Creager and Francou-Rodier envelope curves for extreme floods in the Danube River basin in Croatia

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Abstract This paper presents a comparison of Creager and Francou-Rodier envelope curves for average maximum annual discharges, for the highest observed discharges, and for maximum annual discharges of the 10-, 100- and 1000-year return periods in the Danube River basin in Croatia. They were calculated on the basis of 99 available, sufficiently long and homogenous time series of measured discharges.

Key words Creager's method; Croatia; Danube River basin; envelope curves; Francou-Rodier's method; maximum discharges

INTRODUCTION

The Danube River basin is, after the Volga River basin, the second biggest basin in Europe with a size of about $817\ 000\ \text{km}^2$, with 18 riparian states and about 82 million inhabitants.

In Croatia, the Danube River basin (Fig. 1) covers approximately 34 000 km², roughly 60% of the country's land area, where approximately 65% of the total population of the Republic of Croatia live. Major Croatian rivers, such as the Danube, the Sava, the Drava, the Kupa, the Una and the Mura flow through this area. It is located on the Pannonian plain and its rims, with the water divide separating it from the Adriatic catchments running through the Dinaric karst.

The particular socio-economic significance of this area, not only for the Republic of Croatia, but also for a greater region, emphasizes the importance of efficient flood control. Although certain flood control activities in this area date from the 19th century, systematic development of flood control systems did not begin until after the catastrophic floods on the Sava, the Drava and their tributaries during the 1960s. Gradual development of flood control systems in the last four decades has significantly reduced potential damage, a fact proven by the successful reduction of numerous recent floods. Most of the systems constructed are only partially completed, which results in a continuing significant risk of flooding across large areas. Further development of the flood and torrents control systems remains, therefore, one of the strategic tasks of Croatian water management.

Basic information for further planning and design of flood control systems are maximum discharges of required return periods in adequate locations along the watercourses. These can be estimated by applying stochastic methods for sufficiently long and homogenous time series of measured discharges at gauged locations, or by

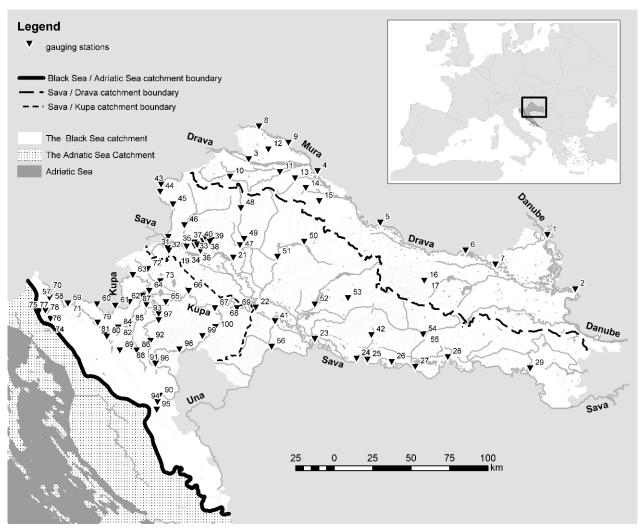


Fig. 1 Overview map of the locations of analysed gauging stations in the Danube River basin in Croatia

deterministic methods at ungauged locations. Common hydrological practice also recognizes the use of various methods for evaluation of reliability of such calculated values. The aim of this paper is to compare two possible methods for evaluation of the reliability of previously estimated values in the Danube catchment area in Croatia: Creager's and Francou-Rodier's envelope curves for average maximum annual discharges, for highest observed discharges, and for maximum annual discharges of the 10, 100 and 1000-year return periods in the Danube River basin in Croatia. Similar investigations for large floods across the whole of Europe were performed by Stanescu & Matreata, 1997.

THEORETICAL APPROACH AND INVESTIGATION PROCEDURE

Creager's envelope curves of specific maximum discharges (Creager & Justin *et al.*, 1945) are formulated as follows:

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$$q = aA^{bA^{c}}$$

where q is specific maximum discharge (m³ s⁻¹ km⁻²); A is catchment area (km²); and a, b, c are regional parameters.

The Francou-Rodier envelope curves of maximum discharges (Francou & Rodier, 1967) are formulated as follows:

$$\frac{Q}{Q_0} = \frac{A}{A_0}^{-1\frac{K}{10}}$$

where Q is maximum discharge (m³ s⁻¹); A is catchment area (km²); K is the Francou-Rodier coefficient; $Q_0 = 10^6 \text{ m}^3 \text{ s}^{-1}$; and $A_0 = 10^8 \text{ km}^2$.

