BANKFULL DISCHARGE RECURRENCE INTERVAL IN GRAVEL-BED RIVERS

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ABSTRACT

Bankfull discharge was identified in some 30 gravel-bed rivers representing in total *c*. 40 gauging stations. The catchment sizes vary from 4 km^2 to nearly 2700 km^2. Bankfull discharge value increases with basin size. In the case of gravel-bed rivers developed on an impermeable substratum, the following equation emerges: $Q_b = 0{\cdot}087\, A^{1{\cdot}044}$. Bankfull discharge recurrence interval was determined by fitting maximum annual floods (T_a) into Gumbel's distribution and then using the partial duration series (T_p) in this same distribution. Recurrence interval is below 0·7 years (T_p) for small pebble-bed rivers developed on an impermeable substratum; it reaches 1·1 to 1·5 years when the catchment size of these rivers exceeds 250 km^2. Rivers incised in the soft schists of the Famenne show larger channel capacity at bankfull stage, a small width/depth ratio and thus higher recurrence intervals (1·4–5·3 years with T_a and 1–4·4 years with T_p). Baseflow-dominated gravel-bed streams and sandy or silty rivers experience less frequent bankfull discharges, with a recurrence interval higher than 2 or even 3 years (T_p). © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Among the characteristic discharges which need to be taken into account in the analysis of river regime, and whose frequency of recurrence it is interesting to know, bankfull discharge is one of the most important, for geomorphological and hydrological reasons (Lambert and Walling, 1987; Archer 1989). On the other hand, bankfull discharge offers itself as the best means of evaluating the risks of overflow with consequent flooding of the alluvial plain and all that this implies, particularly in regional planning. Several studies have shown that the capacity of a river at bankfull stage increases downstream or, in other words, that there exists a relationship between the bankfull discharge value of a river and the area of its catchment (Nixon, 1959; Gregory and Walling, 1973; Petts, 1977; Andrews, 1980). The effect of hydrologic regime on the values of bankfull discharge has been demonstrated by Harvey (1969) and also by Pickup and Warner (1984), with rivers of more variable regime having a greater channel capacity than rivers with a relatively stable regime. Early studies suggested a recurrence interval of bankfull discharge varying between 1 and 2 years (Leopold *et al*., 1964; Tricart, 1977), and subsequently defined at 1·58 years (Dury, 1977). This last value in fact represents the most probable annual flood in the Gumbel Type 1 distribution (EVI), when the series of annual maximum floods alone is examined (Roberts, 1989). Results obtained by Hey (in Richards, 1982) at different stations of a single river show that the recurrence interval of bankfull discharge is significantly below 1·5 years at those stations located at the head of the hydrographic basin, whereas in those sites furthest downstream it distinctly exceeds this value, with bankfull discharge having a recurrence of 1·5 years for a drainage basin area close to 200 km^2. This reduced frequency of bankfull discharge downstream is justified by the fact that generally the duration of a flood of a given frequency increases downstream (Dury, 1961). This results from the attenuation of peak discharges downstream, which is all the more pronounced because the slope of the river is slight (Petts and Foster, 1985). Williams (1978) confirmed that the recurrence interval of bankfull discharge is on average 1·5 years, but he

