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BANKFULL DISCHARGE AND RECURRENCE INTERVALS IN IRISH RIVERS

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Abstract

Different definitions of bankfull condition in rivers are based on morphological characteristics, boundary conditions and geometrical properties. Consequently, magnitude and associated return period of the bankfull discharge can be variable. Knowledge of this discharge is important for regional flood frequency and index flood estimation procedures. This study investigates bankfull discharge intervals at 88 locations in the Irish river network using a combination of levels, rating curve equations and photographic records at the sites. Catchments ranged in area from approximately 23 km^2 to 2778 km^2. Recurrence intervals were determined by fitting Generalised Extreme Value (GEV maximum flow series at the sites investigated. These inter 2.33 years at 53% of the sites. Higher return periods between 2.33 and 10 years and 25 years were observed at a further 20% and 6% of locations respectively. Using multivariate regression analysis the computed bankfull dis with catchment descriptors and three expressions are presented for estimating b

Notation

a, b, c	rating curve constants
AREA	catchment area (km^2)
ARTDRAIN2	arterial drainage (ratio)
AM	annual maximum (cumec)
BFI	base flow index (ratio)
cdf	cumulative distribution function
DRAIND	drainage density (km/ km^2)
FARL	flood attenuation reservoirs and lakes (index no units)

GEV	generalised extreme value distribution
u	location parameter of the GEV distribution
k	shape parameter of the GEV distribution
M_{100} M_{110} M_{120}	probability weighted moments
MSL	main stream length (km)
N	record length (yrs)
NETLEN	network length (km)
PWM	probability weighted moment
P	photographic records
R	rating relationship
S	survey
S1085	mainstream slope (m/ km)
SAAR	standard average annual rainfall (mm/ year)
STRFRQ	stream frequency (number)
T	return period (yr)
Q	discharge (cumec)
Q_{bf}	bankfull discharge (cumec)
Q_{mean}	mean annual discharge (cumec)
Q_{med}	median annual discharge (cumec)
x	water level with respect to a local datum (m)
±	scale parameter of the GEV distribution
	Euler s constant
“( )	incomplete gamma function

Keywords

Hydrology and water resource, river engineering, floods and

1 Introduction

The bankfull discharge, in a river cross section, is the discharge that fills the to the top of its banks and therefore marks the condition of incipient t Although different definitions exist, characteristic discharge is accepted as being a indicator for river management. In addition, understanding bankfull disch associated recurrence intervals is important for regional flood frequency analysis an flood estimation procedures.

Its significance for hydraulic engineers relates to the exchange tur between main channel and floodplain flows that can reduce section and result in overestimated discharge predictions ca channels (Sellin, 1964, Martin and Myers, 1991). River geomorphologists use ban discharge as an important indicator for stream rehabilitation channel geometry that will retain its dimensions and profile t is important (Rosgen, 1994). For ecologists, the bankfull condition represent which nutrient rich sediments are deposited on the floodplains increase the biological div agricultural productivity of these riparian zones (Welcomme 2006; Wimmer, 2003). Furthermore, the flood pulsing that occurs w are exceeded is increasingly being recognised as an impor natural wetland systems in river (Middleton, 2002).

In broad terms, bankfull definitions are based on sedimentary or mor characteristics, boundary conditions or geometrical propert however, can be ambiguous (Lambert and Walling, 1987; which explains why Arc definitions of the bankfull are general. For example, bankfull stage has be the level of the valley flat (Nixon, 1959a; 1959b; Wolman, 19 height of the lower

limit of perennial vegetation Speight (1965), in terms of t

sediments have deposited (Thornbury, 1969; Shelton, 1966), the elevatio

of sand sized particles in the sediments comprising the channel

the elevation at which the width to depth ratio of the cross

1969; Pickup and Warner, 1976) the stage corresponding to a change

of the cross-sectional area to the width (Williams, 1978). Such variation in th

description of the bankfull condition can result in multiple

particular river reach (see for example Williams, 1978; Navratil et al., 2006; Xia et al., 2009).

