^{E2}$
C:	0.28	0.11	0.032
E1:	0.57	0.24	0.81
E2:	0.29	0.12	0.41

Station Name	USGS Gage No.	Q7L2 (cfs)	Average Annual Precip., P (in/yr)	Drainage Area, Ab (sq. mi.)	Relief, H (mi.)	Hyd. Geom. W @ Q7L2 (ft)	Equation 3-61 Estimated W Est (ft)	Hyd. Geom. D @ Q7L2 (ft)	Equation 3-62 Estimated D Est (ft)	Hyd. Geom. A @ Q7L2 (ft^2)	Equation 3-63 Estimated A Est (ft)
Kettle	12401500	120.0	27	2220	0.58	108.7	126.4	1.39	1.44	150.1	189.7
Sheep	12407500	7.2	18	48	0.34	15.6	9.7	0.62	0.49	9.6	4.9
Deer	12407520	3.6	20	36	0.56	9.7	10.1	0.50	0.50	4.9	5.2
L. Pend O.	12408300	14.0	29	132	0.53	24.7	25.7	0.75	0.74	18.4	19.7
Haller	12408420	0.6	20	37	0.44	2.8	9.5	0.30	0.49	0.8	4.8
Mill	12408500	8.5	26	83	0.50	17.5	18.2	0.65	0.64	11.3	12.1
Hangman	12424000	10.1	20	689	0.41	19.7	49.5	0.68	0.97	13.4	50.0

Figure 3-36. Channel Width, Depth and Area Estimations versus Hydraulic Geometry Values at Q7L2 for NE Washington



Summary Comparisons of Regional Analyses

The various phases of analysis covered in Part 3 are summarized for the three regions in Washington, beginning with regional hydraulic geometries. Table 3-19 summarizes the hydraulic geometry equations for the Olympic Peninsula, Puget Lowland and NE Washington Regions.

Table 3-19. Comparison of Three Regional Sets of HYDRAULIC GEOMETRY Equations for Three Characteristic Flows.

Region	At Flood Flow	At Average Flow	At Low Flow
Olympic Peninsula	$W = 2.40(Q1F2)^{0.47}$	$W = 4.02(QAA)^{0.51}$	$W = 8.37(Q7L2)^{0.52}$
	$D = 0.22(Q1F2)^{0.36}$	$D = 0.29(QAA)^{0.32}$	$D = 0.31(Q7L2)^{8.30}$
	$A_c = 0.52(Q1F2)^{0.83}$	$A_c = 1.16(QAA)^{0.83}$	$A_c = 2.56(Q7L2)^{0.82}$
Puget Lowlands	$W = 4.95(Q1F2)^{0.33}$	$W = 4.39(QAA)^{0.44}$	$W = 6.46(Q7L2)^{0.51}$
	$D = 0.98(Q1F2)^{0.20}$	$D = 0.59(QAA)^{0.17}$	$D = 0.36(Q7L2)^{0.16}$
	$A_c = 4.85(Q1F2)^{0.53}$	$A_c = 2.27(QAA)^{0.60}$	$A_c = 2.33(Q7L2)^{0.67}$
NE Washington	$W = 1.67(Q1F2)^{0.53}$	$W = 2.27(QAA)^{0.60}$	$W = 4.00(Q7L2)^{0.69}$
	$D = 0.28(Q1F2)^{0.34}$	$D = 0.34(QAA)^{0.31}$	$D = 0.35(Q7L2)^{0.29}$
	$A_c = 0.47(Q1F2)^{0.87}$	$A_c = 0.76(QAA)^{0.91}$	$A_c = 1.40(Q7L2)^{0.98}$

If one is planning to develop an analysis of "channel condition" there are "office steps" which can be done before going to the field. Regional hydraulic geometry estimates at three characteristic flow stages can be done IF one has estimates of the characteristic flows. These flow estimates can be made from regional models of the flows related to basin characteristics.

The ranges of the characteristic flows used in the analysis are given in Table 3-20.

Table 3-20. Ranges of Flows and Average Annual Basin Precipitation (P) in the Three Regions of Washington Used in Regional Models of Hydraulic Geometry.

Region	*P (in/yr)*	Q1F2 (cfs)	QAA (cfs)	Q7L2 (cfs)
Olympic Peninsula	*40 to 200*	150 - 18300	16 - 2035	2.2 - 610
Puget Lowland	*37 to 66*	144 - 1076	22 - 154	3.2 - 28
NE Washington	*18 to 30*	37 - 11560	7 - 1496	0.6 - 120

Although the flows given in Table 3-20 represent a very broad range from 0.6 to 18,300, a better comparative way to look at the flows is in terms of cfs/mi^2 , or "unit flows". These are the net flows released from the watersheds based on the form of precipitation, which caused those flows. For example, on the West and Southwest sides of the Olympic Peninsula heavy rains on top of an already elevated stream stages result in large floods. Puget Lowland streams usually have rain combined with snowmelt. Northeastern Washington floods are usually a result of snowmelt. The ranges of unit flows in the three regions are summarized in Table 3-21.

The unit flow floods range from just 0.8 to 83.4 cfs/mi^2 (ratio 104), average flows from 0.19 to 12.0 (ratio 63) and low flows from 0.014 to 2.90 (ratio 207). These unit flood values represent the rate of precipitation, or snowmelt, or both, and the valley morphology and slope. Average flow values include the flood and low flow events of record. The low flows are most strongly influenced by the available groundwater storage and/or glacial supply (e.g. the Hoh at 2.90 cfs/mi^2 and Hangman Creek near Spokane at 0.014 cfs/mi^2, a huge watershed with low precipitation, poor ground water storage and is over-appropriated).

An "office step" for estimating characteristic flow for channel condition analysis can be done from: (1) good gaging records; (2) extending short records by correlating them with the same-day flows at a long-term gage; or (3) by using regional models of the types given in Table 3-22. The combined equations for W, D and Ac for the three regions are given for the three characteristic flows on pages 3-29 and 3-30 for the Olympic Peninsula; on pages 3-41 and 3-44 for the Puget Lowlands; and on pages 3-60 and 3-66 for NE Washington.

Table 3-21. **Comparison of Maximum and Minimum Unit Values in cfs per square mile for Q1F2, QAA and Q7L2 in the Three Regions for the Ranges of Flow in Table 3-20.**

Region	*Stream Name*	$Q1F2/A_b$ (cfs/mi^2)	*Stream Name*	QAA/A_b (cfs/mi^2)	*Stream Name*	$Q7L2/A_b$ (cfs/mi^2)
Olympic Peninsula[1]	*NF Quinalt*	83.4	*NF Quinalt*	12.0	*Hoh*	2.90
	Snow	13.4	*Snow*	1.4	*Snow*	0.20
Puget Lowland[2]	*Woods*	19.2	*Woods*	2.8	*Issaq-U*	0.55
	Quilceda	9.6	*Mercer*	1.8	*Swamp*	0.17
NE Washington[3]	*Hangman*	8.3	*Kettle*	0.68	*Sheep*	0.15
	Sheep	0.8	*Haller*	0.19	*Hangman*	0.014

1. Data in Tables 3-1 and 3-2.
2. Data in Table 3-7.
3. Data in Tables 3-11 and 3-13.

Table 3-22. **Comparison of Regional Equations for Estimating CHARACTERISTIC FLOWS in the Three Regions (Streamflow Equations).**

Region	At Flood Flow (cfs)	At Average Flow (cfs)	At Low Flow (cfs)
Olympic Peninsula	$Q1F2 = 0.27(PA_b)^{1.05}$	$QAA = 0.0032(P)^{1.60}(A_b)$	$Q7L2 = 0.0067[PA_b(H)^{0.50}]^{1.06}$
Puget Lowland	$Q1F2 = 0.12(PA_b)^{1.14}$	$QAA = 0.0040(P)^{1.62}(A_b)$	$Q7L2 = 0.0033(PA_b)^{1.10}$
NE Washington	$Q1F2 = 1.87(A_b)^{1.15}(H)^{0.58}$	$QAA = 0.0025(P)^{1.64}(A_b)$	$Q7L2\ (Fall) = 0.021[PA_b(H)^{0.50}]^{0.83}$

Another surveyor in 1918 "...found the course of the river radically different from that shown in Curry's Survey of 1882, his measurements ranging from 330 to 550 ft in the same stretch of stream channel where Curry (1882) found widths of 12 to 49 ft."

(From Burkham 1981, page 594 in a discussion of the Rio Salado near Santa Rita, NM).

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4. APPLICATIONS

Introduction

Flow characteristics and their interactions with the channel boundaries are central to all river management problems. Alluvial streams develop an average geometry that reflects the load of flow and sediment. Because most natural stream channels exist in erodible soils, they alternately aggrade and degrade, depending on the load in the channel. The resultant channel dimensions reflect average values for width and depth imposed by water and sediment discharge, bed sediment size, bank vegetation, and average bed slope. Recognizing the natural channel relationships of a stream thus becomes a basic step in understanding a stream's behavior and characteristics.

Channel condition studies, when coupled with stream hydrology, lead to the following general categories of applications:

Reconnaissance: inventories/analysis and planning.
Restoration: projects and activities that modify existing channel.
Reconstruction: design leading to construction of new channels.

There is not always a strict, clear difference between these applications. Because of the many facets that exist in any given project, overlap most likely will occur. Following is further discussion and examples of these general categories.

Reconnaissance

Reconnaissance is the general term for studies gathering information on historic and/or present channel conditions. This information is used to plan, design, and monitor projects. A common question in these studies is how much have stream channel widths and depths changed with changes in land use? This is particularly true in preparing watershed analyses or basin plans, and exploring the land use effects of urbanization, logging, or agriculture.

Considerable effort is often expended in these studies to identify the natural dimensions of the stream channel under pre-disturbance conditions and following a change in land use, how did the channel respond? It is known that increases in the amount of impervious surface increases the amount and rate and runoff (Leopold 1990). Such changes may trigger channel erosion or stream incision (Booth 1990), and cause significant increases in channel capacity (Knight 1979; Mosley 1975). This information is also central to availability and suitability investigations. Examples include habitat availability studies of instream flow related to water diversion/flow reservation studies.

Fish habitat in its simplest physical terms can be described as hydraulic diversity. Specifically, the basic elements of instream habitat are water depth and velocity. All stream fish have adapted to a particular range of depths and velocities. Even body shapes of fish have adapted. Habitat availability relates to width, depth and velocity at various seasonal flows.

In other reconnaissance studies, channel geometry relationships could serve as preliminary estimates of channel capacity, flood flow characteristics and floodplain inundation. While these estimates have to be confirmed with local topographic data, they would provide the starting point to initiate the investigation. For both planning and design the sizing of bridges and culverts is obviously related to anticipated flow characteristics. New design criteria for sizing culverts in Washington and Oregon, for example, now require the culvert to contain the bankfull width plus a safety factor, as one design alternative. Channel dimension estimates are valuable at a programmatic level in defining culvert size and location.

Recent listings of several salmonids under the Endangered Species Act (ESA) has brought with it new expectations in project analysis. Section 7 of the ESA requires an effects analysis for any proposed action that could modify fish habitat. Channel geometry would be integral in the analysis of channel modifications, dredging for flood control, or gravel and gold mining, or flow reduction. It would also be useful in the analysis of institutional programs such as river management. These programs routinely affect many miles of channel through dredging, straightening, and bank protection projects.

Restoration

Identifying natural channel geometric and flow relationships for a stream is an important step towards understanding the stream's behavior and characteristics. Based on drainage area and other basin characteristics, the channel geometry measurements can be linked to the channel pattern and profile, and used to size stream rehabilitation works that mimic natural conditions.

The geometry of meanders and pool/riffle profile for all river patterns in erodible materials can be related to the bankfull width. Meander radius, wave length, amplitude, belt width, channel entrenchment also relate to bankfull width. Flood prone areas have empirical relationships to bank full width and the 50-year flood flow. Even a preliminary estimate of the hydraulic geometry based on an abbreviated field survey in which only the bankfull width and depth are measured will provide useful guidelines (Rosgen 1996). In planning/design of projects to recreate meander geometry, to what dimensions will we design?

Width to depth relationships lead to other relationships such as the radius of curvature.

Some past projects have achieved undesired results. How can we undo errors of the past (channel dredging, straightening)? There are many examples of stable channel design given in Newbury and Gaboury (1993), Brookes and Shields (1996) and Thorne, Hey and Newson (1996).

Reconstruction

In the course of completing projects for flood alleviation and channel stabilization, many rivers have been considerably modified. River engineering and mining works involving dredging, widening, straightening and diversions have affected hundreds of miles of rivers. These changes have adversely affected the stability of the engineered and adjacent reaches and destroyed the conservation and amenity value of riverine areas (Brookes, 1988; Purseglove, 1988). Consequently there is an urgent need to use more sympathetic engineering design procedures which will preserve the natural stability of the river, its habitat diversity and its amenity values. By designing with nature rather than imposing on nature, such approaches are more cost-effective, require less maintenance and, above all, minimize environmental impacts.

Increasingly, the demands to restore and rehabilitate stream reaches requires the adoption of solutions to recreate channel features that are enduring and in harmony with local flow conditions. Meandering channels with pools, riffles, glides, dead zones and point bars need to be recreated to restore the habitat features destroyed by previous works or natural disasters. These features cannot be installed at random, and badly designed schemes will quickly be made dysfunctional as the river reacts to the unnatural imposed conditions. This emphasizes the need for the development of sympathetic design procedures that are in harmony with local river fluvial geomorphology.

In the remainder of Part 4, four project examples (case studies) have been summarized. Project 1 covers instream habitat and basin improvements made at LeBar Creek, a tributary to the S.F. Skokomish River in the southeast part of the Olympic Peninsula. Project 2 deals with planning for the restoration of channel meanders in Crooked River, a gold-dredged tributary to the South Fork of the Clearwater River in Idaho. Project 3 presents the reconnaissance and comprehensive documentation and analysis of the effects of road building, logging and urbanization on the sediment load, channel geometry and the decline of coho runs in Big Beef Creek west of Bremerton, Washington on Hood Canal. The fourth project examines the effects of dams and diversions on instream channel geometry and habitat in the Lower Elwha River on the north coast of the Olympic Peninsula.