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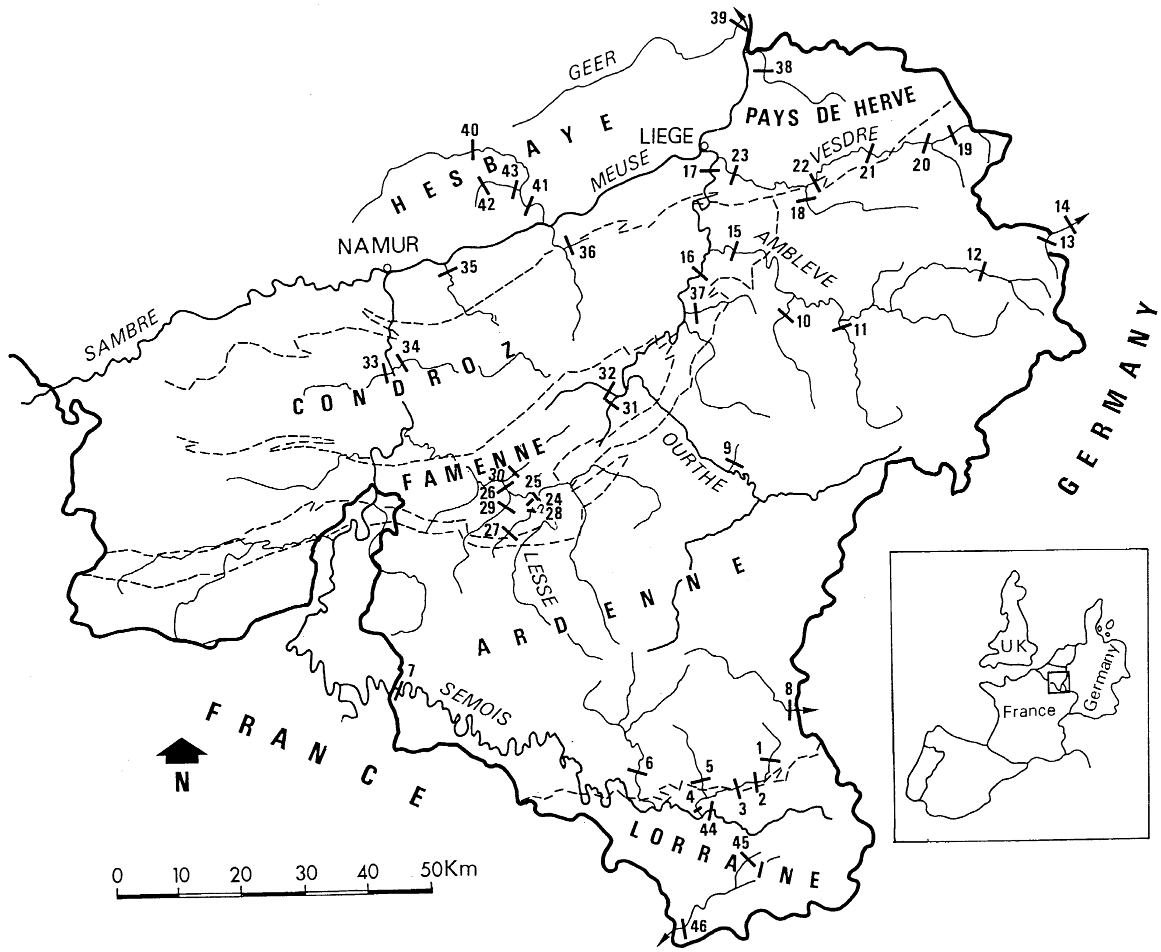

Figure 1. Location of the study rivers and their gauging stations (the numbers refer to Table I)

observed a considerable scatter of points, with extreme values ranging from 1·01 to 32 years. Harvey (1969) showed that in the case of rivers with a variable regime and with a drainage basin composed of boulder clays, the recurrence interval of bankfull discharge was of the order of 1·8 years. Conversely, in the case of a river characterized by dominant base flow due to the permeability of its basin, bankfull recurrence interval reached 7 years. Such behaviour was confirmed by the examples put forward by Roberts (1989): rivers flowing on permeable terrain have a bankfull recurrence interval of more than 2 years (using the partial duration series, T_p; see below), whereas in the case of rivers on impermeable terrain, such recurrence varies between 4 and 8 months.

METHODOLOGY

The selected rivers are spread over five natural regions which show strong lithological differences (Figure 1).

(i) The Ardenne, an impermeable schisto-sandstone substratum of the Cambro-Ordovician and Lower Devonian, has seen the development of pebble-loaded rivers with relatively steep slopes (Group 1, stations 1–26).

