Design Discharge for River Restoration

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Selecting a design discharge is a critical stage in a wide range of river restoration approaches and tasks but is not straightforward in practice and rarely involves following any of the several standardized procedures suggested in the literature on stable channel design because the data required are simply not readily available for most project sites. This chapter reviews the scientific bases of three popular candidates for representing the geomorphologically important dominant discharge that can be adopted as a design discharge for channel restoration: the bankfull discharge, a discharge of specified recurrence interval, and the effective discharge. The chapter goes on to assess how the strengths and weaknesses, inherent to their derivation and application, play out in practice. Experience shows that effective discharge analysis has considerable potential for further advances in computational methods that could provide improved insights into the morphological significance of an effective range of flows, enabling restorers to incorporate not one but a series of nested design discharges into their restoration plan, enhancing both geomorphological sustainability and ecological integrity. It is increasingly recognized that the primary challenge in selecting a suitable design discharge for river restoration lies in accounting for uncertainty in future flow and sediment regimes, associated with global warming and ongoing changes in watershed land use, by making sufficient allowance for restored channels to adjust within their restored, functional floodplains, while maintaining the dynamic equilibrium necessary to conserve key species and ecosystems.

1. INTRODUCTION: DESIGN DISCHARGE IN THE RIVER RESTORATION PROCESS

Designing dynamically stable channels with mobile bed materials and adjustable banklines requires that a range of complex scientific and technical issues are addressed by the project design team and is recognized as being one of the most difficult challenges in river restoration [*Shields*, 1996]. Additionally, the requirement for many restored rivers to support high biodiversity and good aesthetics, while simultaneously meeting objectives for flood control, land drainage, and navigation often imposes constraints on the design outcomes [*Brookes*, 1987; *Natural Resources Conservation Service (NRCS)*, 2007].

In naturally stable, alluvial rivers, the dimensions, geometry, and sediment features of the channel are not designed but evolve over time in response to complex interactions between the sequence of flow and sediment transport events

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that actually occurs and the boundary sediments and vegetation that resist morphological change. It is therefore the magnitude, duration, and sequencing of flows that entrain, transport, and deposit boundary sediments that are the primary driving parameters responsible for molding channel morphology and sediment features over time [*Lane*, 1955]. It follows that it is the diversity of flow and sediment transport events that ultimately provides a broad and dynamic assemblage of physical habitats.

Recognizing the multifunctional objectives of channel restoration projects, and the importance of channel evolution, best practice guidance recommends that careful consideration of the hydrological and sediment regimes should be central to channel restoration design [*Soar and Thorne*, 2001]. In theory, it would seem appropriate to apply deterministic equations to predict the stable geometry of a self-formed, alluvial channel as a function of the full spectrum of sediment-transporting flows for design purposes, but in practice, the assumptions required to overcome mathematical indeterminacy and uncertainty in modeling sediment transport processes remain major concerns [*Petts*, 1995]. To counter this, channel restoration design methods have been developed that embrace concepts of dynamic equilibrium and channel stability by attempting to match the sediment supply from upstream to the transport capacity of the restored channel [e.g., *Shields*, 1996; *Soar and Thorne*, 2001; *NRCS*, 2007; *Shields et al.*, 2003, 2008]. These approaches employ a single design discharge in the initial design specification but, importantly, recommend testing the performance of the proposed channel geometry against the full range of sediment-transporting flows as a closure loop in the design process [*Soar and Thorne*, 2001].

Despite the known limitations of using a single flow to represent the geomorphic effects of the range of flows actually experienced by a channel, the fact is that selecting an appropriate design discharge currently remains an essential step in an increasingly wide range of channel restoration design approaches and tasks. Examples include application of (1) downstream hydraulic geometry or "regime" type equations for stable channel geometry [e.g., *Hey*, 1997; *Federal Interagency Stream Restoration Working Group*, 1998; *Soar and Thorne*, 2001], (2) the "Natural Channel Design" method [*Rosgen*, 1998, 2006a, 2006b; *Hey*, 2006; *NRCS*, 2007], (3) analytical techniques based on simultaneous solution of flow resistance and sediment transport equations [e.g., *Copeland*, 1994; *Shields*, 1996; *Shields et al.*, 2008; *Soar and Thorne*, 2001], (4) empirical methods for laying out restored meanders [e.g., *Dury*, 1976; *Schumm*, 1967, 1968], (5) sizing riffle sediments in restored channels based on tractive force analysis [e.g., *Newbury and Gaboury*, 1993], and (6) conducting postproject channel stability assessments based on stream power screening [*Brookes*, 1987] or hydraulic geometry analysis [e.g., *Thorne et al.*, 1996].

The task of identifying the appropriate design discharge is not straightforward. The textbook scenario of utilizing a record of measured discharges from a nearby gauging station as the basis for deriving a design discharge is seldom possible in practice, as hydrometric stations are sparsely distributed along main stem rivers, and many tributaries are entirely ungauged. The task of specifying a design discharge therefore rarely involves following a standard procedure as the data required are simply unavailable. While it is possible to "synthesize" a flow distribution for an ungauged site by transferring data from other gauged sites, this inevitably introduces further uncertainty concerning the reliability of the resulting design discharge and confidence in the suitability and sustainability of the restored channel morphology.

Common to most of these approaches is the adoption of the "dominant discharge" concept that the spectrum of sediment-transporting flows in a river's flow regime may be represented by a single, "channel-forming flow."

2. DOMINANT DISCHARGE CONCEPT

The concept of there being a single discharge to which the form of the channel adjusts stems from regime theory and empirical research into the relationships between discharge and channel geometry performed to support the design of stable ("in regime") irrigation canals with granular beds, initially, in the Indian subcontinent during the first half of the twentieth century [e.g., *Inglis*, 1941, 1947, 1949] and, later, in North America [e.g., *Blench*, 1952, 1957; *Simons and Albertson*, 1960]. The regime theory revealed that stable channel width, depth, and slope may be expressed as power functions of the supply discharge. Subsequent laboratory studies undertaken at the Hydraulics Research Station, Wallingford, United Kingdom, validated the form of these regime equations [*Ackers and Charlton*, 1970a, 1970b].

Unlike canals, in rivers the discharge varies seasonally, annually, and interannually depending on the occurrence and duration of precipitation events. In alluvial rivers, all discharges competent to mobilize sediment from the channel boundaries influence the channel form, rendering canal-based, regime equations inapplicable to channel design in rivers. The concept of the dominant discharge or channel-forming flow seeks to overcome this problem by proposing that there is a single discharge which, if held constant over a prolonged period, would produce the same channel morphology (width, depth, and slope), planform pattern, and hydraulic roughness as that generated by the actual distribution of flows experienced by the river. Despite being criticized by prominent academics [e.g., *Richards*, 1982], the dominant discharge concept remains a device attractive to practitioners of river restoration.

According to *Inglis* [1947], the dominant discharge is associated with the condition at which equilibrium is most closely approached and the tendency for channel change is at a minimum. This condition can be regarded as the integrated effect of all varying conditions over a long period. The link between the dominant discharge in rivers and the downstream hydraulic geometry was first investigated by *Leopold and Maddock* [1953] and *Leopold et al.* [1964] and later expanded through the collection of data sets for different types of stable rivers [e.g., *Hey and Thorne*, 1986]. In a further development, *Soar and Thorne* [2001] used confidence bands applied to "typed" hydraulic geometry equations as a mechanism through which natural rivers can be used as analogs for channel restoration design.

Application of the dominant discharge concept is best suited to river systems in which flow regimes are sufficiently steady to allow their morphologies to adjust to prevailing conditions. In such cases, most geomorphic work is performed by events that do not significantly overtop the banks, typically having low to moderate recurrence intervals of less than 2 or 3 years in the annual maximum series (AMS) (the series of single highest discharge in each year of interest, ideally derived from the record of gauged flows averaged over 15 min or hourly intervals).

These conditions pertain in humid, temperate environments where the morphology of perennial rivers recovers relatively quickly following major events that perturb the channel, due to the geomorphic effectiveness of short to medium return-period events, coupled with rapid vegetation growth that helps limit flood-driven erosion and encourage sedimentation [*Hack and Goodlett*, 1960; *Gupta and Fox*, 1974]. In contrast, streams in semiarid environments have flood dominated, flashy regimes. They exhibit morphologies that reflect the recent sequence of floods and which are frequently reshaped [*Macklin and Lewin*, 2003]. Morphological recovery in these ephemeral channels tends to take much longer than in more temperate regions, partly reflecting the stress placed on vegetation growth during long dry periods [*Schumm and Lichty*, 1963; *Burkham*, 1972]. In truly arid areas, infrequent floods of very high magnitude leave long lasting imprints on the channel morphology as intermediate flows occurring between floods lack the energy necessary to drive adjustment toward a regime condition [*Schick*, 1974]. It follows that, where these highly variable flow regimes prevail, the notion that there may be a single discharge that can explain channel form is barely tenable [*Stevens et al.*, 1975; *Baker*, 1977].

The "dominant discharge" is a geomorphic concept rather than a measurable parameter. However, there are three popular candidate discharges that could be taken to represent the dominant flow, based on the application of geomorphic and hydrologic principles: (1) bankfull discharge, (2) a discharge of specified recurrence interval, and (3) effective discharge.

Each can be adopted as the design discharge for channel restoration, but each rests on a different set of assumptions, has different data requirements, and is associated with particular problems and challenges. The next section of this chapter introduces the scientific basis for each of these potential design discharges, evaluates their scientific validity and assesses how the strengths and weaknesses inherent to their derivation and application play out in practice.

3. APPROACHES TO CALCULATING THE DESIGN DISCHARGE

3.1. Bankfull Discharge

3.1.1. Science base. The bankfull discharge is essentially the largest flow that can be conveyed by a channel without overtopping its banks. Based on extensive field data, *Inglis* [1947] first considered that flows at or near the bankfull stage might approximate to the dominant discharge, and the link he proposed between the bankfull and dominant discharges has been supported by a wealth of subsequent research findings demonstrating that flows around bankfull exhibit a strong relationship with stable channel dimensions [*Wolman and Leopold*, 1957; *Nixon*, 1959; *Simons and Albertson*, 1960; *Leopold et al.*, 1964; *Kellerhalls*, 1967; *Hey*, 1975, 1982; *Charlton et al.*, 1978; *Hey and Thorne*, 1986; and many others]. Based on these findings, the bankfull discharge in river systems appears to be of comparable morphological significance to the supply discharge in canals that are in regime.

Hey [1997] highlighted that the bankfull elevation often marks a significant discontinuity in the stage-discharge curve. As water spills onto the floodplain, the greater depth of flow and lower hydraulic roughness of the main channel together can result in appreciably higher velocities in the main channel than those occurring on the floodplain. The difference in velocity between in-bank and over-bank flows can then lead to a lateral transfer of momentum and a reduced channel discharge capacity [*Knight and Shiono*, 1990; *Shiono and Knight*, 1991; *Ackers*, 1993; *Ervine et al.*, 1993; *Shiono et al.*, 1999; and many others]. As a result, floodplain flows rarely impose appreciable increases in bed shear stress in the channel, and so high in-bank stages also tend to represent the condition under which the availability of energy to drive in-channel processes of sediment erosion, transport, and deposition is greatest. Above the bankfull level, experimental studies have demonstrated that concentrations of sediment transported as bed load actually decline with further increase in discharge or floodplain roughness, even dropping below the value at bankfull in some cases [*Atabay et al.*, 2005; *Tang and Knight*, 2006]. It is the strong "morphogenetic" significance of bankfull discharge that led *Hey* [1978] to stress the utility of bankfull discharge for stable channel design purposes.

