Abridgment

Determining Design Flows for Culverts and Bridges on Ungauged Streams: A Watershed Rationale

John F. Orsborn, Department of Civil and Environmental Engineering,
Washington State University, Pullman

The determination of the characteristic low, average, and flood flows of ungauged perennial streams is a continuing problem for hydrologists. The acquisition of streamflow records has improved the reliability of flows at or near gauging sites, but at a distant site, say just upstream of the first major tributary, we rapidly lose our prediction confidence.

Methods for predicting ungauged streamflows come in three categories of input-output models: deterministic, rational, and regression. Numerous references that describe their development and use are available (1, 2, 3). Characteristic flows are considered to be "average" low, annual, and flood flows. Knowledge of these flows and their variability at an ungauged site, coupled with the duration curve characteristics at gauges in the province, makes it possible to create a flow duration history for the ungauged site.

The basic concept behind this geohydrologic watershed rationale is that the watershed integrates precipitation and yields flows with certain statistical characteristics. Further, the outflows form channels with geometric characteristics, and the kinetic energy (velocity), channel width, and channel depth can be related to the flow in the channel (4). Thus, in a total geohydrologic analysis of a watershed one should be able to relate flows to watershed characteristics and flows to channel characteristics and thus determine channel characteristics from basin characteristics and vice versa. If these concepts are physically correct, there should be little scale effect between large and small watersheds within the dominant range of sizes that generate perennial streams requiring culverts or bridges. Application of similar concepts to intermittent streams is under investigation.

The three characteristic flows of perennial streams considered here are

1. Q7L2: the 7-day average low flow with a 2-year recurrence interval,
2. QAA: the average annual flow, and
3. QF2P: the peak flood with a 2-year recurrence interval.

These three flows are representative statistical and arithmetic averages and are quite stable over periods of 30-50 years. In addition, the 20-year low flow Q7L20 can be determined and coupled with Q7L2 to yield the low flow recurrence interval graph. When the 50-year flood flow QF50P is determined, a flood recurrence graph can be developed. These five flows, plus the deviation of QAA, give a band of duration curves that describes the usual history of flows at a site.

The three average flows—Q7L2, QAA, and QF2P—will be used to describe watershed parameter relationships. Details of the procedures for estimating these ungauged flows are presented elsewhere (5, 6, 7). The remainder of this paper covers five topics: (a) watershed parameters and their analogies used in streamflow estimation; (b) relationships between the characteristic flows Q7L2, QAA, and QF2P; (c) correlations between watershed parameters and characteristic flows; (d) channel width, depth, velocity, and discharge relationships; and (e) the combination of c and d to yield channel characteristics in terms of watershed parameters.

WATERSHED PARAMETERS AND THEIR ANALOGIES IN STREAMFLOW ESTIMATION

The geohydrologic output:output watershed rationale for streamflow estimation uses four primary watershed linear geometric characteristics. These are summarized in Figure 1 as

1. LS: length of perennial streams of various orders where LT is the total,
2. A: drainage basin (watershed area),
3. LB: basin axis length, and
4. H: basin relief, or differential elevation between the headwaters and the outlet (the gauged or ungauged flow site).

The stream length (LS) is analogous to the linear interface between the groundwater supply and the stream that the aquifer supplies. Drainage area (A) is analogous to the watershed's ability to capture precipitation. The axis length of the basin is combined with the derived mean basin width (WB = A/LB) to give a watershed aspect ratio of LB/WB. This aspect ratio is analogous to the time of concentration when estimating floods. The basin relief (H) represents the driving force, or potential energy, for flow from the watershed. Precipitation is directly related to elevation (relief) in some regions.

RELATIONSHIPS AMONG CHARACTERISTIC FLOWS

A study of low, average, and flood flows in Washington, Oregon, and Idaho (8) has shown that there is a fundamental 1, 2, 3 power relationship between the three characteristic flows of

$$Q7L2 = C(QAA^3/QF2P^2) \qquad (1)$$

The coefficient (C) in Equation 1 varies between hydrologic provinces, but for natural flows and no severe geologic anomalies the coefficient is very consistent within provinces. For the sample area of southwest Washington (8) shown in Figure 2, the coefficient in the form of Equation 1 has an average value of about 10.0; the minimum theoretical value is 1.0.

Figure 1. Watershed parameters and their flow analogies.

