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Bankfull discharge and recurrence intervals in Irish rivers

1 **S. Ahilan** MApplSc, PhD
Postdoctoral Researcher, School of Civil, Structural and Environmental Engineering, University College Dublin, Newstead, Belfield, Ireland

2 **J. J. O'Sullivan** MSc, PhD
College Lecturer, School of Civil, Structural and Environmental Engineering, University College Dublin, Belfield, Dublin, Ireland

3 **M. Bruen** PhD
Associate Professor, School of Civil, Structural and Environmental Engineering, University College Dublin, Belfield, Dublin, Ireland

4 **N. Brauders** BE
Undergraduate Student (formerly), School of Civil, Structural and Environmental Engineering, University College Dublin, Belfield, Dublin, Ireland

5 **D. Healy** BE
Undergraduate student (formerly), School of Civil, Structural and Environmental Engineering, University College Dublin, Belfield, Dublin, Ireland

Different definitions of the bankfull condition in rivers are based on morphological characteristics, boundary conditions and geometrical properties. Consequently, the magnitude and associated return period of the bankfull discharge can be ambiguous. Knowledge of this discharge is important in index flood estimation and subsequent regional flood frequency analysis. This study investigates bankfull discharges and recurrence intervals at 88 locations in the Irish river network using a combination of surveyed bankfull levels, rating curves and equations and photographic records at the sites in question. Catchments ranged in area from approximately 23 km^2 to 2778 km^2. Recurrence intervals were determined by fitting generalised extreme value (GEV) distributions to the annual maximum flow series at the sites investigated. These intervals were found to be less than 2 years (the median annual flood) at 42 stations (48%) and less than 2·33 years (the mean annual flood assuming a GEV type 1 distribution) at 47 stations (53%). Higher return periods of between 2·33 and 10 years and 10 and 25 years were observed at a further 20% and 6% of locations respectively. Using multivariate regression analysis, the computed bankfull discharges are correlated with catchment descriptors and three expressions are presented for estimating bankfull flows.

Notation

a, b, c	rating curve constants
AIC	Akaike information criterion
AREA	catchment area (km^2)
ARTDRAIN2	arterial drainage (ratio)
AM	annual maximum (cumec)
BFI	base flow index (ratio)
DRAIND	drainage density (km/km^2)
FARL	flood attenuation reservoir and lakes (index – no units)
k	number of catchment descriptors
$\hat{k}$	shape parameter of the GEV distribution
M_{100}, M_{110}, M_{120}	probability-weighted moments
N	record length (y)
NETLEN	network length (km)
Q	discharge (cumec)
Q_{bf}	bankfull discharge (cumec)
Q_{mean}	mean annual discharge (cumec)
Q_{med}	median annual discharge (cumec)
RSS	residual sum of squares
S1085	mainstream slope (m/km)
SAAR	standard average annual rainfall (mm/year)
T	return period (y)
$\hat{u}$	location parameter of the GEV distribution
x	water level with respect to a local datum (m)
$\hat{\alpha}$	scale parameter of the GEV distribution
$\Gamma(\,)$	incomplete gamma function
ε	Euler's constant

1. Introduction

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

Its significance for hydraulic engineers relates to the turbulent momentum exchanges between main channel and floodplain flows that can reduce mean velocities in a compound section and result in overestimated discharge predictions relative to non-interacting identical channels (Martin and Myers, 1991; Sellin, 1964). River geomorphologists use the bankfull discharge as an important indicator for stream rehabilitation programmes where creating a stable channel geometry that will retain its dimensions and profile to promote required flow patterns is important (Rosgen, 1994). For ecologists, the bankfull condition represents the level above which nutrient-rich sediments deposit on floodplains and increase the biological diversity and agricultural productivity of these riparian zones (Shome and Steffler, 2006; Welcomme, 1990; Winemiller, 2003). Furthermore, the flood pulsing that occurs when bankfull stages are exceeded is increasingly being recognised as an important process in preserving the natural wetlands in river systems (Middleton, 2002).

In broad terms, bankfull definitions are based on sedimentary or morphological characteristics, boundary conditions or geometrical properties (Williams, 1978). These, however, can be ambiguous (Archer, 1989; Lambert and Walling, 1987), which explains why definitions of the bankfull stage are varied. For example, bankfull stage has been defined as the level of the valley flat (Nixon, 1959a, 1959b; Woodyer, 1968); the height of the lower limit of perennial vegetation (Speight, 1965); in terms of those areas where water-borne sediments have deposited (Shelton, 1966; Thornbury, 1969); the elevation of the upper limit of sand-sized particles in the sediments comprising the channel boundary (Nunnally, 1967); the elevation at which the width-to-depth ratio of the cross-section is a minimum (Harvey, 1969; Pickup and Warner, 1976); and the stage corresponding to a change in the relationship of the cross-sectional area to the channel top-width (Williams, 1978). Such variation in the description of the bankfull condition can result in multiple bankfull discharge magnitudes in a particular river reach (see, for example, Navratil *et al.*, 2006; Williams, 1978; Xia *et al.*, 2009).

Bankfull recurrence intervals are of particular concern to hydrologists concerned with regional flood frequency analysis or index flood estimation methods in ungauged catchments. The relationship in these catchments between the index flood and bankfull return periods dictates whether floodplain storage and frictional resistance that suppress flood growth are likely to be significant in the determination of the index flood magnitude. Bankfull return periods can be influenced by both catchment size (Petit and Pauquet, 1997) and by location within a catchment where longer recurrence intervals with increasing downstream distance are reported (Richards, 1982). This reduced frequency of bankfull discharge at downstream locations is perhaps understandable given that the flood duration of a given frequency also increases with downstream distance where increased attenuation of the flood peak occurs in lower gradient channel reaches (Dury, 1961; Petts and Foster, 1985). Castro and Jackson (2001) report the influence of regional climatic and physiographic factors on bankfull recurrence intervals. Geological catchment characteristics are also important, with return periods increasing with increases in the permeability of the underlying bedrock (Harvey, 1969). By extension, the bankfull flow return period is likely to be influenced by the responsiveness of the catchment (e.g. whether the catchment is sluggish or flashy), which is dependent on its geology.

Despite the diversity in the factors that influence recurrence intervals, the concept of a single bankfull return period has been proposed (Roberts, 1989). However, representing bankfull return periods as unique, or within closely grouped values, represents an oversimplification of the hydrological and hydraulic processes (Hey and Davies, 1975; Williams, 1978) and, as shown in Table 1, considerable variation exists in recurrence intervals reported in different studies.

