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Hydrologic Analyses for Stream Restoration Design

by J. Craig Fischenich and S. Kyle McKay

OVERVIEW: Streamflow is the dominant physical process affecting the structure and composition of aquatic communities in fluvial ecosystems. These communities depend upon the source, timing, duration, frequency, and rate of change of streamflow to regulate habitat conditions and disturbance regimes (Figure 1). The Environmental Advisory Board for the Chief, U.S. Army Corps of Engineers (EAB 2006) summarized the prevailing argument among the scientific community as follows: planners should focus on hydrologic and geomorphic factors when evaluating ecosystem restoration (e.g., the magnitude and duration of peak annual discharges, duration of low flow conditions, timing of bankfull discharge events, connectivity to floodplain habitat, substrate composition, stream velocities, depth distribution, etc.).

Figure 1. Aquatic organisms are dependent upon the hydrologic character of streams. Access to side channel habitat such as this can be critical for spawning, rearing, and refuge for many different organisms, and is entirely dependent upon hydrologic conditions.

Engineers compute many of the above hydrologic parameters for analysis and design of conventional water resources as well as for restoration projects. Planners can and should take advantage of these analyses to support their efforts for ecosystem restoration projects. Guidance on the computation of the more common hydrologic parameters is provided in this technical note. An understanding of the hydrologic conditions and the changes therein over time is essential for problem identification. This generally occurs in conjunction with the development of a conceptual model for the project (Fischenich 2008). Hydrologic parameters can serve directly as metrics for evaluating project alternatives, or they can be used as the basis for habitat, population, or other models used for benefits analysis. Hydrologic parameters are also inevitably used in evaluating project success and for determining the need for adaptive management actions.

INTRODUCTION: Characterizing stream and basin hydrology has been identified as perhaps the most integrating and easily quantified element in stream restoration, working across and governing multiple disciplines and system functions (Palmer and Bernhardt 2006; Fischenich 2006). Knowledge of the hydrologic character of a system allows for hydraulic and sediment transport properties to be computed, ecological implications to be assessed, flows of nutrients and chemicals to be evaluated, channel stability assessments to be conducted, and management decisions to be made (Federal Interagency Stream Restoration Working Group (FISRWG) 1998).

Figure 2. Field measurement of hydrologic parameter (streamflow).

The purpose of these investigations is to develop a sufficient understanding of the hydrology of the system to allow the formulation of designs that meet project objectives while reducing risk and uncertainty to acceptable levels. Project objectives as well as allowable risk and uncertainty vary, so the needed analyses can be expected to vary as well. Availability of data, funding level, and time also influence the analytical requirements for a stream restoration project. Thus, the needed analyses can range from rather cursory qualitative assessments costing a few hundred dollars to detailed numerical and physical modeling efforts costing several million dollars. In general, stream restoration projects lie midway between these extremes, and there exists a common set of tasks that form the basis for developing the needed understanding of the hydrologic character of the stream.

Traditional hydrologic analyses have historically focused on estimating the magnitude and frequency of floods. These analyses are used by engineers and land-use managers in the design of bridges, culverts, dams, and embankments in addition to the assessment of hazards related to the development of floodplains. While these needs exist for most stream restoration projects, several other hydrologic characteristics must be addressed as well. For example, ecologists are concerned about the duration of annual flood pulses or low flow extremes, the timing of those conditions, and the rates at which water levels rise or fall (Poff et al. 1997). Therefore, hydrologic assessment for stream restoration should be extended to estimate the magnitude, frequency, duration, timing, and rate of change of stream discharge. These hydrologic parameters help define the physical, chemical, and biological character of the stream and are typically unique to a specific stream reach. They also form the basis for restoration design procedures. Table 1 summarizes hydrologic parameters that might be of interest. The needs of the specific project will dictate which of the parameters in Table 1 are of import — in most cases the list can be reduced substantially.

Numerous hydrologic analyses may be performed for restoration projects, depending on the nature of the site and the restoration objectives. For nearly all projects, it is helpful to conduct flood frequency analyses, construct a flow duration curve, estimate design discharges, and examine temporal trends within these analyses. Computing these hydrologic characteristics is complicated by difficulties associated with choosing appropriate methodologies, obtaining data with which to calibrate models and verify estimates, and estimating discharges without streamflow data.

Hydrologic Analysis Methodologies. The hydrologic conditions for stream restoration projects should be characterized for existing and future conditions, both with and without projects. If a reference-based approach is to be employed, these analyses should be conducted for both the project and reference system(s). Trend analyses are often needed to evaluate causal mechanisms for degradation and to establish future conditions for designs.

Hydrologic analyses, while often deterministic, are also interpretive and frequently bear high degrees of uncertainty. It is often advisable to use several techniques to assess a particular hydrologic condition, applying reasoned judgment and a weight-of-evidence approach to estimate the condition of interest. Procedures for estimating hydrologic characteristics of streams generally fall into one of three categories: direct measurement, regression relations, and analytical techniques.

Table 1. Sample hydrologic parameters of interest in stream restoration projects.