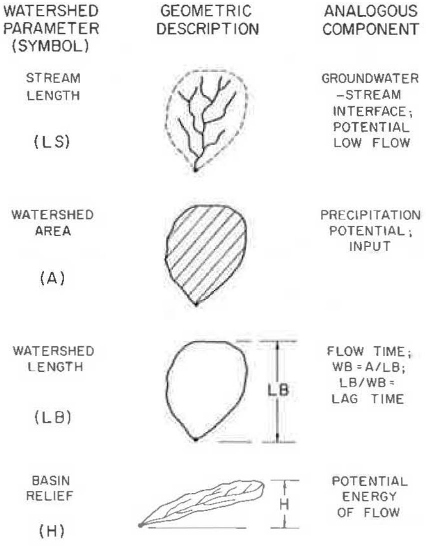
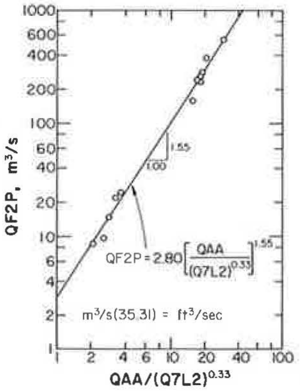


Figure 2. Average flood related to average annual and low flows for data sample from southwestern Washington.



CORRELATIONS BETWEEN WATERSHED PARAMETERS AND CHARACTERISTIC FLOWS

The low, average, and flood flows used in Equation 1 were estimated for ungauged streams by using correlations developed from the gauged watersheds in the hydrologic province. Examples are drawn from a study of the Lake Coeur d'Alene watershed in northern Idaho (9).

Low Flows

The best combination of watershed characteristics (best basin parameters) for making the first estimate of low flows in the Coeur d'Alene province is $(LT)(H)^{0.5}$. For the average low flow (the coefficient 23.30 is 0.32 in EGS units)

$$Q7L2 = 23.35\,[LT(H)^{0.5}] \qquad (2)$$

Average Annual Flows

Provincial relationships between average annual streamflow records and the average annual volume of precipitation are highly correlated. In equation form

$$QAA = C(P \cdot A) \qquad (3)$$

where C is a coefficient that varies as a function of climatic region and is larger for areas with greater values of P, P is the average annual precipitation, and A is the watershed drainage area.

Flood Flows

Within hydrologic provinces, average annual floods have been found to be a consistent multiple of the average annual flow (10). In equation form,

$$QF2P = C(QAA) \qquad (4)$$

In many provinces a stronger relationship has been found between QF2 and QAA raised to some power

$$QF2P = C(QAA)^n \qquad (5)$$

For northern Idaho watersheds (9),

$$QF2P^2 = 1687(QAA)^{1.7} \qquad (6)$$

Noting the similarity between Equations 1 and 6 and rearranging Equation 1 yield

$$QF2P = C(QAA^3/Q7L2)^{0.5} \qquad (7)$$

For example, the results of the Coeur d'Alene study (9) show, as in Equation 1, that

$$Q7L2 = 8.0\,QAA^3/QF2P^2 \qquad (8)$$

This may be combined with Equation 2, $Q7L2 = 23.35\,[(LT)(H)^{0.5}]$, and with Equation 3

$$QAA = 1.85(10^{-4})(P \cdot A) \qquad (9)$$

Also, total stream length (LT) is related to drainage area (A) by

$$LT = 2.08(A)^{0.98} \qquad (10)$$

Substituting Equations 2 and 9 into Equation 8 and rearranging give

$$23.35\,[LT(H)^{0.5}] = [1.85^3(10^{-4})^3(P \cdot A)^3]/QF2P^2 \qquad (11)$$

$$QF2P^2 = 2.71\,[(P \cdot A)^3/LT(H)^{0.5}]\,(10^{-9}) \qquad (12)$$

Substituting Equation 10 into Equation 12, the 2-year peak flood is

$$QF2P = 3.60(P^{1.50}A/H^{0.25})(10^{-5}) \qquad (13)$$

The combination of terms on the right side of Equation 12, $(P \cdot A)/[LT(H)]$, tends to be a constant within hydrologic provinces. Thus, after a provincial correlation is developed, average annual precipitation can be determined for an ungauged watershed by measuring drainage area, relief, and total stream length.

