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Channel-Forming Discharge

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PURPOSE: The purpose of this Technical Note is to provide guidance and cautions to be used in approximating channel-forming discharge with bankfull, specified recurrence interval, and effective discharge methodologies. There are limitations for each of these three methods that the user must recognize.

INTRODUCTION: An alluvial river adjusts the dimensions of its channel to the wide range of flows that mobilize its boundary sediments. For many rivers and streams, it has been observed that a single representative discharge may be used to determine a stable channel geometry. The use of a single representative discharge is the foundation of "regime" and "hydraulic geometry" theories for determining morphological characteristics of alluvial channels. This representative channel-forming (dominant) discharge has been given several names by different researchers, including bankfull, specified recurrence interval, and effective discharge. This has led to confusion with both terminology and understanding of fundamental stream processes.

In this Technical Note the channel-forming (dominant) discharge is defined as a theoretical discharge that if maintained indefinitely would produce the same channel geometry as the natural long-term hydrograph. Channel-forming discharge concepts are applicable to stable alluvial streams (i.e., streams that have the ability to change their shape and are neither aggrading nor degrading). For channels in arid environments where runoff is generated by localized high-intensity storms and the absence of vegetation ensures that the channel will adjust to each major flood event, the channel-forming discharge concept is generally not applicable.

Channel-forming discharge can be estimated in stable alluvial streams using one of three prescribed methodologies. One such deterministic discharge is the bank-full discharge, which is most commonly defined as the maximum discharge that the channel can convey without flowing onto its floodplain. Another deterministic discharge used to represent the channel-forming discharge is a specified recurrence interval discharge, typically between the mean annual and five-year peak. The third deterministic discharge is the effective discharge, which is defined as the discharge that transports the largest fraction of the average annual bed-material load. These three discharges are considered deterministic, not theoretical, because their values can be determined from calculations following a designated procedure. None of these three deterministic discharges should be assumed to be the channel-forming discharge a priori without confirmation using field indicators of geomorphic significance. Limitations of each of these methods must be considered by the user. The selection of the appropriate method will be based on data availability, physical characteristics of the site, level of study, and time and funding constraints. If possible, it is recommended that all three methods be used and cross-checked against each other to reduce the uncertainty in the final estimate.

BANK-FULL DISCHARGE: Bank-full discharge is the maximum discharge that the channel can convey without overflowing onto the floodplain. This discharge is considered to have morphological significance because it represents the breakpoint between the processes of channel formation and floodplain formation.

Bank-full discharge is determined first by identifying bank-full stage and then determining the discharge associated with that stage. Identifying the relevant field features that define the bank-full stage can be problematic. Many field indicators have been proposed, but none appear to be generally applicable or free from subjectivity (Williams 1978). The most common definition of bank-full stage is the elevation of the active floodplain (Wolman and Leopold 1957 and Nixon 1959). Another common definition of bank-full stage is the elevation where the width to depth ratio is a minimum (Wolman 1955; Pickup and Warner 1976). This definition, diagramed in Figure 1, is systematic and relies only on accurate field surveys. In some cases the highest elevation of channel bars may be used as an indicator of bank-full stage (Wolman and Leopold 1957). Woodyer (1968) defines the bank-full stage of rivers having several overflow surfaces as the elevation of the middle bench. Wolman (1955) combines the width to depth ratio criterion with identifying a discontinuity in the channel boundary such as a change in its sedimentary or vegetative characteristics. Schumm (1960) defined bank-full stage as the height of the lower limit of perennial vegetation, primarily trees. Similarly, Leopold (1994) states that bank-full stage is indicated by a change in vegetation, such as herbs, grasses, and shrubs. Given the number of criteria in common use to define bank-full stage and the considerable experience required to apply them, it is not surprising that there can be wide variability in field determination of bank-full stage.