Category	Parameter	Examples of Potential Use
1. and 2. Magnitude and Frequency	1. 100-yr peak discharge	Floodplain delineation/FEMA requirements
	2. 10, 25, 50-yr peak discharge	Infrastructure impacts
	3. 1.5-yr peak discharge	Estimate of dominant or bankfull discharge
	4. Mean monthly discharge	Hydroperiod for impact assessment and basin comparisons, habitat availability for aquatic and terrestrial animals, soil moisture availability for plants, reliability of water supplies, influence on water quality
	5. Annual 3-day low flow	Creation of sites for plant colonization
	6. Annual 7-day low flow	Aquatic organism stress in cool and cold water systems
	7. Annual 7-day high flow	Soil moisture stress in plants
	8. Annual 30-day low flow	Dehydration in animals, and anaerobic stress in plants
	9. Annual 30-day high flow	Nutrient exchanges between rivers and floodplains, spawning, and riparian vegetation composition
	10. Annual 90-day low flow	Stress from low oxygen and concentrated chemicals in warm water environments
	11. Annual 90-day high flow	Distribution of plant communities in riparian wetlands, and assessment of rearing habitat
	12. Number of zero-flow days annually	Hydrologic state and aquatic organism stress
3. Duration of Daily Discharge	1. Flow duration of mean daily discharge for period of record	Risk associated with high and low flow events, effective discharge computations, assessment of geomorphically significant events
	2. Flow duration of mean daily discharge for select period	Habitat assessments, riparian vegetation community structure, construction risk
	3. Flow duration for 15-minute discharges	Assessment of above for “flashy” systems such as urban streams and steep, narrow watersheds
4. Timing of Annual Extreme Discharge Conditions	1. Date of each annual one-day maximum discharge	Spawning cues for migratory fish, predictability and avoidability of stress for organisms, and access to special habitats
	2. Date of each annual one-day minimum discharge	Compatibility with life cycles of organisms, evolution of life history strategies, and behavioral mechanisms
5. Rates of Change in Hydrograph	1. Mean increase between consecutive daily values	Entrapment of organisms on islands or floodplains; spawning signal
	2. Mean decrease between consecutive daily values	Drought stress on plants, desiccation stress on low-mobility stream edge organisms

After The Nature Conservancy (TNC) (2007).

Direct measurement of hydrologic parameters for a particular project is not common. Precipitation estimates for most areas in the United States are reasonably well-established, so there is little benefit in establishing a rain gage network in most circumstances. Stream gauging can be useful for verifying stage-discharge estimates, but developing a full stage-discharge relation requires more time and expense than is available for a typical restoration project. Fortunately, analytical procedures and existing data can usually be employed to establish these relations.

Regression relations are statistical algorithms that present associations among various observable quantities. Regression relations can be and are used in a variety of ways for stream restoration projects. For example, the most common application is the estimation of discharge in ungaged watersheds. Regression relations should be used outside the bounds of the database with extreme caution and applied with recognition that confidence limits are rarely specified and the potential error in the predicted quantities are often unknown.

Analytical procedures offer a theoretically based alternative to empirical equations for assessing hydrology in streams. These equations incorporate the processes controlling runoff, discharge, storage, energy dissipation, and other flow parameters. Most are not fully theoretical; rather, they are semi-empirical, incorporating one or more parameters that are determined from observation or experimentation.

Data Sources. Data collection efforts may be undertaken for project-specific needs, but these efforts are often short term, insufficient in scope, time-consuming, and extremely costly. A substantial amount of data has been collected by federal, state, and local governments at select locations in the United States and is available to support hydrologic analyses for stream restoration projects. Extensive public records of precipitation and other atmospheric parameters are readily available through the internet from multiple sources such as the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) (http://www.ncdc.noaa.gov/) and the U.S. Geological Survey's (USGS) National Water Information System (NWIS) (http://waterdata.usgs.gov/nwis/). These websites provide precipitation data in gage and grid (NEXRAD) formats and provide hydrologists with much of the necessary data for input into hydrologic models.

The USGS-NWIS website also supplies over 850,000 station-years of surface water data in the form of water surface elevations, streamflow discharges, groundwater levels, and water quality observations. The U.S. Army Corps of Engineers also serves as a significant surface water data source for many of the nation's large rivers and reservoirs. In recent years, state and local agencies have become more involved in data collection efforts, and many states have started separate data collection and distribution efforts (e.g., Illinois, http://www.sws.uiuc.edu/data.asp).

In addition to the data, hydrologic parameters of interest are often published through these sources. For instance, summary streamflow statistics are published for active streamflow stations in USGS annual Water Data Reports. The summary statistics published by the USGS include parameters such as maximum and minimum daily mean flows and daily mean flows that are exceeded 10, 50, and 90 percent of the time for the period of record (http://web10capp.er.usgs.gov/adr06_lookup/search.jsp). Annual peak flow data needed for flood frequency analysis are also published by the USGS and are available through the internet at the NWIS website.

Discharge Estimation. The hydrologic analyses that follow require long-term estimates of both continuous and peak discharges from a watershed. This can be accomplished in a variety of ways, depending upon the location of the project reach and the availability of existing data. For basins with historical gage data, the process can be straightforward: collection and interrogation of the data with adjustments based upon drainage area. For ungaged streams, the assessment requires the translation of gage data from similar watersheds in the same physiographic region, the application of regional regression relations, or the use of hydrologic modeling techniques to synthesize discharge data. The following paragraphs provide an overview of these procedures.

Although continuous gage records may exist within a watershed, it is not likely that the project reach is very near a gage. Therefore, methods must be determined for transferring gage data to ungaged reaches. In this instance, the analyses proceed as if the gage(s) were located at the project reach, except that the magnitude of the discharge is adjusted using the following relation:

$$Q_{ungaged} = Q_{gaged} \left(\frac{A_{ungaged}}{A_{gaged}} \right)^{b_1} + b_2 \tag{1}$$

where Q is the discharge, A is the drainage area, and b_1 are regression coefficients depending on the relative character of the watersheds (Wurbs 2006).

In ungaged basins or gaged basins with insufficient periods of record (less than approximately 10 years), hydrologic parameters are estimated in three ways. First, data from nearby gages can be assessed and adapted to the project reach as was displayed for gaged basins. Second, regional regression equations that relate flood discharges (estimated at gaged locations) to basin and/or hydro-climatic characteristics are extended to ungaged watersheds in the same physiographic region. Finally, streamflow discharges can be estimated with event-based or continuous hydrologic simulation using hydrologic models.

The USGS has prepared a number of publications providing runoff regression relations for ungaged watersheds for various regions of the country. To formulate the relations, flood-frequency analyses for a large number of gages are conducted in conjunction with selected physical and climatic basin characteristics to develop generalized least-squares regression equations for estimating flood magnitudes and frequencies. These equations generally relate discharge of a given frequency to basin characteristics via one of the following formulae:

$$Q_j = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3 + \ldots a_i X_i \tag{2}$$

$$Q_j = a_0 X_1^{a_1} X_2^{a_2} X_3^{a_3} \ldots X_i^{a_i} \tag{3}$$

where Q_j is the discharge of a storm of return interval j, a_i are regression coefficients, and X_i are parameters influencing runoff characteristics of a watershed (U.S. Army Corps of Engineers (USACE) 1993, Watson et al. 1999).