This study investigates bankfull discharges and recurrence inter-

Research	Return period	Study location
Wolman and Leopold (1957)	1–2 years	Streams in the Eastern and Midwestern USA
Nixon (1959a, 1959b)	0·46 (average value)	Streams in England and Wales
Brush Jr (1961)	2·3 (average value)	Streams in Central Pennsylvania, USA
Dury (1961)	1–2 years	White and Wabash Rivers, USA
Woodyer (1968)	1–2 years	Streams in New South Wales. Australia
Pickup and Warner (1976)	4–10 years	Streams in the Cumberland Basin, UK
Williams (1978)	1–32 years	Streams in the Western USA
Petit and Pauquet (1997)	0·7–5·3 years	Streams in Belgium
Castro and Jackson (2001)	1·4 years	Streams in the Pacific region in the Northwest of America
Keshavarzi and Nabavi (2006)	1·1 years	Kor River, Iran
Rustomji (2009)	Less than 2 years (increasing to 8 years at some locations)	Daly River, Northern Australia

Table 1. Bankfull recurrence intervals from existing studies

vals at 88 locations in the Irish river network where records of good-quality hydrometric data, rating relationships, surveyed bankfull levels and photographic records were available. Determining bankfull discharge is complex and depends on the chosen definition of bankfull stage. Different definitions of bankfull stage have advantages and disadvantages that depend on the scope and variety of applications in which they are used. Researchers of the topic, therefore, generally use a single definition of bankfull stage and suitable methods of estimating the bankfull discharge that can be applied consistently. In this paper, the bankfull discharge is defined as the flow at which water just fills the channel without overtopping the banks and inundating the floodplain. The magnitudes of these discharges are determined using rating curves and equations. The approach involves using daily mean stage and discharge relationships to provide a field determination of bankfull stage and corresponding discharge, or using rating equations with bankfull stages determined from a survey or extracted from photographic records. The computed bankfull discharges are related to catchment descriptors in a multivariate regression analysis to provide relationships for these bankfull discharges in the context of descriptors that are shown to be important. The catchment descriptors used are those that have been included in the Flood Studies Update (FSU) (the basis of which is described in Reed and Martin (2005)),which supersedes the Flood Studies Report (NERC, 1975) for Irish catchments.

2. Methodology

Responsibility for the maintenance of the Irish hydrometric network resides with the Office of Public Works (OPW) and includes information relating to more than 1800 stations. A review of this database revealed that a full or partial record of both daily mean flow and daily mean stage data, together with recently surveyed bankfull stages, was available at 117 stations. Further analysis revealed that data from 29 of the stations either were of poor quality with low confidence levels or were obtained at cross-sections 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 as being A1 with a further 39 being A2. A1 sites are those with confirmed ratings that include gauged flows greater than 1·3 × Q_{med} (Q_{med} is the median annual flood with a 2-year return period) and which facilitate extrapolation with good confidence for floodplain flows up to twice Q_{med} or Q_{bf} (bankfull discharge). Data from A2 sites are of similar quality and comprise a minimum of one gauged flow to facilitate extrapolation beyond the bankfull level. Sites that are categorised as being B or C (16 and 3 respectively in this study) comprise good-quality ratings with confirmed gauged data to Q_{med} but gaugings of greater discharges beyond this may not be available. Rating curves were developed at these sites using a combination of methods that depended on the quality of the gauged data. At well-gauged sites where a sufficient number of overbank gaugings have been carried out, rating curves can be based solely on these data. In situations where fewer floodplain flows have been gauged, rating curves are generally developed by either or a combination of extrapolating the observed data and hydraulic modelling.

Bankfull discharge is commonly determined by identifying the bankfull stage and then determining the discharge associated with this stage (Copeland *et al.*, 2000). Two approaches were used in this study to obtain the bankfull stage. The first of these was the rating curve approach (Keshavarzi and Nabavi, 2006; Leopold *et al.*, 1964; Woodyer, 1968). The principle of the method is that once the bankfull stage is exceeded and floodplain inundation occurs, the rate of increase of stage or level relative to flow decreases dramatically. This produces a more complex rating curve with a discontinuity, or break, at the bankfull level that separates inbank and overbank relationships (Knight and Demetriou, 1983). Such a relationship (from direct measurement and hydraulic modelling) is shown for the River Island (Station 26004) in Figure 1 where the bankfull stage is shown to be approximately 63·68 m.

The second approach uses bankfull levels determined from a survey or extracted from photographic records at the sites in question. For both approaches, bankfull discharges were determined from empirical rating equations of the form

$$Q(x) = c(x+a)^b \tag{1}$$

where x is the water level with respect to a local datum at the particular cross-section, $Q(x)$ is the discharge corresponding to this stage, and a, b and c are constants that vary with different stage ranges.

Extracting bankfull stages from photographic records initially involved identifying the level of connection between the main channel and adjacent floodplain at a river reach. Between five and 19 digital images were analysed at each of the sites

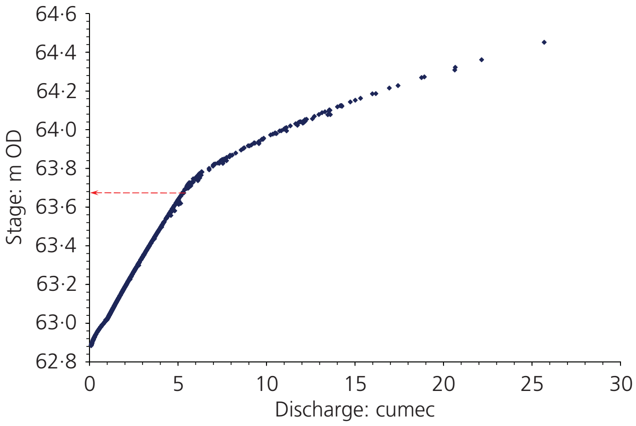

Figure 1. Rating relationship for the River Island at hydrometric Station 26004 (Bookala) showing the bankfull stage using the rating curve method

investigated. The bankfull stage represented by the level of connection was either read directly from the staff gauge (Figure 2) or where required transferred to the gauge by a projection parallel to the water surface and perpendicular to the main channel direction. Confidence in the method was increased by analysing a number of images at each site and ensuring that bankfull estimates from the different images were consistent.

Application of the two approaches potentially results in three estimates of bankfull stage, from which bankfull discharge can be determined: from the rating curve method (R) or from rating equations where bankfull levels are extracted from survey (S) or photographic records (P). Bankfull discharges determined from surveyed bankfull levels in combination with rating equations are considered to be the most reliable and, where no significant conflict with estimates from the other methods were observed, were taken to be the most accurate values. In some cases, however, discrepancies in estimated bankfull stages were noted in the different approaches. These occurred at locations where the river cross-section was complex and included at least one bench (a shelf or level of gently inclined land bounded above and below by river bank of steeper gradient). Benches result in abrupt changes in the main channel cross-section that in some cases produce a discontinuity in the stage–discharge curve which, on application of the rating curve method, yield a stage that is lower than the actual bankfull level. Further interrogation of the photographic records and the surveyed levels identified the most appropriate bankfull stage and confirmed that the stage associated with this type of discontinuity at some sites was not the bankfull condition.

