Toward a Better Understanding of Recurrence Intervals, Bankfull, and Their Importance

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Abstract: Bankfull is a concept that is intimately tied to the annual flood series through the well-accepted tenet that bankfull discharge occurs at approximately the 1.5-year recurrence interval on the annual series. Thus, due to this association the annual series provides a useful diagnostic tool for helping to identify the bankfull elevation in the field. The partial-duration series does not provide an equivalent tool because paired discharge and recurrence interval values from the flood frequency curve depend upon the minimum threshold selected for developing the partial-duration series. However, the interpretation that bankfull discharge occurs on average once every 1.5 years, or two out of every three years from that bankfull discharge/recurrence interval relationship on the annual series is incorrect. Frequencies of small floods (those with recurrence intervals ≤10 years) should be obtained using the partial-duration flood series because it contains a more accurate representation of the size and frequency of small events. We used discharge data from 11 streams in West Virginia watersheds that ranged from about 0.14 to 223 km² to compare the two series and to illustrate the variability in small flood frequencies through time. Flooding to the bankfull stage was absent some years but occurred as many as four or five times during other years.

Keywords: *annual flood series, partial-duration series, flood frequency, bankfull, small floods*

Flood recurrence is an important hydrologic concept from science, policy, management, and social perspectives. Recurrence intervals are used in a myriad of applications, including natural stream design, municipal zoning and planning, flood prediction, and insurance and actuarial purposes, to name just a few. Often interest in flood recurrence intervals is more focused on the more extreme, lower probability events (e.g., 100-year flood), as these typically are more catastrophic and receive substantial media coverage. However, small flood events are also important because they occur much more frequently. In particular, bankfull floods are very important because they are the most effective at changing channel shape and characteristics, and thus been given the title "dominant channel-forming flow" (Wolman and Miller 1960; Dunne and Leopold 1978; Copeland et al. 2000).

Initially, the concepts of bankfull discharge and recurrence intervals appear to be reasonably straight forward and simple. However, students and practitioners of hydrologic sciences often have an incomplete and sometimes incorrect understanding of one or both concepts. In this paper, we attempt to provide a fuller understanding of these concepts, including their identification or development, interpretation, and use in field applications. We explore the conundrum of and confusion that result from bankfull discharge being defined in terms of recurrence intervals derived from the annual flood series while the partial-duration series is recommended for the accurate determination of small flood recurrence intervals or flood frequencies.

Concepts

Bankfull and Bankfull Discharge

The term bankfull is used commonly to describe both a position on the stream or river bank that approximates the stage at which water overflows onto the floodplain as well as the specific discharge present when the water surface is at bankfull. For clarity in this paper, we use the term bankfull to reference the position or associated stage, and the term bankfull discharge to describe the flow rate (e.g., m^3 s^{-1}) at that stage.

To ensure correct estimates of bankfull and bankfull discharge, such as for natural stream design, both metrics should be determined from field observations. Bankfull should be determined along a reach (vs. a single location) using characteristics that are appropriate for that type of channel, and the characteristics should be verified using a reference reach. These include a variety of features, such as the mean elevation of the top of channel bars, the lower edge of perennial vegetation, the top of the streambank, and the highest scour line (Williams 1978; Wiley et al. 2002), with the specific bankfull-defining features in part depending on the type of channel (e.g., alluvial, presence or absence of a developed floodplain, etc.). There are a number of sources, such as Harrelson et al. (1994), Leopold et al. (1995), Wolman et al. (2003), and Verry (2005), that provide detailed instruction for identifying bankfull in various regions or conditions.

Bankfull discharge is unique to each stream or river, depending upon several factors, including size of the waterway and contributing area, underlying geology, channel geometry, and physiographic region. Consequently, bankfull discharge can range from very small values (e.g., less than 1 m^3 s^{-1}) to thousands of m^3 s^{-1}. Estimating bankfull discharge is a relatively straight forward task for streams and rivers that are gauged: determine bankfull, and then use the stream discharge records to identify the stage or flow associated with the bankfull position and confirm that it corresponds with a recurrence interval near 1.5 years on the annual series. If hydrologic records include only river stage, discharge for the site must be determined by other procedures such as Manning's equation.