Bankfull recurrence intervals are of particular concern to

regional flood frequency analysis or index flood methods in ungauged ca

The relationship in these catchments between the index flood and the bankfull return

dictates whether floodplain storage which is a significant proportion of discharge

likely to be significant in the determination of the index flood magnitude. Bankfull return

periods can be influenced by both catchment size (Petit and

within a catchment where longer recurrence intervals with i

are reported (Richards, 1982). This reduced frequency of bankfull

locations is perhaps understandable given that the flood du

increases with downstream distance where increased attenua

lower gradient channel reaches (Dury, 1961; Petit et al., Castro and Jackson

(2001) report the influence of climatic and physiographic factors on bankfull

recurrence intervals. Geological catchment characteristics with

periods increasing with increases in the permeability of th

1969). By extension, the bankfull flow return period is likely responsiveness of the catchment (e.g. flashy), which in turn is dependent on its geology.

Despite the diversity in the factors that influence recurrence inter bankfull return period has been proposed (Robert, 1989). However, representing bankful return period as unique, or within closely grouped values, represe the hydrological and hydraulic processes (Dury, 1975; Williams, 1978) and a shown in Table 1, considerable variation exists in recurrenc from different studies.

Table 1

This study investigates bankfull discharges and recurrence intervals at 88 locations i Irish river network where records of good quality hydromet surveyed bankfull levels and photographic records are available. Determining discharge is complex and depends on the chosen definition of bankfull stage. Different definitions of bankfull stage have advantages and disadvantages and depend on the variety of applications in which they are used. Researchers of the topic, therefore, generally use a single definition of bankfull stage and suitable metho discharge that can be consistently applied. In this paper, th the flow at which water just fills the channel without overtoppin onto the floodplain. The bankfull discharges are determined using rating curves a equations. The approach involves using daily mean stage and provide a field determination of bankfull stage and correspo equations with bankfull stages determined from survey or extracted from photographic records. The computed bankfull discharges are related to catchment descriptors in a multi-variate regression analysis to provide relationships for th[e] context of descriptors that are shown to be important. The catchment descriptors u[sed are] those that have been included in the Flood Studies Update (FSU) the basis of which i[s] described in Reed and [illegible] (2005) which supersede the Flood Studies Report (N[ERC,] 1975) for Irish catchments.

2 Methodology

Responsibility for the maintenance of the Irish hydrometric network resides with the Offic[e] of Public Works (OPW) and includes information relating to stations. Access o[r] review of this database revealed that a full or partial record of both daily m[ean flows and] mean stage together with recently surveyed bankfull stages, was available at 117 stations. Further analysis revealed that data from 29 of these stations were either of [poor] quality with low confidence levels or with cross-sections obtained with uncharacteristically high banks. These stations were excluded and therefore the dataset analysed in this paper was limited to 88 stations. Of these, 33 were categorised a[s A1] with a further 39 being A2. A1 sites are those with confirm[ed ratings for] flows greater than 1.3 x Q_{med} (Q_{med} is the median annual flood with a 2-year return period) and which facilitate extrapolation with good confidence for fl[ows above] Q_{med} or Q_{bf}. Data from A2 sites is of similar quality and comprises a [...] to facilitate extrapolation to bankfull level. Sites that are catego[rised B and] C (16 and 3 respectively in this study) comprise good qualit[y] data to Q_{med} but gauging of greater discharges beyond this may not be availabl[e]. Rating curves were developed at these sites using a combination of me[...] quality of the gauged data. At these sites a sufficient number of overbank gaugings have been carried out, rating curves can be based solely on this

where fewer floodplain flows have been gauged, rating curv

either or a combination of extrapolating the observed data ar

Bankfull discharge is commonly determined by identifying the stage and then determining the discharge associated with this stage (Copeland et al., 2001). Two approaches were used in this study to obtain the bankfull stage. The first is the rating curve approach (Leopold, 1964; Woodyer, 1968; Kashef and Nabavi, 2006). The principle of the method is that once the bankfull stage is ex occurs, the rate of increase of stage or level relative to fl This produces a more complex rating curve with a discontinuity, or break, at the bankf separates inbank and overbank relationships (Knight and S relationship (from direct measurement and hydraulic modelling) is shown for Rivelin (Station 26004) (Figure 1) where the bankfull stage is shown at approximately 0.63 m.

Figure 1

The second approach: bankfull levels determined from surveys or extracted from photographic records at the sites in question. For both approaches were determined from empirical rating equations of the form:

$$Q(h) = c(h + a)^b \qquad (1)$$

where x is the water level with respect to a local datum at the particular cross sec the discharge corresponding to this stage, and a, b and c vary with different stage ranges.

Extracting bankfull stages from photographic records involved initially identifying t of connection between the main channel and adjacent floodp. Between 5 and 19 digital images were analysed for each of the sites. The bankfull stag represented by the level of connection read directly from the gauge (Figure 2) or where required transferred to the gauge by projection parallel to the water surfa perpendicular to the main channel direction. Confidence in the analysing a number of images at each site and ensuring th different images were consistent.