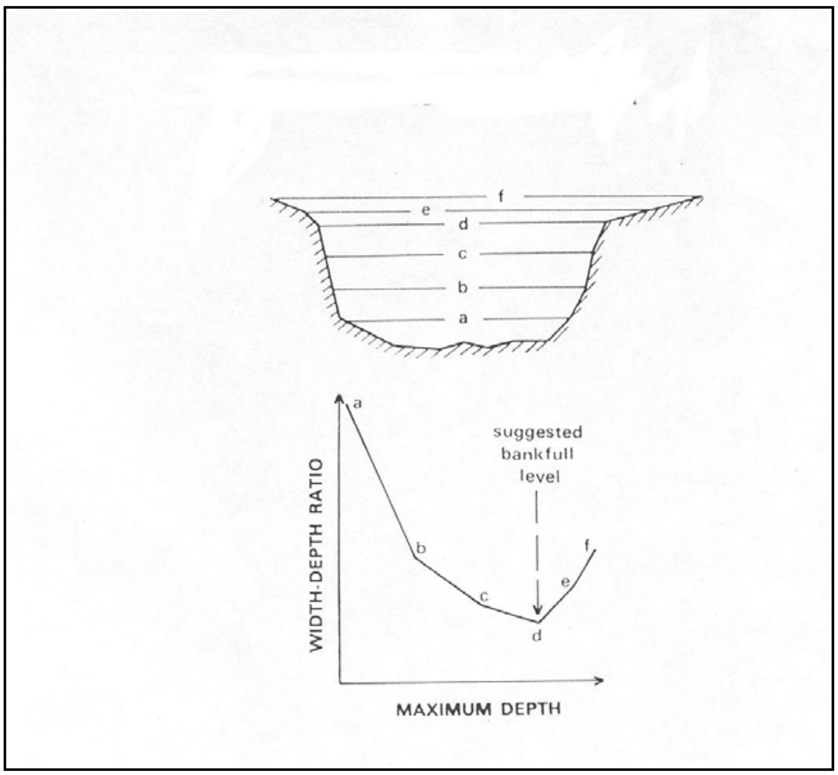

Figure 1. Bank-full depth using width-depth ratio (after Knighton 1984)
(To convert feet to meters, multiply by 0.3048)

The field identification of bank-full indicators is often difficult and subjective and should only be preformed in stream reaches that are stable and alluvial (Knighton 1984). The stream reach should be identified as stable and alluvial before field personnel attempt to identify bank-full stage indicators. If the project reach is unstable (or non-alluvial), it may be possible to find indicators of bank-full stage in stable alluvial reaches upstream or downstream on the same stream. The process of identifying bank-full indicators is often an iterative process that involves a great deal of judgement.

If a reach is not stable and alluvial, indicators of bank-full stage will be unreliable. Some examples are given below:

a. If a reach is non-alluvial, then sediment transport capacity normally exceeds sediment supply, and deposits would be missing or underdeveloped. Using underdeveloped deposits as bank-full indicators would result in too low a channel-forming discharge. Deposits could also be relics of extreme flood events, in which case they would normally give too high a channel-forming discharge.

b. If the channel is degrading, then sediment transport capacity exceeds sediment supply, and the observations above for the non-alluvial channel hold true. In addition, since the bed of the channel is lowering, former floodplain deposits are being abandoned (they are in the process of becoming terraces). Using these features as indicators would give too high a channel-forming discharge.

c. If the channel is aggrading, the in-channel deposits could be incorrectly mistaken for bank-full stage indicators. Since the bed of the stream is rising, using the existing floodplain as an indicator would give too low a discharge. (The floodplain will aggrade as well, but usually at a slower rate than the channel.)

Confusion often occurs when criteria suggest a bank-full stage at an elevation that is not close to the top of either bank. This condition suggests that the channel may not be in equilibrium, that the existing channel geometry may not be stable, and that the channel-forming discharge would be poorly approximated by the bank-full discharge. Since stream restoration is most often practiced in unstable channels and watersheds (instability is often the reason for restoration), field determination of bank-full stage may be impractical or impossible. In fact attempting to determine a channel-forming discharge from an unstable stream is in conflict with the theoretical premise that is the basis for the channel-forming discharge concept.

Once bank-full stages are estimated for a reach of the stream, then bank-full discharge can be estimated. Ideally, the discharge associated with bank-full stage can be determined from a stage-discharge rating curve based on measured data at the project site. When floodplain conveyance is significant with respect to channel conveyance, there will be a distinct break in the stage-discharge rating curve at bank-full stage as shown in Figure 2. The data scatter in Figure 2 occurs because stage is not a unique function of discharge in alluvial streams. It is therefore necessary to estimate a rating curve through the data scatter. It is best to consider that the bank-full discharge will have a range rather than a single discrete value. Uncertainty associated with the stage-discharge relationship is addressed in EM 1110-2-1619 (USAEHQ 1996). In cases