(ii) The Famenne depression is carved into Upper Devonian soft schists, with rivers featuring an impermeable substratum and a relatively reduced pebble load (Group 2, stations 27–32).

(iii) The Condroz is characterized by gravel-bed rivers flowing mainly on Carboniferous limestones, with a dominant baseflow regime (Group 3, stations 33–37). The rivers in the Pays de Herve have the same characteristics (station 38).

(iv) To the north of the Sambre and Meuse axis, Middle Belgium is characterized by a predominantly permeable substratum (Mesozoic chalks and Tertiary sands) covered by a thick layer of Quaternary loess (Group 5, stations 39, 40 and 42). Some of these rivers can nonetheless have a pebble load when they cut across Palaeozoic terrain or when their basins lie in close proximity to the upper terraces of the Meuse (stations 41 and 43).

(v) Finally, in Belgian Lorraine, in the far south, the rivers have a sand load and are mainly developed on calcareous Jurassic sandstones (Group 6, stations 44–46).

Some major rivers flow in different regions but preserve the characteristics of Ardenne rivers with regard to pebble bedload and discharge regime. For example, the Lesse (stations 24 and 25 on Figure 1) and the Lhomme (station 26) have to be considered as Ardenne type rivers (Group 1), although these gauging stations are located in the Famenne.

The most difficult issue was the identification of bankfull discharge for each of the rivers studied. Once this discharge is known, a whole range of statistical laws exist which permit reliable calculation of recurrence intervals of extreme cases (Dubreuil, 1974). All the investigated rivers show a clear contact between the channel and the floodplain and are located close to a gauging station. Field observations were regularly carried out at different stages of discharge and a wide range of techniques was used to determine accurately the value of bankfull discharge for each of these rivers (Petit and Daxhelet, 1989).

After identifying bankfull discharge, recurrence intervals were determined, first by using the daily annual maximum floods in Gumbel's distribution by the method of moments (see Dubreuil, 1974), then bankfull discharge recurrence interval was calculated from partial duration series (T_p). This type of analysis takes into consideration all maximum discharges above an arbitrarily fixed threshold, but needs to preserve the independence of separate events, which depends not only on the size of the rivers but also on other factors which govern their regime (impermeability and catchment slope, for example). Two types of problem then arose: (i) no well-defined rules exist for the choice of the base magnitude, although Dunne and Leopold (1978) suggest that it should be equal to the lowest annual maximum flood on record; (ii) the time interval separating two successive flood events is not well-defined. In the present study, we have selected a threshold discharge equal to 0·6 of the value of bankfull discharge, and an interval between two consecutive maximum discharges of at least 4 days, separated by a minimum discharge equal to at least 50 per cent of the value of the lowest maximum (Pauquet and Petit, 1993). This procedure usually gave three or four events per year. In addition, the threshold defined by Dunne and Leopold was also applied and gave similar recurrence intervals. As a general rule, the relationship between recurrence intervals on the annual series (T_a) and on partial duration series (T_p) is defined as follows (Richards, 1982): $T_a = T_p + 0{\cdot}5$, although Andrews (1980), for example, finds a value close to 0·7 in this relation. On the other hand, Ward (1978) and Petts and Foster (1985) consider that the T_a and T_p series yield marked differences only for more frequent events (for example, about 15 per cent for a return period of 2 years) but give similar results for floods of lower frequency (1 per cent for a return period of 10 years).

RESULTS

Bankfull discharge values in relation to the size of the hydrographic basin

Bankfull discharge values, their recurrence intervals (T_p and T_a) and the size of hydrographic basins are reported in Table I. In the case of pebble-bedded rivers on impermeable substratum alone (Ardenne, Group 1, stations 1–26), a reliable relationship emerges (r=0·989) between bankfull discharge and basin area (Figure 2). The slope of the regression line is more pronounced than those presented by other authors, who have all studied pebble-loaded rivers (Table II). In our case, bankfull discharge values for small pebble-bedded rivers are distinctly lower. Studies conducted on this kind of Ardenne river (Group 1, stations 1–4, 10 and 13) show that this lower bed capacity results from the construction of riffles which act like dams and thus favour overflowing for abnormally low discharges (Petit, 1984, 1987; Molitor, 1991).