3.1.2. Science into practice. In practice, the challenge is less that of estimating the bankfull discharge, per se, and more that of identifying the correct bankfull reference level and measuring the corresponding bankfull elevation. As *Leopold et al.* [1964] pointed out, this is not a simple matter, and small differences in the selected bankfull elevation can lead to large differences in bankfull discharge. *Williams* [1978] presented a detailed review of how to identify the bankfull stage, including a range of definitions based on sedimentary features, cross-sectional morphology, and changes in bank vegetation (Table 1). In a natural river, an appropriate definition is "the discharge conveyed at the elevation of the active floodplain" [after *Wolman and Leopold*, 1957; *Dury*, 1961; *Emmett*, 1972, 1975; *Williams*, 1978; *Andrews*, 1980, 1984; *Nolan et al.*, 1987; *Hey and Thorne*, 1986; and others]. Recently, *Pike and Skatena* [2010] demonstrated that the first occurrence of soil and woody vegetation can be a reliable indicator of the bankfull level.

However, accurate location of bankfull indicators is not a routine procedure with a precise analytical method [*Radecki-Pawlik*, 2002]; it is fraught with difficulty and uncertainty [*Williams*, 1978; *Johnson and Heil*, 1996], with most methods being highly subjective. For individual cross sections, the erosional and depositional forms associated with bank processes, and the presence and character of vegetation interact to yield an indistinct boundary between the channel bank and its floodplain, resulting in a transitional range of bankfull elevations, rather than a single value [*Navratil et al.*, 2006].

A more objective method is to identify the level corresponding to the minimum width-to-depth ratio within the cross section [*Wolman*, 1955]; although *Navratil et al.* [2006] found geometric criteria to be less reliable in locating the bankfull level than identifying geomorphic features. However, despite these documented methods, and the availability of instructions intended to minimize uncertainty and encourage consistency [e.g., *Harrelson et al.*, 1994; *Leopold*, 1994; *Forest Service, U.S. Department of Agriculture*, 1995, 2003], there is no method for defining the bankfull reference level that is universally applicable, comparison between reaches remains difficult [*Richards*, 1982], and accurately locating field indicators continues to remain a major hurdle. In seeking to reduce uncertainty in the identification of the bankfull level, the experience of a fluvial geomorphologist is critical, and several bankfull criteria should be adopted and applied to more than one cross section in order to produce a reliable result [*Harman et al.*, 2008].

Once the bankfull elevation has been identified, the method applied to derive a value for the bankfull discharge is dependent on whether there is a gauging station close to the project reach. If there is a gauging station, the recommended procedure is to survey a long profile of bankfull elevations within the reach of interest, extrapolate this to the gauging station, and then read the corresponding discharge from the gauging station's stage-discharge curve [*Leopold et al.*, 1964]. This approach has been used successfully in many studies [e.g., *Hey and Thorne*, 1986], though, in practice, it is subject to many assumptions and difficulties, particularly regarding the reliability of the gauged flow record and the impacts of any channel or floodplain modifications or structures that complicate extrapolation of the bankfull profile. The accuracy of this approach decreases as the distance to the nearest gauging station increases, especially if channel conditions change significantly en route.

A number of methods may be considered for application to ungauged rivers, including (1) stream gauging, (2) synthesizing a stage-discharge curve using either a flow resistance equation (typically the Manning formula) or a hydraulic model, such as Hydrologic Engineering Center River Analysis System (HEC-RAS) [*Brunner*, 2010], (3) applying a "channel geometry" equation to predict discharge from bankfull width or cross-sectional area [e.g., *Wharton et al.*, 1989; *Wharton*, 1992, 1995a, 1995b; *Osterkamp and Hedman*, 1982], or (4) applying a regional curve relating bankfull discharge to drainage basin area (see discussion below).

Attempts have also been made to estimate bankfull discharge solely from remotely measured data [e.g., *Bjerklie*, 2007], with reasonable success. Table 2 presents the options available to calculate bankfull discharge for gauged and ungauged sites, together with the possible limitations, sources of uncertainty, and constraints.

The association between bankfull and the dominant discharges rests on the assumption that the project reach is dynamically stable; that is, that the reach-averaged channel dimensions and planform are adjusted to the prevailing flow and sediment regimes. If the river is unstable, its channel is likely to reflect either the trend of morphological evolution toward a new, equilibrium condition or the degree of morphological recovery following destabilization [*Wolman and Gerson*, 1978], rather than the magnitude of the channel-forming flow. This is an issue because channel instability is often the reason that a reach is a candidate for restoration.

Table 1. Variable Criteria for Identifying the Bankfull Reference Level

Bankfull Indicator Reference	Source
Geomorphic/Sediment Criteria	
Elevation of active floodplain	*Wolman and Leopold* [1957]
	Nixon [1959]
	Leopold and Skibitzke [1967]
	Emmett [1972, 1975]
Highest elevation of channel bars	*Wolman and Leopold* [1957]
	Hickin [1968]
Elevation of the most prominent bench	*Kilpatrick and Barnes* [1964]
Elevation of the "middle bench" in rivers with several overflow surfaces	*Woodyer* [1968]
Elevation of low bench	*Schumm* [1960]
	Bray [1972]
Elevation of upper limit of sand-sized particles in boundary sediment	*Nunally* [1967]
	Leopold and Skibitzke [1967]
Geometric Criteria	
Minimum width-to-depth ratio	*Wolman* [1955]
	Harvey [1969]
	Pickup and Warner [1976]
Minimum width-to-depth ratio plus a vegetative and or physical discontinuity in the channel boundary	*Wolman* [1955]
Maximum of the bench index (developed from the width-to-depth ratio)	*Riley* [1972]
Change in relation of cross-sectional area to top width	*Williams* [1978]
Vegetative Criteria	
Channelward limit of perennial vegetation (normally trees or tall grasses)	*Schumm* [1960]
	Speight [1965]
	Nunally [1967]
	Bray [1972]
Change in vegetation type (herbs, grass, shrubs)	*Woodyer* [1968]
	Leopold [1994]

Under these circumstances, the bankfull condition in the project reach is unlikely to be a reliable indicator of the channel-forming discharge [*Doyle et al.*, 1999], and it may, therefore, be unsuitable as the design discharge for restoration to a stable condition. This precludes use of bankfull as the design discharge for restoration unless a suitably stable "reference" reach can be identified in relatively close proximity. However, finding a stable reference reach presents a particular challenge in watersheds exhibiting system-wide instability in the drainage network, and nonimpacted neighboring reaches provide bankfull discharge estimates suitable for restoration designs only in situations where channel instability in the project reach can be clearly attributed to a local disturbance [*NRCS*, 2007].

It follows that adoption of bankfull discharge to represent the channel-forming flow relies on geomorphic reconnaissance of the project and adjacent reaches, coupled with accurate interpretation of channel forms and processes within the context of adjustments in the fluvial system, and some knowledge of sediment dynamics at the watershed scale [see *Downs and Thorne*, 1996; *Thorne et al.*, 1996; *Thorne*, 1998; *Sear et al.*, 2010]. A watershed assessment (see *NRCS* [2007] for methodologies) or fluvial audit [*Sear*, 1994; *Sear et al.*, 2009, 2010] provides the ideal baseline from which to establish the catchment context for restoration and is a prerequisite to locating reference reaches from which a bankfull discharge suitable for design purposes can be derived. However, such comprehensive watershed assessments require extensive project resources, which are seldom available. Where project resources constrain background investigations, assessment of the river in the sediment supply reach immediately upstream of the project reach is recommended as the minimum necessary to support channel restoration design [*Soar and Thorne*, 2001].

Given the difficulties involved in determining the bankfull discharge based on field observation, it is unsurprising that application of generalized, regional regression curves is gaining popularity as an alternative approach to estimating

Table 2. Practical Methods for Calculating the Bankfull Discharge at Gauged and Ungauged Sites

Methods	Data Requirements	Limitations, Uncertainties, and Constraints
	Gauged Sites	
Stage-discharge analysis	Surveyed bankfull elevation profile extrapolated from the project reach to the gauging station.	Defining bankfull stage based on field indicators or morphological criteria can be problematic and misleading. Bankfull stages can be highly variable over short distances. Channel modifications and structures can prevent accurate extrapolation of the bankfull level profile. Geomorphic skills and experience are essential.
	Stage-discharge curve generated from the gauged record.	Requires a reliable flow record ideally for the past 10 years or more. Potential unreliable rating at high flows. Nonstationarity in flows through the period of record could indicate that the restored channel might not be sustainable in the future. Time base (mean daily, hourly or 15 min data) can influence the shape of the curve.
	Ungauged Sites	
Direct stream gauging	Velocity-area method (cross section; velocity distribution).	Channel inaccessible at high stages.
Stage-discharge analysis	Bankfull elevation measured over at least 10 channel widths.	Difficulty locating a stable and unmodified reach in the vicinity of the site, often in watersheds with system-wide instability. Defining bankfull stage based on field indicators or morphological criteria can be problematic and misleading. Bankfull stages can be highly variable over short distances. Geomorphic skills and experience are essential.
	Synthesized discharge corresponding to bankfull elevation, based on either	
	(1) flow resistance equation (cross section; roughness coefficient; slope).	Equations assume uniform flow conditions and are widely reported to generate errors. Experience is required to select an appropriate roughness equation for the type of watercourse and assign an appropriate roughness coefficient. Different measures of slope (bed, water surface) can significantly influence discharge calculation.
	(2) computer model (e.g., HEC-RAS) (geo-referenced channel survey extending through reach; roughness coefficients).	Model assumptions for generating water surface profile. Channel surveys are costly and can be problematic. Calibration data are required. Modeling experience is essential.
Channel geometry analysis	Existing relationship predicting bankfull discharge from bankfull width for similar type of region.	Issues related to identification of bankfull stage (see above, for stage-discharge analysis).
	Bankfull elevation measured over at least 10 channel widths to derive an average bankfull width.	Issues related to application of regression equation (see below, for regional curve application).
Regional curve application	Existing relationship predicting bankfull discharge from drainage basin area for similar type of region or new relationship developed for the study watershed.	Often considerable variability of points around the regression lines.
	Drainage basin area at site.	Other variables that influence stream flow are not accounted for. Restored reach must have similar physiography, geologic and hydrologic conditions to sites used to develop regional curve. Limited equations available.

bankfull discharge for restoration design purposes [*Rosgen*, 1998, 2006a, 2006b; *Hey*, 2006; *NRCS*, 2007].