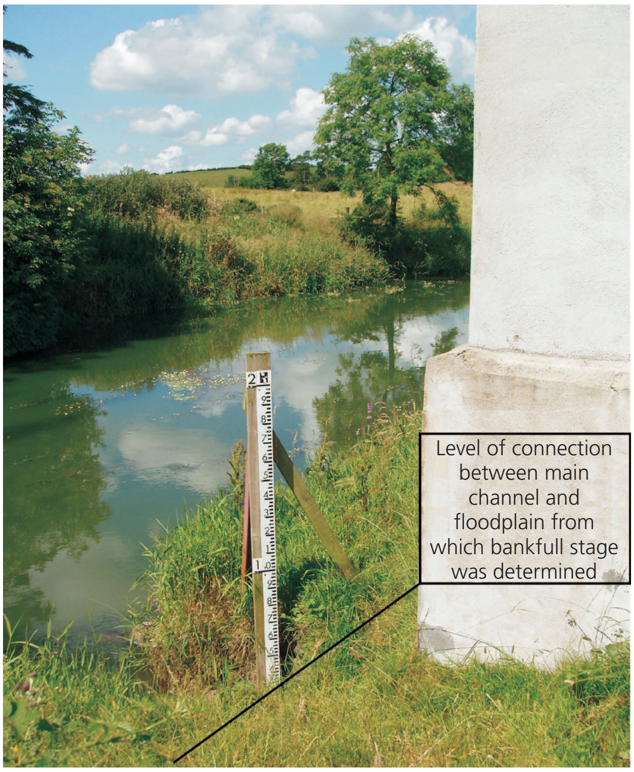

Figure 2. Estimation of bankfull stage using photographic records

Return periods for the bankfull discharges were estimated by relating calculated values to generalised extreme value (GEV) distributions fitted to the annual maximum (AM) flow record at each site. At sites where the historical AM record length exceeded 25 years (80 of the 88 stations), GEV shape parameters ($\hat{k}$) were calculated using the method of Hosking *et al.* (1985), in which (Equation 2)

$$\hat{k} = 7{\cdot}8590c + 2{\cdot}9554c^2 \tag{2}$$

where c is given by Equation 3,

$$c = \frac{2M_{110} - M_{100}}{3M_{120} - M_{100}} - \frac{\ln 2}{\ln 3} \tag{3}$$

and where M_{100}, M_{110} and M_{120} are probability-weighted moments (PWMs) determined from Equations 4 to 6 given as

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

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

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

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

Scale ($\hat{\alpha}$) and location ($\hat{u}$) parameters of the GEV distribution were determined using

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

and

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

where $\Gamma(\,)$ is the standard gamma function.

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

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

and the inverse of Equation 9 is used to determine the return period (T_{bf}) for a given bankfull discharge (Q_{bf}).

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

At locations where the AM record length was less than 25 years, the Hosking *et al.* (1985) method is not recommended. For these stations (8 in total), GEV type I distributions (shape factor, $\hat{k}=0$) were assumed and scale ($\hat{\alpha}$) and location ($\hat{u}$) parameters were determined using Equations 11 and 12.

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

and

$$\hat{u} = M_{100} - \varepsilon\hat{\alpha} \tag{12}$$

where ε is Euler's constant given as 0·5772 and M_{100} and M_{110} are PWMs from Equations 4 and 5. The cumulative distribution function (cdf) of a GEV type I distribution can be written as

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

and the inverse of Equation 13 is used to determine the return period (T_{bf}) for a given bankfull discharge (Q_{bf})

$$Q_{\mathrm{bf}} = \hat{u} - \hat{\alpha}\ln\left[-\ln\left(1-\frac{1}{T_{\mathrm{bf}}}\right)\right] \tag{14}$$

Multivariate regression analysis was undertaken to relate the estimated bankfull discharges at each gauging station to spatial and hydrological catchment descriptors that were developed in the FSU and are available for stations in the Irish hydrometric network. Descriptors deemed influential in the determination of the index flood in the FSU and that, by extension, may also have significance in the bankfull discharge at particular locations within specified river reaches were included and relationships for predicting Q_{bf} were developed. Spatial catchment properties include the catchment area in km^2 (AREA), the standard average annual rainfall in mm (SAAR) and a parameter that allows for the attenuating effects of lakes and reservoirs within a catchment (FARL). Hydrological catchment properties included the average slope in m/km of the river between 10% and 85% of its length from the outlet (S1085), an index that relates the length of the upstream hydrological network in kilometres 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 that is included in drainage schemes (ARTDRAIN2), and the baseflow index (BFI). Main stream length (MSL) and network length (NETLEN), both of which reflect the length of the hydrological network, and stream frequency (STRFRQ), which defines the density of stream junctions relative to the catchment area, were also included.

3. Results and discussion

The magnitudes of index floods that have significance in flood estimation procedures in Irish catchments (Q_{mean} and Q_{med}), together with bankfull stages, discharges (Q_{bf}) and corresponding bankfull return periods (T_{bf}) for the 88 gauging stations analysed in this study, are shown in Table 2. Both Q_{mean} and Q_{med} are determined from an analysis of the annual maximum flow record of *N* years at the stations investigated. The bankfull stage used in the estimation of the bankfull discharge is denoted by an asterisk (*) in 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 1·64 years. The frequency distribution of the bankfull recurrence intervals of the sites investigated is shown in Figure 3(a) and the cumulative frequency distribution shown in Figure 3(b). Figure 3(b) shows that bankfull recurrence intervals are less than 2 years (the median annual flood) at 42 stations (48%) and less than 2·33 years (the mean annual flood assuming a GEV type I distribution) at 47 stations (53%). Table 2 indicates that 18 locations (20%) have recurrence intervals between 2·33 and 10 years and five stations (6%) have recurrence intervals between 10 and 25 years. This study is based on flow and stage records at measured cross-sections. Selection of suitable cross-sections for gauging purposes dictates that the full flow range should be controlled within well-defined channel banks. Although not conclusive, such conditions may be responsible for the uncharacteristically high bankfull stages and associated flow return periods that exceed 100 years at 11 of the sites (13%) investigated. Generally however, the magnitudes of bankfull recurrence intervals in Irish rivers are consistent with those reported in other studies.

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, 07002, 26004 and 26018).

Figure 4 indicates that the magnitude of bankfull discharges increases with increasing catchment area (coefficient of determi-