Creager's and Francou-Rodier's envelope curves for the Danube River basin in Croatia are defined on the basis of available time series of daily discharges which are stored in the hydrological database of the Croatian Meteorological and Hydrological Service (Plantić, 1996).

The theoretical approach described above can be applied only when the series are sufficiently long, homogenous and when there are no significant trends. Analyses of time series homogeneity and trends were performed only for the maximum annual discharge series at all gauging stations on the Danube River basin in Croatia that have observation periods longer than or equal to 25 years (108 stations).

The analyses of homogeneity were performed by application of the Wilcoxon test in such a way that the available series was split into two sub-series, depending on the time of replacement of hydrometric equipment at the stations (rods to limnigraphs) and depending on the timing of construction of major hydrotechnical structures with significant impacts on the water regime (reservoirs, main dykes and distribution structures). The presence of trends in the time series of maximum annual observed discharges was tested using Mann's test. On the basis of the homogeneity and trend analyses performed, 100 time series of maximum annual discharges were selected for further analysis.

The next step was probabilistic analysis of selected time series of maximum annual observed discharges. Maximum annual discharges of 10-year return period were calculated by application of an empirical distribution, and maximum annual discharges of 100 and 1000-year return periods were calculated by applications of the normal distribution (6 stations), log-normal distribution (18 stations), Gamma two-parameter distribution (9 stations), Gumbel distribution (11 stations), Pearson III distribution (27 stations) and log-Pearson III distribution (29 stations). The goodness of fit was tested using the Kolmogoroff-Smirnoff test. The results of the probability analysis of the time series are shown in Table 1.

The last step was to calculate the regional parameters a, b and c of Creager's formula and K of Francou-Rodier's formula for each envelope curve by means of logarithmic and regression analyses. Because of unreliability of the observed and calculated maximum discharges at Petrina gauging station (No. 59) on the Kupa River, these data were excluded from calculations of the regional parameters.

