Stream Simulation

ROAD

- ✔ Long-term commitment and plans for the road.
- ✔ Road management objectives.
- ■ **Location of road and crossing.**
  - ✔ Road and crossing maintenance history: chronic maintenance problems.
  - ✔ Vertical and horizontal constraints on road grade and location.
  - ✔ Rights-of-way.
- ■ **Associated infrastructure.**
- ■ **Fillslopes: height, stability.**
- ■ **Construction closure and detour options.**

WATERSHED RISK FACTORS

- ✔ Geologic or geomorphic hazards (landslides, avalanches, debris torrents, etc.).
- ✔ History of flooding and geomorphic events.
- ✔ Land management history and projected future change: expected changes in sediment and/or flow regimes.
- ✔ Channel stability offsite (location/type/ potential to affect site.)

EXISTING STRUCTURE

- ■ **Dimensions, slope, fill, perch.**
- ■ **Material, condition.**
- ■ **Structure skew to stream and road.**
  - ✔ Flood-plain constriction.
  - ✔ Site restrictions/sensitive areas.
  - ✔ Type of barrier (partial or complete).
  - ✔ Fish and other aquatic organisms affected by barrier.
    - ● Endangered species.
    - ● Timing, swimming ability.
  - ✔ Terrestrial species affected.
  - ✔ Barriers upstream and downstream from structure.
  - ✔ Structure priority for replacement.

RESOURCE VALUES

- ✔ Aquatic- and riparian-dependent fish and wildlife populations.
- ✔ Aquatic habitats requiring protection.
  - ● Quality and extent upstream from structure.
  - ● Critical habitats downstream.
  - ● Flood-plain habitats.
  - ● Work window timing.
- ✔ Terrestrial animal migration routes/ specialized habitats.
- ✔ Flood-plain habitats; wetlands.
- ✔ Critical flood-plain water storage.
- ✔ Water supply.
- ✔ Recreation.

PROJECT REACH

- ■ **Annotated site sketch**
  - ✔ Geomorphic features: channel and valley.
  - ✔ Road features.
  - ✔ Significant vegetation.
  - ✔ Land ownership.
  - ✔ Utilities.
  - ✔ Potential lateral adjustment.
  - ✔ Potential construction access.
  - ✔ Photo points.
  - ✔ Cross section, key feature locations.
- ■ **Channel morphology**
  - ✔ Channel type.
  - ✔ Natural channel location.
    - ● Alignment.

- ✔ Longitudinal profile.
  - Stable endpoints.
  - Key features; mobility.
  - Residual pool depths/scour potential.
  - Natural channel elevation, gradient, and vertical adjustment potential.
- ✔ Cross sections.
  - Bankfull width; variability in width.
  - Bank height.
  - Flood-prone zone width; flood-plain conveyance.
  - Flood-plain roughness.
  - Additional cross sections for backwater model.
- ✔ Bed material.
  - Pebble count or other estimate of gradation.
  - Armoring.
  - Key features; size and mobility.
- ✔ Soils/foundation materials.
- ✔ Ground water.

Channel stability

- ✔ Channel response to existing structure.
- ✔ Vertical adjustment potential.
  - Bed mobility.
  - Perch.
- ✔ Lateral adjustment potential.
  - Bank stability.
- ✔ Flood-plain conveyance.
- ✔ Plugging potential.
  - Woody debris.
  - Ice.

Risk Assessment

- ✔ Site history (flood history, past/future land use, geologic/hydrologic setting, etc.).
- ✔ Potential for change in sediment loading/ flow regime.
- ✔ Vertical adjustment potential.
- ✔ Headcut potential and effects.
- ✔ Aggradation potential and projected effects.
- ✔ Lateral adjustment potential and effects.
- ✔ High flood-plain conveyance; constriction potential.
- ✔ Habitats.

STATEMENT OF PROJECT OBJECTIVES (section 4.6)

- ✔ Road.
  - Traffic level; interruptibility; safety.
  - Maintenance.
  - Diversion potential.
- ✔ Stream-simulation channel.
  - Desired design features.
  - Structure design flow.

REFERENCE REACH

- ✔ Preliminary selection.
- ✔ Longitudinal profile.
  - Gradient.
  - Key features: types, spacing, height.
  - Channel roughness.
- ✔ Cross section
  - Channel form/geometry.
  - Bankfull width.
  - Entrenchment.
  - Channel margins and banklines.
- ✔ Bed material.
  - Bed material: gradation, armoring, angularity.
  - Key features: particle sizes, packing/ consolidation.
  - Bed mobility.