Some common parameters (USACE 1993) used in the above analyses are:

- Contributing drainage area A upstream from the gauging station
- Main channel slope S_0; determined by extending the main stream channel to the basin divide and then locating a point that is 10 percent of the distance from the gage to the divide and another point on the stream that is 85 percent of the distance from the gage to the divide; the slope is equal to the difference in elevation between the two points divided by the distance between the points
- Stream length L from the gage to the basin divide; measured along the channel from the gage to the basin divide

- Basin elevation *E* established as the mean basin elevation above sea level; determined by finding the average elevation of at least 20 equally spaced points in the drainage basin as indicated by a transparent grid overlay
- Storage S_t the percentage of the contributing drainage area made up of lakes, ponds, and swamps
- Cover *C* the percentage of the contributing drainage area covered by a particular land use
- Mean annual rainfall P_{MA}

The principal drawback with the regression approach is the lack of a duration component in the estimated volume. In other words, the approach gives a finite value for a 100-year instantaneous flood volume but does not, for example, give any information about a 100-year 10-day flood volume. The Natural Environment Research Council developed an approach that relates volumes for different durations to the mean annual instantaneous flood. These ratios (called reduction ratios) are then plotted against durations to give reduction curves.

Hydrologic models may also be used to simulate discharges for use in other hydrologic analyses. These models have varying levels of complexity from simple, single-equation, empirical models to three-dimensional models analytically accounting for surface and subsurface processes. Accordingly, these models produce varying levels of accuracy and uncertainty. Wurbs (2006) identified seven significant sources of uncertainty in hydrologic modeling:

1. Temporal and spatial variability in hydrologic variables (e.g. precipitation)
2. Heterogeneity in watershed characteristics (e.g. soil, vegetation)
3. Accurate quantification of watershed characteristics (e.g. subsurface evaporation)
4. Changing basin characteristics in time (e.g. land use)
5. Complex mechanisms associated with streamflow generation
6. Subsurface and streamflow interactive mechanisms
7. Measurement inaccuracy in all parameters

Many simple hydrologic models exist to calculate streamflow from a single storm event (Novotny and Olem 1994). These models rely heavily on the assumption that runoff frequency is equal to precipitation frequency. These models include:

- The Rational Method, where all hydrologic surface and subsurface processes and variability are lumped into a single "runoff coefficient."
- The NRCS Curve Number Method and its derivative models TR-20 and TR-55, which compute infiltration and surface storage characteristics based on an empirically determined curve number, soil conditions, antecedent moisture conditions, and time of concentration and use those parameters to quantify surface runoff (streamflow).
- The Unit Hydrograph Method, which uses the convolution of a known storm magnitude and intensity to calculate all runoff conditions.

Often, more complex analyses and models are used due to the high uncertainty associated with simple, event-based models and the advantage of continuous simulation of hydrologic events. In this case, the model is calibrated to a nearby, hydrologically similar gaged stream. The model parameters are then adjusted to reflect the physical changes between the calibration watershed and the ungaged watershed. Finally, all the available observed meteorological data are used to create a long-term streamflow record for the ungaged stream. This method produces more reliable results than alternative simplified approaches such as indirect approaches equating runoff frequency and precipitation frequency.

In recent years, many continuous simulation hydrologic models have been made available by both government entities and private industry. These models offer varying degrees of spatial and temporal resolution and account for hydrologic processes by different mechanisms. Some preprocessing interfaces have also been developed for importing large quantities of data from georeferencing software to the hydrologic models (ArcHydro, Watershed Modeling Systems (WMS), InfoSWMM). Some common models are the USACE Hydrologic Modeling System (HEC-HMS), the U.S. Environmental Protection Agency's StormWater Management Model (SWMM), the USACE Gridded Surface Subsurface Hydrologic Analysis Model (GSSHA), and its predecessor Colorado State University's CASC2D, the USGS/EPA Hydrological Simulation Fortran Program (HSPF), and the Delft Hydraulic Institute's (DHI) suite of MIKE programs, just to name a few. Each of these models was developed with different objectives in mind, but each of them relies on hydrologic computation at the first level of calculation.

Land use changes can have a significant effect on flood flow frequencies, and historic stream flow records may be non-stationary for basins in which widespread changes are taking place (e.g., urbanization, agricultural development). Hydrologic simulation uses historic flow records to calibrate to the historic conditions and it then incorporates the effects of future urbanization.

In the absence of adequate discharge information, the presented methods provide the tools necessary to conduct further hydrologic assessments of a given basin. Despite their drawbacks, these methods give the best possible estimates of flood volumes in the absence of actual measurements.

FLOW FREQUENCY: The objective of flow frequency analysis is to link the magnitude of a given flow event to the probability of the occurrence of that event in order to assess the risks associated with both high and low extreme events. For instance, if planted riparian vegetation requires x number of days of submergence and y number of days of nonsubmergence for healthy growth, then the probability of these high and low flow events disrupting restoration efforts can be calculated.

Flow frequency analyses rely on statistical properties of historic flow conditions to estimate the frequency of events; therefore, the accuracy of streamflow gage records (or simulated records) is extremely important to this analysis. A robust gage record for this analysis should include more than 10 years of data and should include at least one "wet" year and one "dry" year (Copeland et al. 2001). For maximum or minimum flow conditions, two types of series can be formulated for a given gage record. An annual series is comprised of maximum or minimum instantaneous streamflows from a given year. A partial duration series is comprised of the largest or smallest discharges from a period of record, and does not rely on a time constraint. (Note: Care must be taken when defining a partial duration series to ensure that flows are from independent discharge events.) Most flow frequency estimates are made using annual series, so for the remainder of this document, all flow frequency analyses will refer to annual series, not partial duration series.