CHANNEL WIDTH, CHANNEL DEPTH, VELOCITY, AND FLOW RELATIONSHIPS

Numerous investigators have demonstrated that channel width (W), depth (D), and mean velocity (V) each can be expressed in terms of average annual flow (QAA) or other flows up to bankfull conditions (4).

$$W = a(QAA)^b \qquad (14)$$

Table 1. Width, depth, and velocity related to discharge in typical stream channels, Little Brush Creek, Utah.

Station No.	Width Equation (m)	Depth Equation (m)	Velocity Equation (m/s)
1[a]	$W = 1.22(Q)^{0.65}$	$D = 0.304(Q)^{0.30}$	$V = 1.480(Q)^{0.16}$
2	$W = 27.09(Q)^{0.10}$	$D = 0.082(Q)^{0.52}$	$V = 0.440(Q)^{0.38}$
3	$W = 59.13(Q)^{0.04}$	$D = 0.092(Q)^{0.59}$	$V = 0.184(Q)^{0.37}$

Notes: 1 m = 3.3 ft.
Data derived from Chrostowski (11).

[a] Exponents do not total 1.00 at station 1 because of a sharp change in section shape from triangular to rectangular between stage 1 and stage 0.

Table 2. Comparison of predicted and measured channel widths based on annual precipitation volume and relief.

			Channel Width (WAC) (m)		
			Predicted		
Station No.	State	Stream	Equation 21 or 22	Equation 26	Measured[a]
06 0195	Montana	Ruby	17	14	13
0330		Boulder	13	10	13
0375		Madison	29	21 (34)	27
0485		Bridger	8	5[b] (10)[c]	7
0615		Prickley Pear	9	7	7
0735		Dearborn	20	12 (20)	21
0770		Sheep	8	7	8
0905		Belt	18	16 (21)	19
1185		Musselshell	12	10 (15)	14
2890	Wyoming	Little Bighorn	14	12	15
3145		N.F. Crazy Woman	6	5	8
6160	Colorado	N.F. Michigan	5	5	6
7165		Clear	13	13	18

Notes: 1 m = 3.3 ft.
Data derived from Hedman and Kastner (12).

[a] From Hedman and Kastner (12).

[b] Small basin; $(H)^{0.16}$ is probably less than 1.0.

[c] If P = 69.3 cm (27.3 in) is used as published by SCS rather than 38.1 cm (15.0 in) of Weather Bureau as used elsewhere (12), then the value of WAC in parentheses is given by Equation 26 in column 4.

$$D = c(QAA)^{d} \tag{15}$$

$$V = e(QAA)^{f} \tag{16}$$

Exponents b, d, and f must total 1.0, and the multiple of coefficients a, c, and e must be 1.0.

Channel shapes can range only between the extremes of perfectly triangular and rectangular, assuming various combinations of rectangular, triangular, and trapezoidal shapes depending on the stage of flow between low and bankfull conditions. Some width, depth, and velocity relationships for typical channels are presented as a function of streamflow in Table 1.

CHANNEL CHARACTERISTICS, FLOOD FLOW, AND WATERSHED PARAMETERS

A series of expressions for average annual flows and floods for streams in Montana, Wyoming, and Colorado has been developed (12). One such equation for average annual flow is

$$Q_A = 37.7\,W_{AC}^{2.00} \tag{17}$$

where W_{AC} is the active channel width that carries bankfull and lesser flows. In terminology used thus far

$$QAA = 0.170(WAC)^2 \tag{18}$$

where QAA is Q_A in cubic meters per second and WAC is in meters.

Using Equation 3 and substituting the data from Hedman and Kastner (12, Table 1)

$$QAA = 0.95(P \cdot A)(10^{-4}) \tag{19}$$

$$QAA = 1.85(P \cdot A)(10^{-4}) \tag{20}$$

Setting Equations 18 and 19 and 18 and 20 equal to each other, the following expressions emerge for active channel widths in the eastern Rocky mountains:

$$WAC_{0.95} = 2.36(P \cdot A)^{0.5}(10^{-2}) \tag{21}$$

$$WAC_{1.85} = 3.30(P \cdot A)^{0.5}(10^{-2}) \tag{22}$$

where 0.95 and 1.85 are runoff coefficients in Equations 19 and 20.