Regional curves are based on regression analysis using a power law of the form,

$$Q = aA^b, \tag{1}$$

where Q is bankfull discharge (typically in $ft^3\ s^{-1}$), and A is drainage basin area (typically in square miles). The regression coefficient "a" and exponent "b" depend on regional physiography, hydrology, geology, and vegetation cover. The exponent "b" is typically between 0.7 and 0.75 [*Leopold et al.*, 1964], although considerable variation is found across regions. Early work by *Emmett* [1975] and *Dunne and Leopold* [1978] established that a clear relationship between bankfull discharge and drainage area exists in most watersheds, and regional relationships are available for several areas of the United States (Figure 1 provides an example) and elsewhere [e.g., *Petit and Pauquet*, 1997]. Regional analyses usually also derive downstream hydraulic geometry relationships, expressing bankfull width, depth, and cross-sectional area as functions of drainage basin area (see *Faustini et al.* [2009] for a review and *Johnson and Fecko* [2008] for a statistical comparison between data sets). Where available, regional hydraulic geometry equations may be applied to design stable channels directly, obviating the need for a design discharge.

A comprehensive overview of the "regional curve" method is provided by *NRCS* [2007], while the National Water Management Center (NWMC) of the Natural Resources Conservation Service (NRCS) hosts a dedicated archive of regional curve studies on their web site (http://wmc.ar.nrcs.usda.gov/technical/HHSWR/Geomorphic/). The NWMC is currently partnering other federal, state, and local agencies in a mission to develop regional curves for the entire country, based on the 25 physiographic provinces previously identified by *Fenneman and Johnson* [1946]. Numerous studies reported in the academic literature [e.g., *Castro and Jackson*, 2001; *Doll et al.*, 2002; *Sweet and Geratz*, 2003; *Metcalf et al.*, 2009] and in technical reports [e.g., *McCandless*, 2003; *Metcalf*, 2003; *Chaplin*, 2005; *Dudley*, 2005; *Keaton et al.*, 2005; *Sherwood and Huitger*, 2005; *Mulvihill et al.*, 2007] support the utility of the regional curve approach. However, *Wilkerson* [2008] found that bankfull discharge could be more reliably predicted through regression against the 2 year flow than the drainage area. The *Wilkerson* [2008] approach facilitates the integration of geologic, climatic, and hydrologic factors (in addition to drainage area) into relations for predicting bankfull discharge, and its application is thus not restricted to watersheds with reliable records of gauged flows.

The regional curve method clearly has merit for estimating bankfull discharges, validating field estimates of bankfull stage, and/or establishing stable channel dimensions for river restoration projects in ungauged watersheds. The regional curves produced by federal and state agencies are freely available, and users can be confident that they have been derived with a high degree of care, adhering to best practice

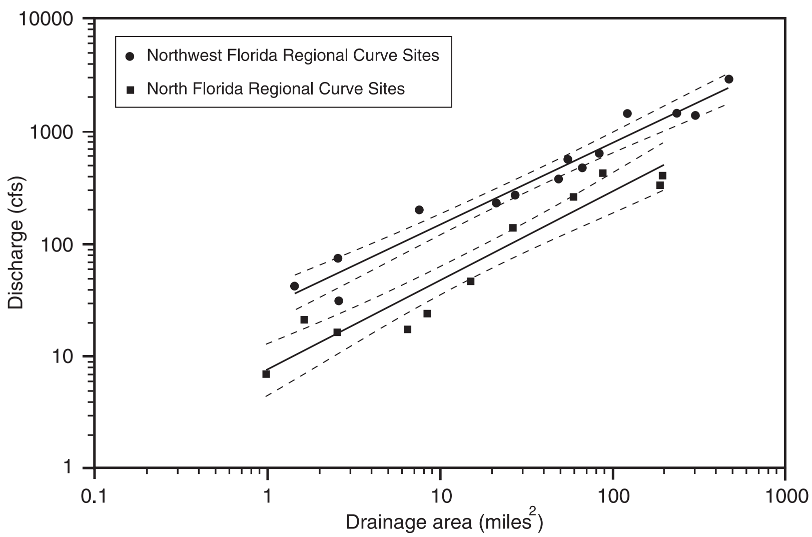

Figure 1. Regional curves for bankfull discharge estimated from drainage basin area for coastal plain streams in Florida. Northwest Florida is represented by the top solid line and north Florida by the bottom solid line with 95% confidence intervals (dashed lines). From *Metcalf et al.* [2009], reprinted with permission from John Wiley and Sons, Ltd.

in data collection and processing. Most studies also examine and report on uncertainties and include useful discussion of the methods' limitations.

However, the development of regional curves still cannot avoid the well-documented problems associated with accurately identifying the bankfull stage and the approach can be criticized as it lacks a basis in physical processes and fails to take into account the multitude of catchment variables that actually influence the flow and sediment regimes responsible for driving channel-forming processes. In practice, many regional curves exhibit considerable data scatter, making the derivation of a single value for the bankfull discharge associated with a given drainage basin area questionable statistically. This issue is also pertinent to the channel geometry method proposed by *Wharton* [1992, 1995a, 1995b] as well as downstream hydraulic geometry relationships in general. Finally, not all regions of the United States currently have regional curves, and uptake of the approach outside the United States has been patchy (however, see *Davidson and North* [2009]).

3.2. Discharge of Specified Recurrence Interval

3.2.1. Science base. The frequencies and durations of candidate channel-forming discharges have been investigated widely since the 1950s. Based on the premise that the dominant discharge must occur often enough to permit alluvial river channels to display a regime condition most of the time [*Nixon*, 1959], numerous studies have revealed a remarkable similarity in the recurrence interval of the bankfull discharge in a variety of rivers, based on the AMS of measured peak flows. Measurements in different regions in the United States by *Wolman and Leopold* [1957] showed that the recurrence interval for bankfull flow in undisturbed rivers with well-developed floodplains ranged between 1 and 5 years. Later, *Leopold et al.* [1964] evaluated 19 river reaches "where the recurrence interval of the incipient flood stage could be accurately fixed" from reliable, nearby gauging stations and found that the frequency of bankfull discharge ranged between 1.07 years and 4.0 years, although the frequency only exceeded 1.9 years at 4 of the 19 sites. While there is no consensus concerning the modal recurrence interval for the bankfull discharge, it is generally considered among practitioners that the bankfull event for perennial rivers in temperate-humid environments will occur, in most cases, every 1 to 2 years, following the findings of *Leopold et al.* [1964] and others, including *Kilpatrick and Barnes* [1964] and *Carlston* [1965].

A recurrence interval of 1.5 years was considered by *Leopold et al.* [1964] to be a representative average frequency for bankfull discharge, a figure that was later corroborated for gravel bed rivers in the United Kingdom by *Hey* [1975], and linked to the "most-probable" (modal) annual flood (with a recurrence interval of 1.58 years) by *Dury* [1973, 1976]. More recently, use of the 1.5 year flood to represent the bankfull discharge has been supported by the results of numerous regional studies in the United States [e.g., *Castro and Jackson*, 2001]. On the basis of observations in a range of hydrophysiographic regions in the United States, *Rosgen* [1998] concluded that the average recurrence interval of the bankfull discharge is 1.1 to 1.8 years, which is remarkably close to the earlier findings.

3.2.2. Science into practice. Adoption of the flood with a recurrence interval of 1 to 2 years in the AMS as a channel-forming flow equivalent to the bankfull discharge has become something of an orthodoxy in applied fluvial geomorphology and river restoration practice, and its use as a design discharge has been actively promoted in situations where use of the morphologically defined bankfull discharge is inappropriate due to past channel modifications or channel instability [*Hey*, 1997]. There is also practical evidence that the 1.5 year flood provides a viable alternative to the bankfull discharge in restoration design [*Hey*, 1994].

While using an objective measure of channel-forming discharge based on measured flows is attractive, especially in light of the potential subjectivity and challenges in deriving a value for the bankfull discharge, numerous cases have been reported where the recurrence interval of bankfull discharge has been found to lie outside the expected range of 1 to 2 years. For example, *Pickup and Warner* [1976] demonstrated that the recurrence interval for bankfull discharge may range from 4 to 10 years in the AMS, while *Williams* [1978] found that bankfull discharge corresponded to a recurrence interval of about 1.5 years in only one third of 36 cases examined, the range being 1.01 to 32 years.

Deviation from a 1.5 year recurrence interval is also supported by *Andrews* [1980], who found that the bankfull discharge for half the sites investigated in the Yampa River basin in Colorado and Wyoming had recurrence intervals that were greater than 1.75 years or less than 1.25 years, the range being from 1.18 to 3.26 years. He attributed this variability to climatic, geological, and physiographic factors. The widely applied U.S. Army Corps of Engineers manual on channel stability assessment [*U.S. Army Corps of Engineers (USACE)*, 1994] recommends, for engineering analysis, a recurrence interval of approximately 2 years for the channel-forming discharge (a frequency given significance by the findings of *Bray* [1973, 1975, 1982] for gravel bed rivers in Alberta and recently by *De Rose et al.* [2008] for rivers in Victoria, Australia), but also acknowledges that this frequency may vary between the 1 and 10 year flood flows.

Table 3 lists some of the ranges of recurrence interval for bankfull discharge reported in the literature, although the list is not exhaustive and does not include the findings of U.S. regional studies documented in a wealth of technical reports. Importantly, small differences in recurrence interval can correspond to marked differences in flow magnitude, which could translate into significant differences in designed channel dimensions for a river restoration scheme. Based on the tabulated data reported by *Crowder and Knapp* [2005] for sites on Illinois streams, the average ratio of the 2 year to 1.5 year flow is 1.27, and the average ratio of the 2 year to 1.25 year flow is 1.62. For example, the 2 year flow for Silver Creek near Freeburg, Illinois, is reported to be 148 $m^3 s^{-1}$; almost twice the 1.25 year flow of 76 $m^3 s^{-1}$. In summary, there is a growing recognition that the bankfull discharge of stable, alluvial rivers may be associated with a range of flows of varying magnitude and frequency [e.g., *Petit and Pauquet*, 1997; *Radecki-Pawlik*, 2002], which challenges the utility of an event with a unique recurrence interval as a design discharge.

A problem associated with use of the AMS to identify the recurrence interval for bankfull discharge is the potential introduction of bias due to its asymptotic lower limit of 1 year as the shortest recurrence interval event that can be identified [*Navratil et al.*, 2006]. For example, *Castro and Jackson* [2001] found the modal recurrence interval for streams in the American Pacific Northwest to be 1.0, based on the AMS. However, studies based on a partial duration analysis that considers all the independent peak discharges that exceed a specified threshold discharge, rather than just the annual maxima, have revealed frequencies of bankfull discharge considerably shorter than 1 year.

Despite methodological difficulties in defining the threshold discharge for the partial duration series of peak flows [*Petit and Pauquet*, 1997], *Hey and Heritage* [1988] discovered a range of recurrence intervals for bankfull discharge between 0.56 and 3.44 years for 14 gravel bed rivers in England and Wales, with a modal value of 0.9 years. This frequency was corroborated by *Carling* [1988] for two gravel bed rivers in northern England. These findings are unsurprising given that *Nixon* [1959] had previously analyzed flow duration data from 29 rivers in England and Wales and demonstrated that the bankfull discharge was equaled or exceeded on average 0.6% of the time; that is, slightly more than 2 days per year. Interestingly, this corresponds to a bank overtopping frequency of 2.2 times per year, which is equivalent to a recurrence interval of approximately 0.5 years (based on the reanalysis by *Leopold et al.* [1964]). In light of this, *Hey* [1998] recommended the use of exceedance durations, rather than annual recurrence intervals, to describe the frequency of the channel-forming discharge for river restoration applications.