No.	River	STN	N: y	Q_{mean}: cumec	Q_{med}: cumec	Bankfull		
						Stage: m	Q_{bf}: cumec	T_{bf}: y
1	Aherlow	16007	55	79·71	75·84	1·6 (P) *2·19 (S)	73·96	1·81
2	Annalee	36010	55	68·94	66·88	2·4 (P) *2·77 (S)	113·18	33·93
3	Anner	16010	37	45·43	44·80	1·5 (P) *1·79 (S)	27·74	1·02
4	Awbeg	18004	49	30·73	30·73	1·41 (S)	24·47	1·10
5	Ballysadare	35005	60	80·78	80·78	1·4 (P) *1·04 (S)	39·54	1·00
6	Bandon	20002	36	146·47	127·63	2 (P) *2·2 (S)	196·55	8·24
7	Barrow	14005	51	52·24	50·63	2·57 (S)	68·92	9·59
8	Barrow	14006	56	84·03	80·26	3·42 (S)	116·75	20·06
9	Barrow	14018	67	149·83	148·07	2·22 (S)	146·47	2·08
10	Barrow	14019	57	105·57	101·72	3·12 (R.)	52·30	1·00
11	Barrow	14029	14	182·39	184·35	1·7 (P) *1·5 (S)	167·18	1·79
12	Black	26009	38	13·62	13·14	1·9 (P) *1·58 (S)	9·11	1·00
13	Blackwater (Kells)	07004	22	23·31	23·74	1·65 (P) *1·18 (S)	15·40	1·00
14	Blackwater (Kells)	7033	16	14·04	13·77	0·47 (R.) *2·36 (S)	89·19	>100
15	Blackwater (Munster)	18002	53	350·34	342·86	2·8 (P) *3 (S)	279·10	1·11
16	Blackwater (Munster)	18003	49	282·76	266·15	4·8 (S)	314·97	3·78
17	Boyle	26108	20	58·01	56·01	*0·56 (R.) 1·85 (S)	11·03	1·00
18	Boyle	26012	51	39·34	40·54	3·25 (S)	117·94	>100
19	Boyne	07007	42	33·43	34·02	2·8 (S)	44·43	9·12
20	Boyne	07009	32	163·31	139·73	*2 (P) 2·9 (S)	135·24	1·60
21	Broadmeadow	08008	28	45·28	39·98	2 (S)	49·89	3·19
22	Camcor	25022	55	27·62	26·31	*2 (P) 2·4 (S)	31·46	4·64
23	Castlebar	34018	32	11·99	11·54	1·46 (S)	32·81	>100
24	Camlin	26019	56	22·28	21·18	2·42 (R.)	18·61	1·39
25	Clare	30004	44	98·54	92·67	5 (S)	180·67	49·40
26	Clare	30007	26	56·61	57·34	1·85 (P) *1·96 (S)	61·17	3·07
27	Clarinbridge	29004	35	10·05	9·94	*1·4 (P) 2 (S)	9·82	1·79
28	Claureen	27001	33	20·79	20·79	3·5 (P) *1·65 (S)	20·94	2·44

Table 2. Bankfull discharge and recurrence interval of Irish rivers (R, S and P denote stages determined from rating relationships, survey data and photographic records respectively; asterisk (*) denotes the bankfull stage used in the analysis) (continued on next page)

No.	River	STN	N: y	Q_{mean}: cumec	Q_{med}: cumec	Bankfull		
						Stage: m	Q_{bf}: cumec	T_{bf}: y
29	Clodiagh	25016	51	23·60	23·08	3·41 (S)	39·40	>100
30	Cushina	14009	28	6·72	6·72	1·32 (S)	6·57	2·18
31	Dee	06013	33	27·35	27·05	*1·35 (P) 1·62 (S)	27·05	2·04
32	Dee	06025	33	18·43	18·64	3·59 (S)	28·53	>100
33	Deel	24011	36	79·40	80·52	3·3 (S)	81·66	2·20
34	Deel	24012	44	111·66	111·64	3·4 (S)	94·39	1·21
35	Deel	24013	49	95·73	101·47	4·4 (S)	185·02	>100
36	Deel	07002	49	19·56	19·16	0·67 (R.)	1·50	1·00
37	Deel	34007	56	89·75	83·23	0·42 (R.)	3·12	1·00
38	Dinin	15003	55	142·92	151·14	2·5 (P) *2·71 (S)	170·57	4·90
39	Drish	16001	36	16·14	15·66	0·6 (P) *0·82 (S)	11·60	1·13
40	Dromore	36018	52	15·28	14·49	1·92 (S)	27·19	>100
41	Dunkellin	29011	25	33·92	29·16	1·74 (S)	35·94	3·56
42	Erne	36011	52	18·05	18·29	1·97 (S)	14·62	1·20
43	Eslin	26015	36	6·52	6·49	0·53 (R.)	1·14	1·00
44	Fane	06011	53	16·03	15·39	*1 (P) 1·48 (S)	13·00	1·23
45	Fane	06012	53	15·28	14·52	*0·7 (P) 1·66 (S)	5·20	1·00
46	Feale	23002	62	401·06	368·19	*2 (P) 2·96 (S)	277·60	1·14
47	Finn	36015	15	21·96	19·31	1 (P)* 1·29 (S)	13·35	1·55
48	Funshion	18005	53	56·75	52·84	1·5 (P) *1·38 (S)	40·71	1·10
49	Galey	23001	48	111·13	102·85	3·38 (S)	148·26	6·28
50	Glyde	06014	33	22·35	21·23	1·86 (S)	74·63	>100
51	Inny	26021	33	104·04	101·92	2·2 (P) *2·96 (S)	110·22	2·86
52	Island	26004	5	20·21	20·66	0·7 (R.)	6·02	1·00
53	Killimor	25020	41	48·15	43·65	*2·8 (P) 3·47 (S)	86·72	23·89
54	Lagan (Glyde)	06026	49	13·72	12·30	3·66 (S)	34·77	>100
55	Little Brosna	25021	47	27·99	28·58	1·89 (S)	28·76	2·23
56	Little Brosna	25023	55	12·44	11·62	1·8 (P) *1·96 (S)	10·04	1·40
57	Moy	34010	12	105·04	97·00	2·08 (S)	59·23	1·05
58	Moy	34001	39	174·66	177·00	1·3 (R.)	43·30	1·00
59	Mulkear	25003	54	68·83	68·44	*1·5 (P) 2·65 (S)	46·08	1·01
60	Multeen	16005	34	23·01	21·79	1·29 (S)	18·81	1·15
61	Multeen	16006	37	30·14	27·87	1·36 (S)	23·69	1·45
62	Nenagh	25029	36	54·00	55·26	2·49 (S)	66·92	6·02
63	Nore	15002	53	230·88	215·98	3·25 (S)	513·84	>100
64	Nore	15004	54	36·67	35·77	2·5 (P) *2·5 (S)	49·89	9·29

Table 2. Continued

No.	River	STN	N: y	Q_{mean}: cumec	Q_{med}: cumec	Bankfull		
						Stage: m	Q_{bf}: cumec	T_{bf}: y
65	Nore	15006	52	301·02	292·52	2·9 (P) *2·9 (S)	250·92	1·32
66	Ollatrim	25027	47	23·72	22·35	2·42 (S)	37·83	40·99
67	Owenavorragh	11001	36	49·70	47·43	2·3 (P) *2·3 (S)	36·54	1·19
68	Owenboy	19001	52	18·36	17·00	*2·5 (P) 3·5 (S)	28·87	12·99
69	Owengarve	34009	29	29·10	28·15	2 (P) *1·62 (S)	10·15	1·00
70	Owenmore	35001	38	34·34	31·62	0·973 (S)	26·81	1·42
71	Owenure	26018	52	9·31	9·29	0·28 (R.)	0·30	1·00
72	Raford	29001	45	14·67	13·95	2·7 (S)	21·22	28·48
73	Rinn	26008	55	23·72	22·94	3·32 (S)	50·53	>100
74	Robe	30005	52	32·45	31·31	2·77 (S)	59·47	65·99
75	Ryewater	09001	51	38·92	35·46	1·83 (S)	59·36	8·52
76	Slaney	12001	53	162·53	160·83	2·19 (S)	119·33	1·25
77	Slate	14011	29	11·90	12·29	1·66 (S)	33·59	>100
78	Stradbally	14007	28	17·04	16·14	1·87 (S)	24·08	10·29
79	Suck	26005	56	94·20	93·21	3·5 (S)	231·21	>100
80	Suck	26006	58	30·12	26·76	1·11 (R.)	3·39	1·00
81	Suir	16002	55	55·30	52·66	1·32 (S)	75·54	9·26
82	Suir	16004	54	21·93	21·00	1·46 (S)	17·37	1·25
83	Suir	16008	55	91·48	93·07	2 (P) *2·05 (S)	86·90	1·53
84	Suir	16009	56	158·58	158·58	2·3 (P) *2·44 (S)	199·17	24·83
85	Silver	25014	57	17·51	16·91	3·6 (P) *3·41 (S)	49·88	>100
86	Tar	16012	45	50·99	50·39	1·8 (P) *2·01 (S)	54·10	2·73
87	Woodford	36027	18	24·99	25·38	2·07 (S)	17·96	1·02
88	Yellow	36021	30	24·94	23·37	2·87 (S)	31·42	8·95