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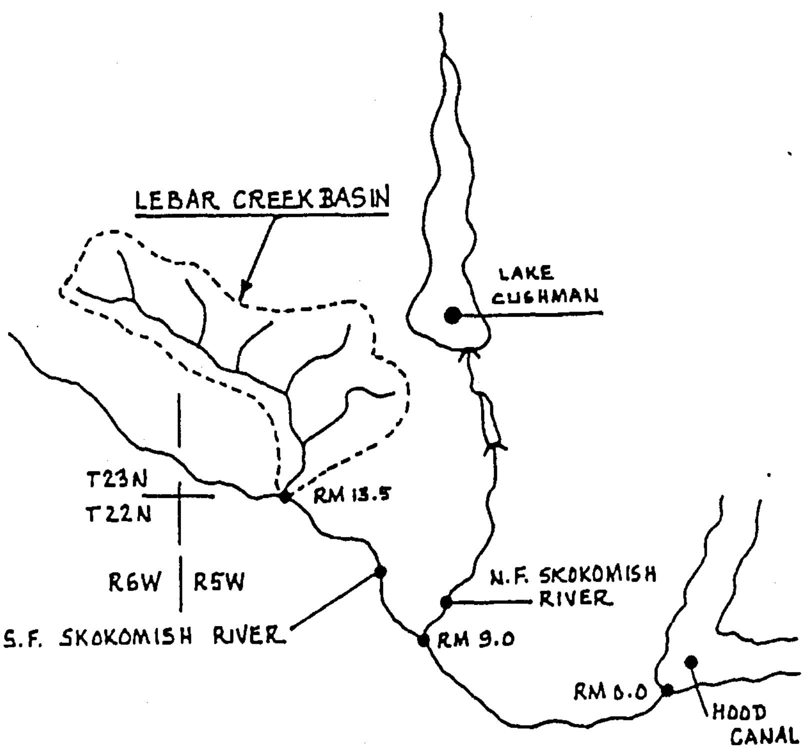
CASE STUDIES

CASE STUDY 1. HABITAT IMPROVEMENT PROJECTS IN LOWER LEBAR CREEK BASIN

LOCATION: LeBar Creek, Tributary to the S. F. Skokomish River, a tributary at the South End of Hood Canal; Water Resource Inventory Area (WRIA) 16; Project Located in S 1/2, Sec 4, T22N, R5W. (See location map in Figure 4-1).

Figure 4-1. Location Map for the LeBar Creek Project (Not to Scale)



MAIN REFERENCE: Orsborn, J. F. 1993. Habitat improvement projects in Lower LeBar Creek Basin. USDA Forest Service, Hood Canal Ranger District, Hoodsport, WA.

OBJECTIVES:

- Restoration of fish habitat and passage in the 1.0 mi. of LeBar Creek below the barrier falls;
- Reconnect the off-channel, point-bar ponds (remnant flood channels) to the main channel in the lower 0.3 mi; and
- Stabilize eroding areas, including the road that crosses the creek and enters the basin.

SUMMARY:

LeBar Creek (Figure 4-1) is a tributary to the South Fork Skokomish River. The South Fork joins the North Fork at RM 9.0 and then flows into Hood Canal near Union, Washington. As is typical of the tributaries to the South fork, a bedrock outcrop forms a hanging valley about 1.0 mile above the confluence of LeBar Creek with the South fork. These hanging valleys form waterfalls and high velocity chutes, which are complete barriers to upstream migration by fish.

The loss in anadromous fish runs in the basin can be attributed to impacts on instream habitat caused by road building, logging activities and associated landslides. The LeBar Creek drainage lies within the boundaries of the Shelton Cooperative Sustained Yield Unit, which was intensively logged between 1955 and 1989. Increased flood flows and sediment loads, and the loss of woody debris from riparian areas, have combined to degrade the fisheries habitat in LeBar Creek.

The Forest Service has undertaken corrective activities on the watershed and in the lower one-mile project reach. On the watershed, hill slopes were replanted, abandoned roads pulled back and stabilized, and unneeded culverts removed. To help restore the habitat in the anadromous reach and to increase the productivity of the fishery below the falls, the following tasks were undertaken in this project:

(1) habitat survey of the lower one-mile reach of LeBar Creek, identifying potential fish habitat improvements within the reaches;

(2) in the lower 0.3 miles fish habitat modification structures were designed, which will: help stabilize the reach, reduce road fill erosion, improve fish passage and habitat diversity, and

complement the development of off-channel rearing habitat on the large adjacent point bar;

(3) survey and design the off-channel rearing habitat on the adjacent point bar; and

(4) design fish habitat improvements for the upper 0.7 mile where there is no heavy equipment access.

A preliminary planning schedule called for:

- completion of the lower 0.3 mile of instream habitat improvements in 1993;

- installation of the off-channel rearing area water supply pipeline (and internal supply channels to ponds), and the lower connecting channel to LeBar Creek in old remnant channels in 1993;

- expansion and refinements in the off-channel rearing site in 1994 after a year of observation and operation; and

- installation of habitat improvement structures in the upper 0.7 mile reach, depending on the results of project monitoring and evaluation in 1993-1995.

The body of the project report was supplemented with six appendices covering: geomorphic analysis of the subbasins and tributaries, hydrologic analysis, topographic survey notes of the lower 0.3 mi, habitat survey notes of the entire 1.0 mi project reach, the project photographic record and drawings.

PHYSICAL SETTING:

This section of the report includes: (1) the physical characteristics of the basin and stream system which are used to characterize basin morphology and to estimate streamflows; (2) recent land use activities (logging and road building) which caused downstream channel adjustments and habitat degradation; (3) an evaluation of watershed conditions [U. S. Forest Service, 1991]; (4) an evaluation of land use changes on channel size; (5) a summary of estimated streamflows at the project site in Lower LeBar Creek; and (7) fisheries information including a life-stage periodicity chart.

Physical Characteristics of the Basin-Stream System and Estimated Stream Flows (See Table 4-1 and Figure 4-2).

Drainage Area (A): 9.7 sq. mi. (Cols. 5 and 6)

Stream Length (LST): 14.0 mi. (Cols. 3 and 4)

1st Order (L1): 7.3 mi.

2nd Order (L2): 6.7 mi.

Total Stream Density (SD) 14.0/9.7 = 1.4 mi/sq. mi. (Col. 8, cumulative)

Average Annual Precipitation (P): 130 in./yr. (Col. 15)

Average Annual Water Input to the Basin (PA): 1265 sq. mi. – in./yr. (Col. 16)

Basin Relief (H): 0.56 mi. (Col 12)

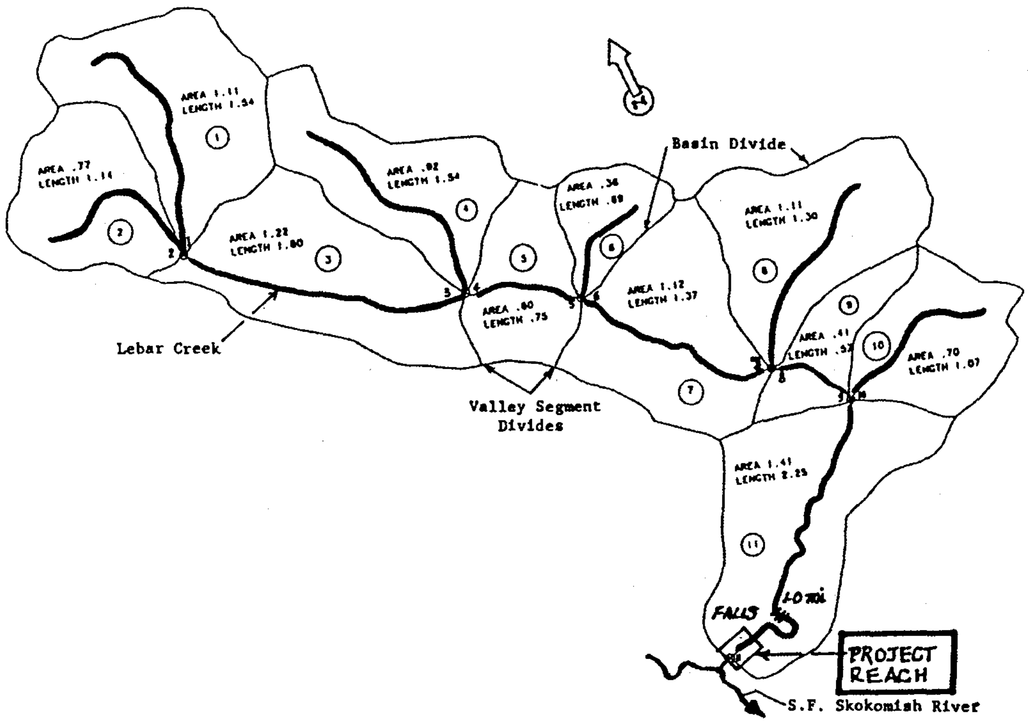
Basin Energy (A) $(H)^{05}$: 7.28 $mi.^{2.5}$ (Col. 14)

The hydrologic analysis used several modeling approaches to estimate floods, low flows, average annual flow and its extremes, and maximum, minimum and mean monthly flows. The average flood flow was related to channel size on a regional basis, as was the average annual flow. Low flows and monthly flows were used to estimate seasonal fisheries flows and minimum flow conditions.

Table 4-1. Geomorphic Characteristics of LeBar Creek Basin

BASIN NO.	STREAM ORDER	STREAM LENGTH	CUMUL. LENGTH	BASIN AREA	CUMUL. AREA	BASIN STREAM DENS.	CUMUL. STREAM .DENS.	HEAD WATER ELEV.	OUTLET ELEV.	RELIEF BASIN	RELIEF CUMUL.	BASIN ENERGY BASIN	BASIN ENERGY CUMUL	AVER. PRECIP	BASIN INPUT	(P*A) / (LT*H^2)
(-)	(-)	LS	LST	A	A	SD	SD	EH	ED	H	H	AH^0.50	AH^0.50	P	(P*A)	
(-)	(-)	(mi)	(mi)	(mi)^2	(mi)^2	(mi)^-1	(mi)^-1	(ft)	(ft)	(mi)	(mi)	(mi)^2.5	(mi)^2.5	(in/yr)	(sq.mi-in/yr)	(in/mi)
Col (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
1	1	1.54	1.54	1.11	1.11	1.38	1.38	4300	2000	0.44	0.44	0.74	0.74	140	155	520
2	1	1.14	2.68	0.77	1.88	1.48	1.42	4200	2000	0.42	0.44	0.51	1.23	138	259	499
3	2	1.80	4.48	1.22	3.10	1.48	1.44	3000	1400	0.30	0.49	0.67	2.17	138	428	398
4	1	1.54	6.02	0.92	4.02	1.67	1.50	4400	1400	0.57	0.49	0.69	2.81	133		
5	2	0.75	6.77	0.60	4.82	1.25	1.46	2500	1300	0.23	0.53	0.28	3.36	136	628	335
6	1	0.69	7.46	0.36	4.98	1.92	1.50	2800	1300	0.28	0.52	0.19	3.62	133		
7	2	1.37	8.83	1.12	6.10	1.22	1.45	2500	1050	0.27	0.52	0.58	4.40	134	817	343
8	1	1.30	10.13	1.11	7.21	1.17	1.40	3000	1050	0.37	0.52	0.68	5.19	131		
9	2	0.57	10.70	0.41	7.62	1.39	1.40	2500	950	0.29	0.48	0.22	5.28	132	1005	408
10	1	1.07	11.77	0.70	8.32	1.52	1.41	3000	950	0.29	0.48	0.38	5.76	127		
11	2	2.25	14.02	1.41	9.73	1.60	1.44	2000	500	0.28	0.47	0.75	6.67	130	1265	288
TOTALS:	Whole Basin	14.02	14.02	9.73	9.73			3500			0.56		7.28			

Figure 4-2. Project Basin and Stream Map for LeBar Creek.



Recent Land Use Activities Which Caused downstream Changes in Channels and Habitat.

LeBar Creek was heavily roaded and logged from 1955 to 1989. Annual data and cumulative totals are summarized in Table 4-2.

Table 4-2: Percent of LeBar Creek Basin Logged, and Estimated Annual Miles of Road Constructed (Based on % cut).

YEAR	ACRES CUT	%BASIN CUT	CUMUL. % CUT	EST. ROADS (mi/yr)
1955	2.9	0.005	0.005	0.59
1956	94.7	1.52	1.53	0.59
1964	112.4	1.80	3.33	0.70
1965	196.6	3.16	6.49	1.23
1966	223.1	3.58	10.07	1.39
1967	145.0	2.33	12.40	0.90
1968	164.8	2.64	15.04	1.02
1969	2.0	0.003	15.04	-
1971	47.1	0.76	15.80	0.29
1972	1.8	0.003	15.80	-
1974	123,0	1.98	17.78	0.77
1975	89.4	1.44	19.22	0.56
1976	214.4	3.44	22.26	1.33
1977	535.5	8.60	31.26	3.33
1978	131.3	2.10	33.36	0.81
1980	73.5	1.18	34.54	0.45
1981	89.8	1.44	35.98	0.50
1982	134.4	2.16	38.14	0.84
1983	85.6	1.37	39.51	0.53
1984	45.1	0.72	40.23	0.28
1985	185.6	2.92	43.15	1.13
1988	58.3	0.90	44.05	0.35
1989	45.2	0.70	44.75	0.27
TOTALS	2800.00	44.75%	44.75%	38.8 mi.

Evaluation of Watershed Conditions (U. S. Forest Service, 1991)

In 1991 the Olympic National Forest made an examination of a series of impacted watersheds on the Forest to determine their relative "condition".

The ONF criteria used threshold values as developed by the interdisciplinary team.

STANDARD CRITERIA	THRESHOLD VALUES
(1) % of basin with elevation between 1500 – 3000 ft to account for rain on snow events, and geologic formations which tend to have pockets of unconsolidated material (bed-rock hollows).	50% of the area
(2) Tree Stand ≤ 35 years. Accounts for logging back to 1955, hillslope instability due to loss of root structure and hydrologic balance (changes).	40% of the area
(3) Soil classes (C, D and/or E) which are STEEP, EROSIVE SOILS.	50% of the area
(4) ROAD DENSITY – to account for increases in surface runoff, runoff concentration and silt/sediment load.	2.5 mi. per sq. mi.

MULTIPLE STANDARD THRESHOLD
VALUE (MSTV) = 0.25 Criteria (1 x 2 x 3 x 4)

The Multiple Standard Threshold Value (MSTV), an extension of the Forest Service Thresholds, provides a way to assign a relative total "condition" rating to a basin, to compare basins with baseline conditions and to compare between basins. Multiplying the threshold values (0.50 x 0.40 x 0.50 x 2.5) gives a baseline MSTV of 0.25. Individual thresholds in a test basin might indicate only one severe value with the other three values being less than the threshold values. Even though the MSTV might be less for the test basin than the threshold MSTV of 0.25, the one or two severe values should not be neglected.

For LeBar Creek the threshold values of the factors, the ratios of LeBar Creek values to standard values (a Severity Ratio), and the multiple of those ratios are listed in Table 4-3. The multiple of the Severity Ratios gives a more descriptive measure of the basin values to the threshold values than does the MSTV. The severity ratios demonstrate how far above (or below) the LeBar values are to the thresholds. The baseline multiple severity factor for the standard thresholds would be 1.00

Table 4-3: LeBar Creek Basin Threshold Rating and Their Severity Compared to the Standard Thresholds Listed Above .