Appendix D—Estimating Design Stream Flows at Road-Stream Crossings

D.1 INTRODUCTION

Assessing the stability of any crossing structure requires estimating design peak flows for the site. This appendix provides guidance and resources for estimating peak flows at gauged and ungauged sites. It is intended as a desk reference rather than an introduction to hydrologic analysis.

Two types of design flows apply to stream-simulation design:

- structural-design flows, for evaluating the structural integrity and stability of the culvert, bridge, etc., during flood events.
- **bed-design flows**, for evaluating the stability of the particles intended to be permanent inside a drainage structure.

Design flows are the flows that, if exceeded, may cause failure of the structure or the bed. The two design flows may be different if the consequences of bed failure are different from those of complete structural failure (see risk discussion in section 6.5.2.1). For example, if the acceptable risk of bed failure is 4 percent in any one year, the bed design flow would be the flow that is exceeded on average only every 25 years—the 25-year flow. The acceptable risk of losing the structure might be lower, perhaps only 1-percent per year, in which case the 100-year flow would be the structural-design flow. These design flows are often taken to be the same in real applications, but it is important to understand the concept that design flows are determined based on acceptable risks and consequences.

All stream-simulation designs require estimating the structural and bed design flows. Some designs also require further hydraulic analysis—comparing key-piece entrainment flows in the reference reach to those in the project reach (appendix E). For the comparative analysis, we do not need to know the flow recurrence interval. However, determining the recurrence interval can be an independent check on the reasonableness of your estimate of entrainment flow. The frequency of the estimated flow can be compared to the bed-mobilization frequencies listed in table 6.5 for each channel type, or to field observations of actual floods of known recurrence interval.

Estimating flood flows on small watersheds is particularly difficult, because relatively few stream gauges exist on small streams. The U.S. Geological Survey (USGS) maintains nearly 6,000 gauges, 26 percent of

which are on or within 10 miles of national forest lands. However, only 132 gauges are on streams with a contributing area of less than 5 square miles, and only 22 of those are on or within 10 miles of a national forest (figure D.1). Fewer still have a long-term flow record to allow for accurate estimates of extreme events.

More inactive gauges exist than active ones and the historic records from inactive gauges are also very useful for estimating flood flows. There are 407 inactive gauged sites with a contributing area of less than 5 square miles and within 10 miles of a national forest.