Table 3. Variable Ranges for the Recurrence Interval of Bankfull Discharge Reported in the Literature

Discharge Frequency (years)	Source of Research or Recommendation
1 to 1.23	*Crowder and Knapp* [2005]
0.3 to 1.4	*Powell et al.* [2006]
1 to 2.5	*Leopold* [1994]; *Simon et al.* [2004]
1.02 to 2.69	*Woodyer* [1968]
1 to 3.1	*Castro and Jackson* [2001]
1.18 to 3.26	*Andrews* [1980]
1.07 to 4	*Leopold et al.* [1964]
1.1 to 4.8	*Whiting et al.* [1999]
1.01 to 5	*Wolman and Leopold* [1957]
0.7 to 5.3	*Petit and Pauquet* [1997]
1 to 10	*Brush* [1961]; *USACE* [1994]
1.01 to 32	*Williams* [1978]

These findings indicate that adoption of the flood with a recurrence interval of 1 to 2 years as the design discharge for river restoration cannot be assumed, but should be corroborated by information from other sources and analyses.

An emerging body of evidence suggests that variability in the flow regime might be responsible for the observed variation in the frequencies of bankfull flow. Flows that tend to be more effective in performing geomorphologic work, through transporting sediment and shaping the channel boundary, are often more frequent than average in base flow-dominated streams and, conversely, less frequent than average in streams with flashy hydrographs. This hydrologic influence is examined further in the discussion of effective discharge, below. It is worthy of note though that published "ranges" of frequencies tend to highlight the low populated tails of the sample distributions and conceal the more significant modal values and central portions. For example, *Soar and Thorne* [2001] used data from 58 stable sand bed rivers in the United States to conclude that, although a wide-range of recurrence intervals are possible for the bankfull condition, 86% of the sites studied fell within the 1 to 2 year range.

Studies that have highlighted inconsistencies in the recurrence intervals for bankfull discharge have variously attributed this to the influence of discharge variability, catchment size, bed material type, and other influences. For example, *Petit and Pauquet* [1997] identified that the recurrence interval for bankfull discharge was 0.5 years for small gravel bed rivers in Belgium, rising to 1.5 years for larger catchments, exceeding 2 years for rivers with base flow-dominated regimes and longer still for rivers with fine-grained beds. Despite this, to date, such investigations have failed to provide any generalized guidance to practitioners on predicting the likely range of recurrence intervals for bankfull discharge on the basis of the characteristics of the study stream or its flow regime.

The statistical treatment of gauged peak flows for flood frequency analysis is a long established practice in applied hydrology and is widely documented in the technical literature [e.g., *Robson and Reed*, 1999; *NRCS*, 1999, 2007]. The United States Geological Survey (USGS) operate and maintain a large network of gauging stations across the United States, with historical peak flow data archived and readily available from their website (http://nwis.waterdata.usgs.gov/usa/nwis/peak/). Additional data sets are also available for thousands of discontinued gauging stations. Currently, peak stream flow data from 27,500 sites can be obtained from the USGS National Water Information System. In the United Kingdom, the HiFlows-UK website (http://www.environment-agency.gov.uk/hiflowsuk/) hosts the hydrometric data archives from the various gauging authorities (the Environment Agency in England and Wales, Scottish Environmental Protection Agency in Scotland and the Rivers Agency in Northern Ireland) and includes updated flood peak data for almost 1000 stations, together with the supporting information necessary to enable hydrologists to make informed judgments concerning the utility of the data.

However, despite the existence of large networks of gauging stations in more economically developed countries like the United States and the United Kingdom, it is rare for a restoration project reach to be sufficiently close to a hydrometric station for the flow record to be applied to the project site without some adjustment to account for the difference in drainage areas. This is particularly the case for small watersheds, remote areas, and headwater streams, where gauging networks tend to be sparse and data availability limited [*Juracek and Fitzpatrick*, 2009]. The fact is that inadequate availability of raw flow data continues to represent a serious impediment to river analysis.

Even where gauge data are available, data quality issues can preclude use of historical peak discharge records for flow frequency analysis [*Juracek and Fitzpatrick*, 2009]. Issues include the following: (1) stage-discharge rating curves that are unreliable for out of bank flows due to flow bypassing the gauged section, (2) gaps and/or spurious records caused by equipment failures, (3) inadequate length of flow record, (4) inadequate representation of recent events if contemporary data are unavailable or the gauge is discontinued, (5) nonstationarity in the record reflecting historical changes to the catchment or drainage system, (6) underestimation of the true peaks if mean daily discharges are recorded/reported rather than 15 min values.

These issues are most problematic when analyzing discharges toward the extremes of the discharge record. In practice, gauge data are usually accurate for relatively frequent, in-bank flows close to bankfull.

Given the sparsity of gauging networks, restoration designers usually have to estimate the discharge of a specific recurrence interval, such as the 2 year event, for ungauged project sites. Most of the approaches they adopt involve translating data from a gauging station elsewhere in the river system or from an analog watershed.

The simplest transfer method, requiring least amount of data, is development of a regional relationship for predicting discharge of specified recurrence intervals as a power function of drainage basin area, in a manner similar to the popular regional curve method for estimating bankfull discharge. A number of relationships are available to do this, though development of a simple regression curve specific to the study watershed or parent region is often preferred [*NRCS*, 1999]. More advanced analyses use multiple regression relationships that account not only for the influence of drainage area, but also watershed climate, slope, and flood storage capacity. The U.S. Geological Survey, together with state and local agencies, has applied this type of approach to gauged watersheds within every American state [*Jennings et al.*, 1994], and the results of these advanced hydrological investigations are available in the National Streamflow Statistics database (http://water.usgs.gov/osw/programs/nss/), which includes regional regression relations for estimating peak discharges at ungauged sites in 289 flood regions nationwide [*Ries*, 2006; *Turnipseed and Ries*, 2007].

As with the regional curves used to predict bankfull discharge, peak flow relationships exhibit varying degrees of reliability, with standard errors of estimate commonly between 30% and 60%, particularly for western areas of the United States, where high flow variability, the sparsity of gauging stations, and the comparatively short duration of available flow records often combine to produce significant uncertainty [*NRCS*, 2007]. The fact is that regional regression equations are not as accurate as frequency analyses applied to the flow series from a single gauging station, and they should be applied with caution, especially when estimating recurrence intervals for flood flows in watersheds whose characteristics lie outside the ranges of values used in the development of the regression equations.

In the United Kingdom, the Flood Estimation Handbook (FEH) and associated hydrologic software [*Institute of Hydrology*, 1999; *Centre for Ecology and Hydrology*, 2007] comprise the nationally applied standard approach for flood magnitude and frequency estimation, and these tools include a number of techniques for dealing with ungauged sites and sites with short periods of record. In such cases, data are "pooled" from a group of gauging stations identified using the standard software as exhibiting similar "catchment descriptors" and assumed to share a common flow regime [*Robson and Reed*, 1999]. This pooling approach offers an alternative to conventional, regional methods that can be unreliable in geographical areas that include watersheds with contrasting hydrologic characteristics.

The FEH also supports rapid estimation of discharges for any selected recurrence interval using a multiple regression model for the median annual maximum flood, which is the standard "index" flood event used by FEH at ungauged sites in the United Kingdom, based on catchment descriptors, and then scaling this value to less frequent events according to a dimensionless growth curve. The median annual maximum flood is a good estimator of the peak flow with a 2 year recurrence interval provided that more than 15 years of AMS data are available [*Reed*, 2002].

Although advanced applications of FEH methods require the attention of an experienced hydrologist, individuals can use the FEH rapid technique to estimate the 2 year flow routinely, with just some basic training. Hence, the rapid technique is an attractive option for generating restoration design discharges for the United Kingdom when limited project resources preclude the use of more detailed analyses.

Flood-frequency estimation is inherently uncertain, and all the approaches outlined above require sound insight and judgment on the part of the individual performing the analysis. In practice, the estimates can only be considered to be reliable if they are consistent with the flood frequency behavior of the river and the characteristics of the parent watershed.

Given the number of factors that influence flood frequency, it would be surprising if the hypothesis that a discharge with a particular recurrence interval equates to the bankfull discharge went unchallenged [*Doyle et al.*, 1999, 2007; *Shields et al.*, 2003, 2008]. In essence, adoption of the flow associated with a selected recurrence interval as the design discharge for a restoration project involves a trade-off between its strengths (ease of application, speed of calculation, and apparent objectivity) and its weaknesses (high uncertainty, inability to account for the influence of fluvial processes, and considerable reliance on gauged data). In light of this, it is recommended that a design discharge based on a specified recurrence interval and derived from flood frequency analysis is only taken to be indicative of the channel-forming flow and that practitioners are encouraged, wherever possible, to validate the reliability of the design discharge using one or more of the other approaches described in this chapter.

3.3. Effective Discharge

3.3.1. Science base. Effective discharge theory is based on the premise that the stable channel morphology is intrinsically linked to the prevailing sediment transport regime. This is argued to be the case because disturbance of a stable (or graded) river generates imbalance in the transfer of sediment along its course, which initiates morphological responses (driven by erosive and/or depositional processes) that cause the channel either to adjust toward a new condition of dynamic equilibrium or recover its predisturbance morphology. According to this reasoning, the bankfull channel geometry of a stable alluvial channel is shaped by the delicate balance between sediment supply and sediment transport so that, over a period of years, sediment inputs and outputs are balanced [*Mackin*, 1948].

Wolman and Miller [1960] built on the concept of the dynamically stable river, with its "graded profile," by proposing that the geomorphic effectiveness of discharges making up the flow regime depends not only the magnitude of a flow event but also its frequency of occurrence. They argued that an alluvial river with a mobile bed will tend to adjust its bankfull capacity to the flow that transports the greatest quantity of sediment over a number of years; that is, the flow doing most geomorphic work on the channel through transporting sediment. The notion that the flow doing most work could be considered to be the dominant discharge was alluded to by *Wolman and Miller* [1960] and later by *Wolman and Gerson* [1978], though it was *Andrews* [1980] who first described this flow as the "effective discharge."

Magnitude-frequency analysis, as described by *Wolman and Miller* [1960], requires integration of the flow duration (the cumulative distribution of gauged discharges) with a sediment rating curve (the relationship between discharge and sediment transport rate) to derive a sediment load histogram (which can be expressed as the percentage of the average annual sediment yield for the range of discharge classes). The effective discharge is then defined by the peak in the sediment load histogram (Figure 2). The specific stages in computation of the effective discharge are described more fully in section 3.3.3.