THRESHOLDS	ELEV.	TREES	SOILS	ROADS (mi/mi^2)	MULTIPLE VALUES (MSTV)
LeBar Cr.	63.5%	44.9%	66%	3.9	0.73
Standard	50%	40%	50%	2.5	0.25
Severity Ratios LeBar/Standard	1.27	1.12	1.32	1.56	2.92

Roads are seen to provide the most severe index at 56% (1.56 Ratio) above the standard. Actual stream densities in the LeBar Creek basin average 1.4 mi/mi^2, only about one-third (36%) of the road density.

Evaluation of Changes in Stream Channels Due to Changes in Land Use

Two basic questions needed to be answered in order to make the most direct evaluation of upstream land use activities on possible downstream channel changes:

(1) What would be the expected impacts on the stream channel in the reach just upstream of the confluence of LeBar Creek and South Fork Skokomish River (widening); and

(2) How can the site channel be checked as to whether or not this impact has occurred?

- by using regional channel geometry models (from USGS gage calibration records) to estimate top width, depth and area at bank full flow (at average 2-year daily flood and at average annual flow); and
- by comparing the regional equation estimated values with actual measurements in LeBar Creek.

Channel measurements were made in a straightened reach of channel between 1600 – 1900 feet upstream of the mouth of LeBar Creek and beside the point bar. It appears that someone straightened this channel, pushed up fill and debris along the left bank, and the channel has steepened resulting in a cobble-bedded channel. During low flow there are places where fish would be hard pressed to have successful migration due to depth and velocity constraints. Floods cannot overtop the left bank.

The regional equations for channel geometry in terms of the daily mean annual flood (1-day average, 2-year recurrence interval flow) are:

Top Width:	$W = 2.38\ (Q1F2)^{0.46}$	(ft)
Mean Depth:	$D = 0.51\ (Q1F2)^{0.28}$	(ft)
Mean Velocity:	$V = 0.82\ (Q1F2)^{0.26}$	(fps)
Flow Area:	$A_c = 1.18\ (Q1F2)^{0.74}$	$(ft)^2$

The regional channel geometry equations were developed from USGS gaging calibration records of the stations on the Little Quilcene, Duckabush and Dungeness Rivers, and Goldsborough and Kennedy Creeks. The S. F. Skokomish River and Skokomish River gages could not be used because of dramatic changes in their channel geometries due to logging-generated sediment aggradation and associated channel widening.

Using 600 cfs as the bankfull flow in the above set of equations says the LeBar Creek channel should have these characteristics:

$$W = 2.38\ (600)^{0.46} = 45 \text{ ft}$$

$$D = 0.51\ (600)^{0.28} = 3.0 \text{ ft}$$

$$V = 0.82\ (600)^{0.26} = 4.2 \text{ fps}$$

$$A_c = 1.18\ (600)^{0.74} = 135 \text{ ft2}$$

The existing channel measured (average of three cross-sections)

$W = 60$ ft; $D = 3.2$ ft; and $A_c = 192$ ft^2

The LeBar Creek ratios of channel size components are:

Values	**W** (ft)	**D** (ft)	**A_c** $(ft)^2$
LeBar	60	3.2	192
Model	45	3.0	135
Ratios	1.33	1.07	1.42

Fisheries Information

Assuming the coho and steelhead will continue to use LeBar Creek in the lower mile it is important to be able to compare the timing of fish utilization with streamflow. Fisheries requirements were displayed in a periodicity chart for the Skokomish-Dosewallips WRIA. Considering the seasonal life stages of upstream migration, spawning, incubation and juvenile outmigration, the monthly flows were modeled and catalogued.

The rest of this report covers these topics: project guidelines and planning; descriptions of the lower instream and the offstream projects; upstream potential project design recommendations; and appendices.

EXAMPLES OF LOWER CREEK PROJECTS

As shown in Figure 4-3, (Drawing LC-1), the lower LeBar Creek habitat modification project involved two components, instream and offstream. The project baseline drawing shows a total of 7 Habitat Improvement Units (HIU), 5 in LeBar Creek and 2 in the off-channel area. The units were selected based on channel reach geometric and physical characteristics and function. An example of the details in one HIU is presented in Figure 4-4, which shows HIU4 in the channel bend where the toe of the access road has been eroding.

The problems in HIU 4 were: steep cut bank and eroding slope (earlier attempts at dumping riprap from the road above have been only partially successful); Unit contains the best pool habitat in the project reach; cover lacking; and passage problems just upstream due to wide, shallow, steep channel.

Proposed solutions included: (Fig. 4-4) start at upstream end with two rock or log deflectors on right bank; add two rows of turning rocks from the downstream deflector across to the point bar; move corner of point bar to opposite cut bank; rearrange existing boulders in a series of deflectors; cable logs along toe between deflectors; need 10 new 2-ft and 10 new 3-ft rocks at this site; and vegetation was planted in bare earth exposures.

The location of HIU 4 within the whole lower creek habitat project is shown in Figure 4-3.

CONCLUSION

To prepare for this habitat project the road and slide conditions on the watershed were addressed. Besides improving habitat in the project reach, the recurring problem of road fill erosion was included in the project and the local problem was corrected mainly with habitat structures.

By using regional hydraulic geometry analysis, the riffle (passage-limiting) reach problems were analyzed and addressed. Channel narrowing log deflectors were installed at 135^0 to the left downstream bank. These structures trapped gravels and restored bank vegetation. Also, installing boulders and log structures periodically along the right side of the reach deepened the thalweg.

Sediment deposition problems arose at the water intake but these have been corrected. Some maintenance and fine-tuning were required in the first years of the project, but now it has hardened. The alders on the point bar were girdled and cedars have been planted to accelerate the succession.

Figure 4-3. LeBar Creek Habitat Project Map and Baselines.

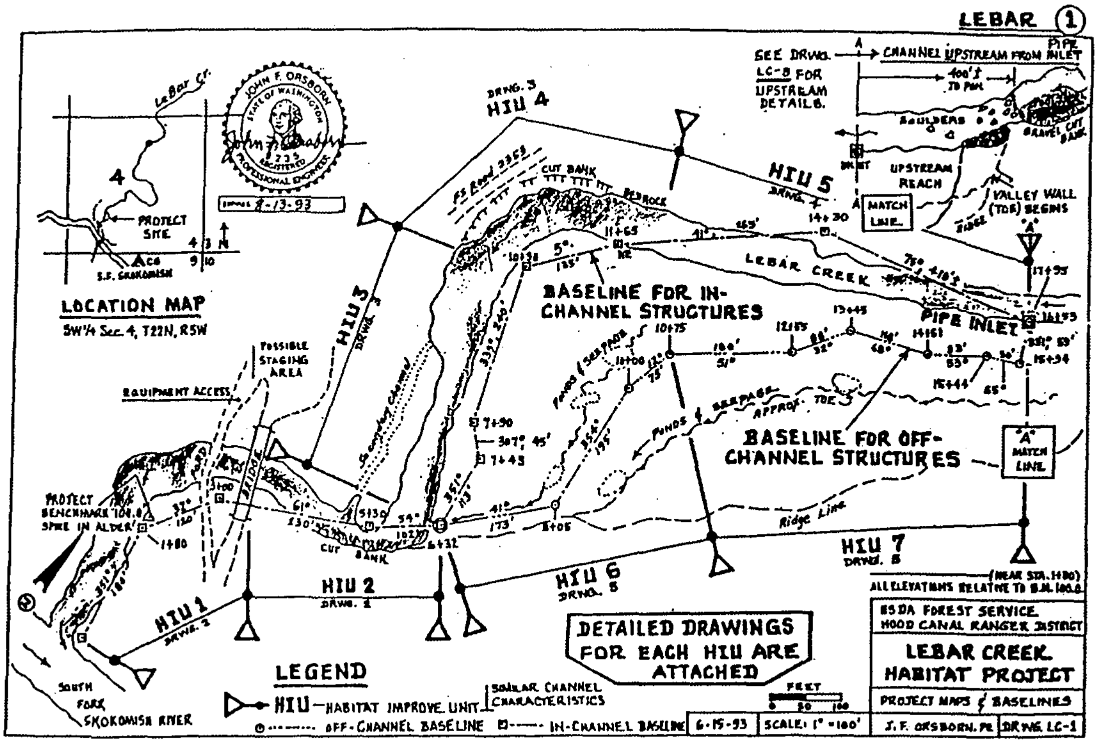
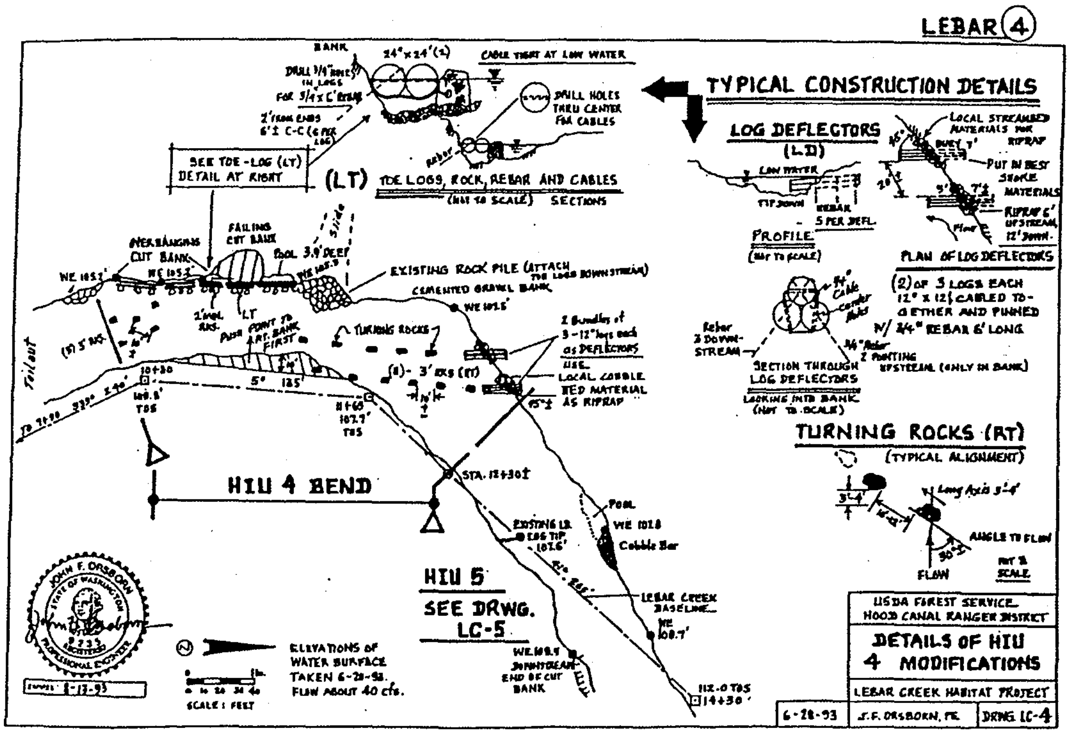


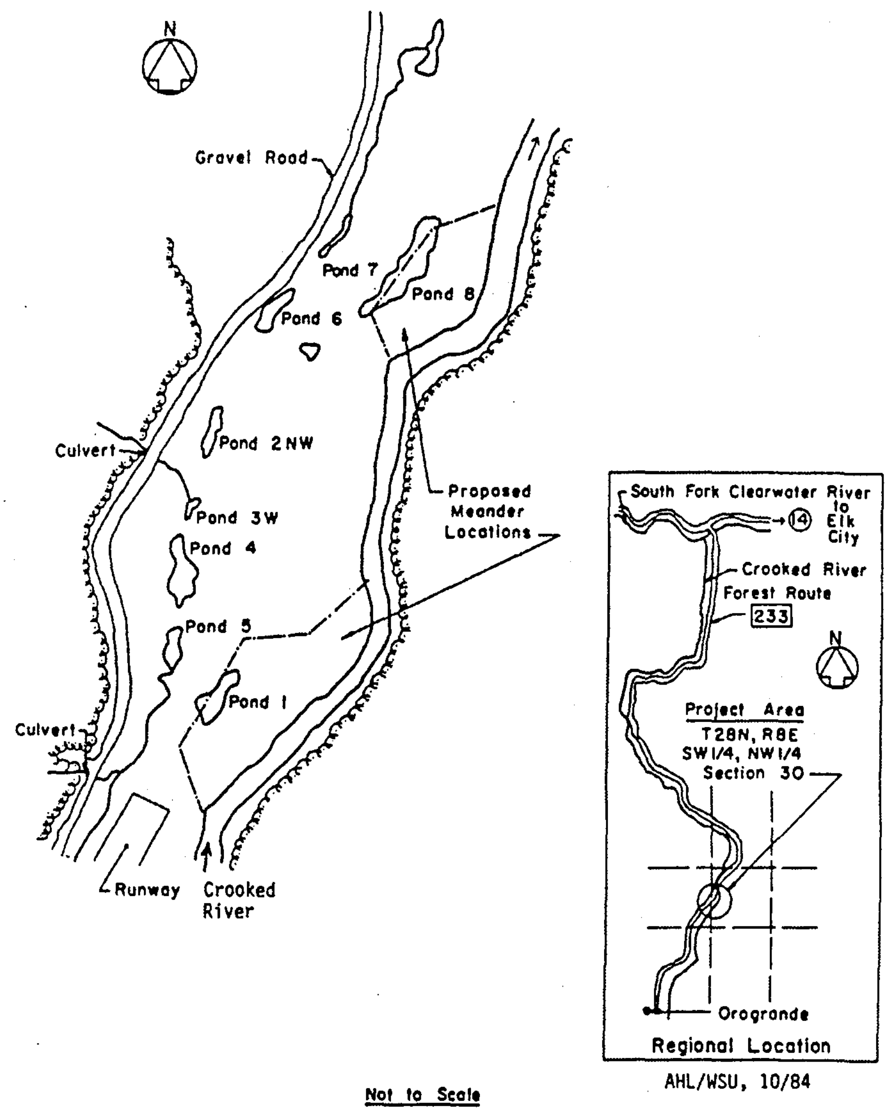
Figure 4-4. LeBar Creek Habitat Project Details of HIU 4 Modifications



CASE STUDY 2. PLANNING AND DESIGN FOR THE RECONSTRUCTION OF A GOLD-DREDGED STREAM, Crooked River (Idaho) Habitat Improvement Project

LOCATION: Crooked River, a tributary of the South Fork Clearwater River, Southwest of Elk City, Idaho, in the SW 1/4, NW 1/4, Sec. 30, T28N, RGE. (See Figure 4-5)

Figure 4-5. Crooked River Study Site and Regional Location



MAIN REFERENCE: Orsborn, J. F., K. Amerman, B. Clark, K. Coulton, B. Naik and J. Stypula. 1985. Planning for the restoration of meanders on a trial basis; Crooked River habitat improvement project. Prepared for the USDA Forest Service, Nez Perce National Forest, Elk City Ranger District, Elk City, Idaho. Department of Civil and Environmental Engineering, Washington State University, Pullman, WA.