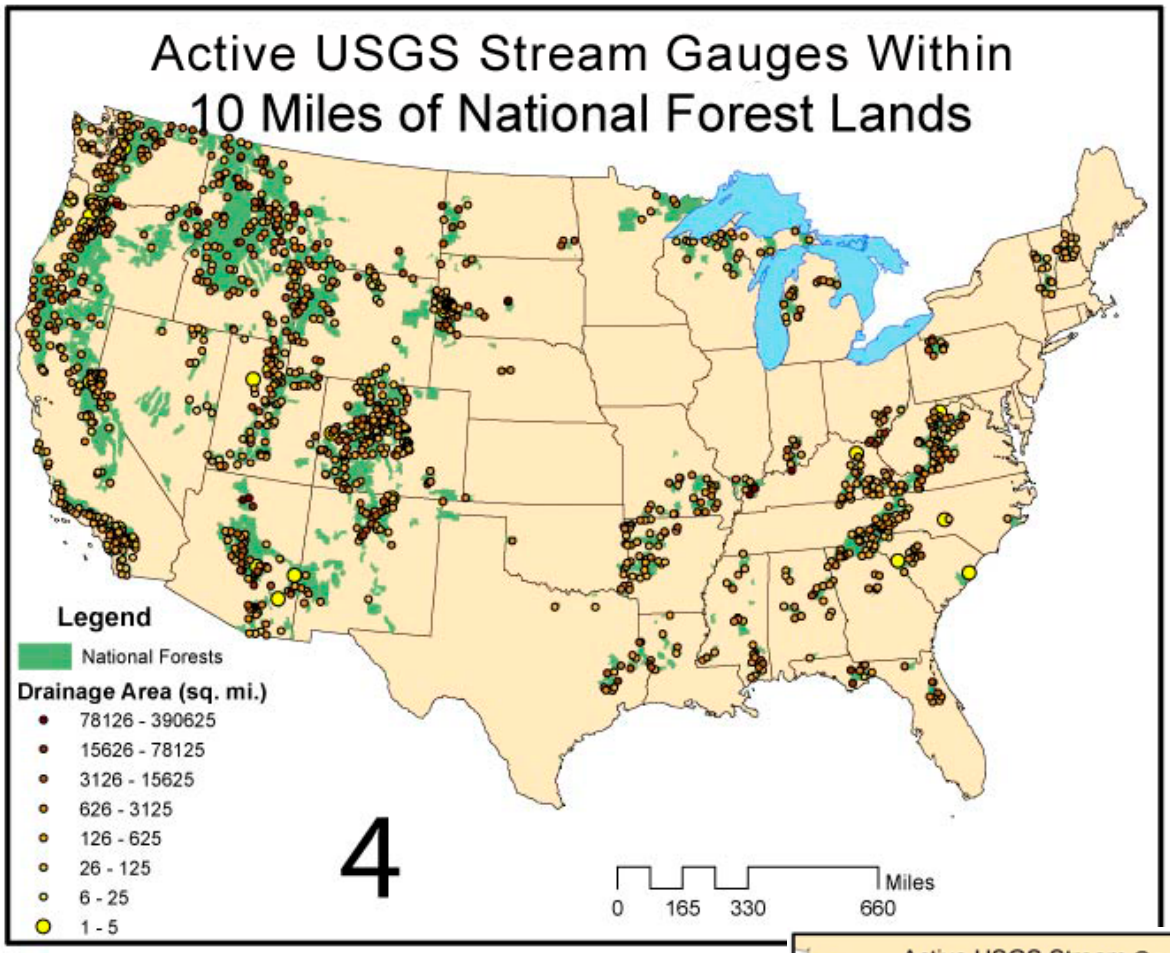
The lack of gauging stations in small, forested watersheds requires the analyst to use varied approaches, employing multiple flow-estimation methods to arrive at the best estimate of design flows. Methods can be grouped according to the project site's proximity to a stream gauge:

- Direct application of gauge data.
- Extrapolation of flow estimates from gauged sites.
  - To ungauged sites on the same stream.
  - To ungauged sites on nearby streams.
- Predictions in ungauged basins with regional regression equations.

To meet project objectives, teams must invest appropriate time and effort in developing both structural- and bed-design flows. If structural-design flows are underestimated, then the risk of hydraulic failure is likewise underestimated. Conversely, if design flows are overestimated, both immobile bed particles and the structure itself may be oversized.

D.2 DESIGN FLOW ESTIMATES

Many sources of streamflow data exist. Stream gauges are most commonly operated by State or Federal agencies or by utilities. The best and most reliable data are generally those published by the USGS, which has well-defined protocols for data collection and quality control. Gauge data collected without defined protocols and documentation may be of lesser quality. At the National Water Information Systems (NWIS) Web site (http://water.usgs.gov/nwis/), you can download gauge station information, field measurements, summary statistics, and mean daily flow, peak flow, and partial peak flow data.



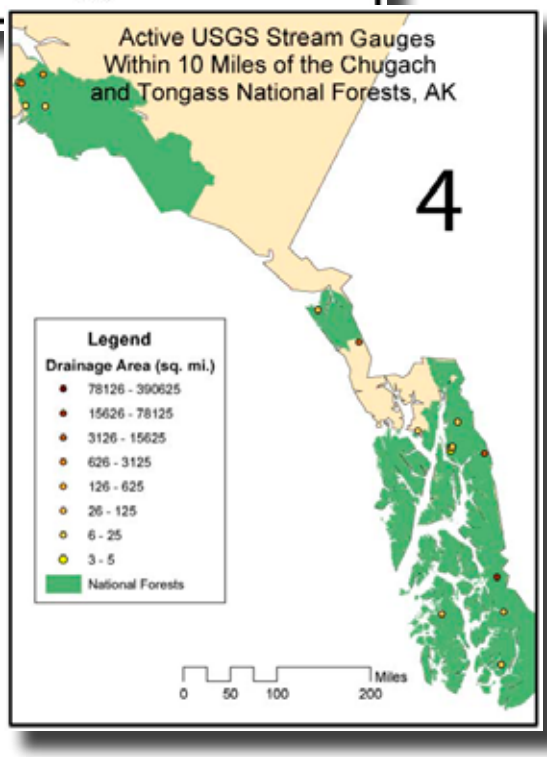


Figure D.1—U.S. Geological Survey stream gauges in and near national forests.