Figure 2

Application of the two approaches results in three estimates of bank which bankfull discharge can be determined; from the rating cu equations where bankfull levels are extracted from survey (S) or photographic r Bankfull discharges determined from surveyed bankfull levels in con equations are considered to be the most reliable and wher estimates from the other methods were observed, were taken In some cases however, discrepancies in estimated bankfull stag approaches. These occurred at locations where the cross-section was complex or included at least one bench (a level or gently inclined land area bounded above and below by river bank of steeper gradient). Benches result in abru cross-section that in some cases produce a discontinuity in the stage-discharge curve which on application of the rating curve method, yield the actual bankfull level. Further interrogation of the photographic records and the field survey identified the most appropriate bankfull stage and confirmed that the stage associated with this discontinuity was in some cases the bankfull condition.

Return periods for the bankfull discharges were estimated by Generalised Extreme Value (GEV) distributions fitted to the annual maximum record at each site. At sites where the record length exceeded 20 AM years (of the 88 sites), GEV shape parameter (k) were calculated using the method of Hosking et al (1985) in which:

$$\hat{k} = 7.859c + 2.9554c^2 \qquad (2)$$

where

$$c = \frac{2M_{110} - M_{100}}{3M_{120} - M_{100}} - \frac{\ln 2}{\ln 3} \qquad (3)$$

and where M_{100}, M_{110} and M_{120} are probability weighted moments determined using Eqns. 4-6 given as:

$$M_{100} = \frac{1}{n}\sum_{j=1}^{n} x_{(j)} \qquad (4)$$

$$M_{110} = \frac{1}{n}\sum_{j=2}^{n}\frac{(j-1)}{(n-1)}x_{(j)} \qquad (5)$$

$$M_{120} = \frac{1}{n}\sum_{j=3}^{n}\frac{(j-1)(j-2)}{(n-1)(n-2)}x_{(j)} \qquad (6)$$

where n is the length, in years, of the AM series.

Scale (α) and location (u) parameters of the GEV distribution using were dete

$$\alpha = \frac{(2M_{110} - M_{100})k}{\Gamma(1+k)\left(1 - 2^{-k}\right)} \qquad (7)$$

and

$$u = M_{100} + \frac{\alpha}{k}\left[\Gamma(1+k) - 1\right] \qquad (8)$$

where Γ(•) is the standard gamma function.

The cumulative distribution function (cdf) of a GEV distribution can be written

$$F(Q_{bf}) = \exp\left\{-\left[1 - \frac{k}{\alpha}(Q_{bf} - u)\right]^{1/k}\right\} \qquad k \neq 0 \qquad (9)$$

and the inverse of Eq. 9 is used to determine the return period (T) for a given bankful

discharge (Q_{bf}):

$$Q_{bf} = u + \frac{\alpha}{k}\left\{1 - \left[-\ln\left(1 - \frac{1}{T_{bf}}\right)\right]^{k}\right\} \qquad (10)$$

At locations where the AM record length was less than 25 years, the [illegible] et al. (1985) method is not recommended. For these stations (8 [illegible] total), shape factor ($k = 0$) were assumed (EV1) and scale (α) and location (u) parameters were determined using

$$\alpha = \frac{(2M_{110} - M_{100})}{\ln 2} \qquad (11)$$

and

$$u = M_{100} - \varepsilon\alpha \qquad (12)$$

where ε is Euler's constant given as 0.5772 and M_{100} and M_{110} are PWMs from Eqn. 4 and Eqn. 5. The cumulative distribution function (cdf) of a GEV written as:

$$F(Q_{bf}) = \exp\left\{-\exp\left[-\frac{1}{\alpha}(Q_{bf} - u)\right]\right\} \qquad k = 0 \qquad (13)$$

and the inverse of Eqn. 13 is used to determine the return period (T_{bf}) for a given peak flood discharge (Q_{bf}).

$$Q_{bf} = u - \alpha \ln\left(-\ln\left(1 - \frac{1}{T_{bf}}\right)\right) \quad (14)$$