Once the series is defined, methods must be obtained for interpolation and extrapolation of discharge magnitudes of specific recurrence intervals (e.g. 100-year flood for FEMA floodplain mapping). Many government agencies have released guidance documents on selection of methods for streamflow frequency computation (Interagency Advisory Committee on Water Data (IACWD) 1982; USACE 1993; Copeland et al. 2001). These techniques can be coarsely divided into two categories: graphical and analytical techniques (Veissman and Lewis 2003).

Graphical methods provide qualitative and quantitative forms of assessing event frequency. In these methods, flows are ranked according to magnitude, and return period is assessed by calculating the probability of each data point. Multiple probability plotting position formulae have been presented, but the most commonly implemented is the Weibull formula (Viessman and Lewis 2003).

$$P = \frac{m}{n+1} \tag{4}$$

where P is the exceedence probability, m is the event rank, and n is the total sample size.

This formula can be used to assess the exceedence probability, and the return period of the event can be calculated as the inverse of the probability $(T = 1/P)$. Accuracy of this type of analysis is highly dependent upon sample size; therefore, return period estimates of a given flow rate may contain a high degree of uncertainty for short periods of record. A sample graphical flood frequency analysis is presented in Figure 3 for the Etowah River near Canton, Georgia.

Analytical flow frequency calculations consist of selecting a theoretical frequency distribution, estimating the necessary parameters of that distribution by sample statistics and fitting techniques, and evaluating the distribution for events of concern (USACE 1993). Many theoretical distributions have been utilized in flow frequency analyses (normal, log-normal, gamma, Pearson type III, Log-Pearson Type III, Gumbel Extreme Value) (USACE 1993). For peak flow analyses, guidelines defined by the Hydrology Subcommittee of the Interagency Advisory Committee on Water Data (IACWD 1982) recommend fitting the Pearson Type III frequency distribution to the logarithms of the annual peak flows using sample statistics (mean, standard deviation, and skew) to estimate the distribution parameters. The guidelines described in Bulletin 17B are used by many federal agencies for water resources planning (*http://water.usgs.gov/osw/bulletin17b/dl_flow.pdf*.) Procedures for outlier detection and adjustment, alteration for historical data, development of generalized skew, and weighting of station and generalized skews are provided in Bulletin 17B. The station skew is computed from the observed peak flows, and the generalized skew is a regional estimate determined from estimates at several long-term stations in the region. The U.S. Army Corps of Engineers has also produced guidance documents for flood frequency analysis (USACE 1992, 1993) that can aid in determining flood frequency distribution parameters.

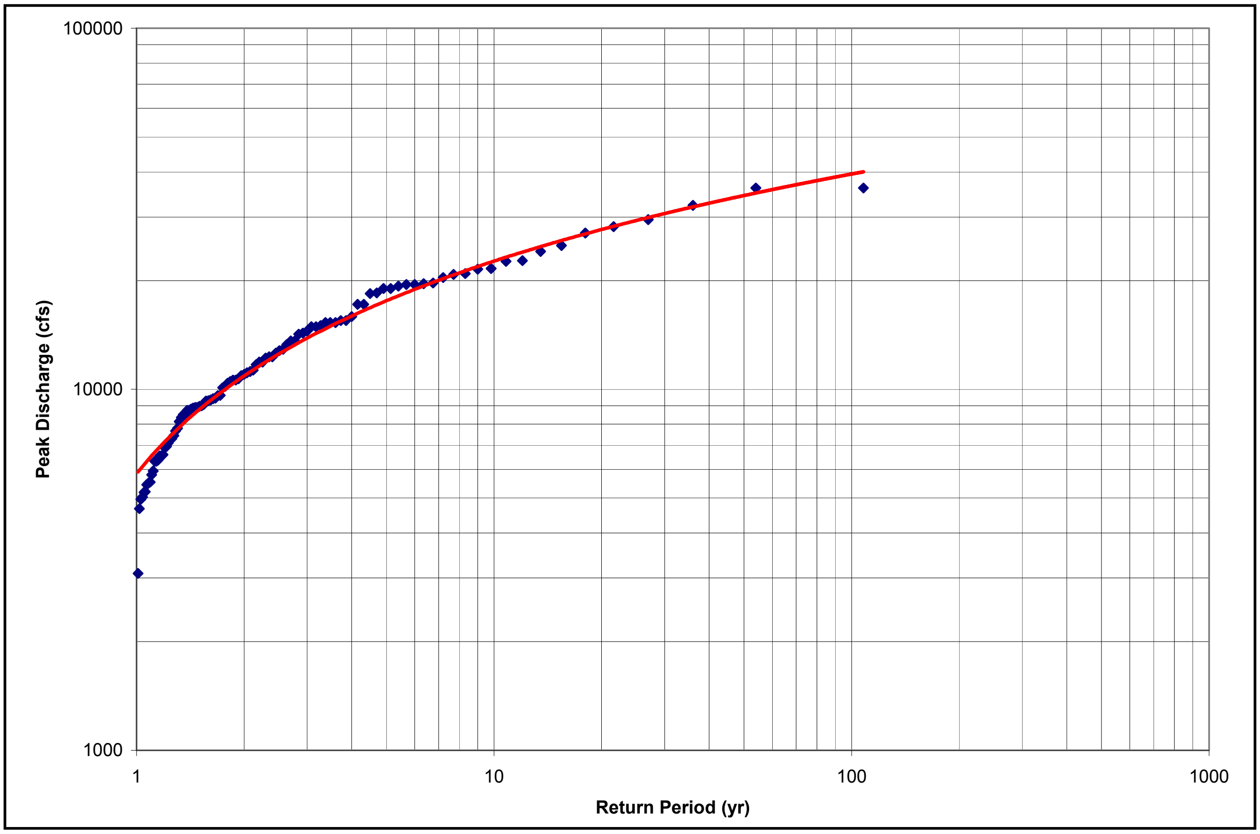

Figure 3. Flood frequency analysis for the Etowah River near Canton, Georgia.

Guidelines for low-flow frequency analysis are not as standardized as those for flood frequency analysis, despite the regulatory and ecological significance of low flow parameters. No single frequency distribution or curve-fitting method has been generally accepted. Data used in low-flow frequency analyses are typically the annual minimum average flow for a specified number of consecutive days *d*. The USGS and USEPA recommend using the Pearson Type III distribution to the logarithms of annual minimum *d*-day low flows to obtain the flow with a nonexceedance probability *p*.