Professional papers and reports are a good source of historical flow data, regional regression equations, and other flow estimation tools. USGS publications for estimating flows describe the methods to be used for each State. Check the National Flood Frequency Program (NFF) Web site for the electronic documentation for the State in which your project lies: http://water.usgs.gov/software/nff.html).

D.2.1 Design Flow Estimates at Gauged Sites

Although aquatic organism passage projects rarely occur at a gauged site, it may be necessary to analyze data from nearby gauges to determine flows of particular recurrence intervals (flood frequency) in the vicinity.

Accuracy of flood frequency estimates at a gauged site depends on the length of record of the gauge. The longer the period of record, the better the estimate. As an example, figure D.2 shows the measured peak discharges for the period of record for the gauge on the North River in Alabama. Notice how the estimated magnitude of the 100-year flood (Q_{100}) changes as different time periods are considered. In the development of flood frequency estimates, the general recommendation is that a gauge station have a minimum of 10 years of record. Gauges with fewer than 10 years of data can be used to develop flow estimates for frequent floods (e.g., Q_2), but they should not be used for higher recurrence interval flood flows.

For flood flow estimates for infrequent events (e.g., 25- to 100-year floods) at a gauged site, use the guidelines in Bulletin 17b (Interagency Advisory Committee on Water Data, 1982 http://www.floodmaps.fema.gov/pdfarchive/dl_flow.pdf). The bulletin suggests using the Log-Pearson type III flood-frequency distribution. The required three parameters for this distribution are the mean, standard deviation, and skew of the logarithms of the annual series of peak streamflows. To determine the values of the parameters, follow the guidelines in the bulletin. In addition to Bulletin 17b, other useful references for flood-frequency analysis include McCuen (2003), Chow et al. (1988), and Linsley et al. (1982).

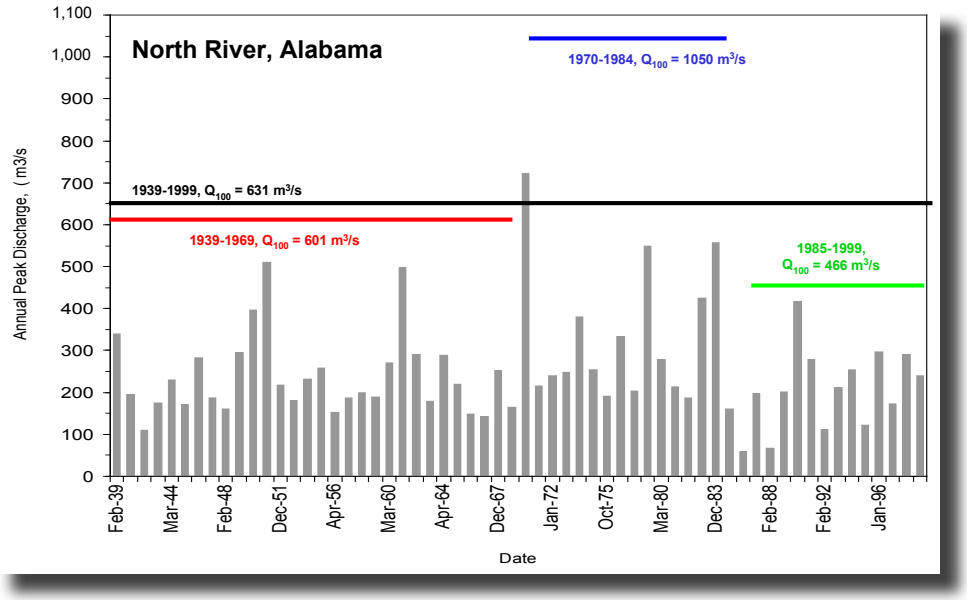


Figure D.2—Variation in peak discharge estimates over different periods of record.

To facilitate flood-frequency analysis using the methods recommended in Bulletin 17b, you can download computer programs from private vendors or the USGS. The USGS program is called PEAKFQ; the most current version (4.1) is a DOS version, last updated in February 2002. You can download the program and user guide at http://water.usgs.gov/software/surface_water.html.

As part of the NFF Program, the USGS has completed flood-frequency analyses for most of their gauges with adequate data. The NFF Web site (http://water.usgs.gov/software/nff.html) has the information for each State, summarizing estimated discharges for a range of flood frequencies. Be aware of the date on which the summary was last updated; it may not include the most recent years of data.