Table 2. Continued

nation $R^2 = 0{\cdot}43$). MSL, NETLEN and STRFRQ are also positively correlated with bankfull discharge ($R^2 = 0{\cdot}44$, 0·38 and 0·28, respectively) in Figure 4 and this reflects the more efficient drainage capacity that characterises catchments with significant tributary networks.

SAAR is derived from long-term average annual rainfall and, surprisingly, does not show a strong relationship with bankfull discharge. The BFI is based on soil characteristics and relates the mean annual base flow to the mean annual flow. Therefore, this descriptor was perhaps expected to be more significant than is shown in Figure 4. Similarly, no clear relationship is apparent between DRAIND, ARTDRAIN, FARL and the bankfull discharge.

Using least-squares multivariate regression analysis, computed bankfull discharges were correlated with the catchment descriptors presented in Figure 4 to provide three equations for estimating this characteristic flow in Irish rivers. The first of these is a single-parameter equation in terms of catchment area. Catchment area is shown to be positively correlated with the bankfull discharge in Figure 4 and is a dominant influence in the generation of flows. The areas of the catchments investigated vary from approximately 23 km^2 to 2778 km^2 and are considered to cover the areas of a significant range of Irish rivers. The regression analysis indicates that the bankfull discharge can be expressed using Equation 15, which has a factorial standard error of 1·552 for the 84 sites studied.

$$15.\quad Q_{\text{bf}} = 0{\cdot}764(\text{AREA})^{0{\cdot}7083}$$

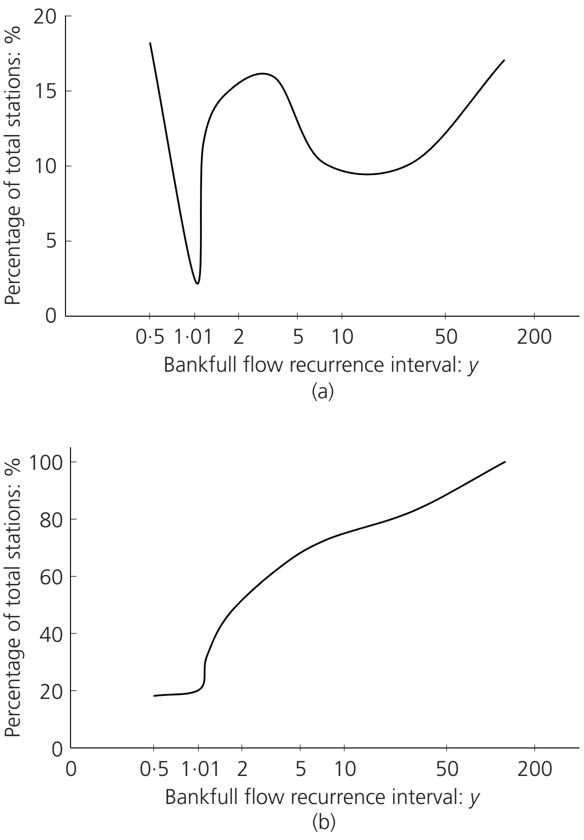

Figure 3. (a) Frequency distribution and (b) cumulative frequency distribution of recurrence intervals for bankfull flow

Equation 15 was determined using a linear relationship between the logarithms of the variables that leads to the power law form of the equation when converted back into the original domain. In the log-domain, the standard error of the estimate is added to/subtracted from the estimated value to provide a 66% confidence interval on the assumption that the model residuals are normally distributed. These additive terms ($\pm e$) become multiplicative terms, 10^{+e} in the original domain and are referred to as factorial standard errors (FSE) (Cawley and Cunnane, 2003).

The second equation includes the catchment descriptors of the FSU index flood equation with the exception that NETLEN rather than MSL defines the characteristic length in the catchment. NETLEN and MSL are somewhat interrelated, but a stronger relationship between NETLEN and bankfull discharge is observed in Figure 4. Furthermore, main channel slope (represented by S1085) will exert a significant influence on the flow velocity in a channel and steep channels of a given cross-sectional geometry will have higher conveyance capacities than similar channels of lower slope. Higher discharges are therefore required for bankfull flows in steeper channels, suggesting that a positive correlation between bankfull discharge and S1085 is expected. Figure 4, however, shows bankfull discharges decreasing with S1085 values in Irish catchments. These S1085 values are heavily influenced by catchment area with larger catchments more likely to have lower S1085 slopes and higher discharges than smaller catchments that may be in the upper reaches of the river where the slopes are greater but discharges are smaller. Decreasing bankfull discharges in this regard may therefore result from the influence of the small, steeper catchments in the dataset. 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 (Equation 16)

$$\begin{aligned} Q_{\mathrm{bf}} &= 0\cdot162\mathrm{AREA}^{0\cdot87}\mathrm{BFI}^{-0\cdot67}\mathrm{SAAR}^{0\cdot01} \\ &\quad \times \mathrm{FARL}^{2\cdot39}\mathrm{DRAIND}^{0\cdot28}\mathrm{S1085}^{0\cdot16} \\ &\quad \times (1+\mathrm{ARTDRAIN2})^{0\cdot10} \end{aligned} \tag{16}$$

The FSE of Equation 16 was 1·553 for the 84 sites investigated.

The third equation for predicting bankfull discharge considers the four catchment descriptors that appear to be significant in Figure 4: AREA, STRFRQ, ARTDRAIN and NETLEN. However, a strong positive correlation also exists between STRFRQ and NETLEN ($R^2 = 0\cdot94$). As bankfull discharge exhibits a higher correlation to NETLEN than it does to STRFRQ, STRFRQ is not included in the equation, defined in terms of three descriptors as in Equation 17.

$$\begin{aligned} Q_{\mathrm{bf}} &= 0\cdot194\mathrm{AREA}^{0\cdot49}\mathrm{NETLEN}^{0\cdot40} \\ &\quad \times \mathrm{S1085}^{0\cdot30}(1+\mathrm{ARTDRAIN2})^{0\cdot09} \end{aligned} \tag{17}$$

The FSE for Equation 17 for the 84 sites studied was 1·58.