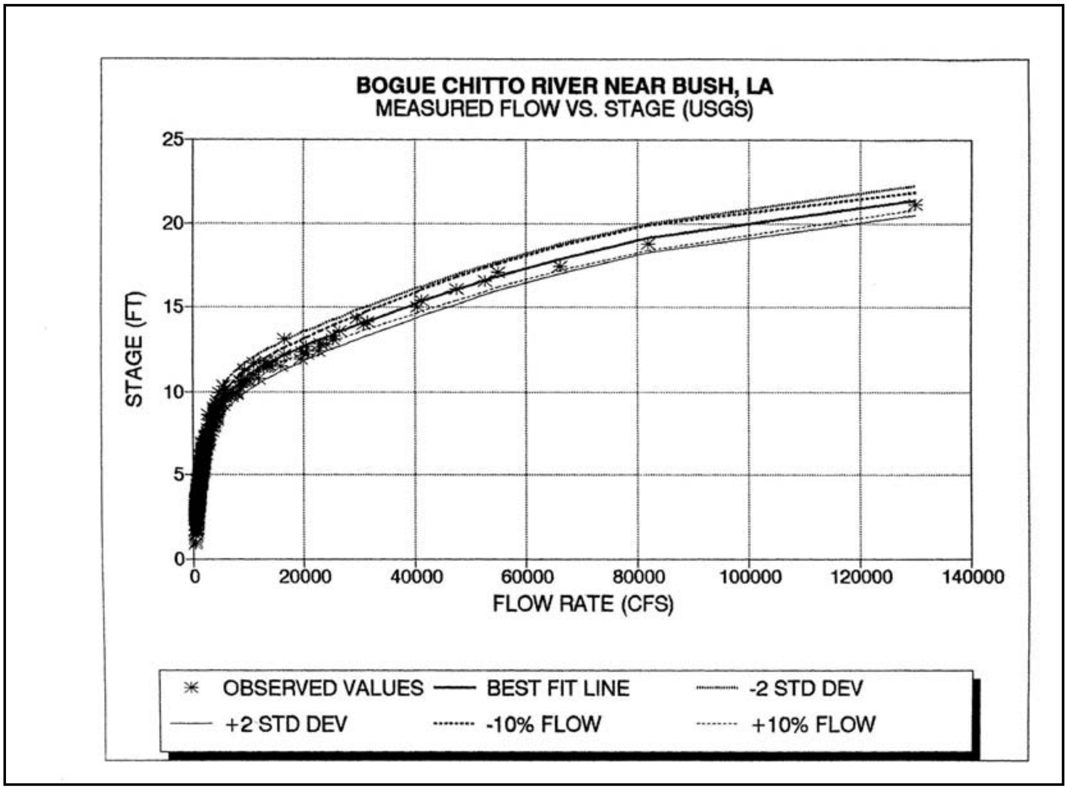

Figure 2. Stage-discharge rating curve Bogue Chitto River near Bush, LA (To convert feet to meters, multiply by 0.3048. To convert cubic feet per second to cubic meters per second, multiply by 0.02831685)

where floodplain conveyance is not significant with respect to channel conveyance, there may not be a distinct break in the stage-discharge rating curve (Figure 3). In this case the bank-full discharge may not have as much morphological significance as when floodplain flow is significant. Lacking gage data at the project site, a stage-discharge rating curve can be determined from a backwater analysis. Ideally, the downstream starting water-surface elevation will be based on data from a gaging station. The accuracy of this rating curve will depend on the uncertainties associated with assigned hydraulic roughness coefficients and the cross-section geometry. Uncertainty is greatest when the stage-discharge rating curve is estimated from a single cross section. In this case both hydraulic roughness and energy slope must be assigned. It is best if the determination of bank-full stage occurs over a reach of at least one wavelength or 10 channel widths. An example of a comparison of bank-full stage and a computed water-surface elevation is shown in Figure 4. Note in Figure 4 that bank-full stage is taken to be at the bottom of the top-of-bank data scatter because this represents the elevation that flow onto the floodplain begins. Also note that considerable variability in bank-full stage could be estimated if only a single top-of-bank point were used in the analysis. The hydraulic engineer determines what method is best suited to compute the bank-full discharge from the bank-full stage indicators. For example, backwater computations may be required in some cases, while normal depth computations will be sufficient in others.