MONITORING REFERENCE: Keifer, R. B. and J. N. Lockhart. 1994. Intensive evaluation and monitoring of chinook salmon and steelhead trout production, Crooked River and Upper Salmon River sites. Annual Progress Report for 1992. Fisheries Research Section, IDFG. Prepared for USDOE, BPA, Portland, OR. Project No. 91-73.

ABSTRACT:

Long reaches of Crooked River, southwest of Elk City, Idaho, were heavily impacted by gold dredging in the 1940's and 1950's. Some reaches have been pushed to one side of the valley, straightened and steepened. Vegetation, woody debris, shade, overhanging banks, and pools . . . components of diverse fish habitat, are in extremely short supply. High velocity riffles and large substrate are predominant. In essence, Crooked River has been turned upside down by gold dredging.

Some preliminary habitat improvements were completed by the Forest Service on several reaches of Crooked River. The project discussed in this report covers the hydrologic, geomorphic, river mechanics and bio-engineering aspects of considering the reconstruction of "pilot meanders" in a reach of Crooked River about three miles north of Orogrande, Idaho (see Figure 4-5).

Consideration was given to several alternatives including: (1) installing habitat structures and building a flood plain in existing, altered reaches of Crooked River; (2) adding recessed backwater areas to the existing channel for rearing habitat; (3) building one or two pilot meanders just north of the emergency airstrip (the project reach); (4) cutting a more random channel through the dredge tailings in a less-constricted valley area upstream (south) of the airstrip; and (5) letting the stream continue to work towards its former natural state (do nothing).

The last alternative is not reasonable in light of the time required for natural restoration in this completely altered environment. The major risk in meander restoration is the possible loss of water through the highly porous bed and banks. These would seal over time, but can be corrected with the addition of gravels, sands and fines during an initial, low-water diversion period. The design of the meanders is based on similar channels in the region and calls for lower than normal floodplains to encourage overbank flow, riparian vegetation and bank stabilization.

COMPONENTS:

In order to evaluate the alternatives for this study, the following functions were completed:

- data collection (survey) and interpretation of existing land surface conditions;
- relations of surface and groundwater elevations;
- sampling of surface water quality;
- a regional hydrologic analysis;
- a regional channel geometry analysis
- a hydraulic design of the pilot meanders including stability of the channels, bed material size and the habitat characteristics of the meanders;
- the new channels were sized by (1) comparing its plan view with Tenmile Creek in the next valley to the West; (2) developing a channel design based on regional models of channel size at bankfull flow; and (3) fine tuning the design to fit the project site constraints such as existing contours, swales and ponds; the elevation of the new meanders with respect to the road; and the location of the north end of the emergency airstrip (Figure 4-5).

An important component of this study was the discussion of methods for habitat improvement. The five alternatives and the factors to be considered are in Table 4-4 with an explanation of terms. The Alternative(s) Matrix in Table 4-5 has been completed to show an example of how the method was used to plan for the alternatives. Further details on the matrix methodology are discussed in the project report.

Table 4-4: Conditions and Explanation of Terms (see text for details), Crooked River habitat Improvements-- Alternatives Matrix

AHL/WSU 10/84

AHL/WSU 10/84

Indices Factors To Consider	Alt. (1): Do Nothing	Alt. (2): Improve Habitat in Existing Channel	Alt. (3): Construct meander(s)		Alt. (4): Split Channels river and meander	Alt. (5): Backwater rearing areas (Compare 5A only with 5B)	
			A. Meander 1 With Habitat Improvement	B. Meander 2 With Habitat Improvement		A. Seepage flow Only	B. Small pipe flow from river
A. Earth Moving	None	Some, to install structures and modify channel.	Largest amount but cuts and fills can be balanced.	Less cut and fill than meander 1. Larger pond.	Earth moving would total Alt. (1) and (3A) or (3B).	Cut channel(s) from pond(s) downstream to river channel.	Some, extra to install supply pipe from river to pond(s).
B. Add Habitat Improvements	None	Only shade and a few poor structures available . . . . requires total flow control.	Shade and pools exist (some). Need to add all new features.	Other factors for Meander No. 2 are Similar to Meander No. 1.	Would have to add all improvements.	Would need to add diversity and stability to outlet channel(s).	Would enhance habitat year around and avoid trapping.
C. Surface and Groundwater Conditions	- FAST - Poor pool: riffle ratio → 0.	River on very steep slope at higher elevation than west ponds. G. W. drops rapidly.	New channel will intercept some G. W. flow. May have to seal.		Low flow is to low (15 cfs ±) to split.	Similar to now, but high flows would back into channels.	Design to use small amount during low flows. Enhances biology.
D. Stability of channel and Habitat Improvement	Poor-in transition to meander.	Run risk of high maintenance . . . stream still steep at high flows.	High stability because meander will be on more natural slope.		Poor in existing channel, good in meander(s).	Good stability, except for silt from backwater.	Would maintain flow path in channel and encourage faster vegetation growth.
E. Relative Time to Achieve High Productivity	Very long.	Much quicker than Alt. (1) depending on habitat improvements used.	Rapid increase depending on degree of improvement.		Same as each alternative in combined form.	Rapid, but would need some vegetation for shade.	Faster than 5A because water supplies certain year around.
F. Risk - or Probability of success.	High risk; or low probability of success.	Higher risk of damage to habitat improvement structures.	Some risk in terms of leakage but can be accounted for.		High risk of seepage loss and dry reaches in August and September.	High probability of rearing success. Does not provide spawning areas.	Better probability of success due to stability of water flow.
G. Other . . . such as Habitat Diversity							
Total Index	Sums for each alternative.						

Note: Indices range from 10 (best) to 0 (poorest) depending on the realtive level of each factor to each Alternative. (see example) These indices are not quantifiable terms--they are relative to each other horizontally.

Table 4-5: Sample Analysis-- Use with Table 1-- Explanation of Terms

CROOKED RIVER HABITAT IMPROVEMENTS ALTERNATIVE MATRIX
For River Reach just north of airfield in Sec. 30, T28N, R8E.
Rated by: JFO Date: 8/84

	FACTORS	ALT. (1): Do nothing	ALT. (2): Improve existing channel	ALT. (3): Construct meander(s) A. Meander 1 with hab. impr.	ALT. (3): Construct meander(s) B. Meander 2 with hab. impr.	ALT. (4): Split channels river plus meander	ALT. (5): Backwater rear areas (Compare 5A only with 5B) A. Seepage flow only	ALT. (5): Backwater rear areas (Compare 5A only with 5B) B. Small pipe flow from river
A	Earth Moving	10	8	1	3	0	7	5
B	Add Habitat Improvements	10	2	3	4	3	5	10
C	Water Conditions surface and ground	1	7	8	9	2	5	8
D	Stability of channel and hab. impr.	1	6	9	10	7	7[a]	8[b]
E	Relative time to achieve high productivity	1	7	8	9	7	8	10
F	Probability of success	1	8	8	8	4	2	9
G	Habitat Diversity	1	9	8	8	9[c]	6[d]	7[e]
	TOTAL INDEX	25	47	45	51	32	40	57

AHL/WSU, 10/84

a. 1 River; 9 Side Channel Combined.
b. 1 River; 10 Side Channel Combined.
c. Assumes Habitat Improvement in Both Channels.
d. Note: Factor D above assumes no improvements in river.
e. No River improvement.

ACTIVITIES:

- Topographic surveys of the project area were conducted over a period of eight days to tie the proposed meander channels and the existing river channel together.

- Stream flows were measured near existing USFS log weirs and at other cross-sections along Crooked River to establish the existing channel hydraulic geometry and the accretion or depletion flows.

- Cross-sections were measured along the two planned two meander lines so the cuts and fills could be estimated.

- The interrelationships of surface and ground-water were measured by surveying pond elevations and establishing staff gages in the ponds, feeder streams and river (Figure 4-6).

- Electrical conductivity and temperature measurements were made in the stream and in the ponds.

- In the hydrologic analysis, regional models were built relating characteristic flows (low, average and flood flows) to basin characteristics (area, average annual precipitation and basin relief).

- The flows estimated by the regional basin characteristics models compared favorably with flows estimated by correlation of Crooked River flows with same-day flows at USGS gages on the Lochsa and the S. F. Clearwater Rivers.

- Using the three characteristic daily flows (low, average and flood) the low, mean and high annual duration curves for Crooked River were estimated.

- For the channel design the following analyses were completed:

  - The Crooked River was compared with Tenmile Creek to determine the stream gradient and the meander length for the restored meanders;

  - regional models were developed for channel hydraulic geometries at seven USGS gages for bankfull width, depth and cross-sectional area (see Figure 4-7 for an example of the region model results);

  - trial values of bankfull flows were estimated for different bottom widths and bed slopes;

  - values of W, D, V, shear stress, critical shear stress and channel slope were estimated using equations developed for gravel-cobble streams by Kellerhals (1967);

Figure 4-6. Staff Gage Locations

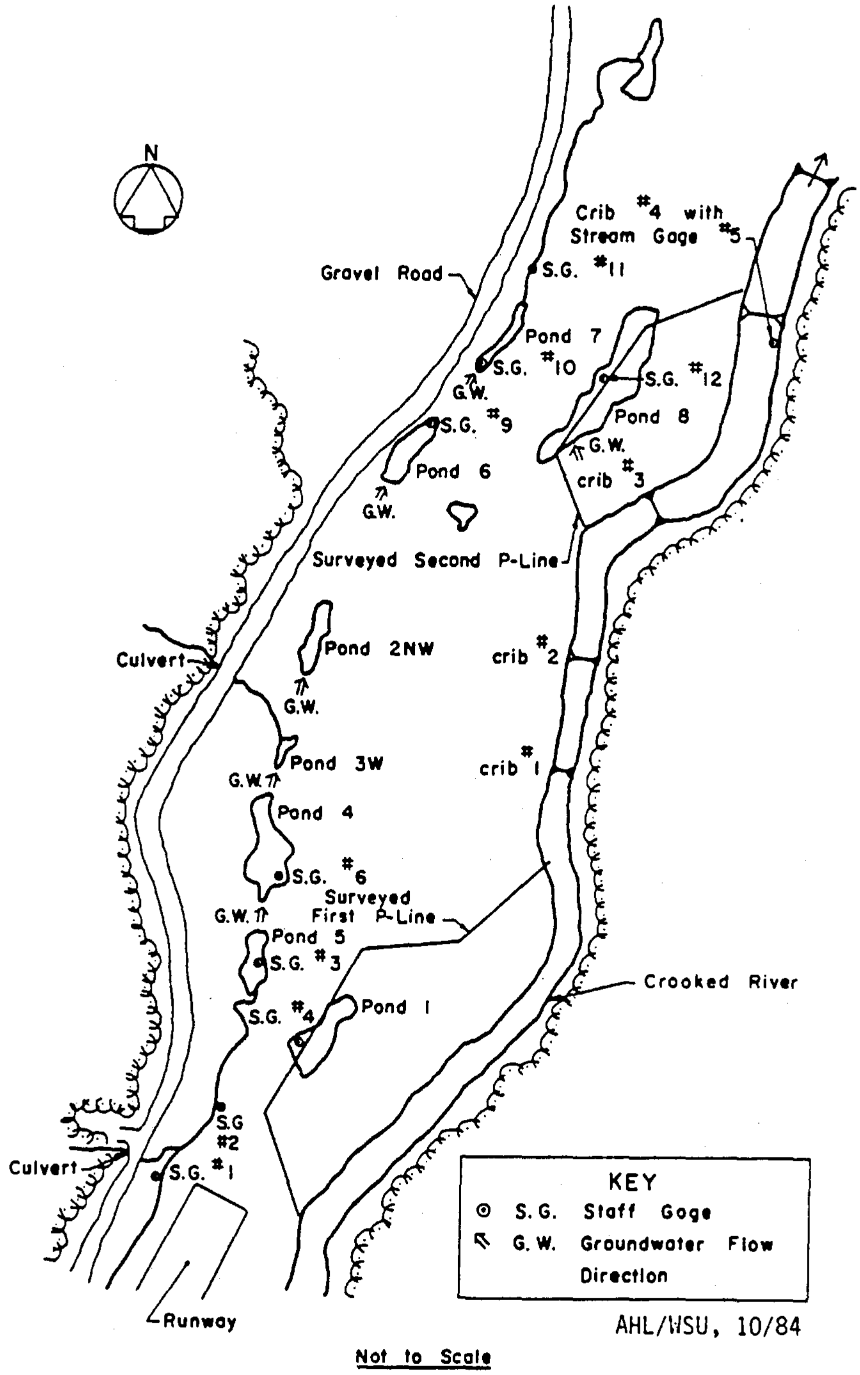
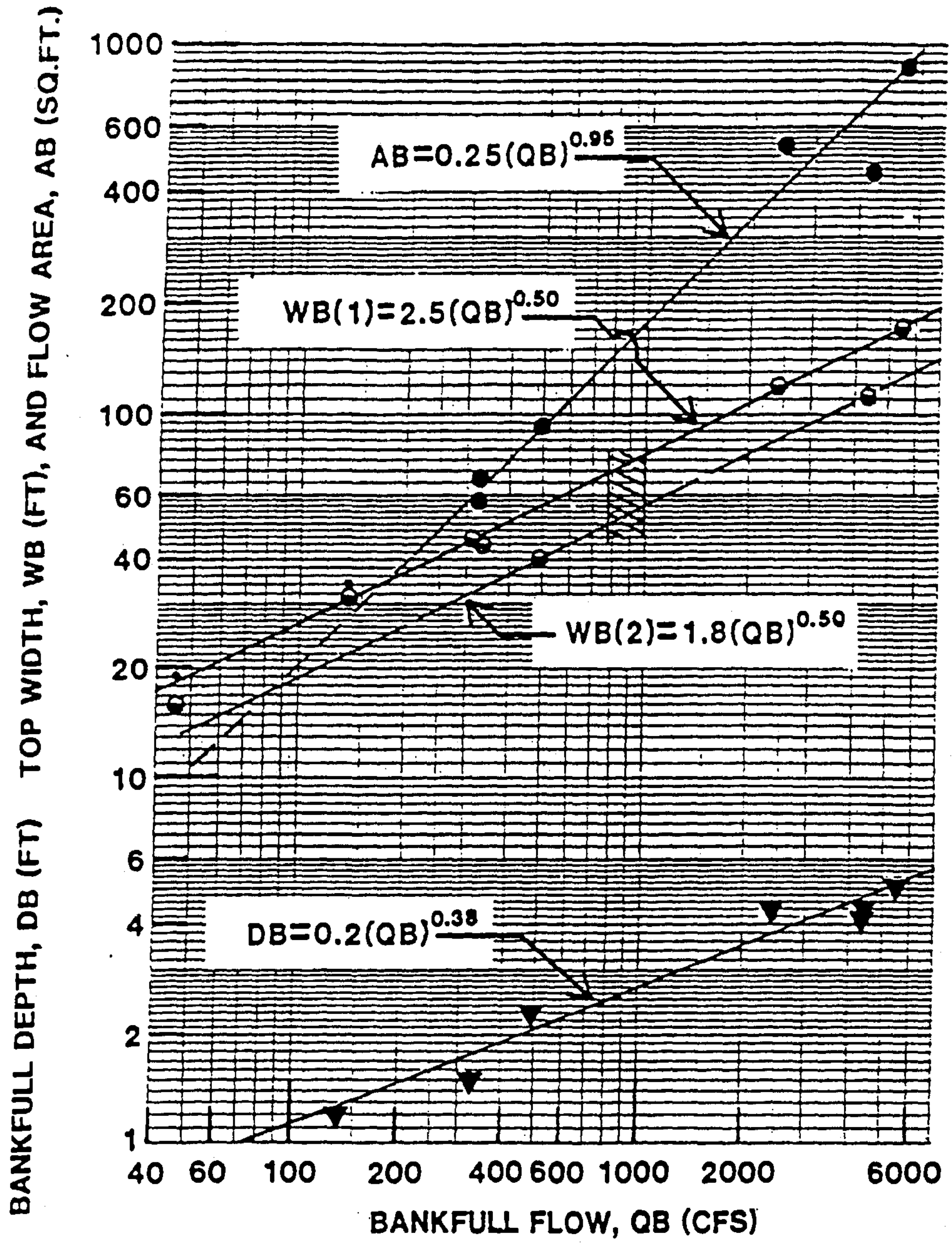