Multivariate regression analysis was undertaken to relate the bankfull discharge at each gauging station to spatial and hydrological catchment descriptors that were developed in the FSU and are available for the Irish hydrometric network. Descriptors deemed influential in the determination of the index flood in the FSU, which may also have significance in the bankfull discharge at a particular location in river reaches were included in the relationships developed for predicting Q_{bf}. Spatial catchment properties include the catchment area in km^2 (AREA), the standard average annual rainfall in mm (SAAR) and a parameter that accounts for the attenuation effects of lakes and reservoirs within a catchment (FARL). Hydrological catchment properties include the average slope in m/km of the river between 10% and 85% of the main stream length (S1085), an index that relates the length of the stream network in km to the area of the gauged catchment in km^2 (DRAIND), another index that represents the arterial drainage extent defined as the percentage area of the catchment river network in drainage schemes (ARTDRAIN2) and the baseflow index (BFI). Main stream length (MSL) and network length (NETLEN) which reflect the length of the hydrometric network, and stream frequency (STRFRQ) which reflects the density of stream junctions relative to the catchment area, were also included.

3 Results and Discussion

The magnitude of the index floods that have significance in flood estimation in Irish catchments (Q_{mean} and Q_{med}), together with bankfull discharges at all gauged sites (Q_{bf}) and corresponding bankfull recurrence intervals (T_{bf}) for the 88 gauging stations used in the analysis in this study are shown in Table 2. Both Q_{mean} and Q_{med} are determined from an annual analysis of maximum flow records at the stations investigated. The bankfull stage used in estimation of the bankfull discharge is denoted by an asterix (*) in Table 2.

Table 2

Analysis of Table 2 indicates that approximately 66% of sites have bankfull recurrence intervals between 1 and 5 years with the median value being ... The frequency distribution of the recurrence intervals of the sites investigated is shown in Figure 3(a) and the cumulative frequency distribution is shown in Figure 3(b). The bankfull recurrence intervals are less than 2 years (the mean annual flood) at 42 (48%) stations and less than 2.33 years (the mean annual flood assuming a GEV type I) at 47 (53%) stations. Table 2 indicates that 18 locations (20%) have recurrence intervals between 2.33 and 10 years and 5 stations (6%) have recurrence between 10 and 25 years. This study is based on flow and stage records. Selection of suitable cross-sections for gauging purposes ensures that the full flow range is controlled within well defined channel banks. Although such conditions may be responsible for the uncharacteristically high bankfull stage return periods that exceed 100 years at 11 of the sites (13%). Generally however, the magnitude of bankfull recurrence intervals in Irish rivers are consistent with other studies.

Figure 3

3.1 Regression Modelling

Plots of catchment descriptors with bankfull discharge are shown in Figure 4 for 84 of the 88 sites investigated (data not available for stations 16010, 17002, 26004 and 26018)

Figure 4

Figure 4 indicates that the magnitude of bankfull discharges catchment area (coefficient of determination r^2 = 0.43). MSL, RNETLEN and STRFRQ are also positively correlated with bankfull discharge (r^2 = 0.44, 0.38 and 0.28 respectively) Figure 4 and reflect the more efficient drainage capacity that charac significant tributary networks.

SAAR is derived from longterm averaged annual rainfall and surprisingly, shows a low strong relationship with bankfull discharge. The BFI is based on soil and characte relates the mean annual baseflow to the mean annual flow. Therefore, this descripto perhaps expected to be more significant than is shown in Figure 4. Similarly, no clea relationship is apparent between DRAIN, LDRAIN, FARL and the bankfull discharge.

Using least-squares multivariate regression analysis, computed bankf correlated with the catchment descriptors presented in Figure 4 to provide three equations for estimating this characteristic. The first of these is a single equation in terms of catchment area. Catchment area is shown to be positive the bankfull discharge in Figure 4 and is a dominant influence in the The areas of the catchments investigated vary from [illegible] km^2 to approximately 2778 km^2 and are considered to cover areas of a significant range. The regressions

analysis indicates that the bankfull discharge can be expressed using Eq
factorial standard error of 1.5584 for the sites studied.

$$Q_{bf} = 0.764 (AREA)^{0.708} \quad (15)$$

Eqn. 15 was determined using a linear relationship between ... which leads to the power law form of the equation when co... domain. In the log-domain the standard error of the estimate is ad... estimated value to provide a 66% confidence interval on the model th... residuals are normally distributed (i.e.). The corresponding additive terms, (10^{se}) in the original domain and are referred to as factorial sta... Cunnane, 2003).