Table I. Catchment area, bankfull discharge and recurrence interval of the studied rivers

River	Catchment area (km^2)	Bankfull discharge ($m^3 s^{-1}$)	Reccur. T_a (yr)	Reccur. T_p (yr)
Group 1. Ardenne				
1 Rulles (F d'A)	16	1·3	–	0·40
2 Rulles (H-Nve)	48	4·8	–	0·44
3 Rulles (H-V)	96	11	1·26	0·60
4 Rulles (Tint)	220	24	1·13	0·44
5 Mellier	63	9·9	1·39	0·71
6 Vierre	226	20	–	0·44
7 Semois (Membre)	1235	170	1·77	0·98
8 Sure	209	26	1·30	0·65
9 Reau Belleva	12·5	0·8	–	–
10 Lienne (Lorcé)	146	16·2	1·65	0·64
11 Salm (Fosse)	202	24	1·96	0·73
12 Warche	118	15	1·3	0·50
13 Schwalm	34·4	3·9	–	0·38
14 Schwalm	54·6	6·7	1·11	0·44
15 Ambleve	1044	140	2·40	1·39
16 Ourthe (Tabreux)	1597	160	2·06	1·17
17 Ourthe (Sauheid)	2691	300	2·05	1·11
18 Hoegne (Theux)	190	35	1·60	0·68
24 Lesse (Eprave)	419	36	–	–
25 Lesse (Villers)	1090	105	2·06	0·98
26 Lhomme (Eprave)	474	52	1·53	0·92
Group 2. Famenne				
27 Ry d'Ave (Wellin)	14	1·8	1·68	0·97
28 Ry d'Ave	24	3·1	1·74	1·08
29 Wimbe	93	9·9	1·99	1·10
30 Vachaux	50	9·5	2·86	1·28
31 Marchette	43	7·2	4·14	4·30
32 Eau d'heure	66	14	5·30	4·40
Group 3. Condroz				
33 Molignee	121	8·2	2·69	1·47
34 Bocq	188	25·2	3·33	3·09
35 Samson	62·1	6	1·16	0·44
36 R'seau Wavelinse	4·3	0·2	–	–
37 Ry de Loegne	53	8·9	2·25	0·91
Group 4. Pays de Herve				
38 Berwinne	118	13	1·77	0·85
Group 5. Hesbaye				
39 Geer	500	7	2·20	–
40 Mehaigne (Ambressin)	195	12	1·81	0·88
41 Mehaigne (Moha)	345	15	2·10	1·23
42 Burdinale (Lam)	7·2	0·8	–	–
43 Burdinale (Marneffe)	26	2·2	–	–
Group 6. Lorraine Belge				
44 Semois (Tintigny)	378	50	1·25	–
45 Rouge eau	10	0·97	>7	–
46 Ton	293	22	4·70	4·10

Rivers flowing exclusively in Famenne (Group 2, stations 27–32) have relatively high bankfull discharge values, owing to the fact that they are in contact with particularly friable bedrock which allows easy deepening of the bed while producing only a minimal pebble load.