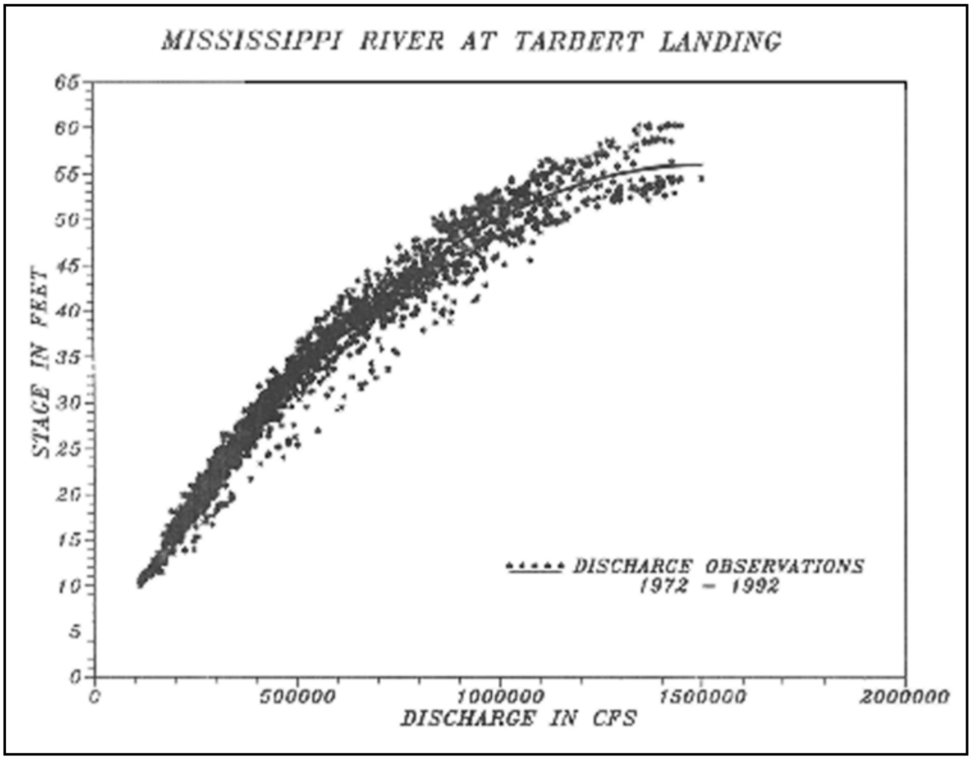

Figure 3. Stage-discharge rating curve Mississippi River at Tarbert Landing, MS (To convert feet to meters, multiply by 0.3048. To convert cubic feet per second, multiply by 0.02831685)