Figure 4-7. Bankfull Flow Area (AB), Top Width (WB), and Mean Depth (DB), Related to Bankfull Flow (QB) in the Crooked River Study Region



- the Kellerhals (1967) bed material mean sizes were compared with methods used by Jackson and Van Haveren (1984) and showed good agreement;
- the Jackson and Van Haveren (1984) methods involved solving for D50 in terms of the channel slope (S) and also in terms of unit stream power (VS); and
- habitat features given consideration were: pool to riffle ratio, spawning gravel sizes, pool depth, revegetation of stream banks, boulders for cover and flow deflection, stream shading, undercut banks, slackwater and backwater areas.

RESULTS:

As it turned out the meanders in this reach were not built. A large area of dredge spoils was crushed and stockpiled for USFS roads. Another spoils area was set aside for historical preservation. Near the crushing operation, the Forest Service installed a variety of habitat instream structures and revegetated the stream banks. A concrete rearing pond was built on a leveled part of the pilot meander project area to offset part of the impacts of the dams on the Snake River.

REFERENCES CITED IN THIS SUMMARY:

Jackson, W. L. and B. P. Van Haveren, 1984. Design of a stable channel in coarse alluvium for riparian zone restoration. AWRA. Water Resources Bulletin 20 (5). October.

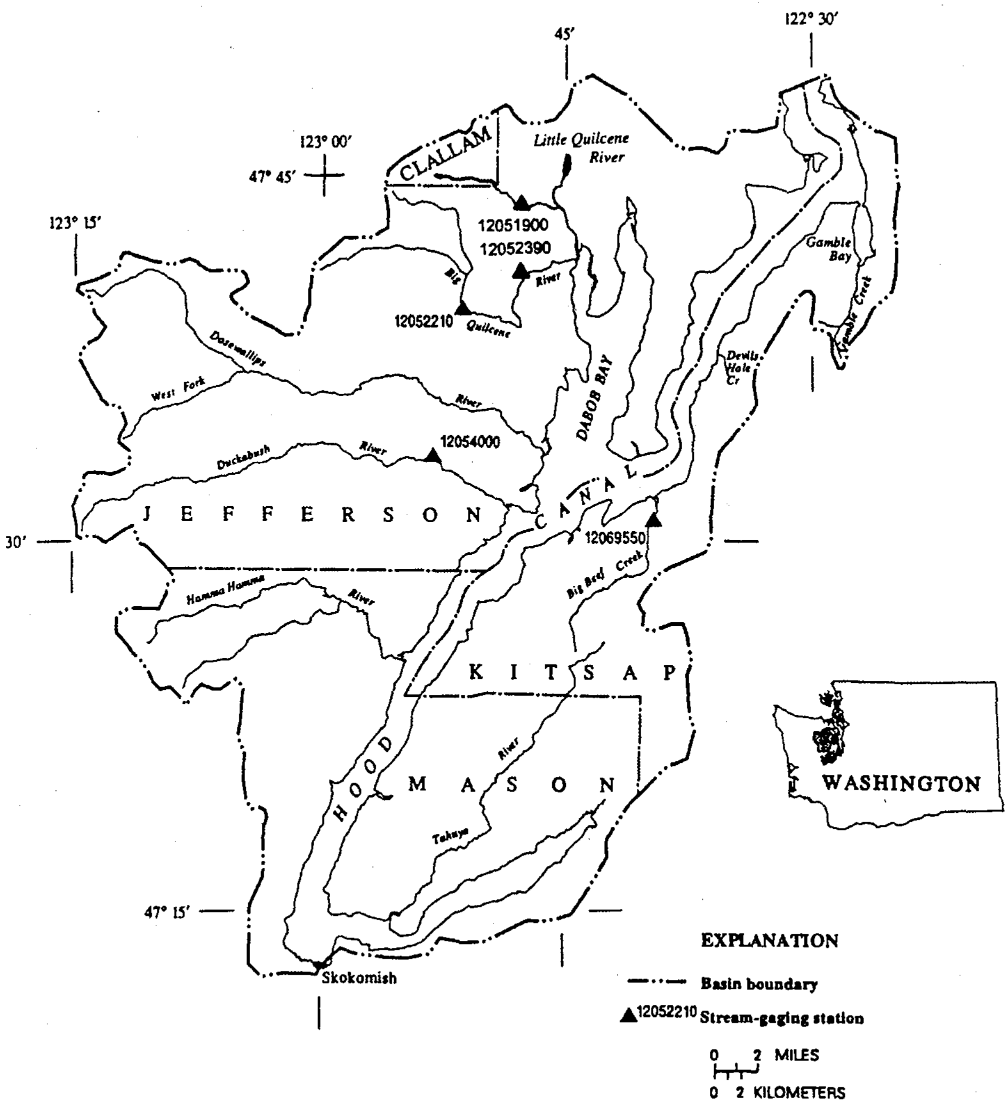
Kellerhals, R. 1967. Stable channels with gravel-paved beds. Journal Waterways and Harbors Division, ASCE, 93 (63-84).

CASE STUDY 3. EVALUATION OF LAND USE IMPACTS ON BIG BEEF CREEK

LOCATION:

South East Side of Hood Canal, the East water Boundary of the Olympic Peninsula; on the West side of the Kitsap Peninsula in Western Washington; Water Resource Inventory Area (WRIA) 15. T24N and T25N, R1W, near Seabeck; Basin area: 38 km^2

Figure 4-8. Location of USGS surface-water stations in the Hood Canal Watershed (USGS 1995)



MAIN REFERENCE: Madej, Mary Ann. 1978. Response of a stream channel to an increase in sediment load. MS Thesis. Department of Geological Sciences, University of Washington. Seattle, WA (111 pages). (Summary of thesis reviewed and approved by M.A. Madej, 3/01).

OBJECTIVES:

- Assess the impacts of land use changes on the sediment load in Big Beef Creek; and

- determine the effects of the increased sediment load on the geometry, and thus the fish habitat, in the Big Beef Creek channel.

COMPONENTS:

A comprehensive base-line reconnaissance survey and monitoring of the impacts of land-use changes on the channel geometry of a salmon-bearing stream. Components of the study included:

- Review of previous studies;
- Background assessment of vegetation, climate, soils, geology, hydrology, and land use;
- Description of stream reaches above and below man-made Lake Symington;
- Channel cross-section surveys;
- Regional channel geometry surveys;
- Spatial distribution of sediment;
- Sediment sampling;
- Calculation of sediment budgets;
- Monitoring of sediment movements;
- Channel changes;
- Storage of sediment in the channel; and
- Relations of channel changes to land use.

ACTIVITIES:

- Resurveyed (in 1976-77) the cross-sections established by Cederholm (1969) in lower Big Beef creek and at five other monitoring sections in the lower 11 km (6.8 mi).

- Evaluated channel changes at the USGS gaging station (No. 12069550) for the period of 1969-77 using USGS forms 9-207 and 9-275.

- Surveyed channel cross-sections in fifteen nearby streams (drainage areas 0.52-52.0 km^2), measuring bankfull width, depth, slope and sediment size.

- These measurements provided the regional channel geometry equations that were used to estimate the undisturbed (pre-logging) conditions in Big Beef Creek.
- The developed equations were: Eq. Nos.

Top Width: $W = 1.60(A_b)^{0.42}$ (meters) (1)

Bankfull Depth: $D = 0.14(A_b)^{0.24}$ (meters) (2)

Mean Sediment Diameter: $D50 = 17.8/(A_b)^{0.10}$ (mm) (3)

Channel Gradient: $S_c = 0.037/(A_b)^{0.18}$ (4)

where: A_b is the basin area in km^2.

- Suspended sediment was measured at several stations on Big Beef Creek and sediment rating curves were constructed for three sites.
- Sediment transport rates were estimated by three methods.
- A painted rock experiment was used to determine the size of the largest bed particle that was moved during high flows.

RESULTS:

- The cross-sectional surveys were conducted at 38 stations and 15 control sites, and the results were used to evaluate the relative erosion or deposition between reaches.
- The plot of the changes in the thalweg elevation and channel cross-sectional area, as a function of drainage area between 1970 and 1977, was one of the most revealing graphics.
- The exponent for width ($W = aQ^b$), b, changed from 0.30 to 0.17 between 1970 and 1977 indicating a shift to a more rectangular channel.
- Results of the regional channel geometry survey are shown in the following table:

Table 4-6. Predicted and Actual Dimensions of the Big Beef Creek Channel at Station 50+50

Dimension	Predicted (Eqs 1 to 4)	Predicted (Kellerhals, 1966)	Actual	Units
w_b *	8.5	10.0	15.5	m
d_b *	0.43	0.41	0.40	m
D50 **	15.0	---	22.0	mm
S	0.0085	0.0017	0.0085	(-)

* w_b and d_b stand for width and depth at bankfull flow
** refers to armor layer

- By plotting D50 against drainage area, the typical decrease in particle size was observed, except in the middle watershed where intensive road construction and logging increased D50 from about 45 to 60 mm.
- During high flows the suspended sediment concentrations increased from 3 ppm above the lake to 600 ppm six km below the lake.
- From the three suspended sediment rating curves (at Stas. 1 + 00, 19 + 00 and 50 + 50 ft) the average sediment load was about 2325 t/yr, with a higher contribution from the lower watershed.
- Log jams temporarily store sediment, and there were 4 jams in the 2 km below the lake, and 14 jams to 18 jams (larger jams) in the lower reaches.
- Three approaches were used to estimate the source and volume of sediment entering the stream, and its rate of movement; a sediment budget; sediment transport equations; and survey measurements.
- The sediment analyses suggest that the sediment load to the stream increased from about 525 t/yr for undisturbed conditions to about 4100 t/yr in 1977.
- The sediment transport rate equations did not agree with the volumes measured by cross-section surveys.

The results were interpreted by the author in terms of actual modifications to the channel. The deposition in the estuary increased, the lower channel widened about 25%, and the depth decreased by a similar amount. (This is typical for widened, shallower channels; flow area stays about the same).

A decrease in Manning's resistance coefficient (n) was noted associated with a small increase in sinuosity and the loss of bank vegetation due to widening. Several methods were tested by the author using a computer program of Einstein's bed load function, to evaluate the increase transport capacity as a function of increased W/D values. Other factors considered were: armoring of the channel bed; changes in Manning's (n); the width to depth ratios; limitations on channel width; critical shear stresses; size distributions of the channel bed materials; storage of sediment in the channel; and channel changes related to land use.

Current conditions (year 2000) in the Big Beef Creek basin show decreased logging, but increased, low-density urbanization around the basin perimeter. The sediment wedge of deposition in the upper estuary is pronounced. The road fill constructed across the mouth of the estuary, with about a 15% bridge opening, has severely constrained the natural functions in the estuary.

The author's conclusions are quoted as statements of the impacts of land-use changes on channel geometry and fish habitat.

CONCLUSION:

"In a forested watershed, sediment is supplied to the stream channel by the processes of soil creep and mass movements. The channel form is adjusted to the amount of the supplied sediment. Logging, road construction, and urban development remove vegetation and cause accelerated soil erosion due to sheetwash, mass movements and rainsplash erosion, and hence increase the sediment load of the stream. Under undisturbed conditions Big Beef Creek would receive 525 t of sediment per year. Land use changes have caused an increase to 4100 t/yr. Construction of a weir at the mouth of the stream has caused the bedload fraction to be caught above the weir, where an average of 2100 t of sand and gravel are deposited annually.

"Dimensions of the stream channel have changed in order to adapt to the increase in sediment load. The channel is wider and shallower than the 1970 channel, more gravel bars are present, and sinuosity has decreased slightly in areas of high sediment transport. Mean flow velocity has remained approximately constant. The result of the changes has been an increase in the shear stress along the bed and banks, which in turn results in a higher rate of sediment transport. Before disturbance, the sediment transport rate of bedload was probably 230 t/yr, whereas it is 970 t/yr at the present.

"The adaptations of the channel are restricted by hydraulic constraints described in the continuity and Manning equations. Velocity and slope are relatively conservative parameters, and much of the change is taken up by the parameters of width and depth.

"The stream channel presently has 141,000 t of sediment in storage. Active sediment, 49,000 t, moves an average of 200 m/yr in the main channel. Thus sediment placed in the channel by present disturbances will take an average of 20-40 years to be removed." (M. A. M., 1978).

REFERENCES CITED IN THIS SUMMARY:

Cederholm, C. J. 1972. The short-term physical and biological effects of stream channelization at Big Beef Creek, Kitsap County, Washington. Masters Thesis, University of Washington. 80 pp.

Kellerhals, R. 1966. Stable channels with gravel-paved beds. American Society of Civil Engineers, Water Resources Engineering Conference. Preprint 330. Denver, CO. 28 pp.