In all analyses, if the computed theoretical curve is significantly different from the graphical methods, the computed curve should be adjusted to the observed data.

FLOW DURATION: Flow frequency analyses provide tools for assessing the probability of instantaneous flow events, but duration of flows is in many cases more ecologically relevant in stream restoration. The ability to identify the duration of flow events has implications for riparian vegetation, local aquatic species health, and soil moisture stress along with many geomorphic implications.

The amount of time that certain flow levels exist in a stream is usually represented by a flow duration curve depicting the percent of time a given streamflow was equaled or exceeded over a given period (Figure 4). Flow duration curves are generally based on daily streamflow (other time intervals have been used as well – e.g. 15-min, monthly) and describe the flow characteristics of a stream throughout a range of discharges without regard to the sequence or timing of occurrence. Flow duration curves are constructed by defining the cumulative histogram of streamflow discharge using a minimum of 20 to 30 well-distributed class intervals of streamflow data (Searcy 1959).

Estimating flow duration characteristics at ungaged sites is usually attempted by adjusting data from a nearby stream gage in a hydrologically similar basin. The accuracy of such a procedure is directly related to the similarity of the two sites. Generally, the drainage areas at the gaged and ungaged sites should be fairly similar, and streamflow characteristics, mean basin elevation, and physiography should also be comparable. Such a procedure does not work well and should not be attempted in stream systems dominated by local convective storm runoff or where land uses vary significantly between the gaged and ungaged basins.

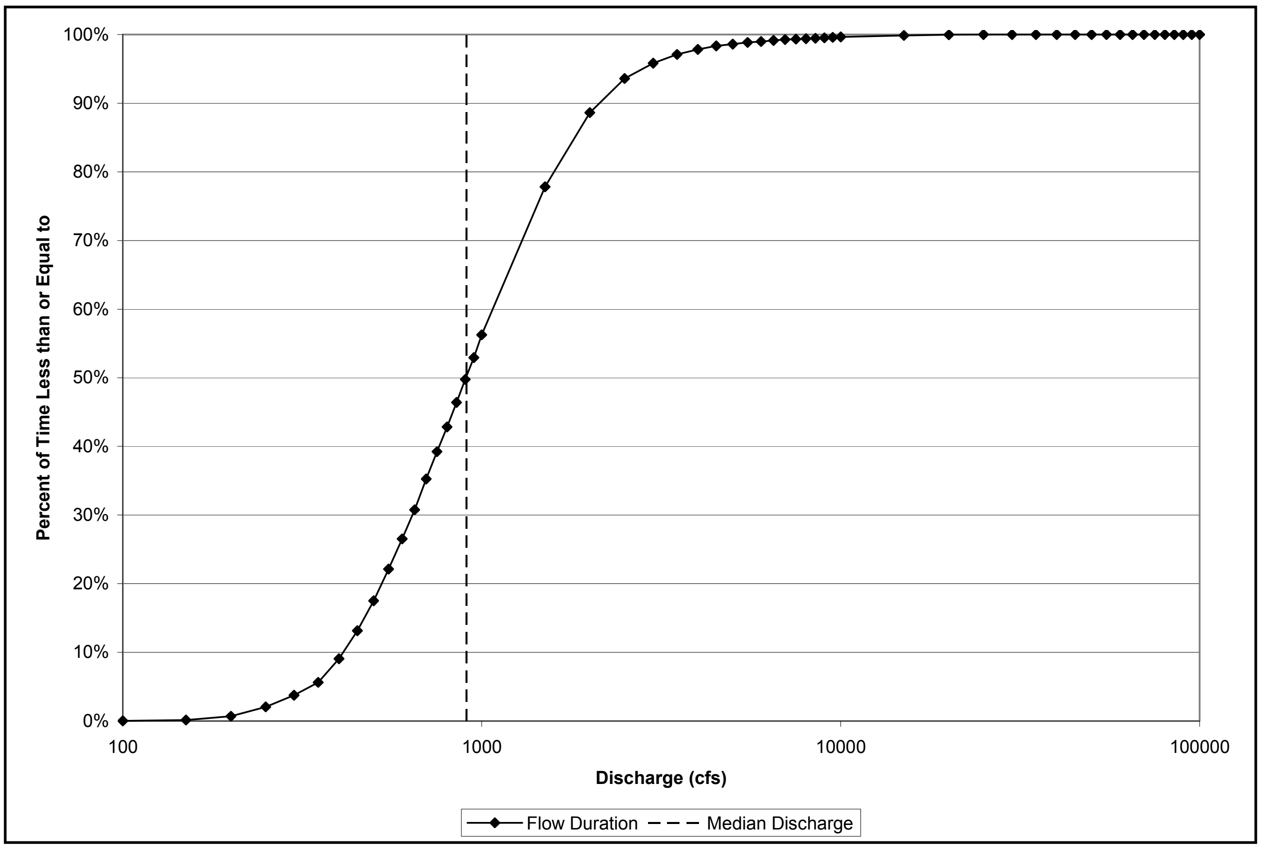

Figure 4. Flow duration curve for the Etowah River near Canton, GA.

The advantage of using a flow duration curve is that it provides information regarding peak flows and droughts, along with assessment of typical system behavior not provided in flow frequency analyses. The shape of the flow duration curve provides qualitative assessment of the deviation of the system from median and mean daily discharges and allows the restoration team to design appropriately for the entire range of discharges encountered.

DESIGN DISCHARGE ESTIMATION: Although channel shape is affected by a range of flows, it has been proposed that a single discharge, if held steady, would produce the same gross channel shapes and dimensions as the natural sequence of discharge events. This discharge is known as the channel-forming or "dominant" discharge (Figure 5). Researchers have used various flows to represent the channel-forming discharge. The most common are 1) bankfull discharge, 2) a specific peak discharge recurrence interval from annual or partial duration frequency curves, and 3) effective discharge. These three flows are approximately equivalent for stable channels, but may vary dramatically for unstable sections.