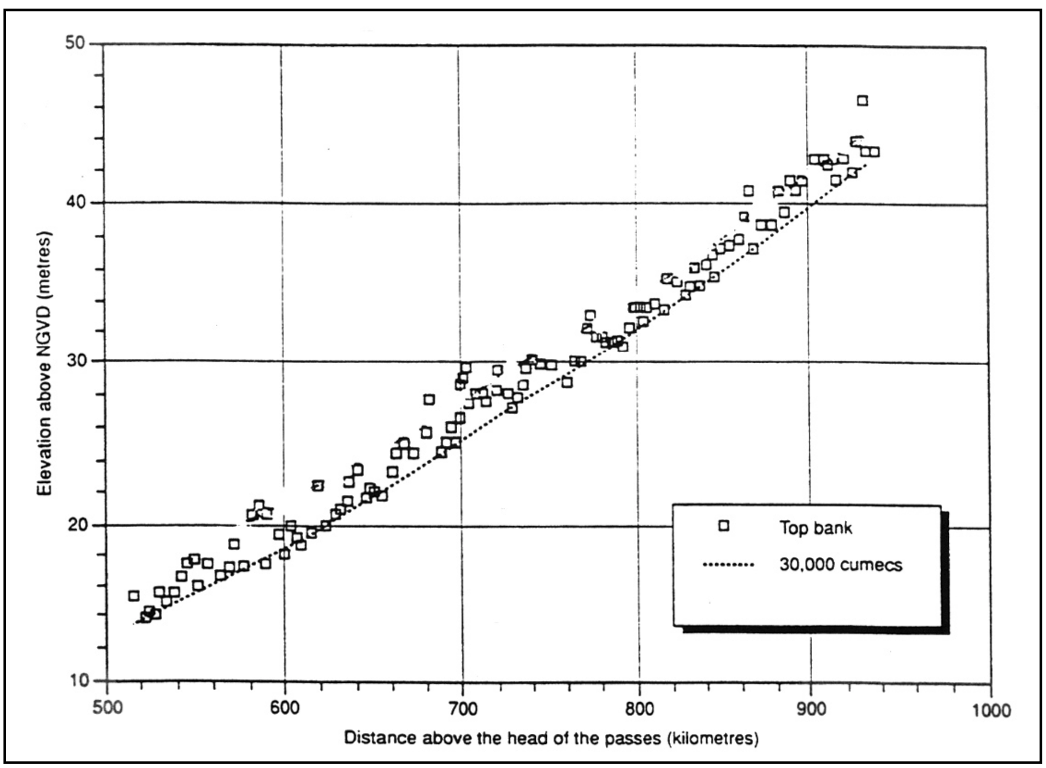

Figure 4. Long-channel variation in bank top elevations: Lower Mississippi River (Biedenharn and Thorne 1994)

The following guidelines are provided relative to field determination of bank-full discharge and use of bank-full discharge as the channel-forming discharge:

a. Bank-full discharge is geomorphologically significant only in stable alluvial channels. Therefore, the reach where bank-full stages are determined should be stable and the streambed should be mobile at bank-full flow.

b. When the bank-full discharge is to be used to determine channel dimensions for the main channel, the field indicators used for the identification of the bank-full stage must be top-of-bank indicators. A stage identified by the edge of the active channel, the beginning of woody vegetation, or the top of channel bars may have value for designing those particular features in a restored channel, but should not be used for establishing the bank height of a stable channel. Only bank-full discharges, which are top-of-bank discharges, are morphologically significant in establishing the channel-forming discharge.

c. An exception to the above rule is in a stable and alluvial incised stream that has formed a new floodplain within the incised channel. In this case, the top of the high bank is now an abandoned floodplain or terrace, and there should be newly formed top-of-bank features within the older incised channel. However, it is important to remember that the new floodplain may not yet be fully formed, that is, the channel may not be stable (it may still be aggrading). This would give misleading values for the bank-full discharge.

d. Assuming that the bank-full discharge for one reach of a stream is the same as the bank-full discharge in another reach may not be appropriate. The location of the break between the channel and the floodplain is influenced by many factors, including (but not limited to) the following:

(1) Confinement of the floodplain.

(2) Hydrologic regime.

(3) Sediment supply.

(4) Bed and bank sediment size and cohesiveness.

(5) Size and type of vegetation on the floodplain and within the channel.

(6) Controls on channel width, slope and alignment.

For example, the bank-full discharge taken from a reach with a narrow floodplain may be inappropriate for use on another reach on the same stream, which has a wide floodplain.

SPECIFIED RECURRENCE INTERVAL DISCHARGE: Due to difficulties in the identification of bank-full discharge and stage, many researchers have related the channel-forming discharge to a specific recurrence interval discharge. In these studies the researchers have typically studied stable streams where bank-full stage could readily be determined and where stream gages were located nearby. Under these conditions, bank-full discharge is assumed to be the channel-forming discharge, and most of the literature addressing specified return interval discharge use the two terms interchangeably. This can be confusing as studies are actually comparing two methods for approximating the channel-forming discharge, and not actually comparing an approximation method to the true value

In general, bank-full discharge in stable channels has been found to correspond to an annual flood recurrence interval of approximately 1 to 2.5 years and the 1.5-year recurrence flood has been shown to be a representative mean of many streams (Leopold 1994). However, there are many instances where the channel-forming discharge does not fall within the 1 to 2.5 year range. Recurrence interval relations are intrinsically different for channels with flashy hydrology than for those with less variable flows. For instance, Williams (1978) clearly showed that out of 35 floodplains he studied in the United States, the bank-full discharge varied between the 1.01- and 32-year recurrence interval, and that only about a third of those streams had a bank-full discharge recurrence interval between one and five years. In a similar study, Pickup and Warner (1976) determined that bank-full recurrence intervals ranged from 4 to 10 years. Because of such discrepancies, many have concluded that recurrence interval approaches tend to generate poor estimates of bank-full discharge. Hence, field verification is recommended to insure that the selected discharge reflects morphologically significant features.