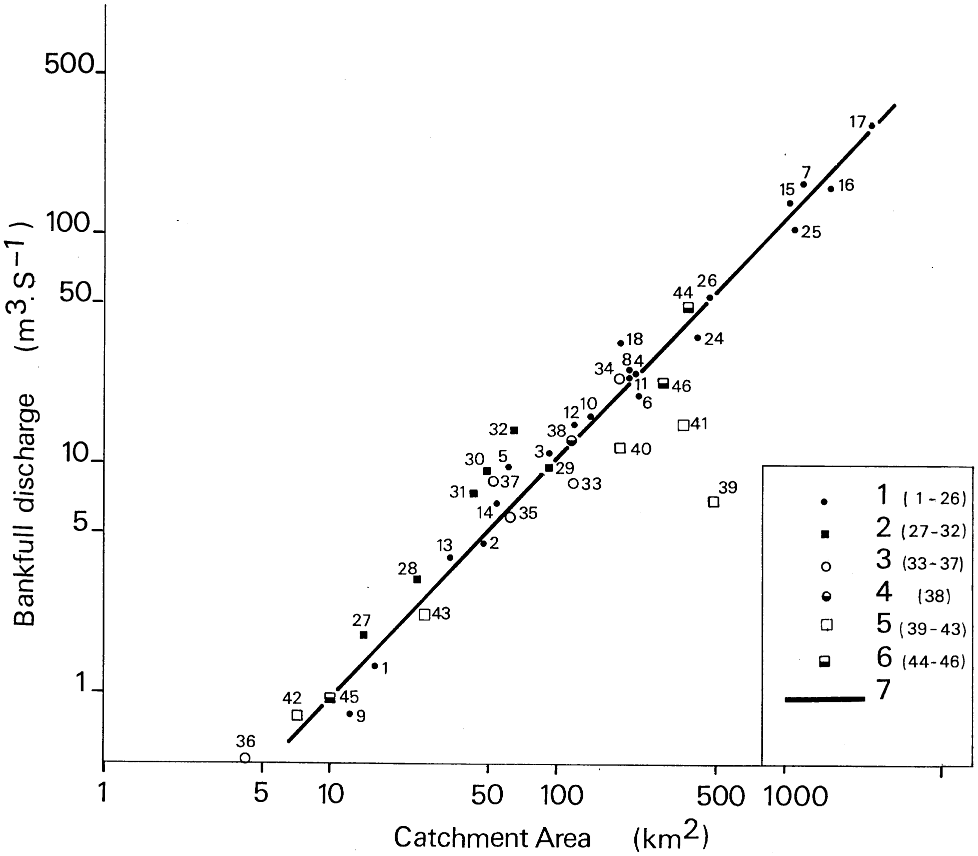

Figure 2. Relation between bankfull discharge values and catchment size. The numbers refer to Table I and Figure 1. (1) Pebble-bedded rivers on impervious substratum (Ardenne); (2) rivers on impervious substratum without pebbles (Famenne); (3) pebble-bedded rivers on permeable substratum (Condroz); (4) pebble-bedded rivers partially on impervious substratum (Pays de Herve); (5) sand- or silt-bedded rivers on permeable substratum (Hesbaye); (6) sand-bedded rivers partially on impervious substratum (Lorraine); (7) relation for pebble-loaded rivers on impervious substratum (Ardenne rivers, solid circle, Group 1, stations 1–26, *n*=21): Q_b=0·087$A^{1·044}$ (*r*=0·989).

Table II. Values of the coefficient (*a*) and the exponent (*b*) in equations of the type $Q_b=aA^b$, linking the value of bankfull discharge (Q_b, expressed in $m^3 s^{-1}$) and the area of the hydrographic basin (*A*, expressed in km^2)

a	*b*	*r**	Source of data
0·277	0·828	0·76	Nixon (1959)
1·705	0·774	0·97	Hey (in Richards, 1982)
0·209	0·791	0·96	Andrews (1980)
1·161	0·666	0·95	UK†
0·087	1·044	0·99	This paper

* Correlation coefficient

† Relationship established according to the values of different authors: Derbyshire (Petts, 1977), Cheshire (Hooke, 1987) and the Pennine Chain (Carling, 1988).