CASE STUDY 4. LOWER ELWHA RIVER LOW FLOW RECONNAISSANCE STUDY

MAIN REFERENCE:

Orsborn, J.F. and M.T. Orsborn, 1999. Low flow assessment of the Lower Elwha River; effects of diversions on channel geometry and fish habitat. Lower Elwha Tribal Fisheries. Port Angeles, WA.

BACKGROUND REFERENCES:

USDI National Park Service, 1994. The Elwha Report: Restoration of the Elwha River Ecosystem & Native Anadromous Fisheries. National Park Service, Department of Commerce and Lower Elwha S'Klallam Tribe.

USDI National Park Service, 1996. Final environmental impact statement: Elwha River ecosystem restoration, Olympic National Park, Washington.

LOCATION:

Northern Olympic Peninsula, 4 miles west of Port Angeles, Sec. 3, T30N, R7W and Sec. 34, T31N, R7W. See Figure 4-9.

OBJECTIVE:

The main objective of this study was to determine the influences of municipal and industrial diversions from the Elwha River at RM 3.4 on the channel hydraulic geometry (and thus on fish habitat) in the lower river, below the diversion dam (Figure 4-10).

COMPONENTS:

The parts of the study included: the existing and developed databases; historical hydrology; flow measurement sites; streamflow measuring procedures; data management and analysis; results; and references. Examples of graphs, tables and summary tables are interspersed throughout the project report and the balance of the database and analytical work is contained in seven appendices.

Figure 4-9. Location Map for the Lower Elwha Project (from USDI, NPS 1996).

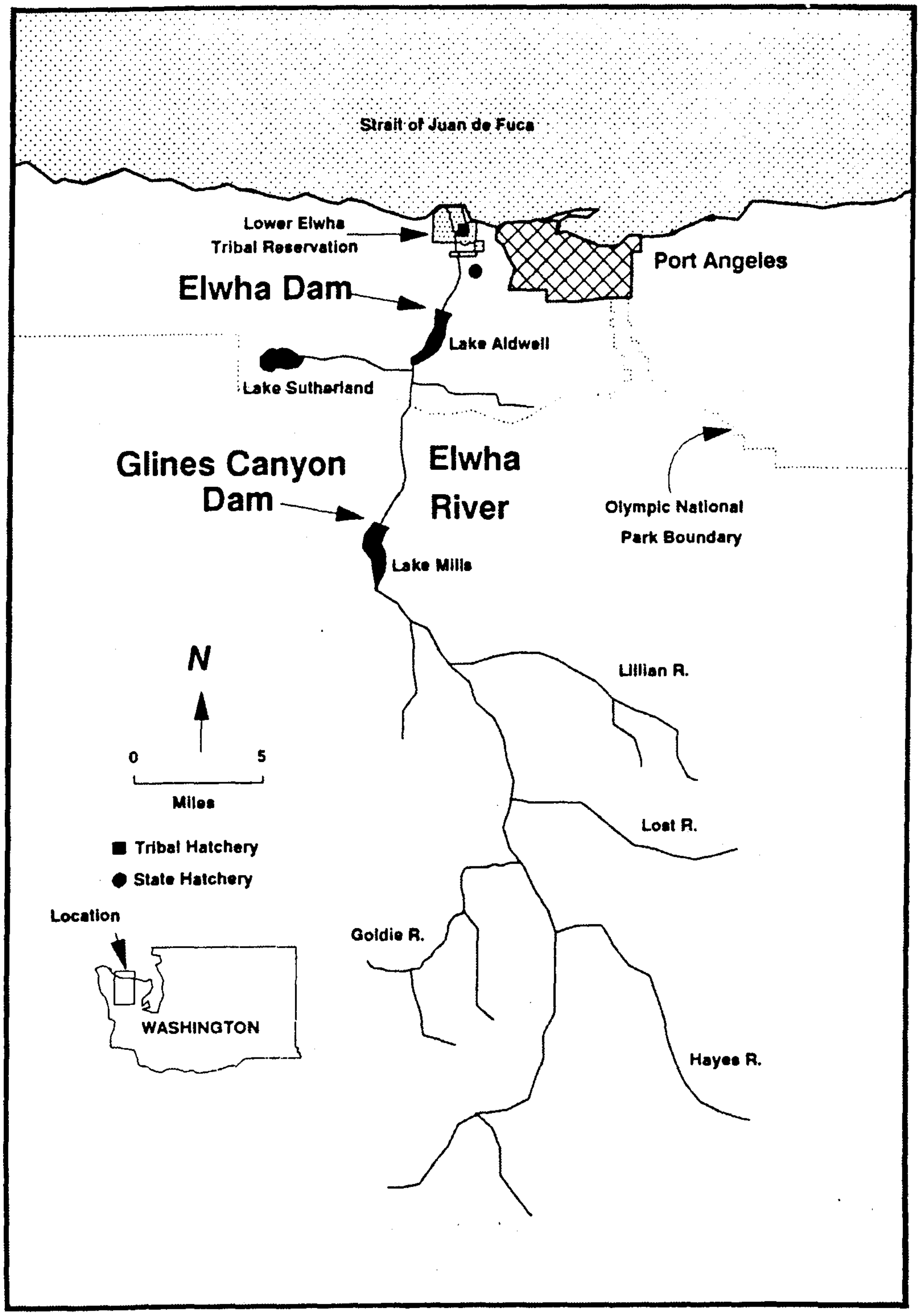
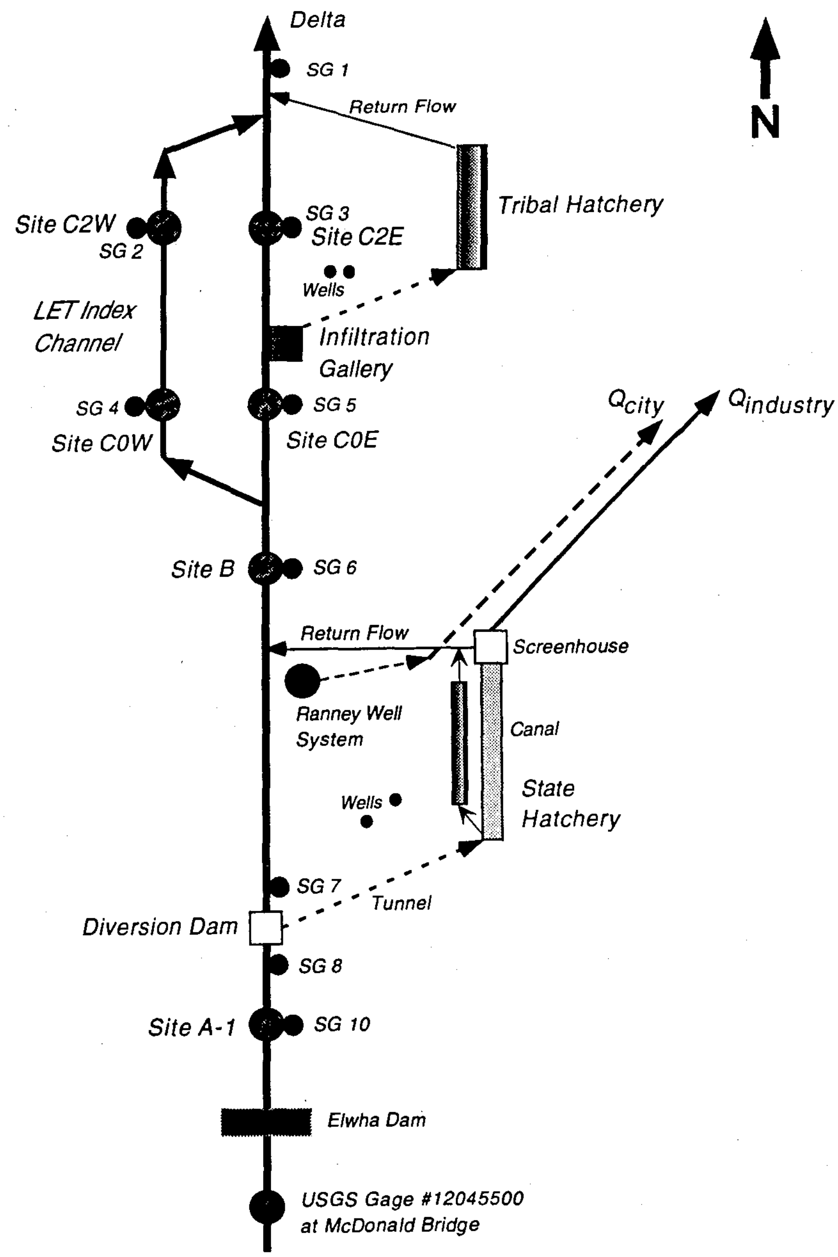


Figure 4-10. Schematic Representation of Measurement Sites and Facilities, Lower Elwha Low Flow Study (Figure 1-1 in Orsborn 1999).



BACKGROUND:
Some environmental factors, which have adversely affected the Lower Elwha River geometry and fish habitat, include:

- the cessation of the upstream gravel supply caused by the dams;
- the continuation of large flood flows due to a lack of reservoir storage; and
- past storage and release operations which ramped flows sharply up and down during the migration and spawning seasons.

As a result of the first two factors, the Lower Elwha River channel is extremely short of bed material in the gravel size-range. Also, the channel is armored with 6 to 12-inch rock. The only gravels are old deposits in vegetated bars, and those derived from local bank erosion. This combination of armoring and reduced gravel supply, and a lack of LWD, have significantly depleted spawning habitat.

SITE CONDITIONS:
The main channel below the Municipal & Industrial (Figure 4-10) diversion dam and the State hatchery is typically very wide and shallow with width to depth ratios ranging from 40-220 for a lower flow range of 100-1000 cfs. (The average annual flow is about 1500 cfs). Also, LWD is mostly locked in jams at the entrances to secondary channels, the upstream supply having been curtailed by the dams. The LWD supply is limited to the jams, and trees (mostly alders) being undercut by bank erosion.

STUDY TASKS:
In order to evaluate the effects of the M & I diversions on downstream flow conditions, channel geometry and habitat, the following information was developed.

DATABASES:
Data for USGS stream gages; description of the M & I diversion system; water rights total 205 cfs, but only about 40-70 cfs were diverted during the monitoring period. Data gathered for the project included: historical hydrology; existing and new cross-sections; site maps; channel elevation surveys; depth and velocity measurements; and photographs. These data were analyzed to provide information on flow amounts related to water surface elevations at selected sites spaced throughout the Lower Elwha River.

HISTORICAL HYDROLOGY
Pre-and post dam natural and regulated flows were evaluated using the USGS gages on the Lower Elwha River (12045500) and the N. F. Skokomish River (12056500). Strong and irregular regulation of low flows by the dams until about 1955 caused poor, unstable habitat conditions. Since then low flow releases have more closely followed natural inflows. Examples of poor and natural regulation are shown in figures 4-11 and 4-12.

Figure 4-11. August to November, 1938 Hydrograph, Recession Flows

Elwha Gage #12045500 & NF Skokomish Gage #12056500

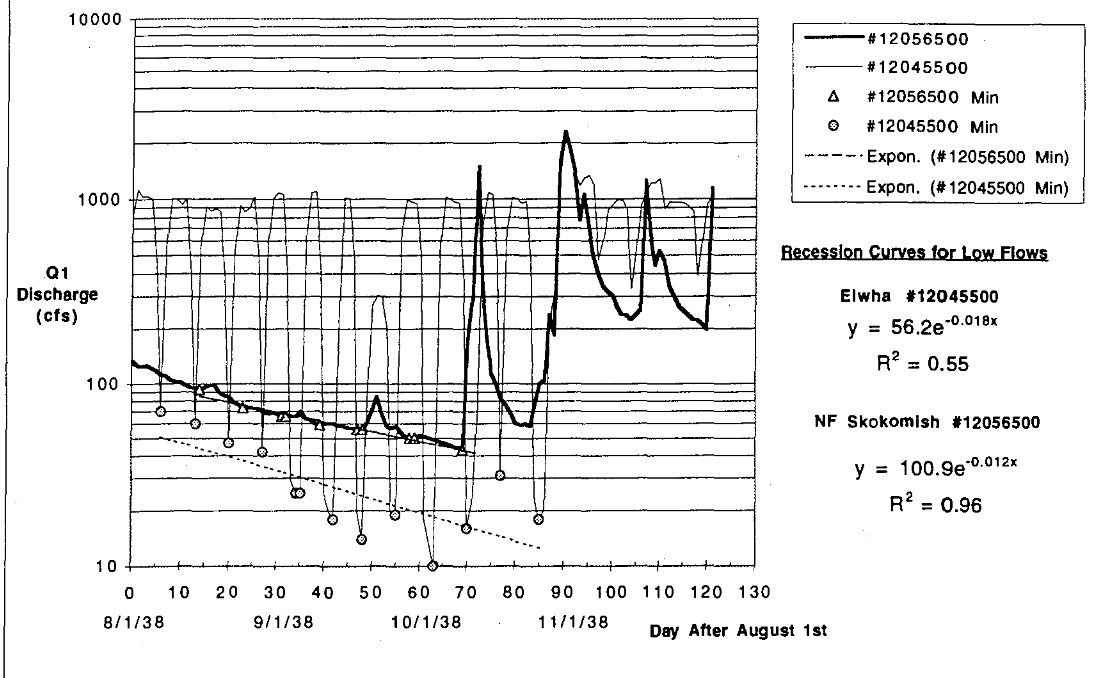
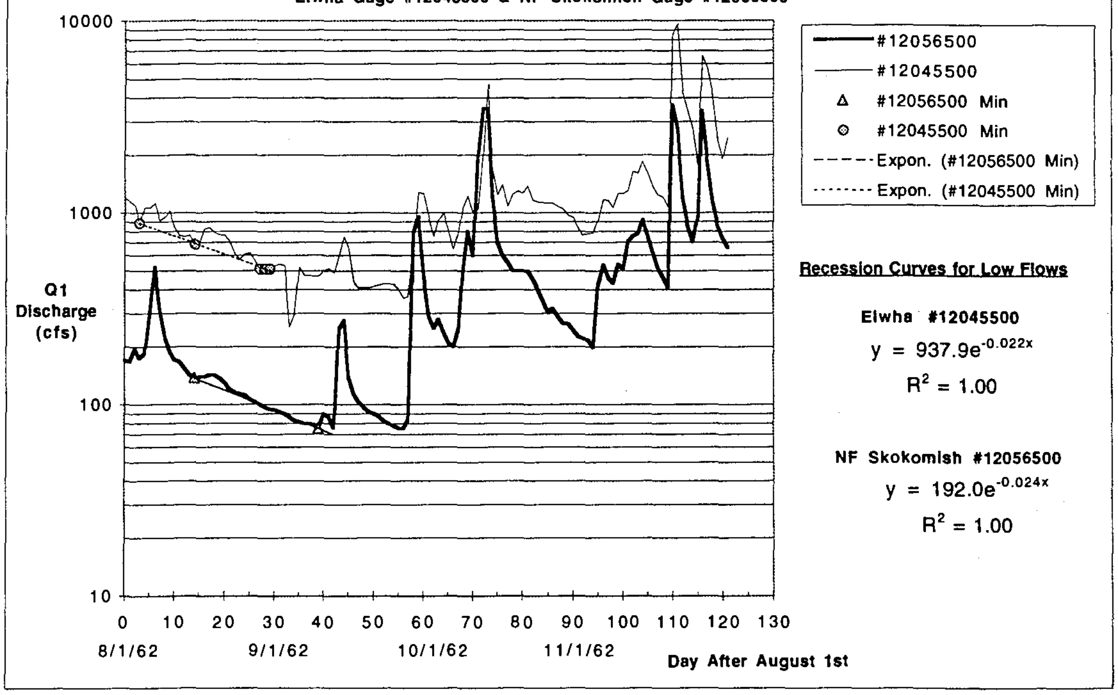


Figure 4-12. August to November, 1962 Hydrograph, Recession Flows

Elwha Gage #12045500 & NF Skokomish Gage #12056500



The mid-day of the average historical 7-day low flow with a 2-year recurrence interval (Q7L2) occurs around October 7th, but it has occurred as early as August 17th and as late as November 28th. The 7-day annual low flows range between 202 and 606 cfs with an average of 404 cfs.