In a given geographical region, the best predictor of bankfull discharge and hydraulic geometry is drainage area. Regional curves can be empirically determined to relate drainage area to bankfull discharge, as well as cross-sectional area, width, and mean depth. Regional curves are valuable for use when no gauging station is present on a stream or river. A regional curve is produced by identifying potential bankfull features at multiple gauging stations in that region and then using the annual series to verify that the features are associated with a flood recurrence of approximately 1.5 years. The curves can be refined with greater numbers and broader distribution of those gauges across the region. The more refined the regional curves, the better they are for validating bankfull features on other ungauged streams within the region. The U.S. Geological Survey (USGS) has taken a lead in developing and publishing regional curves throughout the United States. For a more in-depth discussion of their value and application see Dunne and Leopold (1978), particularly pages 15-17.

Recurrence Intervals

Recurrence intervals describe the frequency, on average, at which specific types of events occur. In hydrologic sciences, recurrence intervals can be developed for streamflow or precipitation. In this paper, we focus only on flow.

Recurrence intervals are calculated from the equation:

$$T = (n+1)/m \qquad \text{(Equation 1)}$$

where T = recurrence interval, n = number of observations, and m = rank of each observation, with observations ranked in descending order (Dunne and Leopold 1978). The observations are peakflows (e.g., m^3 s^{-1}), which can be from either the annual flood series or the partial-duration flood series (described below). Plotting the recurrence interval on the X-axis and the associated instantaneous peakflow value on the Y-axis (typically using graph papers with special distributions, such as Log Pearson Type III, Pearson Type IV, Gumbel Type I, Gumbel Type III semi-logarithmic or double logarithmic, generalized Pareto [Benson 1968; Dunne and Leopold 1978; Keast and Ellison 2013]) and then fitting a smooth line to the plotted data produces the flood frequency curve.

Annual vs. Partial-Duration Series

As alluded to earlier, there are two series of discharge data from which recurrence intervals can be derived: the annual series and the partial-duration series. Both use similar procedures for calculating recurrence intervals but the flow data in each series differ. The annual series builds the resulting flood frequency curve from the single maximum instantaneous peakflow that occurs each year for the stream of interest, while the partial-duration series employs all the single-storm instantaneous peakflows that equal or exceed some minimum threshold (i.e., a low-end high flow) for the stream. Therefore, the partial-duration series contains the annual series as well as additional data, with most of the additional data in the partial-duration series being from smaller flood events and events with less than bankfull discharge. For equation 1 to hold, the peakflows included in the partial-duration series must be temporally independent (Beguería 2005). If peaks occur so closely in time that they are not independent, the greater peakflow is the one included in the partial-duration series (Dunne and Leopold 1978).

Flood frequency curves for the annual series and the partial-duration series converge at or before the 10-year recurrence interval (Langbein 1949; Dunne and Leopold 1978; Keast and Ellison 2013). In other words for the typical duration of records, the data pairs and graphical response are very similar for the two series for events that have recurrence intervals >10 years, but they differ between the two series for recurrence intervals <10 years – the latter being the most common flood events.

This divergence of the two series raises the question: "which data series should be used to develop flood frequency curves for small floods (i.e., those with recurrence intervals <10 years)?" From purely a mathematical perspective, the answer is the partial-duration series, but for field practitioners the answer depends on the use. The partial-duration series provides a more accurate depiction of the relationship between small flood flows and their recurrence intervals or frequencies, which is described in further detail below. But from the perspective of helping to confirm the bankfull position identified in the field, the annual series serves as a diagnostic tool in a way that the partial-duration series cannot. Here is why. Based on data