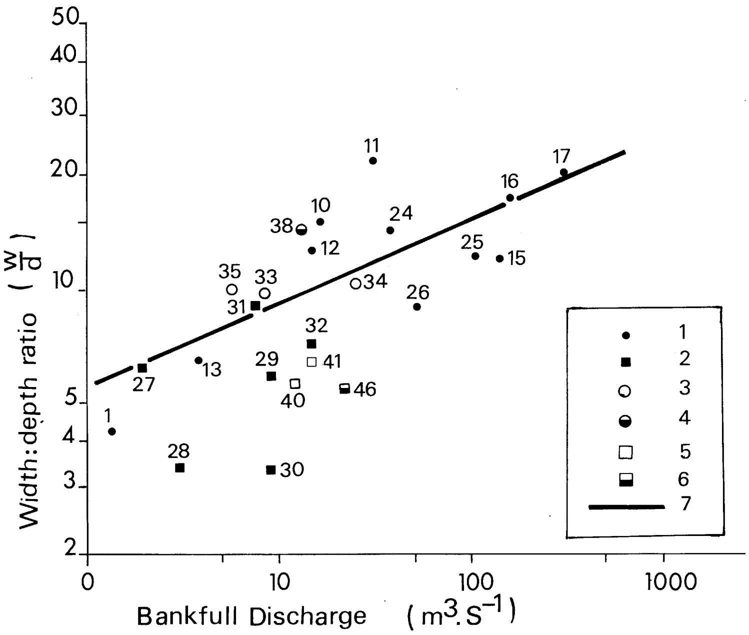

Figure 3. Relation between bankfull discharge values and width/depth ratio. The numbers refer to Table I and Figure 1. (1) Pebble-bedded rivers on impervious substratum (Ardenne); (2) rivers on impervious substratum without pebbles (Famenne); (3) pebble-bedded rivers on permeable substratum (Condroz); (4) pebble-bedded rivers partially on impervious substratum (Pays de Herve); (5) sand- or silt-bedded rivers on permeable substratum (Hesbaye); (6) sand-bedded rivers partially on impervious substratum (Lorraine); (7) relation for pebble-loaded rivers on impervious substratum (Ardenne rivers, solid circle, Group 1, stations 1-26, n=11): $w/d=5{\cdot}61\,Q_b^{0{\cdot}22}$ (r=0·73).

Bankfull discharge, bed morphology and bedload size

Bankfull discharge values were related to the width/depth (*w/d*) ratio for Ardenne rivers (Group 1, Figure 3). As expected, it emerges from this relation that the *w/d* ratio increases with bankfull discharge and thus with the catchment area, given that width tends to increase faster downstream than depth along most rivers. But the low value of the correlation coefficient (r=0·73) results from the fact that some rivers (like the Salm River, station 11) have a coarser bedload material (D_{50}>100 mm), which limits deepening and thus increases lateral erosion (Louette, 1995) compared to other rivers, where the D_{50} ranges from 15 mm in the Rulles (station 1) to 75 mm in the Ourthe (stations 16, 17). In the Famenne rivers (stations 27–32), with fine gravel bedload (D_{50}<5 mm), the *w/d* ratio is usually low, showing the more important incision of the bed. Similar values are observed for the silty and sandy rivers, respectively, located in Hesbaye (station 40) and Lorraine (station 46). On the other hand, dominant baseflow rivers with coarse gravels ($D_{50}\approx$50 mm) located in the Condroz region (Group 3, stations 33–37) and in the Pays de Herve (station 38), present relatively high *w/d* ratios, close to Ardenne rivers values.

Bankfull discharge recurrence interval

The relationship between bankfull discharge recurrence, obtained from the annual series of maximum floods and the size of the hydrographic basin, is reasonably reliable (r=0·74) for Ardenne type rivers (Group 1, stations 1–26) (Figure 4). Some points of detail, however, need to be specified. First, for rivers with a hydrographic basin area of less than 250 km^2, bankfull discharge recurrence interval is of the order of 1 year. In other words, it is very close to the limit value which one can obtain by using annual series. In the case of larger Ardenne type rivers, recurrence interval reaches 1·5 to 2 years. In the case of the Famenne rivers (stations 27–32), the bed capacity of which has been seen to be greater, recurrence is even higher. Finally, in the case of dominantly baseflow rivers developed on permeable terrain, recurrence of bankfull discharge is also high (Condroz, Group 3, stations 33—37; Pays de Herve, station 38; Hesbaye, Group 5, stations 39–43; and Lorraine, Group 6, stations 45, 46).