The Elwha River gage at McDonald Bridge was discontinued in 1997, but its automatic telephone readout was supported by Daishowa America and was functioning in 1999. The N. F. Skokomish gage was used as an index for flows in the Elwha. By relating historical flows in the Elwha to those in the N. F. Skokomish, we were able to correlate the 1998 measured project flows with same-day flows in the North Fork Skokomish River while the Elwha gage at McDonald Bridge was not in operation. Estimated flows from the performance curves of the Lower Elwha Dam turbine-generators were obtained for comparison with the correlated estimates.

STUDY SITES

The study sites were selected in two categories: (1) staff gage sites (SGS); and (2) flow measuring sites (FMS), which also had staff gages for calibration with the measured flows. These gaging sites are shown with respect to other project features in Figure 4-10. Sites A1 and B were used to measure the net amount of diversion.

STREAMFLOW MEASURING PROCEDURES

We modified USGS standard forms to record staff stage readings and depth and velocity measurements. Federal standards for streamflow measurements were followed. All elevations were referenced to a local benchmark on top of the pin at Station 0+00 on the left bank of the baseline transect at each FMS.

We selected measurement dates in September and October and were fortunate to bracket the lowest flow of the year on October 1st. Velocity meters were calibrated in ponds at the Tribal hatchery and were checked against each other in the field. All flow measurements were made by wading, and two sites were measured simultaneously by two teams of three people each. Paired measurements were made between sites: (A1 and B; C2E and C2W). We used radios to transmit depth, velocity and baseline station data from the reader to the recorder. Some later flow measurements were recorded directly into a computer so the measured flow could be compared with the flow determined by reading the staff gage, and entering this elevation into the rating curve. All staff gages were read on days between flow measurement days.

DATA MANAGEMENT AND ANALYSIS

After the field data were acquired at each site, we: made backup copies of the data sheets; developed rating curves; and calculated relationships between streamflow and channel geometric characteristics.

Analytical results included: hydrographs of water surface elevation versus flow; plots of flow versus the dates of measurements; staff gage rating curves; surveyed channel cross-sections; depth and velocity profiles; channel cross-sections for expanding the rating curves and the hydraulic geometry analyses;

the measured hydraulic geometries; and the modeled (expanded) hydraulic geometry, for lower and higher flows than were measured, to expand the rating curves.

RESULTS:
Based on the study objective, and data acquisition and analyses, several methods of presenting the results were selected to demonstrate how channel geometric characteristics change as a function of flow reductions due to diversions. We were dealing with "low flow" conditions and the effects of flow reductions on channel geometry (width, depth, area and wetted perimeter), and the methods selected are summarized below.

Using the four best measuring sites (A1, B, C2E and C2W; see Figure 4-10), the **flow geometry** was analyzed by:

(1) tabulating incoming flows at A1, and net flows below the diversion at B, C2E and C2W; the tabulated incoming flows ranged from 100-1000 cfs in 100 cfs increments, and the diversions ranged from 20-200 cfs in 20 cfs increments; the results are in Table 4-7 and show how the channel geometry characteristics change as a function of the net flow at each site (only one page of the original eleven is included in this summary);

(2) dividing the water surface width (W) by the mean depth (D), is a commonly used habitat parameter; smaller W/D values (10-20) usually indicate better fish habitat, but the Elwha values range from about 40-220; this indicates very wide, shallow conditions (refer to Figure 3-4 on page 2.16 for the Lower Elwha graphs of W/D vs. P^2/A, and the general relationships);

(3) dividing the water surface width(W) by the flow area (A) gives an index of the solar heating surface divided by the volume of water available to absorb heat; smaller ratios are better (such as 0.10-0.20), but the Lower Elwha ratios range from about 0.40-1.40 ;

(4) when the wetted perimeter (P) is plotted versus flow (Q), P initially increases rapidly (above Q = 0); then the graph flattens so that a large change in Q makes only a relatively small change in P. This method is called the "wetted perimeter" or "toe-width" method. Because of the shallow conditions at all four channel sites, P begins to be reduced more rapidly below 300 cfs; a larger reduction in P occurs below 100 cfs.

The application of the study results will be governed by the management objectives in place at the time of their application. The balance of the report expands the information presented in the summary. The appendices contain the background information, databases and analytical tools.

Since the fieldwork for this study was completed in October 1998, high flows have enlarged the west channel. It is now carrying closer to 60% of the total flow as opposed to 40% during the low flow period. The west channel is being carved through the base of a large forested gravel bar (Figure 4-10).

Table 4-7. Example of Modeled Hydraulic Geometry Parameters for Various Flows at Site A1 and Different Rates of Diversion

Power Relation Rating Curves for Sites

Q_A1	Q_DIV	ID_SITE	Q_SITE	W	D	W/D	A	W/A	P	A/P^2	P^2/A	V	R
(cfs)	*(cfs)*		*(cfs)*	*(ft)*	*(ft)*	*(--)*	*(ft^2)*	*(--)*	*(ft)*	*(--)*	*(--)*	*(fps)*	*(ft)*
100	20	Elwha A1	100.0	154.0	0.90	170.75	138.9	1.11	154.3	0.0058	171.5	0.72	0.90
100	20	Elwha B	80.0	113.8	1.20	94.92	136.5	0.83	114.0	0.0105	95.2	0.59	1.20
100	20	Elwha C2E	44.0	112.2	0.91	123.60	101.9	1.10	112.4	0.0081	123.9	0.43	0.91
100	20	Elwha C2W	31.3	54.1	1.02	53.07	55.2	0.98	55.1	0.0182	55.0	0.57	1.00
100	40	Elwha A1	100.0	154.0	0.90	170.75	138.9	1.11	154.3	0.0058	171.5	0.72	0.90
100	40	Elwha B	60.0	106.7	1.08	98.77	115.3	0.93	106.9	0.0101	99.1	0.52	1.08
100	40	Elwha C2E	33.0	109.2	0.83	131.94	90.4	1.21	109.3	0.0076	132.3	0.37	0.83
100	40	Elwha C2W	23.5	53.3	0.90	59.33	47.9	1.11	54.2	0.0163	61.3	0.49	0.88
100	60	Elwha A1	100.0	154.0	0.90	170.75	138.9	1.11	154.3	0.0058	171.5	0.72	0.90
100	60	Elwha B	40.0	93.8	0.96	97.85	89.8	1.04	93.9	0.0102	98.1	0.45	0.96
100	60	Elwha C2E	22.0	104.5	0.72	144.75	75.4	1.39	104.5	0.0069	144.9	0.29	0.72
100	60	Elwha C2W	15.6	51.1	0.75	68.06	38.3	1.33	51.8	0.0143	70.1	0.41	0.74
100	80	Elwha A1	100.0	154.0	0.90	170.75	138.9	1.11	154.3	0.0058	171.5	0.72	0.90
100	80	Elwha B	20.0	76.2	0.74	103.49	56.0	1.36	76.3	0.0096	103.7	0.36	0.73
100	80	Elwha C2E	11.0	91.6	0.59	156.00	53.8	1.70	91.7	0.0064	156.3	0.20	0.59
100	80	Elwha C2W	7.8	40.5	0.62	65.15	25.2	1.61	41.1	0.0149	67.1	0.31	0.61

Definition of Terms for Table 4-7

Term	Definition
Q_A1	Flow at Site A1 Used in Model
Q_DIV	Diversion Flow Used in Model
ID_SITE	Site Name
Q_SITE	Corresponding Flow at each Site (from Correlations App. VII)
W	Channel Width
D	Channel Depth
W/D	Width to Depth Ratio
A	Channel Area
W/A	Width to Area Ratio
P	Wetted Perimeter
A/P^2	Area to Wetted Perimeter Ratio
P^2/A	Wetted Perimeter to Area Ratio
V	Mean Velocity
R	Hydraulic Radius

Comparative Notes on the Four Example Projects

The LeBar Creek, Crooked River, Big Beef Creek and Lower Elwha River projects had many tasks in common, and each project had some unique tasks. The tasks and objectives are summarized in Table 4-6. The ratings from 0-10 are assigned values primarily based on the relative emphases within each project, and some secondary comparative analysis between projects.

Table 4 –8. Comparative Emphasis on Tasks and Objectives for Four Example Projects (0-10 High in Relative Amount of Activity, or Importance to Each Project)

TASKS and OBJECTIVES	LeBar Creek	Crooked River	Big Beef Creek	Lower Elwha River
	WA	ID	WA	WA
	Reconnaissance, Design, Habitat Improvement, **Restoration**	Reconnaissance, Design Alternatives, **Reconstruction**	Channel Impact, Analysis of Land Use, **Reconnaissance**	Diversion Impacts on Habitat, **Reconnaissance**
Tasks				
Hydrology	10	8	5	10
Channel Geometry	8	10	10	10
Channel Morphology	6	9	10	10
Geomorphology/Soils	8	8	10	8
Sediment Effects	8	9	10	10
Basin Land Use	10	1	8	0
Stream Impacts	7	10	9	10
Groundwater	0	8	0	8*
Stream Improvement	8	10	6	8*
Habitat Improvement	8	10	4	8*
Basin Improvement	9	0	6	8*
Objectives				
Planning Alternatives	6	10	4	6
Design	10	10	0	0
Estimate Habitat	10	7	5	8
Documentation	10	10	10	10
Analysis	8	10	10	10
Build Habitat	10	9	6	0
Arrest Erosion	8	7	8	0

*Lower Elwha deals with impacts of dams on downstream channel beds.

For example, compare the Hydrology Task ratings in Table 4-7 for each project: 10 for LeBar Creek, 8 for Crooked River, 5 for Big Beef Creek, and 10 for Lower Elwha. In LeBar, the hydrology was used to determine bankfull floods, low fish passage flows and channel size. Hydrologic analysis was not as comprehensive for the Crooked River (8) because only ranges of high flows were needed to size alternative channels. In the case of Big Beef Creek, there were 8 years of USGS records, and analyses were done to verify average annual and average peak flows, as well as the channel size. The hydrologic analysis for the Lower Elwha River project dealt with reservoir storage effects, calibration of channel sections, correlation with another USGS gage and net flow after diversion.

Whereas the LeBar Creek project emphasized the improvement of basin stability and instream habitat, it had an equal component of off-stream, juvenile coho rearing habitat on the point bar. The point bar channels and ponds had been disconnected from the main channel by construction activities associated with logging. Crooked River had to contend with a complete overturning of the valley floor deposits, as well as channel straightening. In the lower impacted reach the natural meanders were reformed where the dredges cut a regular, unnatural zigzag pattern with 90 percent pool and 10 percent riffle. The pools became huge sand traps and the gravel-sized transport became nil. This was mainly due to the sorting and redeposit of the gold-bearing sands and gravels under mounds of cobble.

In the case of Big Beef Creek, road building, logging and suburbanization caused a rapid increase in sediment load, and impacts on channel geometry and coho habitat from which the stream has not recovered after 30 years.

The Lower Elwha case study dealt with the downstream impacts of two dams, plus the effects of M & I diversions below the dams, on low flows, channel geometry and habitat. All of the projects emphasized the documentation of stream channel condition through stream surveys, aerial surveys, maps, regional channel geometry models and/or other measures of present and past of channel conditions such as local geology.

Although each project had a somewhat unique history, they all had the common thread of man's infinite capacity to modify the finite natural environment in the name of progress and/or profit. Also, the projects reflect a lack of application of county, state and federal regulations that has resulted in a situation that is now upon us, the ESA.

5. SUMMARY AND CONCLUSIONS

In order to evaluate methods for determining the physical condition of a channel, we arranged this study around the physical relationships between basin characteristics (BC), channel characteristics (CC) and the link between basins and channels, the stream flow characteristics (QC). These are the combined fluvial-geomorphic relationships based on available streamflow records. These relationships can be used to estimate historical and future channel conditions.

To introduce these concepts we began by posing some questions about natural and unnatural conditions in a stream, and asked, "What is natural?" A series of settings was listed for which channel condition studies are conducted, ranging from channel capacity to more detailed instream flow habitat analyses.

In Part 2, our discussion of fundamentals which can be applied to channel condition studies, we summarized topics from: the current state of our knowledge about river width adjustment; dimensional analysis and its importance to geomorphology, hydrology and channel hydraulics; channel hydraulic geometry (channel dimensions related to flow) at-a-site and regionally at a series of sites; the influence of flow reductions on channel characteristics and thus habitat; and steps for using channel indices as tools to protect and recover stream habitat.

In Part 3 we reviewed some old methods and introduced some new ones for estimating channel characteristics (CC) as a function of both basin (BC) and stream flow (QC) characteristics. To examine these relationships we chose three regions in Washington for which the necessary data bases had already been developed: the Olympic Peninsula, part of the Puget Lowlands; and northeastern Washington. We could not avoid streams that have already been impacted by logging, urbanization and agricultural activities. But these effects showed up in the analyses as widened streams, those in bedrock, streams where the banks had been armored and those in which the hydrologic regimes had been altered. So, there is a mixture of natural and altered data in our analyses, but this is one of the problems with which we are all faced, as long as we recognize the alterations.