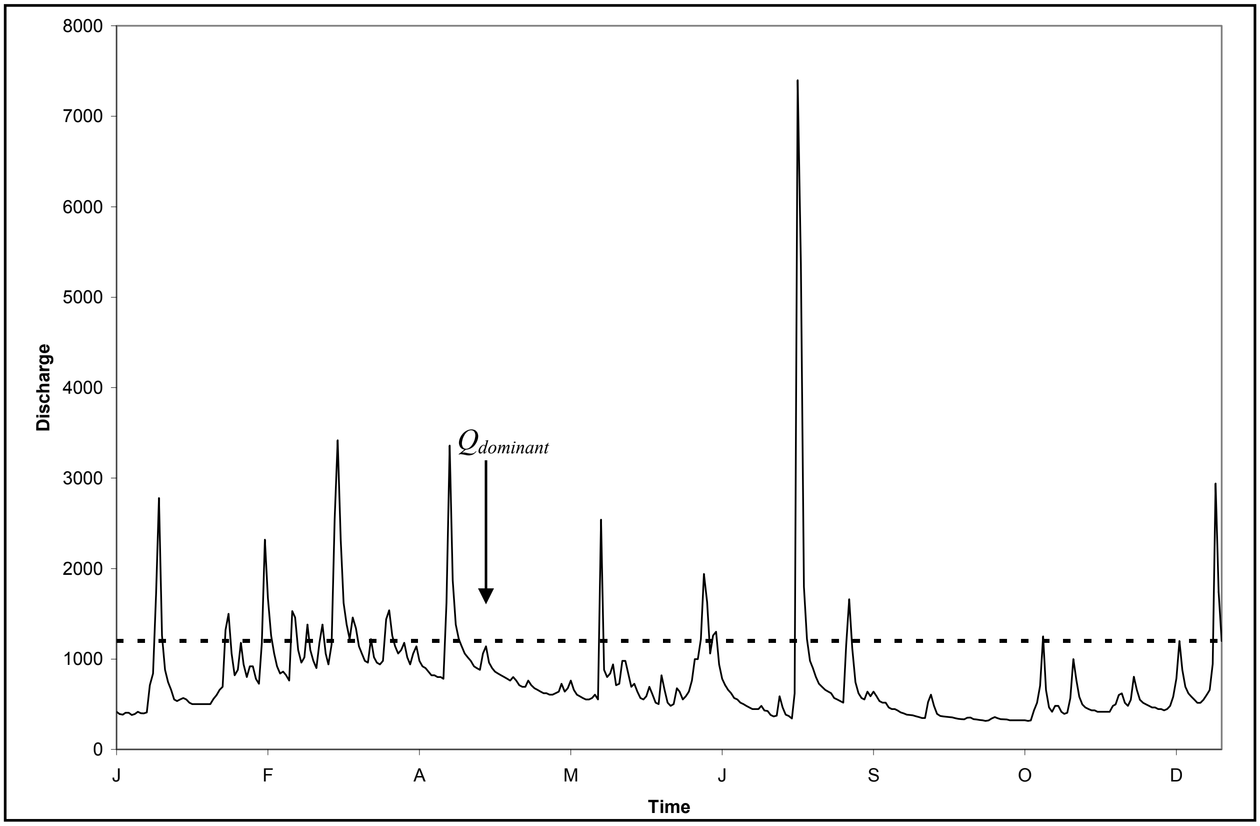

Figure 5. Dominant discharge.

The bankfull discharge is the discharge that fills a stable alluvial channel up to the elevation of the active floodplain. In many natural channels, this is the discharge that just fills the cross section without overtopping the banks, hence the term "bankfull." Active floodplain levels are often difficult to ascertain, however, leading to many inconsistencies in determining the bankfull flow. The USGS provides regional regression equations for estimating bankfull discharge throughout the United States.

To avoid difficulties associated with field determination of bankfull stage, the channel-forming discharge is often assumed to be a specific recurrence interval discharge. Most investigations have concluded that the dominant discharge recurrence intervals range from 1 to 2 years with an average of 1.5 years. There are many instances where the bankfull discharge does not fall within this range, particularly for highly impacted watersheds (Knighton 1998).

Effective discharge is the modal (peak) value of a curve generated by integrating a bed material sediment rating curve with a flow duration curve for the stream reach in question (Figure 6). In other words, it is the discharge that on average moves the most sediment in a stream. Of the three dominant discharge determinants, effective discharge is the only one that can be consistently computed. The effective discharge also has morphological significance since it is the discharge that transports the bulk of the sediment over time. However, computation of this value requires sediment transport data that are rarely available and are difficult to reliably quantify.