from many studies (e.g., Dury et al. 1963; Leopold et al. 1964; Hickin 1968; Leopold 1994), the statement "bankfull discharge from most rivers has a recurrence interval on the annual flood series of 1.5 years" (Dunne and Leopold 1978, page 315) is a well-accepted hydrologic tenet. Individual streams often show some variation in this value, but 1.5 is typically a good approximation regionally (e.g., see Castro and Jackson 2007). Therefore, once a flood frequency curve is developed from the annual series, the discharge associated with the 1.5-year recurrence interval can be used for most streams and rivers to help confirm or fine tune the position of bankfull in the field. From a practical standpoint there are few gauged streams, but even fewer gauged with equipment that provide continuous streamflow measurement to allow identification of individual storm peakflows (i.e., instantaneous peakflows) throughout the year, over multiple years as required for development of the partial-duration series. The maximum annual peakflow datasets are more readily available, which may be why the discovery of the relationship between recurrence interval and bankfull discharge was developed and reported from annual series curves.

The partial-duration series does not provide this same diagnostic capability. This is because the recurrence interval determined from the partial-duration series depends upon the selection of the minimum threshold used to define which instantaneous peaks are included in the partial-duration series dataset. Raising or lowering that minimum will change the associated recurrence interval (T in eq. 1) because the number of events and rank values (respectively, n and m in eq. 1) will change. By including only the highest instantaneous value in each year, the annual series avoids the subjectivity in defining the minimum threshold and the associated variability in recurrence intervals for bankfull discharge (and other small flood events) that results.

The question about which series is appropriate for specific purposes is made even more confusing by a common misinterpretation of flood frequency recurrence intervals derived from the bankfull discharge recurrence definition. The subsequent sentence from Dunne and Leopold (1978, page 315) states – "This means that 1 year out of 1.5 or 2 years out of 3, the highest discharge for the year will

be equal to or will exceed the bankfull capacity of the channel." Nearly identical, though sometimes simpler pronouncements are found elsewhere in landmark hydrologic literature (e.g., Leopold et al. 1964). Unfortunately this interpretation is incorrect, even though it is still commonly repeated by practitioners. The error in interpretation stems from the composition of the annual flood series. To estimate recurrence intervals or flood frequencies (or probability, which is the inverse of recurrence interval) accurately, the dataset must include a sufficient number of data points and sufficient duration of measurements to adequately represent the true frequency of different sized flood events. The annual series fails to represent the frequency of small floods (<10-year recurrence intervals) due to the limited amount of data (single highest discharge per year) included in the annual series. Consequently, even though bankfull discharge is *associated with* approximately the 1.5-year recurrence interval on the annual series, the actual recurrence interval or flood frequency of bankfull discharge is generally underestimated by the annual series (Armstrong et al. 2012). In other words, events that equal or exceed bankfull discharge typically occur more frequently than once out of 1.5 years or two out of three years on average, and often much more frequently.

The requirement for adequate representation of flood frequencies is the reason that the partial-duration series is better suited for flood frequency analysis, especially of small events. Establishment of the minimum threshold for the development of the partial-duration series is somewhat arbitrary, but the minimum instantaneous peakflow value from the annual series is a common recommendation for use as the threshold (Dunne and Leopold 1978). With a sufficiently long record (at least 10 years), use of that threshold typically provides a robust estimate of the minimum annual peak that might be expected for a stream or river within expected climate and runoff conditions.

Flood Frequency Analysis Using Data

To examine the frequency of small floods and illustrate that the interpretation of bankfull discharge frequency is incorrect using the annual series results, we compared bankfull discharge frequency results from annual and partial-duration series data for 11 streams within West Virginia. The corresponding watersheds ranged in size from about 0.14 to 223 km^2 (Table 1). The four smallest of these are located in the Fernow Experimental Forest (FEF) (https://www.nrs.fs.fed.us/ef/locations/wv/fernow/data/), which is administered by the U.S. Forest Service's Northern Research Station. The remaining streams are gauged by the USGS (webpage: USGS Surface-Water Historical Instantaneous Data for West Virginia: Build Time Series; https://waterdata.usgs.gov/wv/nwis/uv/?referred_module=sw). FEF data were collected continuously while USGS data were collected on 15-, 30-, or 60-minute time steps. Peakflows were determined for each individual storm. FEF and USGS data span the periods shown in Table 1. The USGS data include only years for which non-provisional data were available for each stream (Table 1).