D.2.1.1 Weighted flood frequency

Because a gauging station's period of record is limited, computed flood-frequency values may contain some bias. The period of record for the station may or may not include years when large floods occurred (see figure D.2). Flood-frequency values calculated from a record that includes several large floods will be very different from one that happens to lack any large floods. To improve the reliability of the estimate—especially for gauges with short periods of record—you can weight the flow computed from streamflow data (Q_G) for a specific recurrence interval (RI) with the

same RI flow computed from regression equations (Q_R). The weighting is based on the number of years of record for the gauging station and the equivalent period of record for the regression equation (see equation D.1). The equivalent period of record for the regression equation is the number of years of actual gauge record that would be required for producing the same accuracy as the equation. Hardison (1971) describes the calculations involved in estimating an equivalent number of years of record. For many States, equivalent years of record for regional regression equations are displayed on the NFF Web site.

To obtain a weighted flood frequency for a gauging station, multiply the flow estimate for the station by the years of record at the station (N), and multiply the flow computed from the appropriate regional regression equation by the equivalent years of record (N_E). Add the two values and divide by the sum of the years of record to obtain a weighted flood frequency for the stream at the gauging station (Stuckey and Reed 2000). Weighting of flood frequency records using the following equation is also discussed in detail by Cooper (2002) and Wiley et al. (2000).

Equation D.1

$$Q_W = (Q_G \times N + Q_R \times N_E) / (N + N_E)$$

where:

Q_W = Weighted discharge for a return interval of T-years.

Q_G = T-year discharge computed from measured streamflow data.

Q_R = T-year discharge computed from regional regression equations.

N = Number of years of record at the gauging station.

N_E = Equivalent years of record for regional regression equations.

D.2.2 Design-flow Estimates Near Gauged Sites

Flood frequency estimates at gauged sites must be in hand before you can estimate flood flows at ungauged sites.

D.2.2.1 Ungauged site on a gauged stream

If a project site is on the same stream as a gauge, you can calculate peak discharges at the ungauged site by weighting the gauge data by a ratio of drainage areas (e.g., Thomas et al. 1993; Sumioka 1997) as follows:

Equation D.2

$$Q_{(ungauged)} = Q_{(gauged)} (A_{ungauged} / A_{gauged})^x$$

where:

Q = Discharge.

A = Basin area at gauge site and project site.

x = Slope exponent of the curve (power function) relating Q to A for suitable gauges in the **hydro-physiographic province**.

The slope exponent (*x*) accounts for the difference between the ways in which larger basins and smaller basins react to precipitation. Larger basins usually have smaller peak discharges per unit area than smaller basins, because of differences in the amount of water storage (in ponds and soils), time of concentration, and spatial differences in precipitation during a storm. The exponent *x* is approximately the same value as the average exponent on basin area in the regional regression equation for that flood region.

If necessary, you can directly determine the value of the exponent for any subset of gauges simply by plotting the flow estimates from flood-frequency analysis for a given recurrence interval (dependent variable) against drainage area (independent variable), and fitting a power function through the data (figure D.3). You can then average the drainage area exponents determined from this regression for several RI flows, to produce a single exponent for each flood region. However, you do not usually have to do this analysis, because the slope exponent is often reported by flood region in the USGS publications for individual States (see NFF Web site).