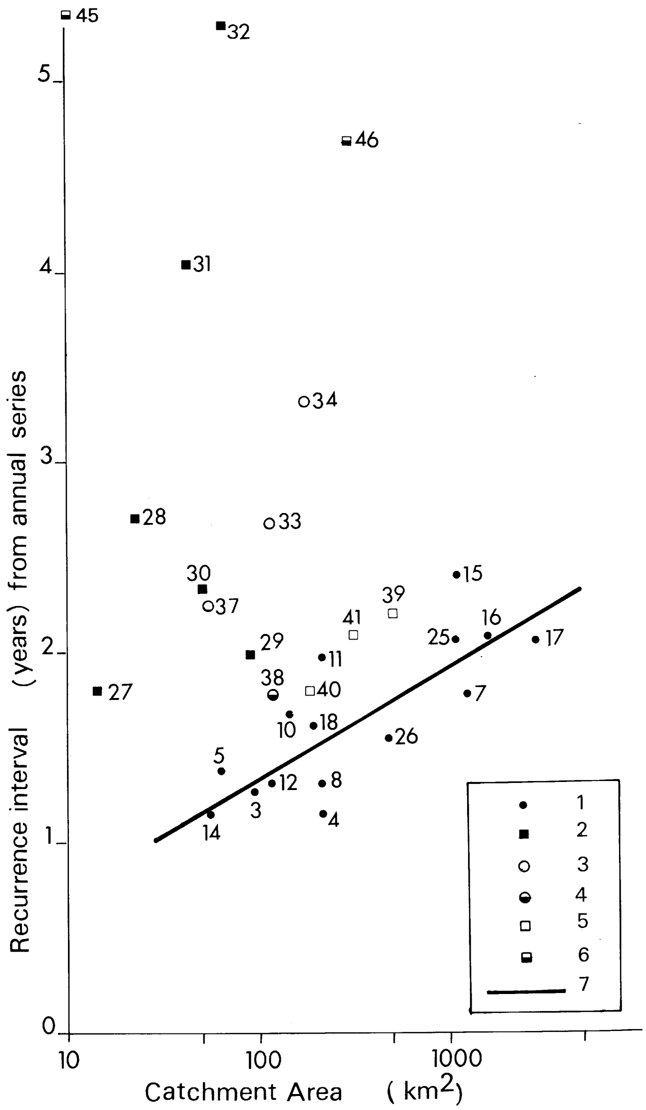

Figure 4. Relation between bankfull discharge recurrence interval, calculated by using the maximum annual flood series (T_a), and catchment size. The numbers refer to Table I and Figure 1. (1) Pebble-bedded rivers on impervious substratum (Ardenne); (2) rivers on impervious substratum without pebbles (Famenne); (3) pebble-bedded rivers on permeable substratum (Condroz); (4) pebble-bedded rivers partially on impervious substratum (Pays de Herve); (5) sand- or silt-bedded rivers on permeable substratum (Hesbaye); (6) sand-bedded rivers partially on impervious substratum (Lorraine); (7) relation for pebble-loaded rivers on impervious substratum (Ardenne rivers, solid circle, Group 1, stations 1–26, n=15): $T_a = 0{\cdot}579 \log A + 0{\cdot}193$ (r=0·79).

Results involving partial duration series are given in Figure 5. Ardenne type rivers with a basin area of less than 250 km^2 have a recurrence interval of the order of 0·4 to 0·7 years. For larger Ardenne rivers (with areas of the order of 2000 km^2), recurrence interval is about 1·2 years. Moreover, the same differentiations as in Figure 4, are found for the Famenne rivers and dominant baseflow rivers, but with a slightly lower recurrence interval than that obtained using the annual series. This corresponds with results obtained elsewhere (Richards, 1982).