Individual storm hydrographs were identified from the FEF and USGS data files by projecting a line with a slope of 0.0005 m^3 s^{-1} km^{-2} (0.05 ft^3 s^{-1} mi^{-2}) per decimal hour from the point where each storm hydrograph began to rise through the point where that line intersected the receding limb of the hydrograph (Hewlett and Hibbert 1967; Harr et al. 1975; Dunne and Leopold 1978; Dingman 2002; Blume et al. 2007). Once all individual storm hydrographs were identified for each watershed across the available time series, the instantaneous peakflow (m^3 s^{-1}) for each storm (or snowmelt) event was identified. From these, the annual maximum instantaneous peakflow for each waterway was identified for each year of record to develop its annual series. The overall largest instantaneous peakflow for the period of record for each stream is given in the maximum peakflow column in Table 1. The minimum instantaneous peakflow value in the annual series (minimum peakflow column, Table 1) was used as the threshold for the associated partial-duration series (Dunne and Leopold 1978).

The recurrence interval was calculated using equation 1 for each peakflow value in each annual series, and flood frequency graphs were developed from those results. For each of the FEF streams, there was one flood, which was the flood of record, that was well outside the population of

Table 1. Streams and rivers used in the annual series and partial-duration (PD) series analysis. RI = recurrence interval. The minimum annual peakflow for each waterway was used as its threshold for the partial-duration series.

Waterway	Drainage area (km²)	Years gauged	Number of years	Maximum peakflow from annual series (m³ s⁻¹)	Minimum peakflow from annual series (m³ s⁻¹)	Flow at 1.5-yr RI from annual series (m³ s⁻¹)	RI from PD series associated with annual 1.5-yr RI (yr)
Fernow WS13	0.14	1989-2016	28	0.282	0.035	0.084	4.63
Fernow WS10	0.15	1985-2016	32	0.279	0.030	0.068	3.98
Fernow WS4	0.39	1952-2016	65	0.72	0.077	0.157	3.75
Fernow WS14	1.32	1994-2016	23	1.96	0.345	0.56	2.84
Sand Run (USGS 03052500)	37.0	1998-2017	20	84.7	11.3	19.0	2.37
Panther Creek (USGS 03213500)	80.3	2003-2017	15	162.5	13.4	37.6	3.19
East Fork Twelvepole Creek (USGS 03206600)	98.2	1997-2017	21	214.4	11.7	38.5	4.12
Peters Creek (USGS 03191500)	104.1	2004-2017	14	214.4	20.0	35.8	2.67
Piney Creek (USGS 03185000)	136.5	2003-2017	15	85.8	17.2	32.8	2.95
Shavers Fork River (USGS 03067510)	155.9	2001-2017	17	300.2	73.9	122.8	2.76
Blackwater River (USGS 03066000)	222.5	1997-2017	21	117.2	34.3	57.5	4.80

the remaining instantaneous peakflow values. Each of those extreme values was included in the rankings and recurrence interval calculations, but as recommended by Dalrymple (1960) those extreme values were not used for fitting the flood frequency curves.

The values in the second to last column in Table 1 are the discharges (m³ s⁻¹) associated with the 1.5-year recurrence interval on the annual series, or bankfull discharge, for purposes of illustration. Each of the bankfull discharge values from the annual series then was applied to the flood frequency curves developed from the partial-duration series to determine the corresponding

recurrence intervals for each stream for the partial series. Those recurrence intervals from the partial-duration series are all larger than those from the annual series (last column in Table 1), which is expected since the partial-duration series contains more flood events than the annual series.

The numbers of events included in the partial-duration series (i.e., those that were above the minimum threshold) for the watersheds are shown in Table 2. The peakflows identified as being above the minimum threshold within each watershed were found to be independent using the Durbin-Watson test for autocorrelation (SAS Institute Inc. 2013). Consequently, all peakflows above the

Table 2. Metrics associated with the partial-duration (PD) series. RI = recurrence interval.