Generally, the effective discharge corresponds to a moderate discharge of intermediate frequency, as demonstrated by *Costa and O'Connor* [1995] using stream power concepts. *Wolman and Miller* [1960] showed that 90% of the sediment transported in suspension (the suspended load) in the alluvial rivers they studied in the west of the United States is transported by flows with recurrence intervals of less than 5 years. It follows that, according to magnitude-frequency analysis, both low discharges with high frequencies and large, rare events with long recurrence intervals play relatively minor roles in forming the channel. This is the case because high frequency flows smaller than the effective discharge are capable of transporting little sediment and, hence, are

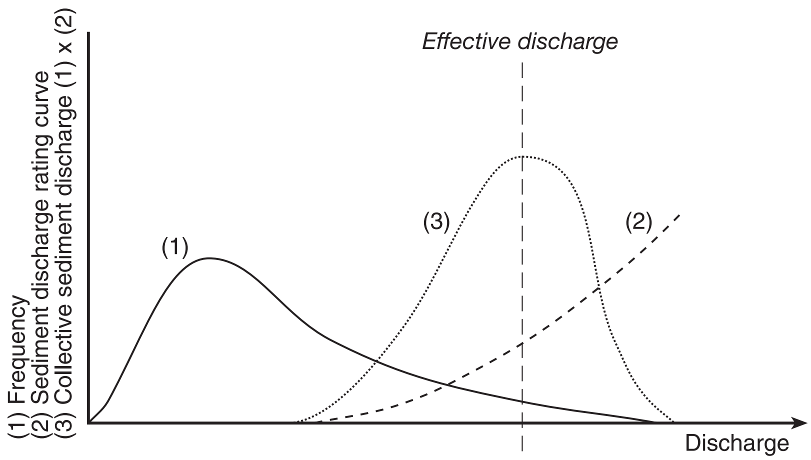

Figure 2. Calculation of the effective discharge from magnitude-frequency analysis, showing the derivation of bed material load-discharge histogram (labeled 3) from flow frequency (labeled 1) and bed material load rating curves (labeled 2).

ineffectual as channel-forming agents. Conversely, flow events significantly greater in magnitude than the effective discharge, while having the capacity to transport sediment at very high rates, occur too infrequently to have a marked, long-term influence in shaping the channel boundary.

It follows that the morphological impacts of long recurrence interval events tend to be significant only for relatively short time periods, whereas the intermediate events that occur multiple times between these extreme events cause the channel to recover its stable, or regime, morphology [*Wolman and Gerson*, 1978] by adjusting its bankfull dimensions to accommodate the effective discharge [*Hey*, 1975]. However, it should be noted that in river systems where the length of time required for full morphological recovery following disturbance from high magnitude floods is long, the recovery driven by lesser intermediate size flows is likely to be interrupted by other high magnitude events, and the hypothesis that channel dimensions are "adjusted" to the flow doing most work through sediment transport becomes less tenable. Hence, in highly responsive systems, such as those found in semiarid and arid regions, the effective discharge would not be a good representation of a channel-forming flow [*Hey*, 1975].

Despite this limitation, the effective discharge is widely regarded as the preferred choice for representing the channel-forming or dominant discharge and therefore the best candidate for acting as a design discharge for river restoration. The effective discharge has also been shown to be useful when analyzing stream ecosystems [*Doyle et al.*, 2005].

A strong case has been made that the effective discharge should equate to the bankfull discharge in dynamically stable rivers with mobile beds [*Knighton*, 1984]. This argument rests on the argument that the bankfull condition maximizes energy efficiency by minimizing the impact of in-bank boundary roughness, while avoiding energy losses to floodplain vegetation resistance and lateral momentum exchange, so maximizing the amount of energy available to be expended in performing geomorphic work through sediment transport. This theoretical argument is supported by the results of empirical studies that have described how sediment transport rate increases rapidly during high in-bank flows approaching the bankfull level [e.g., *Parker et al.*, 1982; *Andrews*, 1984; *Carling*, 1988; *Ashworth and Ferguson*, 1989; *Warburton*, 1992; *Andrews and Nankervis*, 1995; *Whiting et al.*, 1999; *Ryan et al.*, 2005].

Equivalence between the effective and bankfull flows has been demonstrated in a wide range of river types and settings [*Wolman and Miller*, 1960; *Leopold et al.*, 1964; *Andrews*, 1980; *Knighton*, 1984; *Carling*, 1988; *Andrews and Nankervis*, 1995; *Batalla and Sala*, 1995; *Pitlick and Van Steeter*, 1998; *Torizzo and Pitlick*, 2004; *Powell et al.*, 2006]. Magnitude-frequency analyses of the Lower Mississippi and Pearl Rivers reported by *Biedenharn et al.* [1987] revealed that the effective discharge had a recurrence interval close to 2 years at many sites, while *Watson et al.* [1997] suggested an upper frequency bound of 5 years for streams in north Mississippi and *Whiting et al.* [1999] calculated an average effective discharge recurrence interval of 1.4 years for headwater, gravel bed streams in Idaho, which is remarkably close to the 1.5 years modal value found by *Leopold et al.* [1964], *Hey* [1975], and others. *Simon et al.* [2004] considered the 1.5 year peak flow to be a fair representation of the effective discharge for rivers dominated by suspended sediment transport across the United States.

Since its conception in 1960, magnitude-frequency analysis has proven to be a popular geomorphic technique with a wide range of applications. Examples include detailed investigations of sediment transport [e.g., *Ashmore and Day*, 1988; *Lyons et al.*, 1992; *Biedenharn and Thorne*, 1994] and studies reexamining the magnitude-frequency methodology itself [e.g., *Sichingabula*, 1999; *Orndorff and Whiting*, 1999; *Biedenharn et al.*, 2000, 2001]. The technique has also been employed to facilitate prediction of the trend and magnitude of channel response to hydrological change [*Tilleard*, 1999] and has been used as a mechanism to assess the restorative potential of rehabilitation schemes by comparing observed channel response (a function of flow events since project implementation) with the potential for morphological change, inferred from the full spectrum and range of flows in the long-term record [*Downs et al.*, 1999].

3.3.2. Science into practice. Numerous studies have advocated use of the effective discharge as the design discharge for river restoration [e.g., *Orndorff and Whiting*, 1999; *Shields et al.*, 2003, 2008; *Goodwin*, 2004], with reliance on bankfull discharge or a recurrence interval flow considered "risky and unwise" [*Doyle et al.*, 2007]. In addition, magnitude-frequency analysis of sediment transporting flows allows quantification of the total sediment yield and enables sediment continuity objectives to be tested as part of the restoration process, so providing the best chance of achieving dynamically stable channel morphology.

However, prior to calculating and using the effective discharge as a design discharge for river restoration, three issues should be considered:

1. Selecting a single design discharge of intermediate magnitude implies that the morphological impacts of all other flows may be ignored, which has been shown in numerous studies not to be the case.

2. There is a body of evidence that suggests a degree of discordance between the effective and bankfull discharges, yet currently there are no generally accepted deterministic or probabilistic methods for relating the two.

3. Of the available approaches to specifying the design discharge for river restoration, the effective discharge requires the most effort and data. In light of this, practitioners desire a standardized procedure for calculating the effective discharge with practical guidance for data collection and processing.

These issues represent real challenges to restorers wishing to use the effective discharge as a design flow and impose potential constraints on the use of magnitude-frequency analysis in practice.

The magnitude and recurrence interval of the effective discharge are functions of the flow frequency distribution (usually represented by a histogram of measured discharges), the sediment rating curve and, most importantly, how the flow and sediment regimes represented by these two relationships interact.

The most significant influence on the effective discharge is often the degree and type of skewness in the flow frequency distribution. Negatively skewed distributions indicate a highly variable, flashy regime. In a flashy flow regime, a greater proportion of the sediment load is likely to be transported by infrequent, high magnitude flows. This explains why major flood flows are channel-forming events in semiarid and arid regions [*Wolman and Miller*, 1960; *Werrity*, 1997], particularly for streams with resistant boundaries that render more frequent, in-bank flows ineffective in shaping the channel [*Harvey*, 1969; *Baker*, 1977].

Wolman and Miller [1960], *Baker* [1977], *Andrews* [1980], and *Andrews and Nankervis* [1995] reported that negative skewness in flow frequency increases as drainage basin area decreases, so that, in very small catchments, the effective discharge is likely to correspond to a low frequency event. However, the influence of watershed area was found to be insignificant by *Whiting et al.* [1999] and *Torrizo and Pitlick* [2004]. It may be the case that the lower frequency of effective discharges observed in smaller watersheds may stem simply from the associated increase in the discharge variance, with some evidence linking flow variability to bankfull depth [*Pizzuto*, 1986], possibly due to a greater number of events capable of exporting sediment onto the floodplain.

In streams that exhibit positively skewed flow frequency distributions (base flow dominated) but rarely experience discharges capable of overtopping their banks, high frequency, in-bank flows with relatively low stages may be the most effective in terms of sediment transport over a period of years, especially when the river bed material is highly mobile. Where this is the case, the overall form of the channel is related to events less frequent than the effective discharge based on magnitude-frequency analysis [*Harvey*, 1969]. The geomorphological significance of flows below bankfull, resulting in the effective discharge being smaller than the bankfull discharge, is supported by a number of field studies [e.g., *Benson and Thomas*, 1966; *Pickup and Warner*, 1976; *Webb and Walling*, 1982; *Nolan et al.*, 1987; *Lyons et al.*, 1992; *Whiting et al.*, 1999; *Orndorff and Glonek*, 2004; and others].

The significance of the sediment transport threshold and mobility of bed sediments was addressed by *Werrity* [1997], who noted that the streams studied by *Wolman and Miller* [1960] were predominantly sand bedded and that the effective discharge concept is most valid in these streams because the threshold discharge for sediment entrainment is low. Indeed, in channels with beds comprising easily mobilized, fine sands and positively skewed flow distributions, it is conceivable that base flow is the most effective discharge in terms of long-term sediment transport, especially where there is an abundant sediment supply [*Hey*, 1975]. However, as the entrainment threshold increases, the frequency of the effective discharge tends to decrease and, in gravel bed rivers, a significant proportion of the low flow distribution may be argued to be entirely ineffective. Extending this line of reasoning to cobble and boulder-bed streams with low stream powers and negligible sediment loads indicates that the effective discharge concept is inapplicable to such watercourses.

There is a tendency for the effective discharge to have a high magnitude and low frequency of occurrence if the sediment-rating curve has a steep gradient (a high exponent in the power relationship of sediment transport rate as a function of water discharge). As a result, in streams that transport fine sediment, predominantly in suspension, the effective discharge is lower and more frequently occurring (possibly less than the bankfull discharge) than in streams predominantly transporting coarse sediments as bed load [*Hey*, 1975].

Emmett and Wolman [2001] revealed that the ratio of effective to bankfull discharges in gravel bed streams ranged from 0.98 to 1.31 (representing a doubling of the recurrence interval), the ratio correlating significantly with the exponent of the bed load rating curve, which was shown to increase with bed surface particle size. They demonstrated that, in very coarse bed streams, flows above bankfull appear to be the most effective, in terms of transporting sediment. In line with these findings, *Whiting et al.* [1999] demonstrated that up to 37% of the bed load can be transported by flows above the bankfull discharge. The exponent in the bed load rating curve was found by *Emmett and Wolman* [2001] to be 2.5 when bankfull and effective discharges were equivalent. Similarly, *Quadar and Guo* [2009] discovered that the effective discharge has a recurrence interval of 1.5 years when the exponent was 3.5. Interestingly, if sediment transport rate only increases weakly with discharge, this could counter the influence of a high entrainment threshold on the frequency of the effective discharge [*Wolman and Miller*, 1960; *Andrews*, 1980].