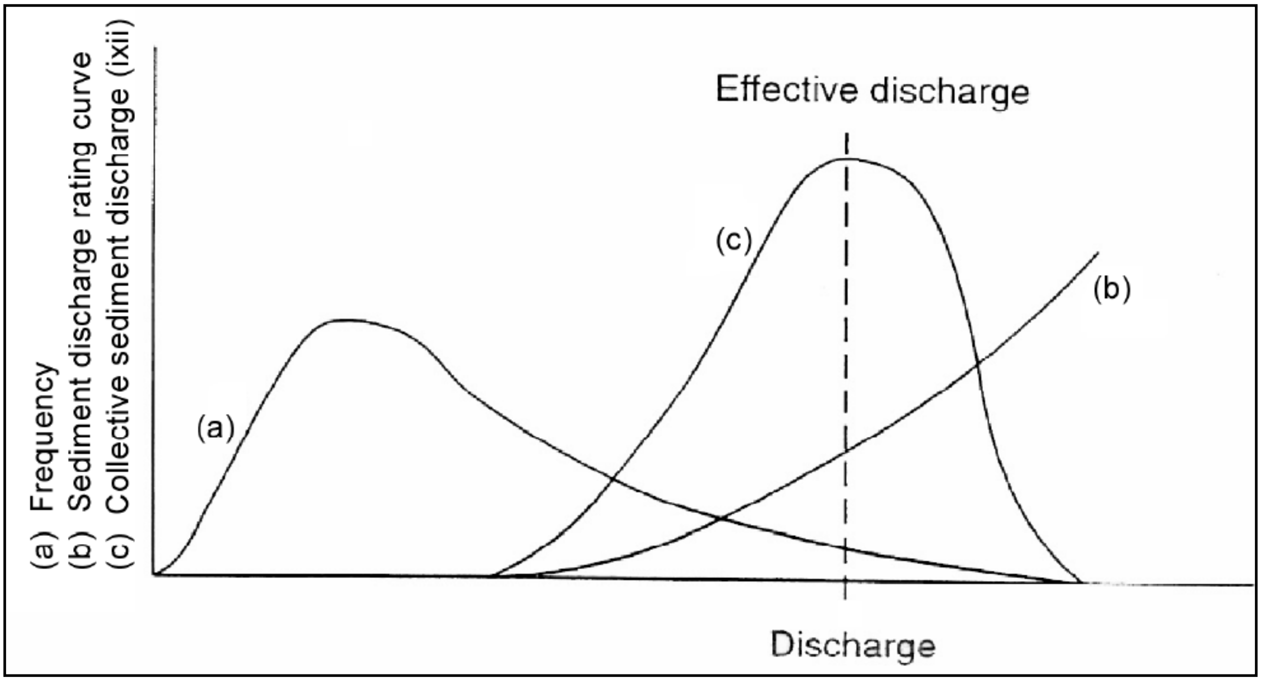

Figure 6. Effective Discharge (after Watson et al. 1999).

The notion that streams can be represented by a single discharge is appealing because it simplifies the analytical challenges facing the designers of stabilization and restoration projects on streams. Unfortunately, a single discharge is seldom sufficient to evaluate the functional characteristics and performance of streams along with the habitat and stabilization features in a design. The dominant discharge is a logical starting point for such evaluations, but consideration must also be given to other flow events that could affect the performance of the system. For example, designers of habitat improvement projects might need to consider a low flow condition (e.g. the seven-day ten-year low flow discharge) to select site habitat features, an extreme flow condition (typically near the dominant discharge) to design the features for structural stability, and a design flood (generally a 100-year event) to assess infrastructure impacts.

TEMPORAL DEPENDENCE OF HYDROLOGIC PARAMETERS: The methods presented herein offer a set of hydrologic analyses involved in most stream restoration projects; however, these calculations should be approached with the recognition that a system's hydrology may be dynamic in time due to natural and human-induced factors, and each of these analyses should be examined carefully for temporal trends. Factors influencing changes in watershed hydrology could include (but are not limited to): climate change, land use change (via urban development, deforestation, agricultural development, etc.), changes in local channel morphology at a gaging site (headcut moving through system, large storm event, systematic channel incision, etc.), and human-induced changes in channel dynamics (dam construction, reach channelization, sand mining, etc.). These influences on watershed hydrology should be carefully considered in any hydrologic analysis, and the methods previously described should be adapted to account for these temporal influences. For instance, if a local streamflow gage has a period of record of 100 years, but in the 50th year a dam was constructed upstream, the period of record used for flood frequency analyses should be limited to the last 50 years of record.

Trend analyses are often used to examine the temporal trends of many of the hydrologic parameters of the basin to determine whether basin changes are significant enough to alter hydrologic analyses. The temporal variability of each of Poff et al.'s (1997) parameters should be examined: magnitude, frequency, duration, timing, and rate of change. For instance, analyses to examine changes in these variables may involve examining the time series of daily flows, mean monthly flows, annual peaks, annual flow duration curves, effective discharge, time of concentration, and any number of other hydrologic parameters. Figures 7 and 8 present examples of trend analyses.