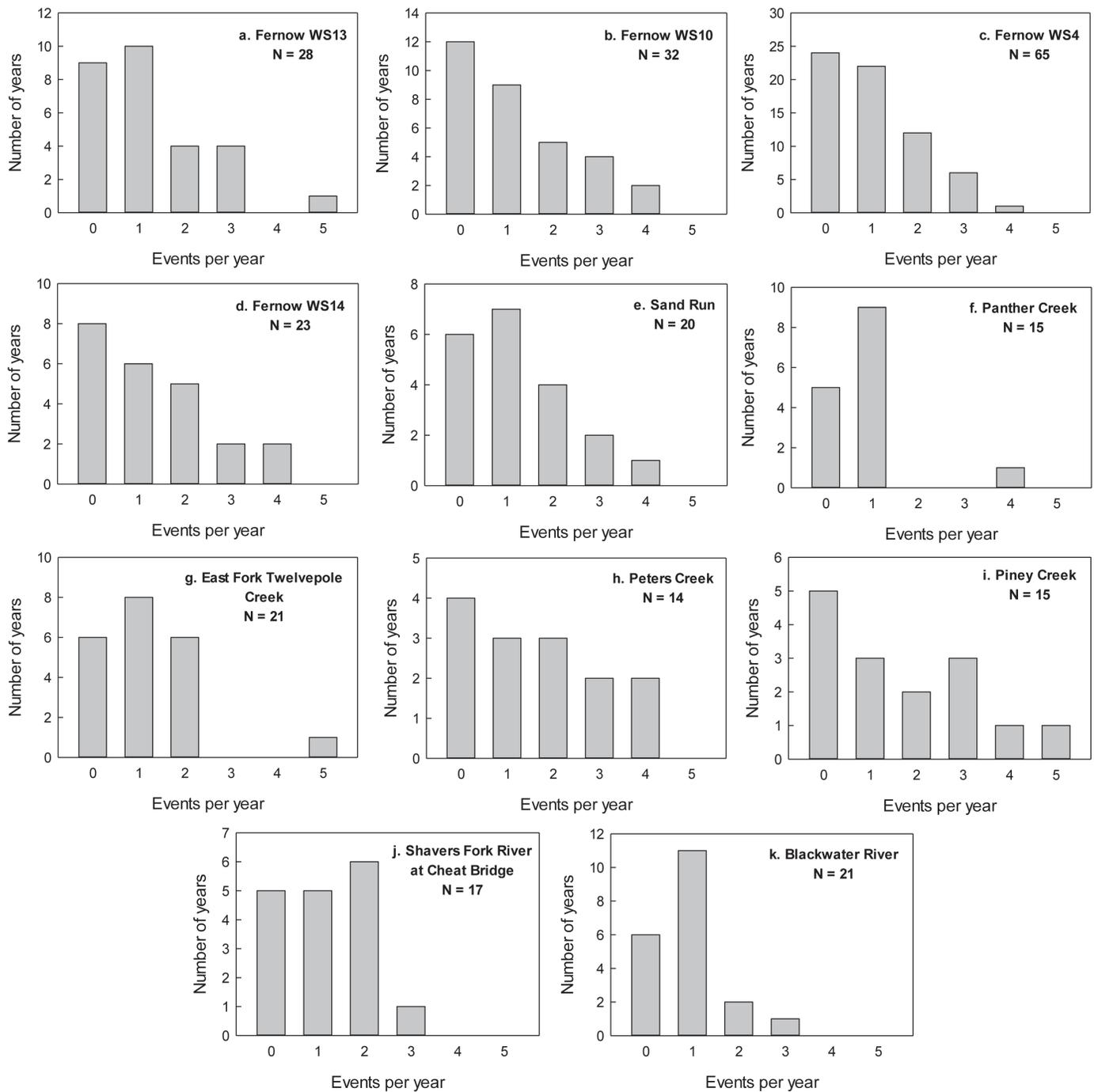| Waterway	Number of years	Total number of events with peakflow ≥ PD threshold	Number of events with peakflow ≥ annual 1.5-yr RI	Mean number of events/year ≥ annual 1.5-yr RI
Fernow WS13	28	167	35	1.25
Fernow WS10	32	170	40	1.25
Fernow WS4	65	274	68	1.05
Fernow WS14	23	95	30	1.30
Sand Run (USGS 03052500)	20	58	25	1.25
Panther Creek (USGS 03213500)	15	51	13	0.87
East Fork Twelvepole Creek (USGS 03206600)	21	104	25	1.19
Peters Creek (USGS 03191500)	14	54	23	1.64
Piney Creek (USGS 03185000)	15	68	25	1.67
Shavers Fork River (USGS 03067510)	17	52	20	1.18
Blackwater River (USGS 03066000)	21	88	18	0.86