The comparison of bankfull discharges determined from field observations in this study with those calculated from Equations 15, 16 and 17 are shown to be in reasonably good agreement in Figure 5, indicating that these regression equations provide an acceptable means of estimating bankfull discharges in Irish catchments. Estimates are shown to be improved in larger rivers.

The Akaike information criterion (AIC) (Akaike, 1974) was used to compare the relative goodness of fit of the bankfull discharge estimates determined from Equations 15, 16 and 17 with observed values. The AICs for the three equations were determined from Equation 18.

$$\mathrm{AIC} = n\ln(\mathrm{RSS}/n) + 2K + 2K(K+1)/(n-K-1) \tag{18}$$

where *n*, RSS and *K* are the number of data points (observations), residual sum of squares and number of catchment descriptors (parameters) in each respective equation. The AIC for Equation

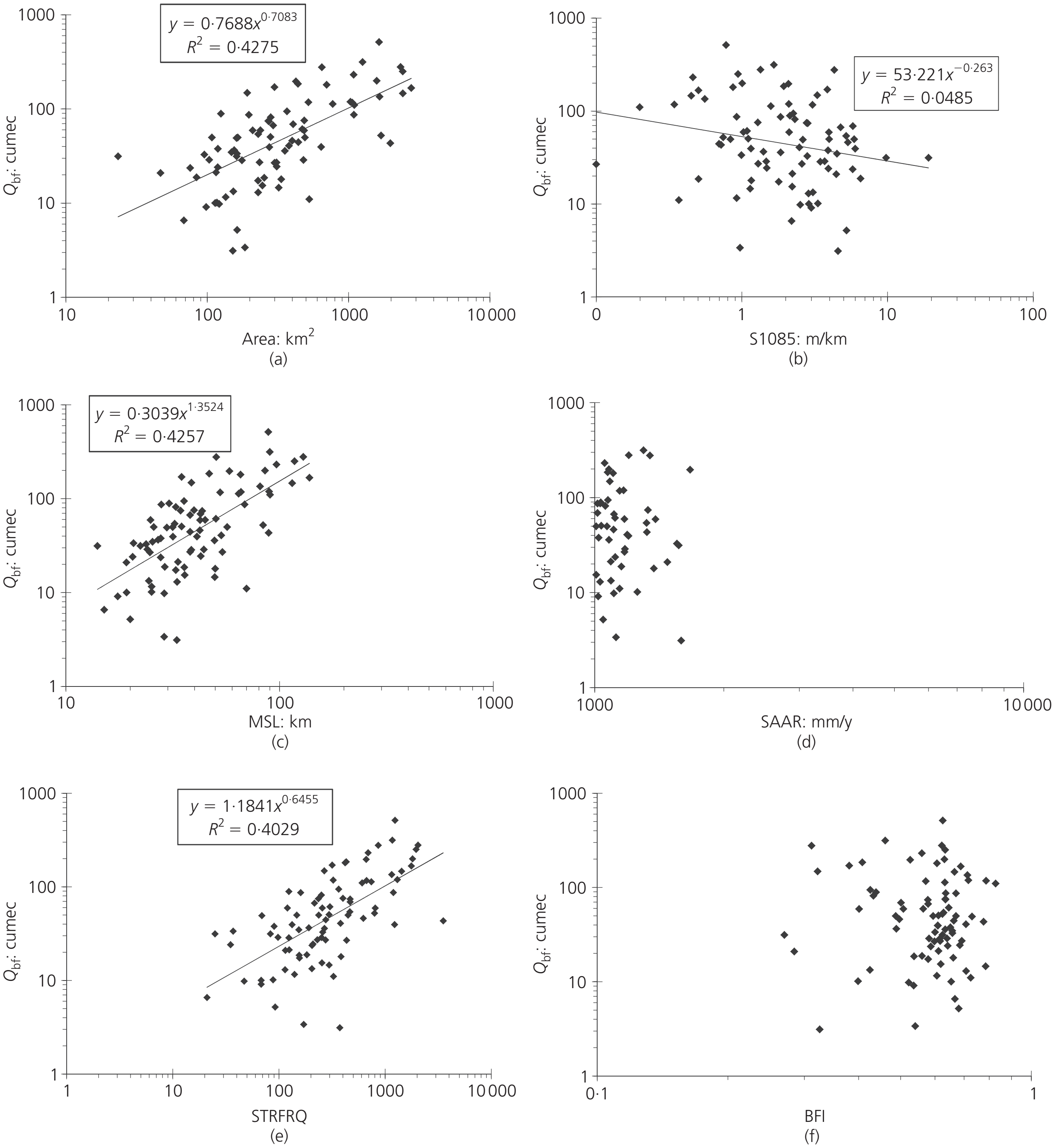

Figure 4. (a) to (i): Influence of individual catchment properties on bankfull discharge (Q_{bf})

15 (single parameter), Equation 16 (seven parameters) and Equation 17 (four parameters) was 712·47, 706·70 and 718·47, respectively, indicating that while all three equations are similar in their performance, Equation 16 is the most appropriate for predicting bankfull discharges in Irish rivers.

4. Conclusions

This paper presents an investigation of the magnitude of bankfull discharges and associated return periods in Irish rivers with catchment areas ranging from 23 km^2 to 2778 km^2. The bankfull discharge used in the study was the flow at which water just fills