By using combined solutions of channel characteristics (such as width, depth, area and wetted perimeter) as functions of both basin characteristics and flow characteristics, we were usually able to improve on the strictly empirical graphs of say just width related to drainage area. However, in northeastern Washington there were some instances where channel width to basin area relationships were very strong. In all of these regional relationships they were done for: (1) a particular flow such as the average flood, average annual flow and average low flow; and (2) they depended on USGS gaging station calibration records for the measured channel characteristics. These could have been changing over time, and so we used average power equations in all relationships. We devoted Part 3 in its entirety to the analysis of regional channel stream cross-sectional geometry (W, D, A_c) as functions of basin characteristics (area, A_b; relief, H; and average annual precipitation, P). Part 3 concludes with a comparison of the three regional sets of equations and ranges of flow values for each region.

In Part 4 we selected four example projects to demonstrate the application of channel condition studies to streams in Washington and Idaho. Reconnaissance, restoration and reconstruction were three terms we used to compare these example projects. LeBar Creek, a tributary to the South Fork Skokomish River (SE Olympic Peninsula) was a habitat restoration project. Crooked River, a gold-dredged tributary to the S. F. Clearwater in north central Idaho, was a reconnaissance and planning study of stream and habitat reconstruction alternatives. Big Beef Creek, a tributary to SE Hood Canal, was a reconnaissance and analytical study to determine pre-logging and post-logging conditions and sediment loads in the stream. On the Lower Elwha River, the fourth example project was a detailed reconnaissance study. The effects of the diversions on channel geometry and habitat were documented. The calibrations were expanded to any combination of streamflow and diversion flow. The net flow in the Elwha River just below the diversion was projected to the downstream monitoring transects.

There are a variety of circumstances, which are fundamental to any channel condition study. Some of these are listed here:

- In a recent document Reid and Furniss (2000) discussed the use of regional channel-based indicators for monitoring purposes. Their conclusion was that there is no general solution to "the monitoring problem", and that no single set of indicators is applicable everywhere. "In channel physical parameters often are the most useful monitoring variables for such applications (e.g. for cause-effect, or hypothesized, relationships), but in each case the variables used are selected to be relevant to the specific application" (Reid and Furniss 2000). This is why we chose to use dimensional analysis for each component we explored whether it was basin, flow or channel characteristics. Dimensional analysis in each case relates the solution for the dependent variable in terms of dimensionless numbers, thus reducing scale effects.

- The ASCE Task Committee (TC) on Hydraulics, Bank Mechanics and Modeling of River Width Adjustment in 1998 reviewed and evaluated the current methods of predicting equilibrium (channel) width adjustments. **The TC's first recommendation proposed that stream reconnaissance procedures should be developed that emphasizes the geomorphic context of width adjustments.**

- We demonstrated that using channel hydraulic geometry in the geomorphic context we could relate channel to basin characteristics more comprehensively.

- The **graded stream and regime theory concepts** both use average conditions and the variability in those average conditions, as we have done in this report.

- **A new approach for calculating channel flow (without using Manning's equation)** as a function of regional hydraulic geometry and a shear-shape relationship in the stream channel has been demonstrated (Table 2-2, page 2-15). This relationship could be combined with basin characteristics to estimate W/D and P^2/A_c values for channels, but this phase has not yet been accomplished.

- Williams (1978) found that predictions of channel size using the exponents of width in hydraulic geometry are more reliable than the exponents of depth and velocity.

- A simple hydraulic geometry analysis of three data points at low, near average and high (within the banks) flows will fall within the range of any hydraulic geometry analysis done with more data points (Figure 2-5, page 2-19).

- A first-level channel geometry analysis can be conducted with a minimum amount of information: a cross-section (or series of cross-sections in riffles) from tops of banks or high water marks; measure the flow while doing the transect; make hydrologic model estimates of the three characteristic flows (Q7L2, QAA, Q1F2); insert the estimated flows into regional hydraulic geometry to obtain W, D, A_c and P estimates; and conduct a graphical comparison of the estimated values (by regional hydraulic geometry models) versus the field measured values. This will tell you which parameters are within "reasonable" accuracy based on the combined accuracy of the regional gaging records, the channel cross-sections and the flow measurements you made.

- The variability in streamflow periods of record sometimes causes errors in regional hydraulic geometry models, especially at the average flood flows and average low flows; dry or wet spells during the shorter periods of record may skew the analysis.

- Short periods of record should be compared with a regional, long-term "base" USGS gaging station to determine coincidence with wet or dry cycles (Orsborn and Orsborn 2000).

- The Severity Factor Analysis (page 2-19) is a flexible, straightforward way to evaluate the influences of flow reductions on channel geometry, and habitat features.

- Plotting undistorted channel cross-sections will help in the visualization of the true channel shape.

- Some examples of stream reaches that are in a natural or an unnatural condition are listed below:

Natural Stream Reaches

- **a meandering meadow stream with grassy banks** and very little, if any, in-channel LWD;

- **a stream in old growth timber** with numerous pieces of LWD and good habitat diversity;

- **a stream** with no buffer strips in a rocky geologic environment **with no flood plain**;

- **a stream with buffer strips in which some blowdown has occurred**;

- **a braided stream** with large amounts of LWD on the **bars at the outlet of a canyon**;

- a stream flowing in a **forced meander pattern in a canyon** between side controls of rock outcrops, and with no LWD;

- **a stream with a large mass-wasting deposit from a hill slope failure**; the stream immediately begins to store water upstream of the slide, wash out fines, and downcut through the fill until it reaches an armor layer and a graded (equilibrium) state; and

- streams that have been heavily impacted by **extreme floods or droughts in natural environments.**

Altered Stream Reaches

- any stream reach which has had its **natural flow regime changed** by reducing floods, or diverting flows, and increasing or decreasing low flows;

- **urbanizing basins** result in similar alterations of the natural stream flow regime as do storage and diversion projects;

- streams that have been heavily impacted by large floods due to **unnatural flow releases from dams;**

- a reach **near a clear-cut;**

- a reach in a **clear-cut with no buffers;**

- a stream reach with a **hardened side** (or sides) that limit the capability of the stream to deform naturally;

- streams whose **valleys are blocked by road fills** for 80-90 per cent of their valley width leaving only a culvert or bridge opening;

- these **valley constrictions** cause contractions that dam the flow, raise flood levels upstream, change channel patterns up- and downstream, and

- even more importantly, **road fills at the upstream ends of estuaries,** keep the estuaries from fully functioning to their natural potential (e.g. the Skokomish River estuary operates while being choked (throttled down) by two road fills, each having 15% of the valley width left open at bridges; requiring that all new and replacement bridges be designed to have their approaches built on pilings would restore the estuaries to a much improved, near-natural state.

The usual reaction to the estuary-road fill problem is to say that pilings would be too expensive---compared to what? These reaches of streams upstream and downstream of any road fill have been impacted and opportunities for improvement have been foregone. Reconstruction and restoration of estuary roads and estuary functions will be crucial to ESA opportunities. Not all road fill across valleys need to be placed on pilings, but their hydraulic competencies need to be checked and improved.

In conclusion, let us review the primary purpose of the project: "to evaluate the concept of regional indices of channel morphology and to determine if they (the regional indices) can provide a useful diagnostic and predictive tool to help evaluate existing and potential channel characteristics" (page 1-1). The answer to both of these questions is a qualified "yes", qualified in that the quality of the answers depends on the quality of the data base (regional streamflow, basin, land-use, precipitation, in-channel and stream corridor records). The steps involved in any evaluation of channel condition have been summarized in various places throughout the report and are repeated here in conclusion.

The general procedure for approaching width-adjustment analyses was outlined by the ASCE Task Committee on page 2-2 and is modified below:

(1) **Problem identification (including careful definition);**
(2) **Reconnaissance** and **data** collection;

(3) **Desk assessment** of channel conditions;
(4) Application of **empirical channel regional** models;
(5) Application of numerical **models** (if warranted);
(6) **Validate the model results** against field data ;
(7) Numerical models should be applied to **existing conditions** and to assess any known or anticipated **future impacts**;
(8) comparison and assessment of **alternatives**; and
(9) Selection of a **solution**.

Note in Steps 5 and 6 that value judgements have to be made as to whether or not numerical models should be applied and if enough field data is available for validation. Recall that simpler models are better in that they are less data intensive. Note also that key words in each step have been made bold for emphasis.

Near the end of Part 2 (page 2-27) we listed some conditions to consider in accounting for changes in channel geometry dealing with scales of indices, followed by a systematic method of analysis.

Evaluation Conditions

(1) A channel may be "in balance" with its water and debris load, and still not fit a cross-sectional template for the region due to geologic or human geometric constraints;

(2) the main stream channel may be underfit due to excessive diversions of flow out of the watershed, and the accumulation of sediment in the mainstem from unaffected tributary sediment flows;

(3) the channel may be over- or under-sized due to a modified flow regime caused by either a natural extended increase of decrease in flow, or a regulated flow regime, or both; and

(4) an historical mass wasting may have been deposited in a stream valley, and the stream is now downcutting (as a function of the existing flow regime) with a narrower, deeper channel than "normal".

Analytical Steps

Review of historical records of flow (database):

(1) a method of classification is used to put some geomorphic boundaries on the site being investigated, and to help in the visualization of the site;

(2) a simple hydrologic analysis to estimate the characteristic flows at a site (average low (Q7L2), average annual (QAA) and average flood

(Q1F2)), and major changes in these characteristic flows and in precipitation over time;

(3) an abbreviated analysis of the channel hydraulic geometry of the site to provide relationships of geometric characteristic (W, D, V, A and P) as a function of discharge;

(4) regional channel hydraulic geometry models for comparison with the present site geometry, and with similar, template streams;

(5) an integrating analysis of how the W/D ratio, and other geometric dimensionless ratios, change as a function of streamflow reduction; a type of severity factor analysis which ties flow to geometric characteristics which serve as analogs to water quantity and quality parameters; and

(6) an assessment of the history of major land-use and water-use changes on the watershed.

Can you imagine the condition that our streams and fish stocks would be in now if, as was proposed in the early 1970's, buffers had been mandated by the Forest Practices Board on all streams, clear to the drainage divides?

Ruling on a controversy over logging in a redwood forest in California, Judge R. H. Kroniger wrote the following: "While numerous expert witnesses in the field of geology, forestry, engineering, and biology were presented, their conclusions and the opinions they derived from them are hopelessly irreconcilable in such critical questions as how much and how far solid particles will be moved by any given flow of surface water. They were able to agree only that sediment will not be transported upstream' [State of California, Marin County versus E. Richetti and others, 1969]. (Wolman 1977 in Burkham 1981).

And as for Rivers, I believe it is evident, that they are furnished by a superior circulation of Vapours drawn from the Sea by the heat of the sun, which by Calculation are abundantly sufficient for such a supply. For it is certain that nature never provides two distinct ways to produce the same effect, when one will serve. But the increase and decrease of Rivers, according to wet and dry Seasons of the year, do sufficiently show their Origination from a Superior circulation of Rains and Vapours (From John Keill 1698, in White 1968)

References for Part 5

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6. NOTATION

English Gravitational System (EGS) of Units followed by Dimensions of Force (F), Mass (M), Length (L) and Time (T).

Symbol	Description	EGS Units	Dimensions
a	acceleration	ft/sec^2	L/T^2
a - j	empirical coefficients and exponents in hydraulic geometry equations (e.g. $W = aQ^b$)	(-)	(-)
A_b	basin area	mi^2	L^2
A_c	channel flow area	ft^2	L^2
BC	basin characteristics	(-)	(-)
BE	basin energy, $AH^{0.50}$	mi$^{2.50}$	L$^{2.50}$
B3, B4, C3, etc.	channel types	(-)	(-)
C	general notation for coefficients	(-)	(-)
CC	channel characteristics	(-)	(-)
D	mean depth of flow, A_c/W	ft	L
D_{max}	maximum flow depth	ft	L
E	general notation for exponents	(-)	(-)

Symbol	Description	EGS Units	Dimensions
E	mean basin elevation above mean sea level	ft	L
F	forest cover	%	(-)
F	force	lbs_F	F
g	acceleration due to gravity	ft/sec^2	L / T^2
H	basin relief (potential energy)	mi	L
LR / LV	River Length / Valley Length	(-)	(-)
LS	length of perennial streams (solid blue lines on USGS topographic maps)	mi	L
M	mass from matter	lbs_M	M
N_F	Froude No., dimensionless ratio of water velocity to gravity wave velocity, or inertia to gravity forces. Examples: N_F (Channel), N_F(Model), N_F(Prototype), N_F(Watershed)	(-)	(-)
n	Manning's resistance coefficient	$sec/ft^{0.33}$	$T / L^{0.33}$
P	average annual precipitation	in/yr	L / T
PA_b	average annual inflow to the basin	mi^2 - in/yr	L^3 / T
PBE	average annual precipitation times basin energy	$mi^{2.50} \bullet$ in/yr	$L^{3.5} / T$

Symbol	Description	EGS Units	Dimensions
P	wetted perimeter of channel or conduit	ft	L
Q	stream flow	ft^3/sec (or cfs)	L^3/T
QAA	average annual flow (also called QAD)	ft^3/sec (or cfs)	L^3/T
QAD	average daily flow (see QAA)	ft^3/sec (or cfs)	L^3/T
QC	characteristic flows (Q1F2, QAA, Q7L2, ...) at a gage or site	ft^3/sec (or cfs)	L^3/T
Q1 / Q2	dimensionless flow reduction ratio	(-)	(-)
QPF Max	maximum instantaneous peak flow of record	ft^3/sec (or cfs)	L^3/T
QPF2	average peak flood (with a 2-yr RI)	ft^3/sec (or cfs)	L^3/T
QPF25	average peak flood (with a 25-yr RI)	ft^3/sec (or cfs)	L^3/T
QPF50	average peak flood (with a 50-yr RI)	ft^3/sec (or cfs)	L^3/T
QPF100	average peak flood (with a 100-yr RI)	ft^3/sec (or cfs)	L^3/T
Q1F2	average daily flood (1-day) with a 2-yr RI; also Q1F25, Q1F50 and Q1F100	ft^3/sec (or cfs)	L^3/T
Q7L2	seven-day average low flow with 2 yr RI; also Q7L20, Q30L2, etc.	ft^3/sec (or cfs)	L^3/T
QX	any characteristic flow	ft^3/sec (or cfs)	L^3/T

Symbol	Description	EGS Units	Dimensions
R^2	correlation coefficient	(-)	(-)
RI	recurrence interval	years	T
V	mean flow velocity	ft/sec	L / T
W	water surface width	ft	L
W/D	dimensionless width to depth ratio of channel at a particular flow	(-)	(-)
W2:D2/W1:D1	dimensionless width to depth reduction, ratio used in Severity Factor Analysis	(-)	(-)
X SF	multiple Severity Factor	(-)	(-)
Σ SF	summation Severity Factor	(-)	(-)
x	horizontal axis on graphs; independent variable		
y	vertical axis on graphs; dependent variable		

7. INDEX OF TERMS AND AUTHORS