threshold were retained in the final partial-duration series dataset.

One-fifth to just under half of those events, depending on the stream/river, had instantaneous peakflows that equaled or exceeded the bankfull discharge associated with the annual 1.5-year recurrence interval on the annual series (Table 2, Events with flow ≥ annual RI 1.5 column). The mean number of events per year (Table 2) confirms that the frequency of events for which at least bankfull discharge occurred exceeds the average frequency of once every 1.5 years (or 0.666). For most of these waterways, floods with peakflows that equaled or exceeded bankfull discharge occurred, on average, at least twice that frequently. However, those values represent only the averages and every year is unique. Years with no flood events or only one flood did occur, as did years with multiple events (Figure 1). Indeed, 9 of the 11 waterways had at least one year with four or five flood events, and that flood frequency was observed even for shorter-duration streamflow records. That all 11 channels had at least a single year with no bankfull discharge (Figure 1), indicates that using the minimum annual value for the threshold provided robust datasets of low-end high flow data for examining small flood frequencies.

Discussion

For illustrative purposes, the concepts and analyses presented in this paper were framed in terms of the accepted tenet that the bankfull discharge recurrence interval is at 1.5 years on the annual series. However, we fully recognize that

Figure 1. Frequency that each number of events per year with peakflows equal or exceeding bankfull discharge (based on 1.5-year recurrence interval) occurred for each of the watersheds. N refers to the number of years of record included in the analysis. See Table 1 for the specific years included.

there is variation among streams in the bankfull recurrence interval. Most values reported in the literature appear to fall somewhere within the 1- to 4-year recurrence interval on the annual series (e.g., Williams 1978; Andrews 1980; Petit and Pauquet 1997; Castro and Jackson 2007; Ahilan et al. 2013), but some streams have bankfull discharge recurrence intervals reported to be as high as a few decades (Williams 1978; Ahilan et al. 2013). In practice it is necessary to collect sufficient data and make thorough observations for streams in the region of interest to more accurately estimate and confirm bankfull in the field. Throughout much of West Virginia we have found that bankfull often is associated with a 1.3-year recurrence interval on the annual series, rather than 1.5 years; consequently, where appropriate we use the 1.3-year recurrence interval and associated discharge in fluvial applications. In all situations, bankfull should be determined locally from field conditions, and the associated discharge should be determined before proceeding with any type of action or assessment.

As noted previously, the annual series provides a useful diagnostic tool for estimating and confirming bankfull, while the frequency of bankfull discharges or other small floods should be determined from the partial-duration series. It is incorrect to describe bankfull discharge as the event that occurs only two out of every three years (or once every 1.5 years), even though this remains a commonly held and repeated interpretation and definition (e.g., Rosgen 1994, 1996; Harman and Jennings 1999; Vermont Agency of Natural Resources 2004; Mulvihill et al. 2009), largely due to this original misinterpretation in several important, early hydrology treatises (Leopold et al. 1964; Dunne and Leopold 1978) that otherwise provided indispensable information. However, for most waterways, a flood that occurs only two out of every three years is much bigger than the true bankfull flood.