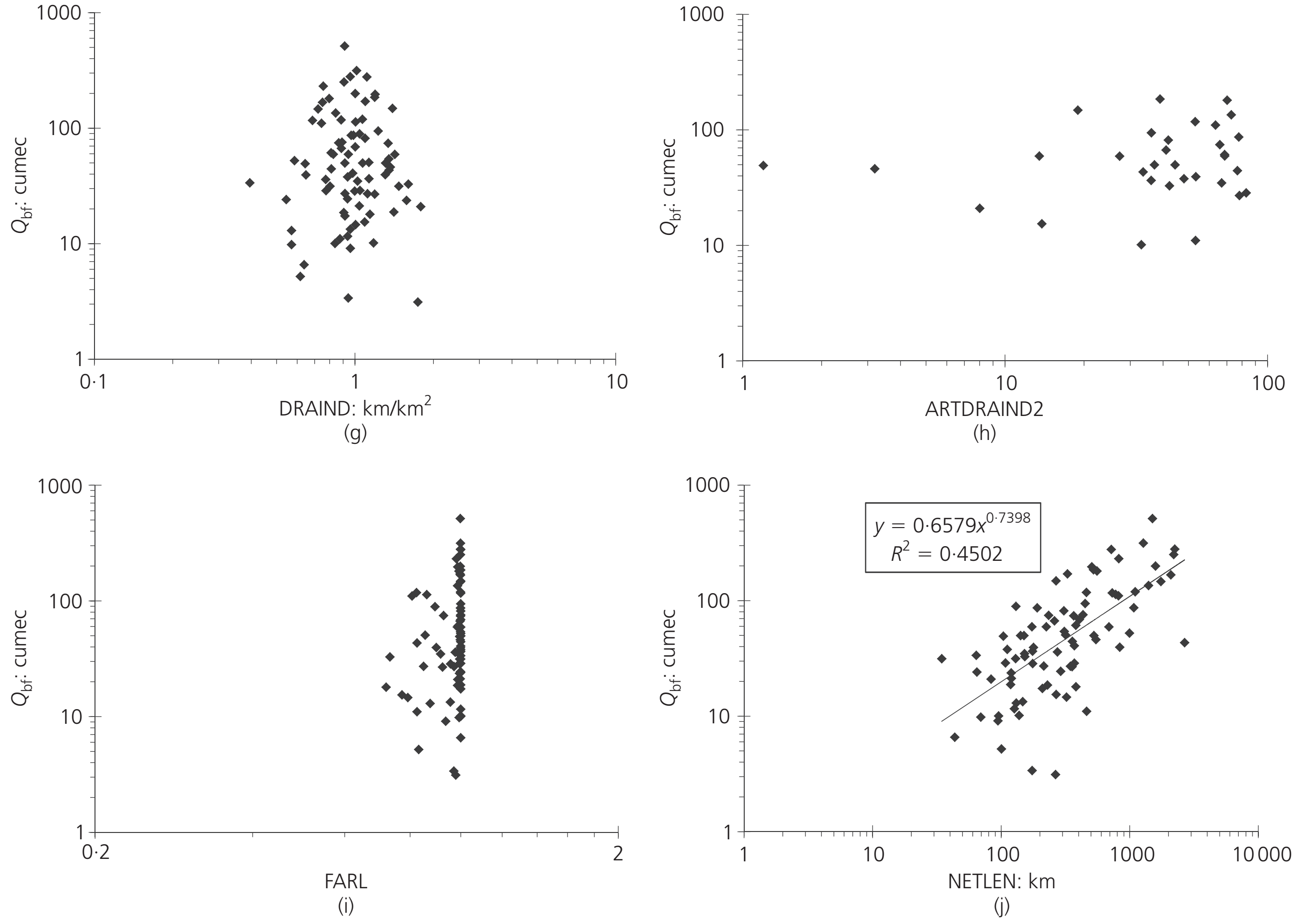

Figure 4. (continued)

the channel without overtopping the banks and inundating the adjacent floodplains. Bankfull discharges were calculated from corresponding bankfull stages estimated from a combination of the rating curve method, surveyed levels and photographic records.

The recurrence intervals of the discharges were determined by fitting generalised extreme value (GEV) distributions to the annual maximum flow series at the sites investigated. These intervals were found to be less than 2·33 years at 53% of these sites with higher return periods of between 2·33 and 10 years and 10 and 25 years, respectively, being observed at a further 20% and 6% of locations. Furthermore, approximately 66% of sites investigated had bankfull recurrence intervals of between 1 and 5 years, with the median value being 1·64 years.

The bankfull discharge estimates were related to catchment descriptors using multivariate regression analysis. The most suitable expression for estimating the bankfull discharge based on estimates at the 84 sites investigated was (Equation 19)

$$\begin{aligned} Q_{\mathrm{bf}} &= 0{\cdot}162\mathrm{AREA}^{0{\cdot}87}\mathrm{BFI}^{-0{\cdot}67}\mathrm{SAAR}^{0{\cdot}01} \\ &\quad \times \mathrm{FARL}^{2{\cdot}39}\mathrm{DRAIND}^{0{\cdot}28}\mathrm{S1085}^{0{\cdot}16} \\ &\quad \times (1+\mathrm{ARTDRAIN2})^{0{\cdot}10} \end{aligned} \tag{19}$$

While estimates from the equation are improved in larger catchments, the FSE of 1·55 results in a 66% confidence interval of ($0{\cdot}65Q_{\mathrm{bf}}$ to $1{\cdot}55Q_{\mathrm{bf}}$). Although the magnitude of the FSE is consistent with regression equations for determining mean and median flows in the Flood Studies Report (NERC, 1975) and Flood Estimation Handbook (CEH, 1999), this confidence interval is wide and caution is advised.

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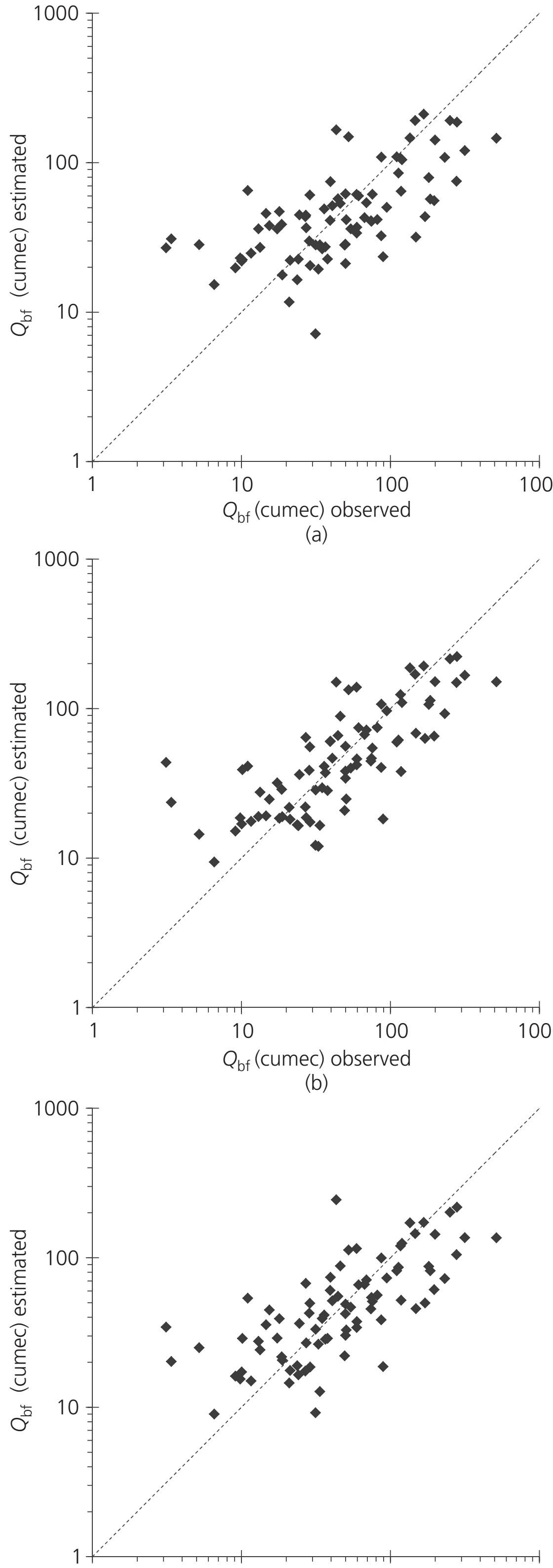

Figure 5. Comparison of estimated Qbf from (a) Equation 15, (b) Equation 16 and (c) Equation 17 with observed values

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REFERENCES

Akaike H (1974) A new look at the statistical model identification. *IEEE Transactions on Automatic Control* **19(6)**: 176–723, http://dx.doi.org/10.1109/TAC.1974.1100705.