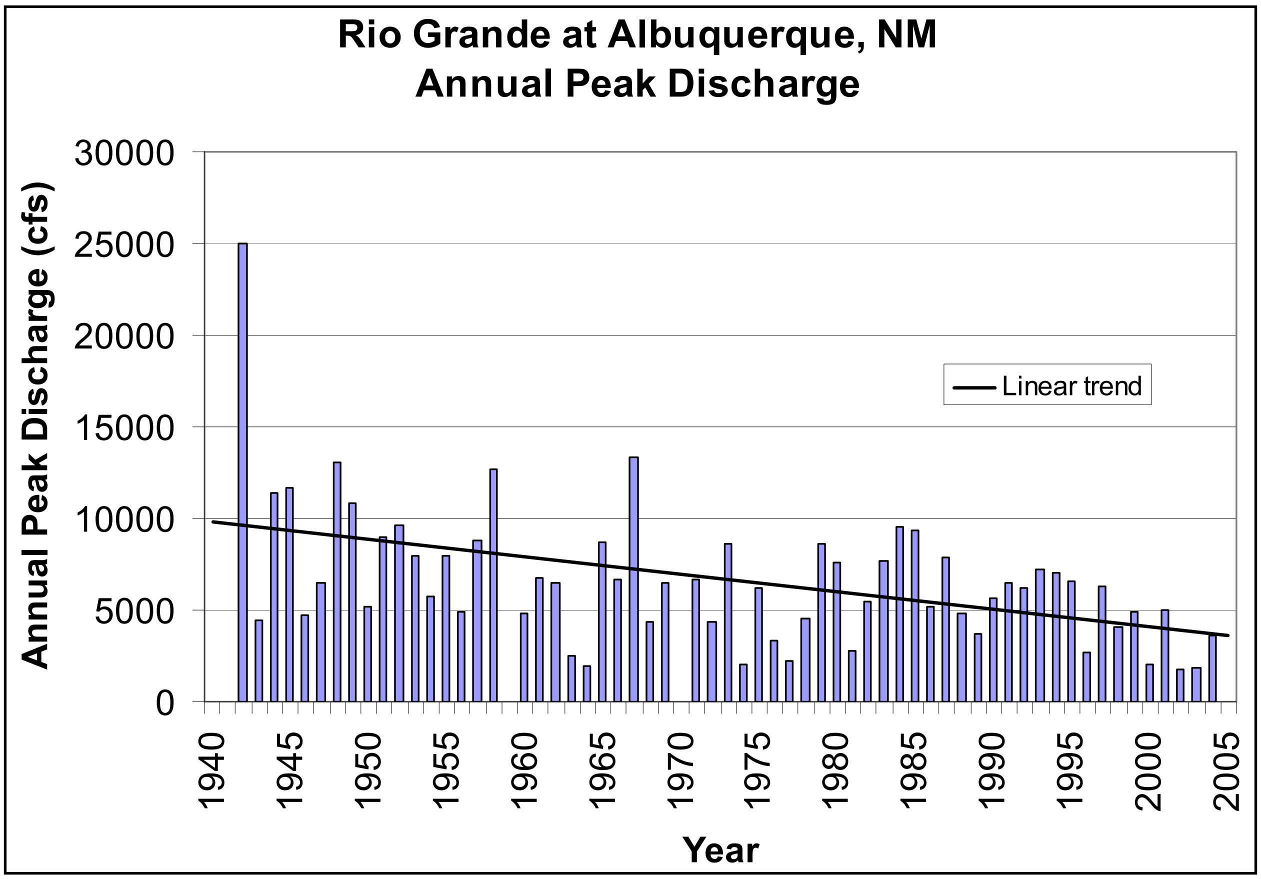

Figure 7. A declining trend in annual peak discharge on the Middle Rio Grande.

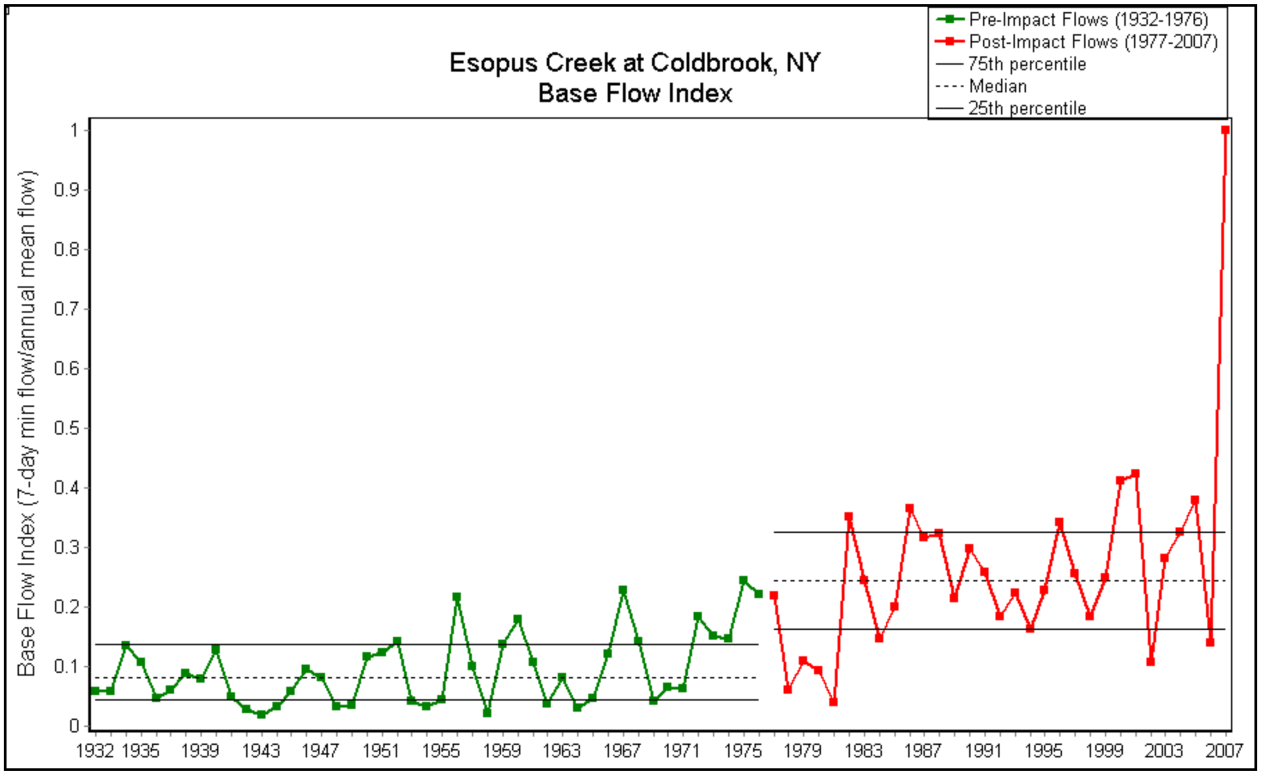

Figure 8. Baseflow index for Esopus Creek at Coldbrook, NY showing the increase in baseflow resulting from a trans-basin diversion that went online in 1977.

OTHER ECOLOGICALLY RELEVANT PARAMETERS: The hydrologic parameters discussed in the previous sections represent those that are most commonly employed by engineers when developing designs for the restoration of stream systems. They also form the basis for the assessment of a number of other hydrologic variables, many of which might be ecologically relevant. The relevance will vary from project to project, and it is left to the project delivery teams to make the appropriate linkages and determinations of relevance.

CONCLUSIONS: The dimensions, slope, and resistance characteristics of streams and their valleys collaborate with runoff to generate a streamflow pattern that is as unique as a fingerprint. Qualitative knowledge of basic system character (flooding behavior, land use, ecological needs) should be examined for every stream restoration effort and analyses adjusted accordingly; this paper has, however, presented the hydrologic analyses needed for a majority of stream restoration efforts. Many restoration projects may require much greater or far less hydrologic analysis, but the methods presented herein serve as the basis for a majority of stream restoration designs. Due to the uncertainty in analyses and stochastic nature of watershed hydrology, all stream restoration efforts should include multiple analyses to create a weight of evidence for restoration design.

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POINTS OF CONTACT: For additional information, contact the authors, Dr. J. Craig Fischenich (601-634-3449, *Craig.J.Fischenich@usace.army.mil*) or S. Kyle McKay (706-850-1974, *Kyle.McKay@usace.army.mil*), or the manager of the EMRRP, Glenn Rhett (601-634-3717, *Glenn.G.Rhett@usace.army.mil*). This technical note should be cited as follows:

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