In streams where the gradient of the sediment-rating curve is mild, there may be no discernible peak in the sediment load histogram derived through the magnitude-frequency analysis, indicating the existence of a range of geomorphic effective flows that, cumulatively, are responsible for shaping the channel and maintaining its morphological forms and features [e.g., *Biedenharn and Thorne*, 1994]. It is not surprising then that *Ashmore and Day* [1988], for streams in the Saskatchewan basin, Alberta, and *Nash* [1994], for American streams in a range of physiographic regions, concluded that that no generalization can be made regarding the recurrence interval of the effective discharge.

This discussion indicates that subtle changes in the character of the flow distribution and/or the shape of the sediment transport rating curve can have marked impacts on the magnitude and frequency of the effective discharge and its relationship to bankfull discharge. Owing to the combined influence of climatic, geologic, and physiographic factors, the frequency of the effective discharge can also vary along length of a watercourse as well as between streams [*Andrews*, 1980]. Application of the effective discharge concept may be inappropriate in very small catchments featuring very highly variable or strongly skewed flow distributions and streams with boulder or cobble beds and very low sediment transport rates at all discharges below bankfull.

Summarizing, the effective discharge methodology is the most advanced and scientific representation of the channel-forming or dominant discharge, but it is also the most demanding in terms of data and is subject to considerable uncertainty when the input data are synthesized for ungauged sites. Magnitude-frequency analysis involves subjective decision making [*Crowder and Knapp*, 2005; *Lenzi et al.*, 2006], and despite wide support among river restoration practitioners, application of the effective discharge theory for stable channel design remains problematic in many situations. However, it is encouraging that 50 years after Wolman and Miller's groundbreaking paper on the geomorphic effectiveness of floods, research on this important topic continues, with new representations of the effective discharge forthcoming.

For example, *Emmett and Wolman* [2001], *Vogel et al.* [2003], and *Klonsky and Vogel* [2011] have found close agreement between the effective discharge and the half-load discharge, which is defined as the discharge above and below which 50% of the overall sediment load has been transported over time, while *Copeland et al.* [2005] found that the 75th percentile flow on the cumulative sediment transport curve provides an improvement in the relationship with bankfull discharge compared to that for the conventionally calculated, effective discharge (Figure 3).

Finally, *Doyle and Shields* [2008] recently introduced the "functionally equivalent discharge" as the single flow that would produce the same sediment yield as that generated by the entire range of discharges actually experienced by the river. This approach is commendable for attempting to account, albeit indirectly, for all the flows capable of performing geomorphic work through transporting bed material; an aspiration for channel restoration design that continues to elude any of the currently employed, rational, scientific methods.

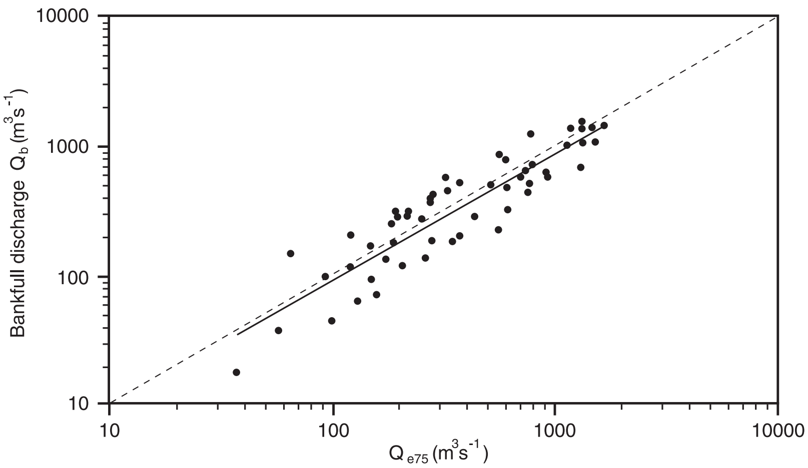

Figure 3. Relationship between the discharge marking the upper limit of the range of discharges that cumulatively transport 75% of the average annual bed material load, Q_{e75}, and the bankfull discharge, Q_b, for 57 American sand bed rivers. Solid line is the best fit power relationship. Dotted line marks equality [*Copeland et al.*, 2005].

3.3.3. Standardized procedure for calculation. The challenges of deriving an effective discharge value in practice have been highlighted by *Orndorff and Whiting* [1999] and *Shields et al.* [2008] who demonstrated the use of statistical software to facilitate the calculations. A standardized procedure for calculating the effective discharge has been proposed and described in detail by *Biedenharn et al.* [2000, 2001] who argued that a procedure is required in order that effective discharges for different sites may be compared and so that practitioners know how to avoid common data collection and processing pitfalls that introduce uncertainty into a magnitude-frequency analysis. Also, while the procedure appears relatively straightforward, in practice, there are a number of potential difficulties with the assimilation, processing, and interpretation of data; meaning that the effective discharge is not only sensitive to the availability and caliber of data, but also influenced by decision making during the analysis.

Biedenharn et al.'s [2000, 2001] procedure adheres to the approach of *Wolman and Miller* [1960] and involves three stages: (1) constructing a frequency distribution of discharges, (2) constructing a sediment transport rating from measured data or using an appropriate sediment transport equation, and (3) integrating the two relationships by calculating the sediment transport rate (in units of mass per year) for the median value of each discharge class and then multiplying that rate by the frequency of occurrence of that discharge to yield a histogram of average annual sediment yields for the range of discharge classes. The effective discharge is then defined as the median discharge of the modal class in the sediment load histogram.

Two obvious constraints on deriving the effective discharge stem from the limited availability of gauged flow records and measured sediment transport rates for the great majority of candidate river restoration project sites. However, if the restoration site is close to a gauging station, a flow frequency distribution can be derived from the record of measured discharges. The quality of the distribution depends upon the reliability of the gauged discharges (particularly measurements at very low and high stages), the period of record and the time-base of the recorded discharges. Ideally, the period of record should be at least 10 years, though for long periods of record, care should be taken to ensure that the record is representative of the prevailing hydrology by checking for nonstationarity in the flow regime. To accurately capture the magnitude of the peak flows, hourly, or better still, 15 min data (as collected by the USGS) are essential, as the more readily available, mean daily discharge values can significantly underestimate instantaneous peak flows and sediment transport associated with high magnitude events in small- and medium-sized catchments. These recommendations for assimilating gauged flow data are also valid for calculating the dominant discharge as an event with a specified recurrence interval (see section 3.2.2).

The effective discharge can be sensitive to the number of discharge classes used to generate the flow frequency distribution [*Orndorff and Whiting*, 1999; *Sichingabula*, 1999; *Crowder and Knapp*, 2005; *Lenzi et al.*, 2006]. *Biedenharn et al.* [2000, 2001] and *Soar and Thorne* [2001] recommend starting with 25 discharge classes and then applying an iterative process of adjusting the number to achieve intervals that are as small as possible while maintaining a "smooth" frequency distribution. The minimum discharge should be set to zero in streams transporting fine sediment in suspension and to the critical discharge for the threshold of bed load motion for coarse-bedded channels. Uniform, arithmetic discharge classes must be used to prevent bias [*Soar and Thorne*, 2001], which means that the effective discharge might fall within the first class when the flow distribution is base flow-dominated and highly skewed toward the smaller flows. Increasing the number of discharge classes may provide improved resolution of the effective discharge when this is the case.

Recognizing that discretizing the discharge series can influence the magnitude and frequency of the effective discharge by masking the true variability and episodic nature of sediment transport events, several researchers have sought alternatives to conventional "class-based" calculation of the effective discharge. *Sichingabula* [1999] recommended calculating an "event-based" effective discharge, defined as that with the maximum sediment load considering all of the individual events, and *Goodwin* [2004] and *Klonsky and Vogel* [2011] experimented with analytical solutions using theoretical probability density functions to represent the distributions of discharges and sediment loads. A different approach was outlined by *Soar and Thorne* [2001] in which very small discharge intervals (potentially hundreds or thousands of classes) could be employed by discretizing an event-based flow duration curve (cumulative flow distribution), rather than developing a flow frequency histogram directly from the raw discharge series, and then identifying a quasi-event-based effective discharge through repeated, moving average, smoothing of the resultant sediment load histogram.

These methods can more accurately describe the empirical distribution of sediment transport effectiveness and so potentially overcome some of the common limitations of the methodology. However, further research, testing, and standardization would be required before these innovative approaches could be considered for routine application to river restoration design based on gauge records from hydrologic stations.

At ungauged sites, and gauged sites where the flow record is considered unreliable or unrepresentative, it is necessary to "synthesize" a flow distribution. There are two approaches to achieving this, both involving the transfer of gauged flows from nearby gauging stations within the same watershed or analog sites in watersheds with similar physiographic and hydrologic characteristics. The approaches are (1) drainage area-flow duration curve method and (2) regionalized flow duration curve method.

The first approach involves fitting power relationships to data sets linking discharge exceedance duration to upstream drainage basin area, ideally based on data from several gauging stations [see *Hey*, 1975]. The second approach involves scaling flow duration according to a nondimensional discharge index such as the ratio of discharge to the 2 year flow, as proposed by *Watson et al.* [1997]. Reference should be made to the works of *Biedenharn et al.* [2000, 2001] for further details on these methods.

Extrapolation of flow duration curves from gauged to ungauged sites can also be achieved by using bankfull discharge as the normalization parameter, although this can introduce additional uncertainty as calculating the bankfull discharge is itself subject to error and, in any case, been shown to have an inconsistent recurrence interval. An alternative approach is available that derives dimensionless flow duration statistics scaled on the mean flow for a suite of regions identified as sharing similar watershed characteristics [*Holmes et al.*, 2002]. This approach has been adopted in a component of the Low Flows 2000 suite of hydrologic models for use in England and Wales [*Young et al.*, 2003].

In developing the sediment rating curve for an effective discharge calculation, it is the bed material load that should be used, rather than the total load, as this excludes the wash load component. The bed material load is the proportion of the total sediment load composed of grain sizes found in appreciable quantities in the stream bed. It should be noted that in gravel bed rivers, the bed material load moves as bed load, but in sand bed streams, significant quantities of bed material load are distributed through the water column as suspended load. The wash load is the portion of the total sediment load composed of grain sizes finer than those found in appreciable quantities in the stream bed, with the 10th percentile in the bed sediment particle size distribution often taken as the boundary between the wash load and bed material load components of the total load. It is usually assumed that wash load plays no significant role in shaping the channel, passing through the reach, but not long residing there.