Archer D (1989) Flood wave attenuation due to channel and floodplain storage and effects on flood frequency. In *Floods: Hydrological, Sedimentological and Geomorphological Implications* (Beven K and Carling PA (eds)). Wiley, Chichester, pp. 37–46.

Brush Jr LM (1961) *Drainage Basins, Channels, and Flow Characteristics of Selected Streams in Central Pennsylvania*. US Geological Survey, Washington, DC, USA, Professional Paper 282 (F), pp. 145–181.

Castro JM and Jackson PL (2001) Bankfull discharge recurrence intervals and regional hydraulic geometry relationships patterns in the Pacific Northwest, USA. *Journal of the American Water Resources Association* **37(5)**: 1249–1262.

Cawley AM and Cunnane C (2003) Comment on estimation of greenfield runoff rates. *Proceedings of the Irish National Hydrology Seminar, Tullamore, Ireland*, pp. 29–43.

CEH (Centre for Ecology and Hydrology) (1999) *Flood Estimation Handbook*. CRH, Bailrigg, UK.

Copeland RR, Biedenharn DS and Fischenich JC (2000) *Channel Forming Discharge*. US Army Corps of Engineers, EDRC/CHL CHETN-VIII-5: 1–10.

Dury GH (1961) Bankfull discharge: an example of its statistical relationship. *Bulletin of the International Association of Scientific Hydrology* **6(3)**: 48–55.

Harvey AM (1969) Channel capacity and the adjustment of streams to hydrologic regime. *Journal of Hydrology* **8(1)**, 82–98.

Hey RD and Davies JD (1975) Design discharge for natural channels. In *Science Technology and Environmental Management*. Saxon House, Farnborough, UK, pp. 73–88.

Hosking JRM, Wallis JR and Wood EF (1985) Estimation of the generalized extreme value distribution by the method of probability-weighted moments. *Technometrics* **27(3)**: 251–260.

Keshavarzi AR and Nabavi SH (2006) Dominant discharge in the Kor River, Fars province, Iran. *Proceedings of the 10th International Water Technology Conference, IWTC10, Alexandria, Egypt*, 299–306.

Knight DW and Demetriou JD (1983) Floodplain and main channel flow interaction. *Journal of Hydraulic Engineering, ASCE* **109(8)**: 1073–1092.

Lambert CP and Walling DE (1987) Floodplain sedimentation: a preliminary investigation of contemporary deposition within the lower reaches of the River Culm, Devon, UK. *Geografisko Annaler* **69(3–4)**: 393–404.

Leopold LB, Wolman MG and Miller JP (1964) *Fluvial Processes in Geomorphology*. WH Freeman, San Francisco, CA, USA.

Martin LA and Myers WRC (1991) Measurement of overbank flow in a compound river channel. *Proceedings of the Institution of Civil Engineers – Water, Maritime and Energy* **91(4)**: 645–657.

Middleton BA (2002) *Flood Pulsing in Wetlands: Restoring the Natural Hydrological Balance*. Wiley, Chichester, UK, pp. 1–10.

Navratil O, Albert MB, Herouin E and Gresillon JM (2006) Determination of bankfull discharge magnitude and frequency: comparison of methods on 16 gravel bed river reaches. *Earth Surface Processes and Landforms* **31(11)**: 1345–1363.

NERC (Natural Environment Research Council) (1975) *Flood Studies Report*. NERC, London, UK, vol. I–V.

Nixon M (1959a) A study on the bank-full discharges of rivers in England and Wales. *Proceedings of the Institution of Civil Engineers* **12(2)**: 157–174.

Nixon M (1959b) A study of the bank-full discharge of rivers in England and Wales. *Proceedings of the Institution of Civil Engineers* **14(4)**: 395–425.

Nunnally NR (1967) Definition and identification of channel and over bank deposits and their respective roles in floodplain formation. *Professional Geographer* **19(1)**: 1–4.

Petit F and Pauquet A (1997) Bankfull discharge recurrence interval in gravel-bed rivers. *Earth Surface Processes and Landforms* **22(7)**: 685–693.

Petts GE and Foster J (1985) *Rivers and Landscape*. Arnold, London, UK.

Pickup G and Warner RF (1976) Effects of hydrologic regime on magnitude and frequency of dominant discharge. *Journal of Hydrology* **29(1–2)**: 51–75.

Reed D and Martin J (2005) Flood studies update: a new look at flood estimation for Ireland. *Proceedings of UNESCO International Hydrological Programme, OPW, Ireland National Hydrology Seminar*, pp. 26–33.

Richards K (1982) *Rivers, Form and Process in Alluvial Channels*. Methuen, London, UK.

Roberts CE (1989) Flood frequency and urban-induced channel change: some British examples. In *Floods: Hydrological, Sedimentological and Geomorphological Implications* (Beven K and Carling P (eds)). Wiley, Chichester, UK, pp. 57–82.

Rosgen DL (1994) A classification of natural rivers. *Catena* **22(3)**: 169–199.

Rustomji P (2009) *A Statistical Analysis of Flood Hydrology and Bankfull Discharge for The Daly River Catchment, Northern Territory, Australia*. National Research technical report, CSIRO Land and Water, Clayton South, Australia.

Sellin RHJ (1964) A laboratory investigation into the interaction between the flow in the channel of a river and that over its flood plain. *La Houille Blanche* **19(7)**: 793–801.

Shelton JS (1966) *Geology Illustrated*. WH Freeman, San Francisco, CA, USA.

Shome ML and Steffler PM (2006) Flood plain filling by a monoclinal flood wave. *Journal of Hydraulic Engineering, ASCE* **132(5)**: 529–532.

Speight JG (1965) Flow and channel characteristics of the Angabunga River Papua. *Journal of Hydrology* **3(1)**: 16–36.

Thornbury WD (1969) *Principles of Geomorphology*, 2nd edn. Wiley, New York, NY, USA.

Welcomme RL (1990) Status of fisheries in South American Rivers. *Interciencia* **15(6)**: 337–345.

Williams GP (1978) Bankfull discharge of rivers. *Water Resource Research* **14(6)**: 1141–1154.

Winemiller KO (2003) Floodplain river food webs: generalisations and implications for fisheries management. *Proceedings of the 2nd International Symposium on the Management of Large Rivers for Fisheries* **2**: 1–16.

Wolman MG and Leopold LB (1957) *River Flood Plains: Some Observations on Their Formation*. US Geological Survey, Washington, DC, USA, Geological Survey professional paper, 282-C, pp. 87–107.

Woodyer KD (1968) Bankfull frequency in rivers. *Journal of Hydrology* **6(2)**: 114–142.

Xia J, Wu B, Wang G and Wang Y (2009) Estimation of bankfull discharge in the Lower Yellow River using different approaches. *Geomorphology* **117(1–2)**: 66–77.

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