CONCLUSION

In a homogeneous geographical context, it is clear that bankfull discharge value increases with basin size; this is also the case with the recurrence interval of this discharge, which is about 0·5 years (T_p) in the case of small

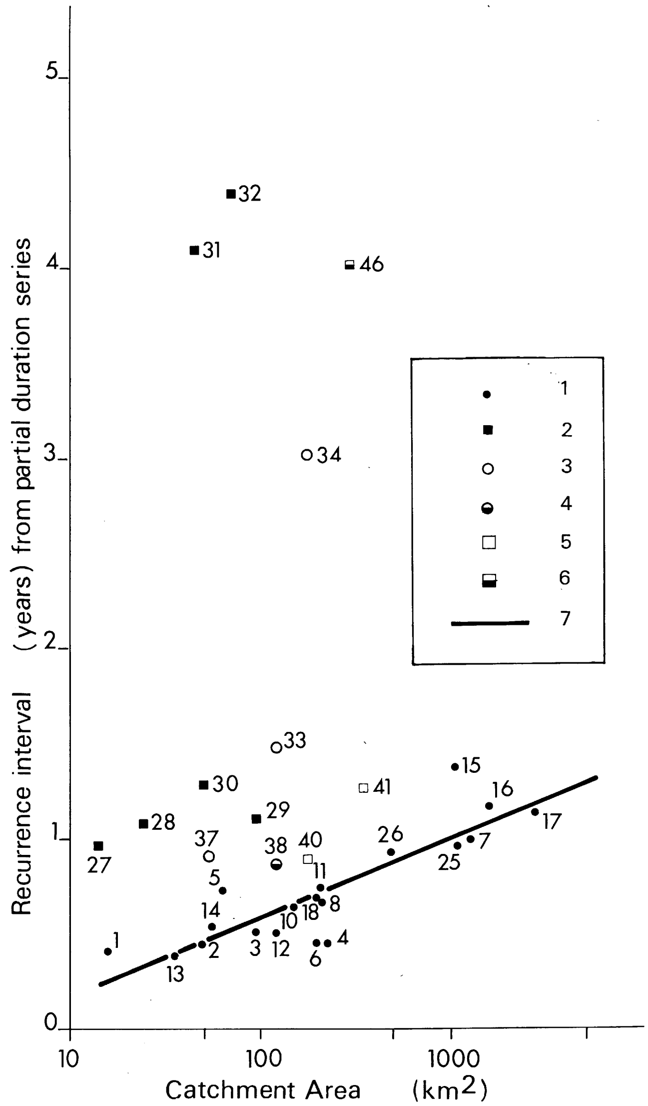

Figure 5. Relation between bankfull discharge recurrence interval, calculated by using the partial duration series (T_p), and catchment size. The numbers refer to Table I and Figure 1. (1) Pebble-bedded rivers on impervious substratum (Ardenne); (2) rivers on impervious substratum without pebbles (Famenne); (3) pebble-bedded rivers on permeable substratum (Condroz); (4) pebble-bedded rivers partially on impervious substratum (Pays de Herve); (5) sand- or silt-bedded rivers on permeable substratum (Hesbaye); (6) sand-bedded rivers partially on impervious substratum (Lorraine); (7) relation for pebble-loaded rivers on impervious substratum (Ardenne rivers, solid circle, Group 1, stations 1–26, n=19): $T_p = 0{\cdot}414 \log A - 0{\cdot}248$ (r=0·86).

rivers with pebble beds on impermeable substrata, but reaches 1·5 years (T_p) for larger rivers of this kind. Rivers with dominantly baseflow regimes are confirmed to have a high bankfull discharge recurrence interval, always exceeding 2 years (T_a) and often much more. Furthermore, rivers with a low pebble load developed on a soft substratum (Famenne rivers) have a larger bed capacity before overflowing and consequently higher bankfull discharge recurrence intervals.

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