EFFECTIVE DISCHARGE: Effective discharge is defined as the mean of the discharge increment that transports the largest fraction of the annual sediment load over a period of years (Andrews 1980). The effective discharge incorporates the principle prescribed by Wolman and Miller (1960) that the channel-forming discharge is a function of both the magnitude of the event and its frequency of occurrence. It is calculated by integrating the flow-duration curve and a bed-material-sediment rating curve. A graphical representation of the relationship between sediment transport, frequency of the transport, and the effective discharge is shown in Figure 5. The peak of curve C from Figure 5 marks the discharge, which is most effective in transporting sediment, and therefore it is hypothesized that it does the most work in forming the channel.

Effective and bank-full discharges are not always equivalent as reported by Benson and Thomas (1966), Pickup and Warner (1976), Webb and Walling (1982), Nolan, Lyle, and Kelsy (1987), and Lyons, Pucherelli, and Clark (1992). This suggests that the effective discharge may not always be an adequate surrogate for the channel-forming discharge.

The recommended procedure to determine the effective discharge is further discussed in a Technical Report by Biedenharn et al. (in preparation), and summarized in a Technical Note by Biedenharn and Copeland (in preparation).

CHANNEL-FORMING DISCHARGE RELATED TO DRAINAGE AREA: Use of regional regression curves for determining channel-forming discharge as a sole function of the drainage area is not recommended, as drainage area is only one of many parameters affecting runoff. However, within physiographically similar watersheds, it may be useful to develop a channel-forming discharge versus drainage area curve for use in that watershed. Emmett (1975)

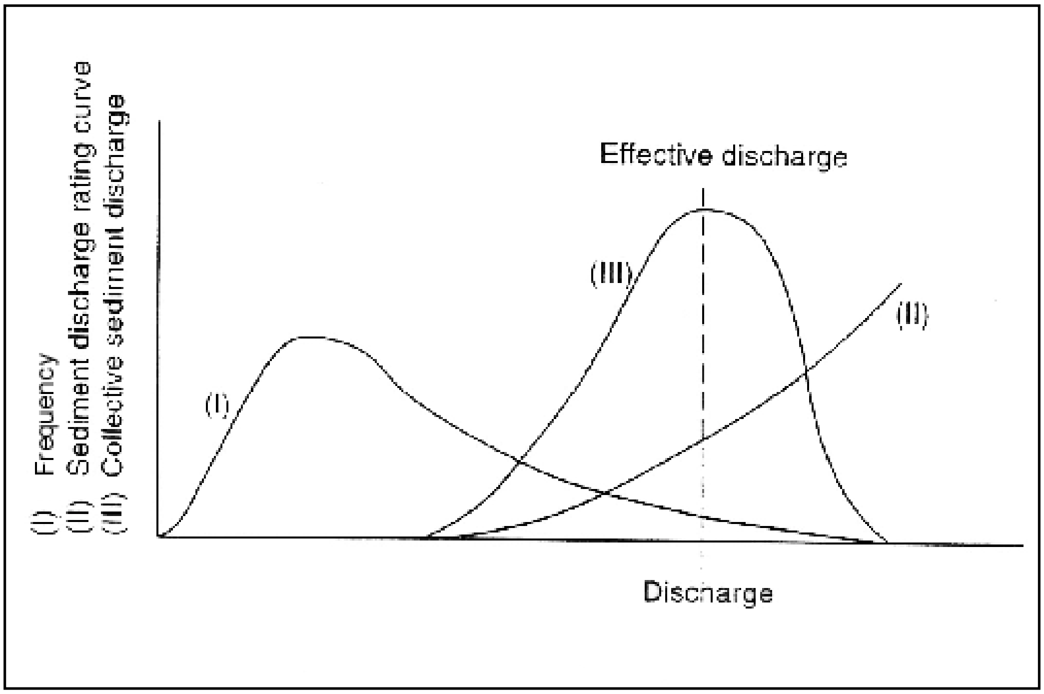

Figure 5. Derivation of total sediment load-discharge histogram (III) from flow frequency (I) and sediment load rating curves (II)

developed such a curve for the Salmon River in Idaho (Figure 6). Emmett (1975) chose stable channel reaches for his study and assumed that bank-full discharge was equivalent to channel-forming discharge. Although the regression line fits the data in a visually satisfactory fashion, it should be noted that for a drainage area of about 80.6 sq km (70 square miles), the bank-full discharge varied between about 8.50 cu m/s (300 cfs) and 25.48 cu m/s (900 cfs). This large range should not necessarily be attributed to errors in field measurements, but rather to the natural variation in bank-full discharge with drainage area.