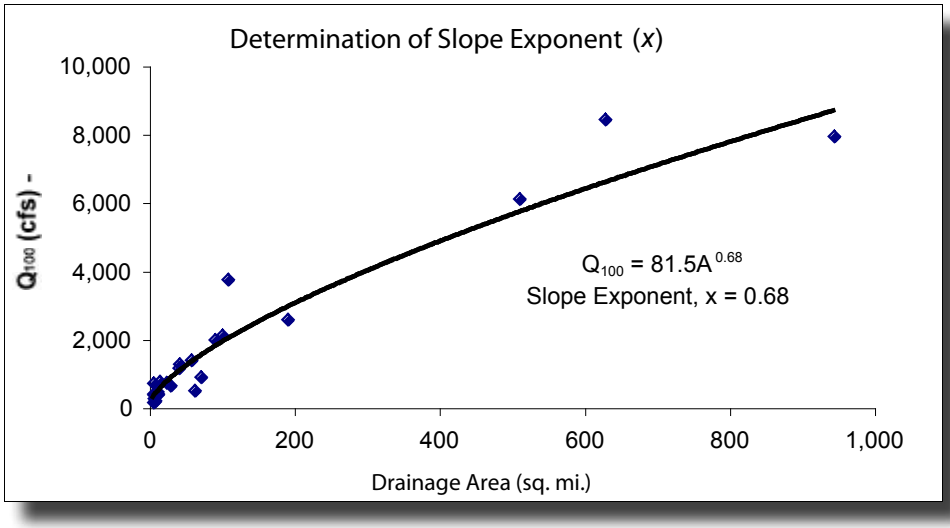


Figure D.3—Typical example of the relationship of drainage area to flow of a specific recurrence interval (or exceedence probability), for determining the exponent (x) in equation D.2.

Equation D.2 is valid as long as the drainage area of the ungauged site is between 0.5 and 1.5 times the area of the gauged site and the watersheds have similar characteristics. If the watersheds differ appreciably in topography, vegetative cover, geology, etc., make the peak discharge estimates using appropriate regional regression equations.

Some investigators (e.g., Wiley et al. 2000; Stuckey and Reed 2000) recommend a different method of transferring gauged data to an ungauged site. This method uses a linear correction factor for the difference in drainage areas between the gauged and ungauged sites (equation D.3).

Equation D.3

$$C_u = C_g - [2(|A_g - A_u|)/ A_g](C_g - 1)$$

where:

C_u = Correction factor for the ungauged site.

C_g = Weighted flow for the gauged site (Q_w from equation 1) divided by the regional regression estimate of the flow for the gauged site (Q_R).

A_g = Drainage area at the streamflow gauge.

A_u = Drainage area at the ungauged site.

The flow estimate for the ungauged site is determined by multiplying the correction factor for the ungauged site (C_u) by the regional regression estimate for the ungauged site. Decide which transfer method (equation 2 or 3) to use, given the recommendations in the applicable USGS **flood frequency analysis** documentation within the NFF program (FEMA 1995).

D.2.2.2 Ungauged site near a gauged stream

If the project site is near a gauge—even if the project site is not in the same watershed—you can often use the gauge data to estimate design flows. The methodology is the same as that presented in section D.2.2.1. When extrapolating the data from a specific gauged site to a site in a nearby watershed, the two sites must have similar:

- Precipitation.
- Drainage area and shape.
- Orographic expression.
- Aspect.
- Vegetation.
- Lithology/geology.

Again, when you transfer gauge data to an ungauged site, the basin area should be within 0.5 to 1.5 times that of the gauged site. The accuracy and validity of the flow estimates are directly tied to the similarity of watershed characteristics between the gauged and ungauged sites. As the differences between the watersheds increase, be more cautious in using this technique. Be familiar with the gauged site and recognize the hydrologic influence of lakes, water diversions, **regulated rivers**, or dams. In addition, be cautious when using gauges on **losing streams** in arid areas, in **karst** terrain, or in areas with evident regional ground water contributions to streamflow. Extrapolation in these situations can produce invalid results.

D.2.3 Flow Estimates on Ungauged Streams

You can also estimate peak stream flows for an ungauged watershed from equations that relate peak flows to climatologic and physical characteristics of the watershed (Thomas and Benson 1969; Riggs 1973). The equations are derived using multiple linear regression techniques. This generalization or regionalization of peak discharges from measured to unmeasured watersheds is known as “regional regression analysis.” Defining regions of relatively consistent geography, geology, and hydrology improves the accuracy of regional regression equations. States have different numbers

of equations, depending on the number of flood regions they have defined. For example, the State of Colorado has a different set of regional regression equations for each of five different flood regions; New Mexico has eight flood regions, and Maine has one.

For most States, the USGS has completed regional regression analyses and developed predictive equations. First, gauge-site peak discharges corresponding to a suite of recurrence intervals are computed using the flood-frequency analysis techniques discussed previously. These peak flows are then used as dependent variables in a multiple regression analysis against independent variables such as drainage area, mean basin elevation, mean maximum January air temperature, area of lakes and ponds, etc. Although the list of independent variables is extensive, only a small subset correlates well enough with peak flows to be used in predictive equations. Drainage area and some measure of precipitation are commonly the most important variables. The form of the regional regression equations takes the general form:

Equation D.4

$$Q = b_0 + b_1x_1 + b_2x_2 + \ldots.. + b_mx_m$$

Where Q represents the predicted streamflow for a selected recurrence interval and $x_1, x_2, \ldots, x_m$ represent the m watershed characteristics used as predictive variables. The regression coefficients $b_1, b_2, \ldots, b_m$ define the relationship among variables and are determined from the measured data in the flood region.