One flood equation (12) in standard units is

$$Q_2 = 0.87\,W_{AC}^{1.579}\,A^{0.162} \tag{23}$$

and in metric units is

$$QF2P = 5.52(WAC)^{1.58}(A)^{0.16} \tag{24}$$

By setting Equations 24 and 13 equal to each other and solving for WAC,

$$5.52(WAC)^{1.58}(A)^{0.16} = 3.60(P)^{1.50}(A)/(H)^{0.25}(10^{-5}) \tag{25}$$

$$WAC = 5.22\{[(P)^{0.94}(A)^{0.53}]/(H)^{0.16}\}(10^{-4}) \tag{26}$$

Applying Equations 21, 22, and 26, widths of the active channels were predicted for the set of stations in Table 2 by two equations and compared with the measured widths from Hedman and Kastner (12), where relief (H) was not given but $(H)^{0.16} \rightarrow 1.0 \pm 10$ percent within normal ranges.

This brief example derived for Orsborn and Deane (13) has shown how relationships between basin characteristics and streamflow, and channel characteristics and streamflow, can be combined to predict channel characteristics in terms of basin characteristics. It therefore completes the development of the two tenets basic to the watershed rationale: the integrative effects of the watershed on outflows and the channel characteristics that result from those flows.

SUMMARY

A watershed rationale that assumes that outflows are integrated by the watershed to yield floods and low flows with certain provincial correlations has been explored. The provincial correlations use combinations of various watershed geomorphic characteristics, including stream length and watershed area, length, and relief. A 1, 2, 3 power relationship among average low, flood, and annual flows opens new opportunities for flood flow predictions.

The possibility of being able to predict flood flows in terms of channel characteristics has been presented. To complete the integrated watershed rationale, channel characteristics have been predicted in terms of watershed characteristics by setting two flood flow equations from different mountainous regions equal to each other. The only input term used in the analysis is the average annual watershed precipitation. Floods have been shown to be strongly dependent on watershed area, relief, and stream length—those geomorphic parameters that are analogous to certain physical hydrologic processes and that make the integrated watershed rationale possible.

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Rainfall Intensity-Duration-Frequency Curves Developed From (not by) Computer Output

Brian M. Reich, Pima County Flood Control District, Tucson

Thirty-two years of maxima observed at Tucson International Airport from the National Oceanic and Atmospheric Administration's recording raingage are used to prepare a sheet of intensity-duration-frequency curves commonly used in the design of storm drainage for small urban areas. The example is employed to stress the need for examining computer printouts of mathematical statistical analysis of the rains and their logarithms by plotting data on four types of probability paper. Stress is laid on dangers of blindly extrapolating a mathematical distribution that does not fit recorded amounts for the long return periods in which engineers are usually interested. Misapplication of scales involving a logarithmic transformation are discussed. The fact that longer durations may require a different type of frequency paper than do shorter durations is illustrated and rationalized on the basis of the physical process. Internal compatibility of results for 2-, 5-, 10-, 50-, and 100-year estimates of 5-, 10-, 20-, 30-, 45-, 60-, 120-, and 180-min rainfalls is preserved when examining a tabular array of as many as five frequency analyses on one of these 48 cells.

Intensity-duration-frequency (IDF) curves are a long-standing tool of the storm-drain designer (1, 2, 3). A U.S. Weather Bureau publication (4) gave depths of maximum rainfall for various durations and return periods on many separate maps. Since then, recording gages have provided additional data on rainstorms, often more than doubling record lengths at newer sites.

Local governments and consulting engineers may wish to prepare their own intensity-duration-frequency curves, like Figure 1, from their most up-to-date gage records. The purpose of this paper is to discuss topics that an engineer must consider while preparing such design curves.

There is an urgent need for engineers to gain at least a "feel" for statistical techniques. The availability of canned digital computer programs to fit preselected statistical distributions places the responsibility on the user for testing the validity of those automated analyses with respect to his or her particular data or engineering application. In outlining various means for exercising necessary discretion, this paper will refer to common statistical terms, concepts, and equations. They will be introduced in an informal, intuitive vein. Readers desiring additional pragmatic explanations of these extreme value statistics may wish to study Magnitude and Frequency of Floods (5). That 50-page review of terms and methods also contains complete tables needed in computation and various graph papers needed in plotting extreme rainfall data. Two excellent texts (6, 7) were recently published for engineers with deeper and wider interests in statistics.