Mean Mean <th< th=""><th>No.</th><th>River</th><th>Gauging station</th><th>Catch-</th><th>Observing period</th><th>Discharg</th><th>es Q (m³ s</th><th>¹)</th><th></th><th></th><th></th></th<>	No.	River	Gauging station	Catch-	Observing period	Discharg	es Q (m ³ s	¹)			
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30 Bregana Bregana Remont 88.5 1970-1998 (29) 1.38 21.5 34.1 (1972) 31.1 41.2 51.8 31 Lipovačka Hamor 19.11 1948-1998 (50) 0.381 4.26 7.4 (1989) 6.1 8.75 11.3 32 Rudarska Gradna Comje Vrapče 11.7 1970-1998 (29) 0.12 3.68 15.4 (1975) 6.79 16.1 34.9 33 Vrapčak Zagreb 15 1961-1998 (38) 0.255 4.49 8.79 (1962) 6.88 9.57 11.9 33 Vrapčak Zagreb 15 1961-1998 (38) 0.168 4.73 17.4 (1975) 7.15 13.4 18.4 35 Črnomerec Fraterščica 7.37 1953-1998 (46) 0.084 2.18 8.42 (1954) 4.21 11.6 27.3 36 Kustošak Kustošak Kustošak Kustošak Kustošak 1971-1998 (28) 0.131 3.61 7.61 (1989) 3.52 19		Sava	Slavonski Brod		1945–1993 (49)	944		. ,			
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34VrapčakZagreb151961–1998 (38)0.1684.7317.4 (1975)7.1513.418.435ČmomerecFraterščica7.371953–1998 (46)0.0842.188.42 (1954)4.2111.627.336KustošakKustošija6.081956–1998 (32)0.0542.5810 (1961)6.4912.725.337MedveščakMihaljevac14.151971–1998 (28)0.135311.6 (1989)4.521118.138BiznecMarkuševac4.971969–1998 (30)0.0761.515.08 (1995)3.758.521939ŠtefanovecDubrava8.031961–1994 (30)0.1313.617.61 (1989)5.858.4111.240TrnavaGranešina28.951954–1998 (31)2.8487.5141 (1972)13417720842ŠumetlicaCernik33.51972–1998 (27)0.2916.4513.7 (1986)9.81519.943SutlaBrezno1091946–1975 (30)1.3421.838.6 (1969)31.440.349.844SutlaMiljana2631977–1976 (30)4.1965.877 (1964)70.976.18045SutlaZelenjak4551958–1998 (41)7.27123250 (1964)18424631046KrapinaKupljenovo11501964–1998 (35)11.8154268 (1989)207<	32		Rudarska Draga	15.6	1957–1994 (38)	0.255	4.49	8.79 (1962)	6.88	9.57	11.9
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36KustošakKustošija6.081956–1998 (32)0.0542.5810 (1961)6.4912.725.337MedveščakMihaljevac14.151971–1998 (28)0.135311.6 (1989)4.521118.138BliznecMarkuševac4.971969–1998 (30)0.0761.515.08 (1995)3.758.521939ŠtefanovecDubrava8.031961–1994 (30)0.1313.617.61 (1989)5.858.4111.240TrnavaGranešina28.951954–1998 (24)0.317.1327.1 (1980)12.628.25241SunjaSunja2251965–1998 (37)0.2916.4513.7 (1986)9.81519.942ŠumetlicaCernik33.51972–1998 (27)0.2916.4513.7 (1986)9.81519.943SutlaBrezno1091946–1975 (30)1.3421.838.6 (1969)31.440.349.844SutlaMijana2631947–1976 (30)4.1965.877 (1964)70.976.18045SutlaZelenjak4551958–1998 (41)7.27123250 (1964)18424631046KrapinaKupljenovo11501964–1998 (35)11.8154268 (1989)20727432947ZelinaBožjakovina1861957–1998 (27)1.8821.622.8 (1966)18.921.5 </td <td>34</td> <td>Vrapčak</td> <td>Zagreb</td> <td>15</td> <td>1961–1998 (38)</td> <td>0.168</td> <td>4.73</td> <td>17.4 (1975)</td> <td>7.15</td> <td>13.4</td> <td>18.4</td>	34	Vrapčak	Zagreb	15	1961–1998 (38)	0.168	4.73	17.4 (1975)	7.15	13.4	18.4
37MedveščakMihaljevac14.151971–1998 (28)0.135311.6 (1989)4.521118.138BliznecMarkuševac4.971969–1998 (30)0.0761.515.08 (1995)3.758.521939ŠtefanovecDubrava8.031961–1994 (30)0.1313.617.61 (1989)5.858.4111.240TrnavaGranešina28.951954–1998 (44)0.317.1327.1 (1980)12.628.25241SunjaSunja2251965–1998 (31)2.8487.5141 (1972)13417720842ŠumetlicaCernik33.51972–1998 (27)0.2916.4513.7 (1986)9.81519.943SutlaBrezno1091946–1975 (30)1.3421.838.6 (1969)31.440.349.844SutlaMiljana2631947–1976 (30)4.1965.877 (1964)70.976.18045SutlaZelenjak4551958–1998 (41)7.27123250 (1964)18424631046KrapinaKupljenovo11501964–1998 (35)11.8154268 (1989)20727432947ZelinaBožjakovina1861957–1998 (32)0.76815.622.8 (1966)18.921.522.949LonjaLonjica32.61972–1998 (27)1.8821.852.7 (1976)27.751.3<	35	Črnomerec	Fraterščica	7.37	1953–1998 (46)	0.084	2.18	8.42 (1954)	4.21	11.6	27.3
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54 Orljava Pleternica 745 1970–1998 (29) 5.25 63.4 117 (1987) 98.2 120 139 55 Londža Pleternica 483 1973–1998 (25) 1.87 36.8 87.2 (1987) 64.3 101 138	52	llova	Veliko Vukovje	995	1945–1998 (52)	7.36	71.5	151 (1972)	89.6	139	169
55 Londža Pleternica 483 1973–1998 (25) 1.87 36.8 87.2 (1987) 64.3 101 138	53	Bijela	Badljevina	170	. ,	1.61	23.6	36.7 (1980)	30.5	33.7	35.1
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56 Una Hrvatska Kostajnica 8876 1926–1991 (65) 228 1138 1808 (1955) 1392 1677 1823											
	56	Una	Hrvatska Kostajnica	8876	1926–1991 (65)	228	1138	1808 (1955)	1392	1677	1823

 Table 1 Basic characteristics of analysed gauging stations in the Danube catchment area in Croatia.

Creager and Francou-Rodier envelope curves for extreme floods in the Danube River basin								
River	Gauging station	Catch-	Observing period	Discharges Q (m ³ s ⁻¹)				