Published regression equations typically provide some measure of their accuracy. The standard errors of prediction typically range between 30 and 60 percent, although some exceed a standard error of 100 percent. An example of predictions using regional regression equations from Oregon (figure D.4) shows the range of potential error included within 95-percent prediction limits.

All of the published regional regression equations have limitations. First, they should only be applied where basin characteristics are within the limits of those used for developing the equations. For example, if regional regression equations were developed from gauges with drainage areas between 10 and 100 square miles, the accuracy of those equations is suspect for a site with a 5-square-mile drainage area.

A second limitation is that the names of the independent variables within the regional regression equations do not necessarily convey the method by which they should be quantified. For example, watershed slope can be characterized in a variety of ways. Carefully read the supporting documentation for the equations to fully understand the methodology in which the predictor variables are determined.

Third, regressions may not be applicable in areas with unique geo-hydrologic features affecting floods, such as seeps or springs that contribute large parts of streamflow or areas with extremely high soil permeability (Omang 1992).

Fourth, be aware that urbanization, roads, timber harvest, streamflow diversions, or other land use changes will affect water yield and can thus have an influence on calculated design flows.

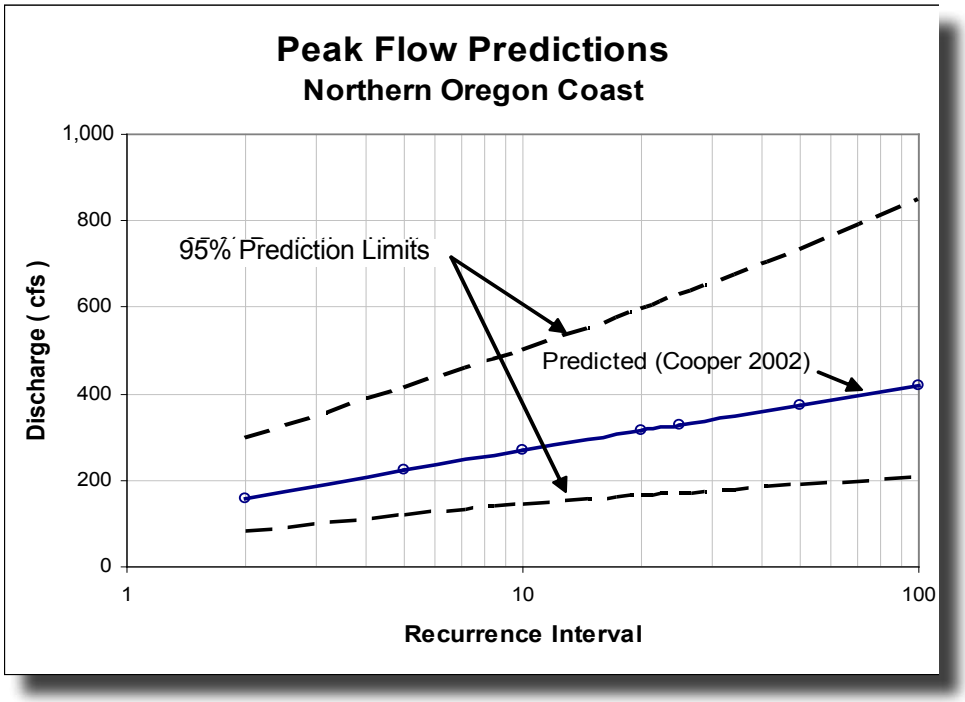


Figure D.4—Example of prediction errors associated with regional regression equations.

D.3 VERIFYING FLOW ESTIMATES AT UNGAUGED STREAMS

Given the potential errors in estimating flows at ungauged sites, using field data to check flow estimates can greatly enhance their credibility. Keep in mind that the accuracy-checking methods described here are likely to allow detection only of gross errors.