CONCLUSIONS: Due to the limited scope of many stream restoration projects, hydraulic design has been attempted using only a single representative discharge. Using a representative or channel-forming discharge may be appropriate for determining initial or preliminary design dimensions, but the difficulty in the determination of the channel-forming discharge and the uncertainty related to the concept itself makes its sole use untenable for reliable and effective hydraulic design. However, the concept of channel-forming discharge is useful and has become an accepted part of channel restoration design and therefore methods to calculate this value are required. All three methodologies for estimating the channel-forming discharge present challenges. The selection of the appropriate method will be based on data availability, physical characteristics of the site, level of studs, and time and funding constraints. It is recommended that all three methods be used and crosschecked against each other to reduce the constraints in the final estimate of the channel-forming discharge.

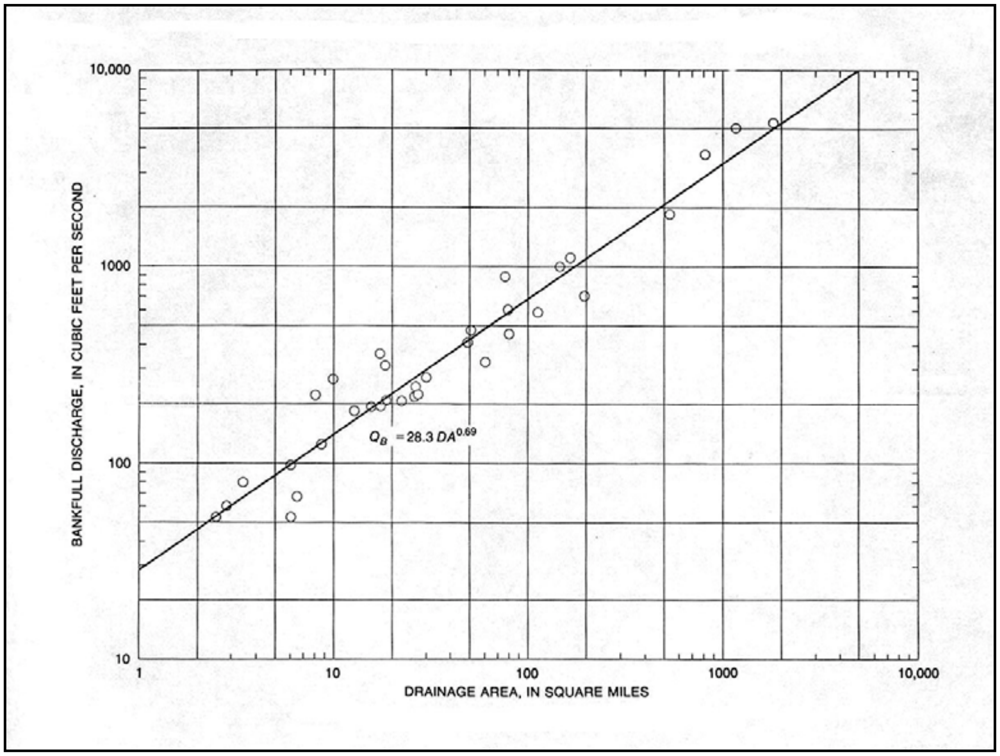

Figure 6. Bank-full discharge as a function of drainage area (To convert to square kilometers, multiply by 2.58. To convert to cubic meters per second, multiply by 0.02831685) (Emmett 1975)

ADDITIONAL INFORMATION: Additional information may be obtained from Dr. R. R. Copeland, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center (ERDC), 3909 Halls Ferry Road, Vicksburg, MS 39180, at 601-634-2623 or e-mail *Ronald.R.Copeland@erdc.usace.army.mil;* Dr. D. S. Biedenharn, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center (ERDC), 3909 Halls Ferry Road, Vicksburg, MS 39180, at 601-634-4653 or e-mail *David.S.Biedenharn@erdc.usace.army.mil;* or Dr. C. J. Fischenich, Environmental Laboratory, U.S. Army Engineer Research and Development Center (ERDC), 3909 Halls Ferry Road, Vicksburg, MS 39180, at 601-634-3449 or e-mail *Craig.J.Fischenich@erdc.usace.army.mil.*

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