Fundamentally, bankfull discharge is independent of the series from which it is associated or determined; bankfull discharge is whatever it is for the stream or river of interest – only the accurate estimation of flood frequency depends upon flood series. Because hydrologists and fluvial geomorphologists involved in natural stream design develop channel designs based on bankfull discharge and not flood frequency, there is little chance that errors in design dimensions will result simply from using the wrong series. That said, the authors have had experience with a regulator whose metric of an approved design was based on requiring a specified flood frequency (three floods per year). While flood frequency and bankfull discharge are related on the partial-duration series, we have shown that there is substantial variability in the frequency from year to year (Figure 1). Therefore, there is risk in predicating channel design on a required number of floods per year, rather than an average number per year (based on the flood frequency curve from the partial-duration series). The former channel would likely have a much smaller width and depth, and be able to convey less water than a stable channel in order to ensure flooding a predefined number of times per year, including during years when no bankfull events would have occurred.

Eventually such undersized channels will re-adjust and develop larger and more stable width and depth dimensions, but during the period of re-adjustment the location of the channel may move laterally within the floodplain. This is because in a channel, bankfull discharge has the power to move a certain amount of sediment and a certain maximum particle size, and stream reaches do not exist in isolation and are influenced by both upstream and downstream conditions. Bedload delivery from upstream, where channel dimensions are not undersized, will fill and clog the smaller, re-designed reach since it is too small to transport the full volume of water and bedload. The energy of the water will cut around the reach in areas of the bank that are less resistant to eroding than the bedload-choked channel. Eventually a channel will develop that has width and depth dimensions and other energy-controlling attributes that are appropriate for the true bankfull discharge. Unfortunately from the human perspective the position of the new channel may be less desirable than the original position.

Undesirable outcomes also result when channels are intentionally manipulated to reduce the frequency of flooding. These actions disregard, often due to ignorance, the processes to which all channels are subject in their continued evolution

to maintain or return to dynamically stable conditions. Reducing the frequency of flooding usually takes the form of treatments that increase in-channel water storage; thus, overflow onto the floodplain occurs less frequently than it would naturally. Actions aimed at reducing flooding include dredging, flood wall construction, and other similar types of flood containment.

Most treatments aimed at increasing storage are focused primarily on deepening the channel because surface landowners are sensitive to losing acreage. A channel that is deepened below its natural bankfull depth is considered disconnected from its floodplain – which is actually the desired effect of dredging. However, disconnection from the floodplain results in drier floodplain soils, which can significantly affect floodplain-dependent land uses such as agricultural operations. A lower channel bed also can deplete groundwater reserves; more of the aquifer is intercepted by the channel, allowing emergent flow to leave the watershed quickly as concentrated streamflow rather than remaining in the aquifer. Lowering the water table further disconnects groundwater from floodplain soils, thereby exacerbating droughty conditions.

Channel widening is sometimes included as part of flood control operations. Unintended effects of widening include intensifying low-flow conditions. In an over-widened channel, low flows are spread over a wider distance, making them shallower than they would be in a more-stable channel configuration. This condition often results in disconnected refugia in which aquatic organisms are stranded in small pools where food, oxygen, suitable temperatures, and cover may be limited, exceeding tolerances for organism survival.

Regardless of the technique used to increase water storage (dredging, flood walls, etc.), during high flows the water's energy continues to build within the channel, exceeding the maximum energy of true bankfull because the flow cannot spill onto the floodplain. As the energy of the water builds with increasing volume, the shear stress likewise increases, leading to channel scour, erosion of the floodplain once flooding begins (which can include lateral channel migration and re-alignment elsewhere on the floodplain), and the transport and deposition within and outside the channel of more sediment, as well as more and larger-sized bedload.

Conclusion

The annual flood series, while extremely useful as a diagnostic tool for identifying and/ or confirming bankfull discharge, is misleading when used to quantify the frequency of high probability events (i.e., small floods). Even some practitioners of hydrology do not fully understand the differences, applications, and interpretations of the annual and partial-duration series. It is extremely important for these series to be taught comprehensively so their uses are fully understood. It is important to understand that floods are natural events that do and should occur frequently and floodplains are an integral part of every river system. This understanding is critical to protecting water resources and aquatic health, as well as for protecting human lives and making informed decisions for watershed planning and management.

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