No.	River	Gauging station	Catch- ment	Observing period	Discharges Q (m ³ s ⁻¹)					
			area (km ²)	(no. of years)	Mean	Average max	Max obs'd (year of	Maximum for return periods (years)		
			(111)		annual		occurrence)	10	100	1000
	A RIVER BASIN									
57	Kupa	Kupari	208	1951–1998 (48)	13.5	141	195 (1966)	170	199	222
58	Kupa	Hrvatsko	370	1957–1998 (40)	20.5	287	419 (1966)	384	485	599
59	Kupa	Petrina	528	1951–1992 (42)	26.6	455	1079 (1952)	641	898	1140
60	Kupa	Radenci	1304	1951–1992 (42)	53.7	647	920 (1968)	809	945	1034
61	Kupa	Pribanjci	1492	1949–1985 (37)	61.8	675	1021 (1966)	862	1028	1167
62	Kupa	Ladešić Draga	1590	1956–1998 (42)	58.4	700	1010 (1966)	851	975	1049
63	Kupa	Kamanje	2192	1957–1998 (40)	73.3	811	1145 (1966)	967	1139	1266
64	Kupa	Brodarci	3405	1957–1998 (41)	110	944	1237 (1968)	1160	1305	1419
65	Kupa	Rečica	5923	1948–1982 (35)	171	1137	1533 (1966)	1450	1667	1791
66	Kupa	Jamnička Kiselica	6805	1948–1978 (31)	180	967	1581 (1953)	1416	1791	2351
67	Kupa	Šišinec	7274	1950–1991 (41)	182	949	1259 (1974)	1114	1338	1503
68	Kupa	Farkašić	8902	1965–1992 (26)	196	1048	1631 (1974)	1281	1593	1839
69	Kupa	Brest	9021	1926–1974 (49)	206	1006	1523 (1974)	1204	1382	1481
70	Čabranka	Zamost	103	1950–1998 (49)	3.72	76	128 (1984)	115	143	169
71	Kupica	Brod na Kupi	291	1951–1998 (48)	13.7	146	357 (1993)	194	293	377
72	Kupčina	Strmac	125	1959–1998 (40)	2.18	22.7	45.8 (1974)	38.7	57.4	88
73	Kupčina	Lazina Brana	169	1973–1998 (26)	2.07	22.9	28.8 (1989)	27.7	30.8	32.4
74	Križ Potok	CP Križ	5.4	1963–1998 (36)	0.312	14.3	28.3 (1982)	22.5	29.9	37.6
75	Vela Voda	Crni Lug	3.7	1963–1998 (36)	0.208	7.98	12.7 (1965)	12	16.8	22.4
76	Bela Voda	Crni Lug	1.8	1963–1998 (36)	0.106	5.42	9.78 (1963)	9.13	11.5	14.3
77	Leska	Leska	0.25	1963–1998 (26)	0.015	0.603	1.31 (1963)	0.933	1.44	1.92
78	Klada	Klada	0.33	1963–1998 (26)	0.018	0.443	1.2 (1963)	0.904	1.49	2.34
79	Gornja Dobra	Luke	175	1947–1998 (51)	7.04	109	166 (1968)	135	161	179
80	Gornja Dobra	Turkovići	296	1963–1998 (33)	10	118	154 (1998)	148	178	205
81	Vitunjčica	Brestovac	34	1967–1998 (31)	3.28	31.3	40 (1998)	36.8	39.6	41.9
82	Donja Dobra	Trošmarija	821	1960–1998 (39)	27.9	163	246 (1966)	194	226	246
83	Donja Dobra	Donje Stative	1049	1960–1998 (39)	34.9	249	372 (1966)	309	393	451
84	Ribnjak	Lučanjek	50	1948–1975 (27)	3.01	16.4	25.7 (1962)	22.8	28.5	33.8
85	Globornica	Generalski Stol	32	1949–1975 (27)	1.02	18.8	31.4 (1966)	30.7	42.5	60.6
86	Mrežnica	Juzbašići	683	1947–1998 (46)	12.4	92.4	166 (1989)	122	148	166
87	Mrežnica	Mrzlo Polje	975	1947–1998 (52)	29.5	254	373 (1974)	329	390	445
88	Tounjčica	Ožanići	118	1948–1975 (28)	10.4	70.1	95.6 (1952)	89.4	98.8	108
89	Munjavčica	Josipdol	44.1	1948–1975 (27)	0.431	3	5.84 (1968)	4.85	6.78	9.06
90	Korana	Korana	232	1952–1986 (35)	3.09	19.2	36.2 (1957)	28	37.4	50.5
91	Korana	Slunj	614	1964–1998 (29)	11.1	137	271 (1973)	217	298	402
92	Korana	Veljun	943	1949–1998 (44)	23	264	460 (1955)	363	438	495
93	Korana	Velemerić	1297	1946–1997 (46)	28.8	327	571 (1948)	453	616	769
94	Plitvice – Kozjak	Kozjak Most	169	1953–1991 (33)	3.55	16.2	28.9 (1955)	24.2	33.2	40
05	Plitvice –	Plitvički	20 E	1052 1004 (37)	2 4 2	10	40 E (4076)	14.2	<u></u>	20.7
95 06	Matica	Ljeskovac	20.6	1952–1991 (37)	2.42	12 59 5	49.5 (1976)	14.3	23.4	29.7
96	Slunjčica	Slunj	220	1949–1983 (35)	9.48	58.5	80 (1962)	72.6	80.6	86.5
97	Radonja	Tušilović	224	1967–1998 (26)	3.32	27.5	40.7 (1987)	35.1	43.6	50.2
98	Glina	Maljevac	183	1953–1986 (34)	3.37	38.5	90.6 (1959)	52.7	82.4	108
99	Glina	Vranovina	889	1947–1998 (45)	14.1	146	344 (1974)	275	411	619
100	Glina	Glina	1145	1952–1998 (40)	18.3	178	395 (1955)	290	438	607