One method of verifying flood-flow predictions at ungauged sites is to compare the predictions to real flows that were observed or that left evidence on the landscape from which to calculate flow. Information about flood frequency and water-surface elevations can come from querying long-time residents and/or identifying historic flood markers in the field. Knowing the flood elevation and the morphology of the stream **reach**, you can use a hydraulic model to route a calculated flood flow (e.g., Q_{100}) through the stream reach. Compare the modeled water-surface elevation for the predicted flow to observed or field-identified flood levels to get an idea of whether your estimate is reasonable. Although you rarely know exactly what recurrence interval the historic flood was, news accounts or anecdotal information from residents often offer some indication of how unusual the flood was. You also can compare the modeled water-surface elevation to a geomorphic feature, such as a **terrace**, for which you can identify an approximate frequency of flooding. This check helps verify that the predictions are at the right order of magnitude so long as watershed changes (dam building, development of impervious areas, etc.) have not altered flow frequencies from those observed in the past.

The routing analysis requires a measured cross section (or series of cross sections) and stream gradient at the site, along with some estimate of **flow resistance** in the channel and on the **flood plain**. You can perform hydraulic routing using Manning's or other equations (see Hardy et al. 2005) in uniform reaches or, for reaches where gradient or cross-sectional characteristics are changing, with **backwater** analysis programs such as HEC-RAS.

Accurately determining flow resistance (typically the Manning's **roughness** coefficient, n) is a key element in hydraulic modeling aimed at verifying predicted flows. A number of publications are available for estimating channel roughness from photos (Barnes 1967) or descriptive tables (Chow 1959). Equations exist for estimating n from physical channel characteristics such as slope and sediment size distribution (e.g.,

Bathurst 1985; Jarrett 1985). Other methods use a combination of photos and physical channel characteristics (Hicks and Mason 1998). A USGS publication also is available to estimate roughness characteristics of flood plains from photographs and site descriptions (Arcement and Schneider 1989). Although these methods can give good estimates of channel roughness, the preferred method is to perform discharge measurements at high flows, then use Manning's equation to back-calculate the actual roughness.

The most direct way of verifying the validity of calculated design flows is to check their reasonableness against measured values at nearby gauges (if they exist). Before doing so, check that the conditions affecting flow at the nearby gauge(s) (e.g., watershed characteristics and stream type) are similar to those at the project site. As a starting point, develop unit runoff relations at the local gauges: divide the flow for a given RI at the gauge by drainage area at the gauge to arrive at a discharge per unit area (i.e., cubic feet per second per square mile). These normalized values can provide a rough check on the magnitude of estimates made with regional regression equations at the project site.

Bankfull is the flow we can most confidently estimate from field observations alone, and when the field data confirms the bankfull discharge value estimated using regional regression equations or other indirect methods, we have more confidence in estimates of larger floods made using the same methods. (Depending on the region of the country, bankfull discharge at gauging stations often corresponds to a recurrence interval between 1 and 2 years.) At the project site, estimate bankfull discharge directly from a regional regression equation, if one is available for such a frequent flood. Alternatively, make a plot of discharge vs. RI (figure D.4), and extrapolate the curve to arrive at a flow estimate with the same recurrence interval as bankfull discharge. Then, route this estimate of bankfull flow through a representative cross section, using WinXSPRO (Hardy et al. 2005) or another hydraulic model, and check how well the calculated water surface matches the field-identified bankfull indicators. If the calculated discharge corresponds to a water-surface elevation significantly different from the bankfull indicators, adjustments in the calculated flood estimates may be necessary. On the other hand, if the calculated discharge is a reasonable representation of the bankfull **stage**, this suggests, although it doesn't guarantee, that flood predictions of higher recurrence intervals are reasonable. We recommend confirming the accuracy of higher recurrence interval floods using other methods such as those described above.

Another way of checking on the reasonableness of an estimated flow is to check the Froude number (F) for that flow. The Froude number is a measure of whether flow is subcritical, critical, or supercritical. It is a ratio of inertial forces to gravitational forces and is calculated as follows:

Equation D.5

$$Fr = V/\sqrt{gD}$$

where:

Fr = Froude Number	V = Average velocity = Q/A
g = Gravitational acceleration	D = Hydraulic mean depth = A/T
A = Cross-sectional area	T = Top width of water

If:

Fr < 1 the **flow regime** is subcritical.

Fr = 1 the flow regime is critical.

Fr > 1 the flow regime is supercritical.

Flows in natural channels are rarely critical or supercritical, so determining the Froude number for a calculated flood discharge at the project site may indicate whether problems with the estimate exist. For example, if the Froude number is greater than 1 for the calculated flood flow at the project site, this may indicate that the flow estimate is too high. Be sure to check the Froude number at local gauged sites. If the stream type is unusual (say, a bedrock channel), or the flow is extremely high, the high Froude number may be real.