When measured, suspended load data are available from a gauged site; particles finer than sand (that is less than 0.062 mm) should be excluded when deriving the sediment rating curve as these are likely to constitute wash load only. Routine bed load measurements are rare, but if a data set does exist, it can be combined with the coarse fraction of the measured suspended load to produce a better representation of the bed material load. Typically, sediment rating curves have the form of a power relationship expressing sediment concentration or transport rate as a function of discharge, although in some cases, two or even three log-log segments are necessary to describe the relationship adequately [see *Simon et al.*, 2004; *Shields et al.*, 2008].

When measured sediment transport data are unavailable, a suitable sediment transport equation can be used to synthesize a rating curve. If the bed material load moves predominantly as bed load (as in gravel bed rivers), then a dedicated bed load transport equation should be used. Alternatively, other equations are available that account for both the bed load and suspended load components of the bed material load. While there are a range of equations available to the practitioner [e.g., see *Yang*, 1996], selecting the equation best-suited to the type of river and bed material is critical to minimize uncertainty in calculated sediment loads. In this context, the Stable channel Analytical Method (SAM) hydraulic design package [*Raphelt*, 1990; *Thomas et al.*, 2002] provides useful guidance on matching the equation selected to the scale of stream and type of sediment involved. However, it should be remembered that uncalibrated calculations of bed material load are prone to substantive uncertainty. In practice, the absolute magnitudes of calculated sediment loads will vary markedly depending on the sediment transport equation selected, and experience shows that calculated loads are unlikely be within ±50% of the actual load more than 70% of the time. Recognizing this, it is fortunate that prediction of the effective discharge based on the modal class in the bed material load histogram has been shown to be insensitive to both the choice of sediment transport relationship [*Barry et al.*, 2008] and the coefficient in the sediment transport rating curve [*Goodwin*, 2004].

The bed material load histogram should display a continuous distribution with a single modal discharge class, and conventionally, the effective discharge corresponds to the median discharge of the modal class. Alternatively, the effective discharge can be estimated by drawing a smooth curve through the tops of the histogram bars and inferring the effective discharge from the peak of that curve.

As checks on the reliability of the calculation, the magnitude of the effective discharge should be compared to that of the bankfull discharge, where available, and predicted effective discharges with recurrence intervals outside the range of 1 to 3 years, based on the AMS, should be queried and possibly reexamined. Finally, it is recommended that a cumulative frequency curve be plotted from the bed material load data to identify other potentially important flows and the possible existence of a range of effective discharges, as indicated by breakpoints in the gradient of the curve [after *Biedenharn and Thorne*, 1994].

4. PROGRESS AND PROSPECTS: TOWARD THE USE OF MULTIPLE DESIGN DISCHARGES

While the effective discharge is clearly important geomorphologically, unless it relates closely to the bankfull discharge, its utility as a design discharge for river restoration may be limited. There is clearly a need for further, concerted research to provide improved guidance on the application of magnitude-frequency analysis and to develop objective methods of predicting and accounting for differences between the effective and bankfull flows.

As a rule of thumb for meandering sand bed rivers in the United States, *Soar and Thorne* [2001] found that mean annual and bankfull discharges, respectively, formed the lower and upper bounds to a range of effective flows. The effective discharge was found to be less than bankfull at 86% of the sites studied. *Biedenharn and Thorne* [1994] also demonstrated for the lower Mississippi River that the longitudinal water surface profile at the upper limit of the range of effective flows (with a recurrence interval of 5 years) coincided with the upper boundary of the range of top of bank elevations.

These findings challenge the existence of a single channel-forming flow, in that the effective discharge in sand bed streams only appears to correspond to the bankfull discharge in certain cases. In fact, based simply on numerical analysis, *Soar and Thorne* [2001] hypothesized that equivalence was unlikely because the effective discharge corresponds to the inflection point (point of steepest gradient) in the cumulative sediment load frequency curve (the cumulative distribution of sediment yield as a function of discharge, derived through the magnitude-frequency analysis), whereas the bankfull discharge tends to coincide with the upper breakpoint in the curve, which is associated with the transition from in-channel to overbank flow, and a marked discontinuity in the sediment rating curve due to the break in bank slope, rapid increase in width, increased flow resistance on the floodplain, and exchange of momentum between in-bank and overbank flows (Figure 4).

Research on large rivers with both single-thread and multi-thread planforms has provided some support for this hypothesis, whereby the effective discharge has been shown to correspond to an elevation at the top of channel bars (i.e., barfull discharge), at a stage well below bankfull [see *Latrubesse*, 2008]. This phenomenon is demonstrated in the results of magnitude-frequency analysis of the Brahmaputra River, Bangladesh [*Thorne et al.*, 1993], confirming also that the effective discharge has morphological significance in braided as well as meandering rivers and suggesting that it might provide a useful design flow in the restoration of multithread as well as single-thread channels.

Further analysis of the data set of American sand bed rivers compiled by *Soar and Thorne* [2001] revealed that the variance in discharges appears to exert an important influence on the magnitude and variability of the ratio between bankfull discharge, Q_b, and effective discharge, Q_e. Specifically, this ratio appears to be largest when the flow distribution is skewed toward small discharges, as represented by the ratio of the 2 year peak flow, Q_2, to the mean annual (time averaged) discharge, Q_m. The best fit relationship is a power function (Figure 5) which explains 73% of the variance in Q_b/Q_e, and is given by

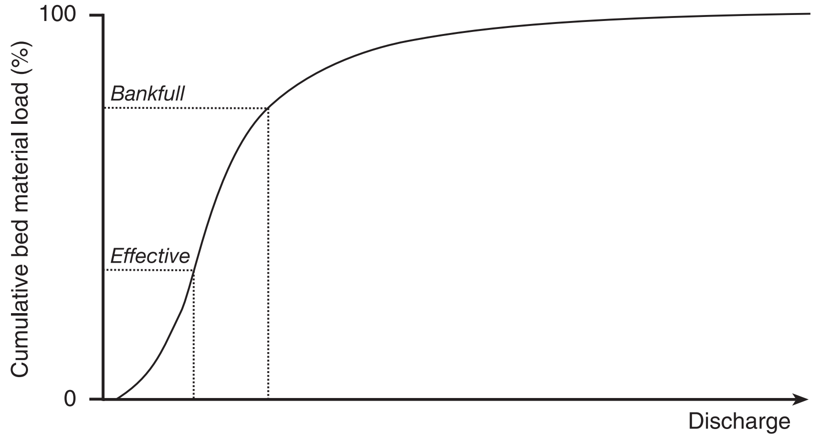

Figure 4. Hypothetical curve of cumulative bed material load as a function of discharge, derived from magnitude-frequency analysis, showing the locations of the effective discharge at the inflection point and the bankfull discharge at the upper break point [*Soar and Thorne*, 2001].

$$\frac{Q_b}{Q_e} = 0 \cdot 16 \left(\frac{Q_2}{Q_m} \right)^{1 \cdot 35}. \tag{2}$$

In base flow–dominated streams with infrequent flood flows, it appears that the small to intermediate floods that occur frequently in between the high-magnitude events are highly effective in transporting sediment over a period of years. In such cases, the bankfull flow, rather than the effective discharge, might be a better representation of the dominant discharge, in that it exerts a stronger influence on and corresponds more closely with the channel morphology.

The impact of flow variability on discordance between the bankfull and effective discharges is illustrated in Figure 6 for three of the American sand bed streams analyzed by *Soar and Thorne* [2001]. However, while equation (2) provides initial guidance for channel restoration design in sand bed rivers, further research is strongly recommended to verify and develop this approach.

In addition to more deterministic understanding of the discordance between effective and bankfull discharges, further development of regional curves used for predicting bankfull discharges should be encouraged, with research focused on the evaluation of uncertainties, broadening of the databases from which regional curves are developed within

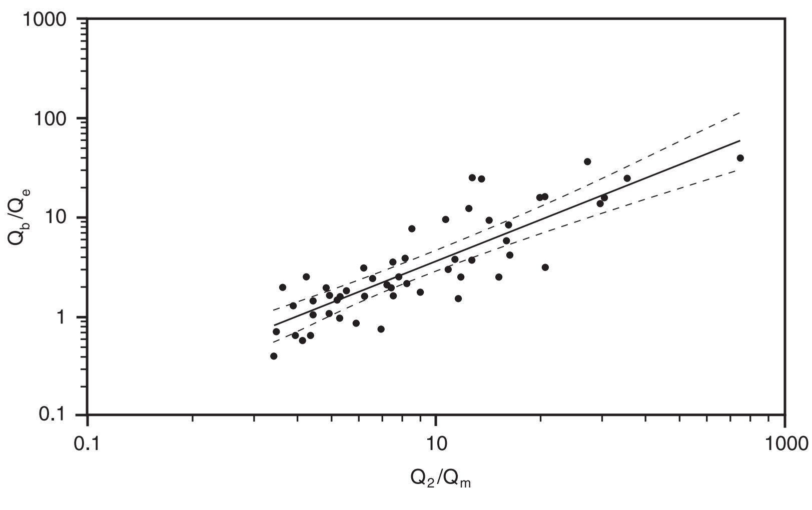

Figure 5. Ratio between bankfull discharge, Q_b, and effective discharge, Q_e, for American sand bed rivers expressed as a function of flow variability, defined as the ratio between the 2 year recurrence interval flow, Q_2, and the mean annual (time averaged) discharge, Q_m [*Soar and Thorne*, 2001].

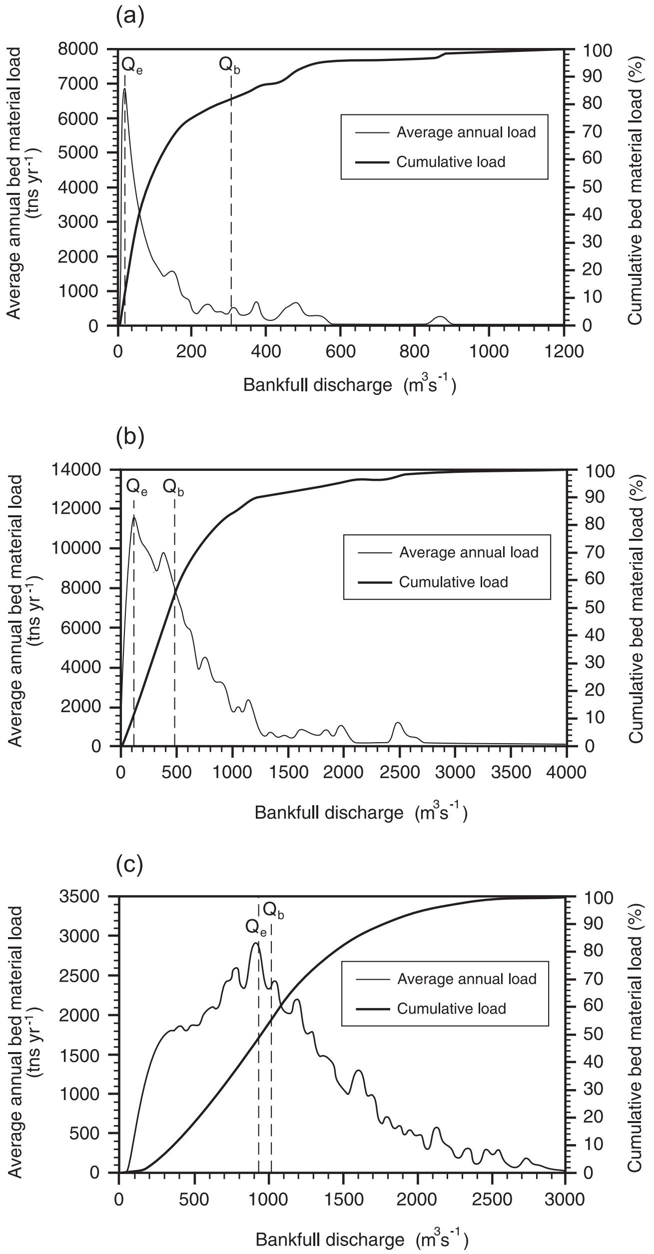

Figure 6. Bed material load histograms and cumulative sediment curves for: (a) the East Nishnabotna River at Red Oak, Iowa (Q_2/Q_m = 20.3), (b) the Tombigbee River near Amory, Mississippi (Q_2/Q_m = 11.4), and (c) the Wabash River at Riverton, Indiana (Q_2/Q_m = 4.5) [*Soar and Thorne*, 2001].

and between regions and clear identification of limitations to applicability of the concept in restoration design.