The second equation includes the catchment descriptors of the first equation wi... the exception that NETLEN rather than MSL is used to define the length ... catchment. NETLEN and MSL are interrelated, but NETLEN has a stronger relatio... between NETLEN and bankfull discharge is shown in Figure 14. Furthermore, main channel slope (represented by S1085) will exert a significant ... a channel and steep channels of a given cross-sectional geometry will have higher conveyance capacities than similar channels of lower slope. Higher disc... bankfull flows in steeper channels suggesting that a positiv... discharge and S1085 is expected, however Figure 14 shows bankfull discharges decreasin... with S1085 values in Irish catchments. These S1085 values ... catchment area with larger catchments more likely to have ... discharges than smaller catchments which may be in the upper reaches of the riv...

slopes are greater but discharge is small. Decreasing bankfull discharges may therefore result from the influence of the small, steeper catchments. To reduce this influence, bankfull discharge was normalised by dividing Q_{bf} and S1085 by Q_{med} such that the expression for bankfull discharge is:

$$Q_{bf} = 0.162\,AREA^{0.87}\,BFI^{-0.67}\,SAAR^{0.01}\,FARL^{2.39}\,DRAIND^{0.28}\,S1085^{0.16}\,(1 + ARTDRAIN2)^{-0.10} \qquad (16)$$

The FSE of Eqn. 16 for the 84 sites investigated was 1.53.

The third equation for predicting bankfull discharge considers four catchment descriptors that appear to be significant: AREA, STRFRQ, ARTDRAIN2 and NETLEN (Figure 4). However, a strong positive correlation exists between STRFRQ and NETLEN (R^2 = 0.49). As bankfull discharge has a higher correlation to NETLEN than STRFRQ, STRFRQ is not included, and the equation is defined in terms of three descriptors:

$$Q_{bf} = 0.194\,AREA^{0.49}\,NETLEN^{0.40}\,S1085^{0.30}\,(1 + ARTDRAIN2)^{-0.09} \qquad (17)$$

The FSE for Eqn. 17 for the 84 sites studied was 1.58.

The comparison of bankfull discharges determined from field observations and those calculated from Eqns. 15, 16 and 17 are shown to be in reasonable agreement in Figure 15, indicating that the regression equations provide a means of estimating bankfull discharges in Irish catchments. Estimates are shown to be improved for larger rivers.

Figure 5

The Akaike information criterion (AIC) (Akaike, 1974) was used to co

goodness of fit of the bankfull discharge estimates derived from Eqn. 15, Eqn. 16

Eqn. 17 to observed values. The AIC for the three equations were determine

$$AIC = n \ln\left(RSS/n\right) + 2K + 2K\left(K+1\right)/\left(n-K-1\right) \qquad (18)$$

where n, RSS and K are the number of data points (observations), res

and number of model descriptors (parameters) in each equation. The AIC r

for Eqn. 15 (single parameter), Eqn. 16 (4 parameters) and Eqn.

712.47, 706.70 and 718.47 respectively, indicating that while all three equations are similar in their performance, Eqn. 16 is the most appropriate for predicting bankfu

rivers.

4 Conclusions

This paper presents an investigation of the magnitude of bankfull discharge and associated return periods in Irish rivers with catchment areas ranging from 23 to 2778 km^2. The

bankfull discharge used in the study was the flow at which w

overtopping the banks and inundating the adjacent floodpla

calculated from corresponding bankfull stages estimated from a combinat

curve method, surveys and photographic records.

The recurrence intervals of the discharges were determined

Value (GEV) distributions to the annual maximum series of flows in inves

These intervals were found to be less than 2.33 years at 53%
periods of between 2.33 and 10 years and 10 and 25 years respe
further 20% and 6%. Furthermore, approximately 66% of sites investigated h
bankfull recurrence intervals of between 1 and 5 years with
years.

The bankfull discharges were related to catchment descriptors using multivariate
regression analysis. The most suitable expression for estimating the bankfull discharg
on estimates at the 84 sites investigated was:

$$Q_{bf} = 0.162\,AREA^{0.87}\,BFI^{-0.67}\,SAAR^{0.01}\,FARL^{2.39}\,DRAIND^{0.28}\,S1085^{0.16}\,(1+ARTDRAIN)^{0.1}$$

While estimates from the equation improve for larger catchments, the FSE of 1.55 results
in a 66% confidence interval of (0.65 Q_{bf} to 1.55 Q_{bf}). Although the magnitude of the
consistent with regression equations for determining mean a
Studies Report (NERC, 1975) and Flood Estimation Handbook
interval is wide and caution is advised.

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