RESULTS

By applying the described methodology, Creager's and Francou-Rodier's envelope curves of maximum specific discharges and maximum discharges were defined for average maximum annual discharges, for the highest observed discharges and for maximum annual discharges of the 10, 100 and 1000-year return periods. The results obtained are shown in Figs 2, 3, 4 and 5.

The summary overview of the calculated regional parameters a, b, c of Creager's formula, and K of Francou-Rodier's formula is shown in Table 2.

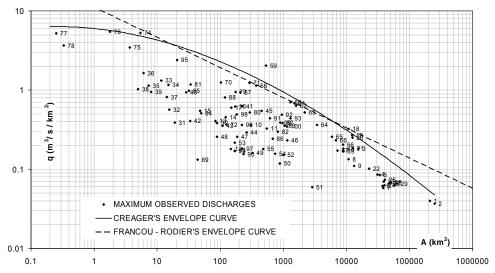


Fig. 2 Creager's and Francou-Rodier's envelope curves of maximum observed specific discharges in the Danube River basin in Croatia.

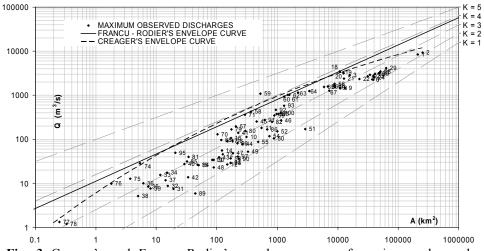


Fig. 3 Creager's and Francou-Rodier's envelope curves of maximum observed discharges in the Danube catchment area in Croatia

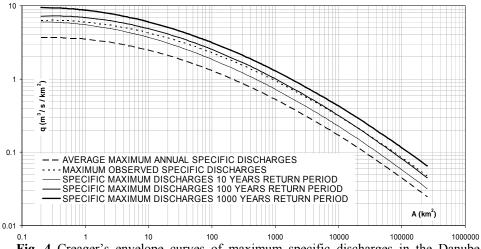


Fig. 4 Creager's envelope curves of maximum specific discharges in the Danube River basin in Croatia.

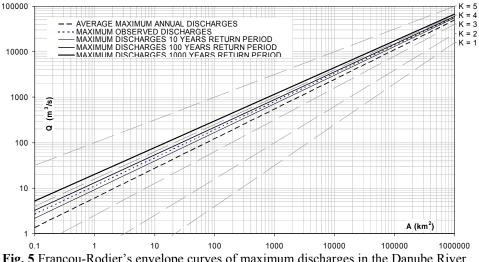


Fig. 5 Francou-Rodier's envelope curves of maximum discharges in the Danube River basin in Croatia.

Table 2 Summary ov	erview of	calculated	regional	parameters.
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Discharges	Creage	er's formula		Francou–Rodier formula
	а	b	С	K
Average maximum annual	3.5	0.918	-0.034	3.478
Maximum observed	6.0	0.920	-0.033	3.808
Maximum of 10-year return period	5.5	0.894	-0.034	3.711
Maximum of 100-year return period	6.9	0.919	-0.035	3.899
Maximum of 1000-year return period	8.7	0.903	-0.032	4.132

CONCLUSION

The relationships presented in this paper were calculated on the basis of 99 available and sufficiently long homogenous time series of observed discharges at gauging stations on the Danube River basin in Croatia and can be used for evaluation of the reliability of previously calculated maximum discharges for this area. Comparisons between the calculated envelope curves show that the Francou-Rodier envelopes give smaller values of maximum discharges than Creager's envelopes for all catchment areas except very small and very large ones.

Because of the climate, relief and geological diversity of the investigated area, further studies of envelope curves of maximum discharges in the Danube River basin in Croatia should be directed to sub-regionalization. Further regional studies of flood characteristics in the Danube catchment area in Croatia should be also directed to analysis of flood wave volumes and durations.

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