The three design approaches outlined and discussed here offer river restorers flexibility in specifying a design discharge, but cannot account objectively for the constructive, destructive, and restorative impacts of the "range" of flows which are actually likely to occur in nature and which are recognized as important in shaping the plethora of morphological features found in alluvial stream channels [*Wolman and Gerson*, 1978; *Yu and Wolman*, 1987].

For mountain streams, both *Phillips* [2002] and *Lenzi et al.* [2006] described the occurrence of two potentially dominant discharges that can exert significant geomorphic impacts: a relatively frequent discharge responsible for maintaining the channel, shaping in-stream sediment features, and preventing significant accumulations of fine sediment, and a second, less frequently occurring discharge responsible for shaping the channel's banks, controlling its width and configuring its planform. The existence of multiple formative discharges was corroborated in research on the Tagliamento River, Italy, by *Surian et al.* [2009], where flows less than half bankfull discharge appear to be formative for the channel bed sediment, the bankfull discharge (with just over a 1 year recurrence interval) is formative with respect to low elevation bars, while larger events (with recurrence intervals of up to 5 years) are the most effective for gravel transport on the high bar features and are responsible for morphological changes to the islands.

In their original treatise on magnitude-frequency analysis, *Wolman and Miller* [1960] clearly stressed that the channel shape is affected by a *range* of flows rather than a single, formative flow. It follows that channel reconstruction should be based on the precept that every competent flow event that occurs exerts some influence on channel form and that the shape and dimensions of the channel at any time are the weighted sum of the effects of all the preceding discharges [*Pickup and Reiger*, 1979]. However, at present, the science base underpinning channel restoration design is insufficiently advanced to support morphological modeling of the complex process-form interactions involved in the semicontinuous evolution of channel morphology that occurs in natural, alluvial streams.

Recognizing this, a feasible first step in accounting for the significant impacts of competent flows other than the single, effective discharge would be careful inspection of the cumulative sediment transport curve to identify the *range of effective flows* responsible for transporting the great majority (say 70–80%) of the sediment load and, importantly, break points in the cumulative curve associated with sedimentary and morphological features in the cross section that have particular ecohydraulic and hydromorphological significance (e.g., the base flow channel, low and high bar tops, bankfull stage) in dynamically stable, alluvial channels [*Biedenharn and Thorne*, 1994; *Surian et al.*, 2009]. This would allow restorers to incorporate not one but a series of nested design discharges into their restoration plan.

A more ambitious approach to accounting, first, for the full spectrum of competent flows and, second, for the fact that the future occurrence, timing, and sequencing of events cannot be predicted or even known, is to perform a series of future channel stability assessments to check that probable design outcomes are acceptable with respect to erosion, sedimentation, and channel evolution [see *Soar and Thorne*, 2001; *Shields et al.*, 2003, 2008].

In this context, the concept of "total restoration potential" may be useful [*Downs et al.*, 1999]. This approach has been used to assess the anticipated performance of in-stream river rehabilitation structures and is based on the ability of the natural sequence of flows to transport the quantity of sediment necessary to modify the channel morphology significantly. By adopting this approach, the potential for geomorphic success of a restored channel can be assessed according to whether the average annual bed material load in the restored channel (transport capacity) matches the mean annual bed material load input from upstream (sediment supply). As the annualized computations can be performed quickly once the supply-capacity model has been developed, it is possible to run them for a large number of possible hydrologic futures, featuring selected frequencies and sequences of transport events, in effect, to model multiple scenarios for the hydrologic and sediment loadings imposed on the restored reach.

Use of this design closure loop would not only validate the efficiency and resilience of the restored channel geometry but also identify particular events or combinations of events likely to destabilize the channel and, so, facilitate the design modifications necessary to reduce the risk of a loss of dynamic stability in the medium- to long-term to a tolerable level. Testing the sensitivity of a restoration design to future sediment impacts based on analysis of a range of realistic possible scenarios seems likely to become an essential component of restoration design as it becomes clearer that future flow and sediment regimes will be different from those of the past, an inevitable response to global warming and ongoing changes in watershed land use.

Consideration of the ecological significance of the design flows alongside their morphological significance is further emphasized by emerging evidence that a suite of flows must be considered for successful restoration of the diversity of physical habitats necessary to support sustainable ecological functioning in a restored river [e.g., *Kondolf et al.*, 2001; *Doyle et al.*, 2005; *Smith and Prestegaard*, 2005]. The significance of both low and flood flows to riverine ecosystems is now well established [*Poff et al.*, 1997; *Postel and Richter*, 2003] and is manifest in the emerging field of "ecohydrology" [*Hannah et al.*, 2007]. Clearly, channel restoration designs will, in future, have to account fully for the diverse ecological roles of flows other than the channel-forming discharge. In this context, it is significant that new guidance for federal and state services staff responsible for permitting river restoration proposals in rivers draining to the west coast of the United States [*Skidmore et al.*, 2011] stresses that restoration designers must demonstrate a thorough understanding of the entire flow regime before being permitted to proceed to construction.

The importance of in-channel fluvial features is widely recognized, particularly during summer low flows (often measured by the 95th percentile flow or the mean annual minimum 7 day flow) that may limit the combinations of depth and velocity necessary for particular species or life stages. Habitat diversity at low flows is often created through the construction of in-stream structures, such as weirs and flow deflectors that are sited significantly below the bankfull level. Interactions between these structures, the flow field and sediment dynamics at discharges well below the conventional design flow are responsible for generating the desired patterns of velocity, depth, scour, and fill. However, in-stream rehabilitation structures can adversely impact channel conveyance capacity, and this aspect of their functioning must also be addressed in their design. Clearly, it is essential to consider multiple discharges in the design, testing, and appraisal of restoration schemes that employ in-stream structures [*Downs and Thorne*, 1998].

This is not to underestimate the significance of flood flows with recurrence intervals considerably longer than that of bankfull discharge, which impart numerous advantages to riverine ecology, at multiple scales within the fluvial hydrosystem [*Petts and Amoros*, 1996]. These "environmental maintenance flows" [*Whiting*, 2002] are crucial in several ways, including "power washing" coarse bed materials to remove suffocating blankets of fines, removing overly mature bank and riparian vegetation, depositing sediment, plant seeds, and propagules on floodplains, recharging floodplain aquifers, improving the productivity of floodplain habitats and driving wetland dynamics.

Many restoration schemes are implemented in channels with multiple functions, requiring designs that balance targets for ecology and biodiversity with those for flood control, land drainage, and channel stability. Restoration designs for such multifunctional restorations commonly employ multistage channels comprising a "regime" channel, sized to convey the channel-forming (design) discharge, within a wider floodway, sized to convey a much larger flood event with a designated recurrence interval. As noted above, in such situations, the need to promote habitat diversity and sustain fish passage during critical low flows is often addressed through the construction of in-stream structures within the "regime'" channel.

Designing these complex channel configurations requires optimization of fluvial conditions at multiple flow stages based on design discharges that cannot be derived using the conventional, regime-based methods described herein. This is the case because regime approaches cannot account for the significant energy exchanges that take place at the interfaces between the inner channel, regime channel, and the high stage floodway, and therefore cannot properly mitigate against the risk of lesser channels being infilled during sediment transporting events that overtop them or channel scour due to elevated boundary shear stresses when flood flows are contained between levees bounding the floodway. Recognizing this, there is a strong research need for improved understanding and modeling capability in the design of multistage channels.

5. CONCLUSIONS

Each of the approaches to defining a design discharge for river restoration described here employs different arguments to support the case that it can adequately represent the "dominant discharge" or channel-forming flow for restoration design purposes.

The case for the bankfull discharge rests on its clear morphological association with the capacity and dimensions of stable channels that are "in regime." Selection of a flow with a recurrence interval of 1 to 2 years is supported by the premise that the dominant discharge must occur sufficiently often for alluvial river channels to maintain regime dimensions most of the time, coupled with the widely established similarity in the recurrence intervals for bankfull flows in a variety of river types. The effective discharge concept seeks to integrate the sediment transport processes responsible for doing work on the channel and so forming its dimensions.

In practice, each of these approaches has been demonstrated to have some utility in the river restoration design process. However, as discussed in this chapter, relationships between the design flows produced by the different prescribed methods remain deeply equivocal, and none of them can be applied routinely or universally.

Recognizing this, it is recommended that river restoration projects employ all applicable methods, so that the results can be cross-checked against each other to improve confidence that the selected design discharge does adequately represent the channel-forming flow.

Looking ahead, effective discharge analysis has considerable potential for further advances in computational methods that could provide improved insights into the morphological significance of different discharges within the effective range of flows and so increase their utility in restoration design. In addition, further development of regional curves used for predicting bankfull discharges should be encouraged, with research focused on the evaluation of uncertainties, broadening of the databases from which regional curves are developed within and between regions, and clear identification of limitations to applicabilily of the concept for river restoration.

In conclusion, river restoration design must work toward improving the biological integrity and sustainability of degraded riverine ecosystems by mimicking not only the morphological diversity that is appropriate to the type of restored channel within what is usually a modified watershed setting [*Dufour and Piégay*, 2009] but also restoring the fluvial processes that sustain the ecological functionality of the stream. This requires restoration goals that center on the creation of an allied distribution of patches and ecological spaces within the fluvial hydrosystem rather than focusing on target species or habitats that may or may not be sustainable geomorphologically.

Such goals will continue to prove elusive until the scope of restoration expands from the channel to the riparian corridor and, ideally, the "functional floodplain." Adoption of corridor and floodplain templates for restoration will inevitably lead designers away from the use of single-value design discharges, generating demand for new approaches that account for ranges and suites of design discharges that are not only morphologically effective but also ecologically appropriate. In short, restoring not only heterogeneity but also the capacity for dynamic adjustment of the river channel's boundaries, sedimentary features, planform configurations, and floodplain environments will provide a near-term research impetus that will require improved design discharges capable of simultaneously supporting goals for morphological reconstruction and ecological restoration.

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