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STABILITY OF HIGH AND LOW FLOW PERIODS ON EUROPEAN RIVERS

DARIUSZ WRZESIŃSKI

Department of Hydrology and Water Management, Adam Mickiewicz University
Dzięgielowa 27, 61-680 Poznań

Abstract: The aim of this paper is to examine regional differences in the flow regime of European rivers. The stability of a flow regime is defined as the regularity of high and low flow periods during a year (Corbus and Stanescu, 2004). The first, second, and third maximum and minimum values of the mean monthly flows during the year served as regime characteristics, i.e. descriptors of the regime phases. A series of monthly discharges recorded during the years 1951–1990 at 510 stations on 369 European rivers were analysed. The coefficient of stability used in the analysis enables an extension of classical hydrological regime analysis. The proposed approach allows not only to establish the term of high and low flow periods of the river, but it also shows the regularity (stability) of their occurrence.

Keywords: river regime, high and low flow, coefficient of stability, Europe

INTRODUCTION

The consequences of the destabilisation of river flow regimes are not only a hydrological issue, but they also affect the economic and social aspects of human development. Multi-year variations in river discharge may result from environmental changes at a local-scale (e.g. caused by human activity) or at regional and global scales (caused by climate changes). Hydrological data, including river discharge, may, therefore, serve as an indicator of climate changes.

The pattern of changes in any phenomena occurring in a river can be described by its flow regime. It describes the state of a river system, taking into consideration the climatic conditions and features of a catchment. Research concerning the impact of climate variability and change on water resources has been conducted by many authors. Some of this research is dedicated to the climatic drivers of the river flow regime (Krasovskaia and Gottschalk 1992; Krasovskaia 1995; Krasovskaia 1996; Krasovskaia and Sælthun 1997; Wilson et al. 2012). These drivers include the so-called "global warming", which creates temporary changes in river discharge (Westmacott and Burn 1997). New methodological approaches and regional syntheses have been discussed by Arnell 1999a, Krasovskaia et al. 1999, Shorthouse and Arnell 1999, Gutry-Korycka and Rotnicka 1998, Wrzesiński 2008, 2010, Wrzesiński and Paluszkiewicz 2011. The influence of climate change and changeability on the hydrological regime of European rivers has been documented by N.W. Arnell (1999b). Furthermore, Bower et al. (2004) present an interesting analysis and critical evaluation of the current methods of determining the climatic causes of river flow regime instability.

The runoff of European rivers and their seasonal distribution have a specific spatial variability. As a result, rivers represent 13 types of hydrological regime typology proposed by Lvovich (1979). The aim of this paper is to examine the regional differences in the stability of flow regime of European rivers. Runoff regime stability should be understood as the regularity of high and low flow periods during a full year. Corbus and Stanescu (2004) defined the so-called "coefficient of stability" as the frequency of the regime descriptors. i.e. the maximum and minimum monthly discharges, recorded over the shortest possible time interval.

STUDY AREA AND DATA

Use was made of a series of mean monthly flows from 510 gauging stations located on 369 European rivers (Fig. 1). The figures embraced the period 1951–1990. The data came from the following sources: the Global Runoff Data Centre, HYDRO banquenationale de données pour l'hydrométrie et l'hydrologie (France), HydrometeorologicalCenter of Belarus, Institute of Meteorology and Water Management (Poland), National River Flow Archive (UK), Sistema Nacional de Informaçao de RecursosHidricos (Portugal), and UNESCO's International Hydrological Programme.

The majority of the rivers chosen for study have small basins. Those under 5,000 km^2 in area constituted 68% of the sample, and those under 1000 km^2, 27%. The remaining 32% were streams with basins of more than 5,000 km^2. Only a mere 4% of the analysed rivers have basins exceeding 100,000 km^2.

METHODS

The stability of the river flow regime is defined as the regularity of high and low flow periods during any given year characterised by a chosen regime descriptor (Corbus and Stanescu 1999, 2004). Six descriptors were selected: the first, second and third maximum and minimum values of the mean monthly discharges during the year – $1^{st}max$, $2^{nd}max$, $3^{rd}max$ during high flow period, and $1^{st}min$, $2^{nd}min$, $3^{rd}min$ during low flow period.

According to Corbus and Stanescu (2004) stability is determined by the frequency of a given regime descriptor in the shortest possible period of time, therefore, the stability coefficient can be described by the following equation:

$$C_S = F_A \cdot C_R$$

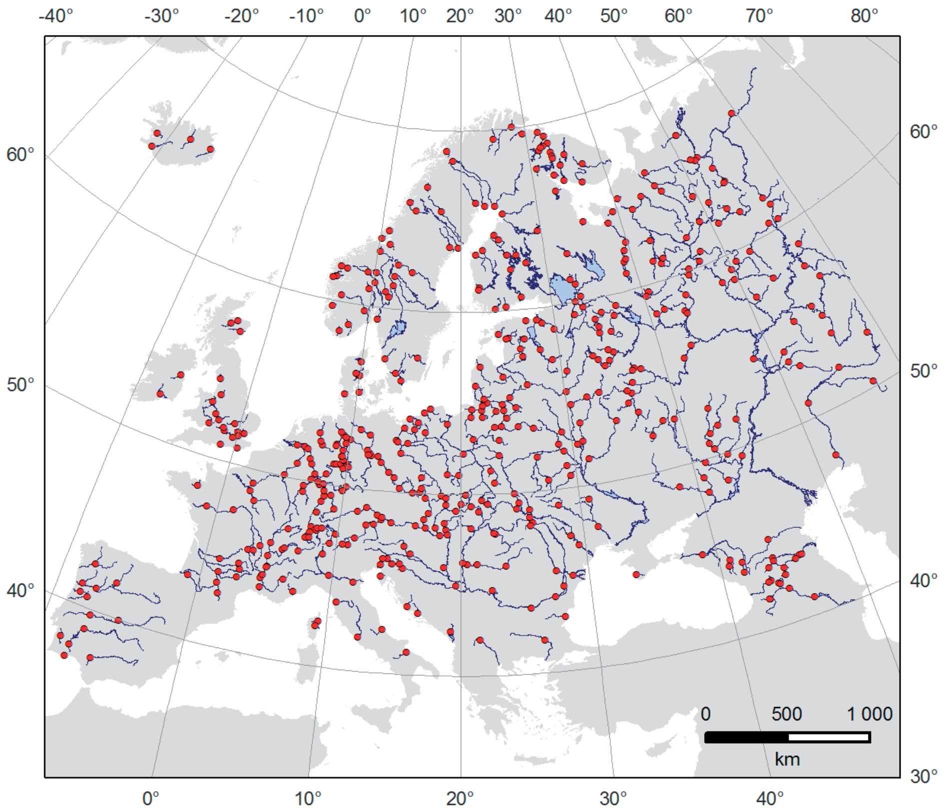

Fig. 1. Location of the gauging stations

where F_A is the frequency of a regime descriptor (number of occurrences in m – consecutive months during a multiyear period, $m = 1,\dots, 12$), and C_R is the distribution coefficient for the analysed period of time:

$$C_R = \left[\frac{13 - m}{12}\right]^2$$

Thus, the stability of a river flow regime increases if the frequency of a given regime descriptor also increases, but its duration decreases. The nature of the flow regime stability in relation to the stability coefficient is presented in Table 1.

The stability coefficient C_S reaches a maximum value only in specific optimal situations, since an increase in the length of the analysed interval of time (duration of the descriptor) causes a decrease in the distribution coefficient C_R, and an increase in the frequency of a regime descriptor. Therefore, periods

Table 1. The nature of flow regime stability depending on the stability coefficient according to Corbus and Stanescu (2004)

F_A	C_R		C_S	Regime character
	m	$C_R = f(m)$		
0.9–1.0	1–2	0.69–1.00	0.62–1.00	Very stable
0.8–0.9	2–3	0.56–0.69	0.45–0.62	Stable
0.7–0.8	3–4	0.44–0.56	0.31–0.45	Relatively stable
0.6–0.7	4–5	0.34–0.44	0.20–0.31	Relatively unstable
0.0–0.6	6–12	0.00–0.34	0.00–0.20	Unstable

characterising certain phases of the runoff regime (*1st max*, *2nd max*, *3rd max*, *1st min*, *2nd min*, *3rd min*) were chosen on the basis of maximising the values of the C_S coefficient.

The stability coefficients for the six regime descriptors were calculated for average values observed in 1951–1990. In order to maximise the stability coefficient of each regime descriptor, its occurrence was analysed for different time intervals, from monthly (January, February,…, December) to half-yearly (January-June, February-July,…, December-May), therefore, a total of 72 variants of time periods were analysed. An example of calculating the stability coefficient is shown in Table 2.

RESULTS AND DISCUSSION

The stability of maximum flows

The regularity of the first maximum of mean monthly flows (*1stmax*) on European rivers is relatively high, but regionally diverse (Fig. 2). The highest regularity is observed on the rivers of Eastern and Northern Europe (with the exception of the southern parts of Norway, Sweden and Finland), as well as on the rivers of the Alps and Iceland. In this part of Europe the time of the *1stmax* occurrence varies from region to region and depends on the time of snow or glacial melt. It is recorded during the early spring months (March-April) in the westernmost parts of Europe, mid-spring in the central regions, and late spring or early summer (May-June) in the north-western parts of the continent. The spring-summer maxima (May-June) also occur on the rivers of Central Finland, Northern Norway, Russia, and locally also in the Pyrenees. A summer (June-July) maximum is characteristic of the glacial flow regime found in the Alps, the Caucasus Mountains and Norway. The earliest, highly stable first maximum in

Table 2. An example of stability coefficient calculations for *1stmax* in 1951–1990 for 6 periods selected from the 72 periods analysed (Warta River – Poznań gauging station)

Years	Months											
	J	F	M	A	M	J	J	A	S	O	N	D
1951			x									
1952												x
1953		x										
1954				x								
…..	…..	…..	…..	…..	…..	…..	…..	…..	…..	…..	…..	…..
1988			x									
1989	x											
1990												x
Sum	5	5	12	10	0	1	1	2	0	1	1	2

Periods	F_A	C_R	C_S
March	12/40 = 0.300	1.000	0.300
March-April	22/40 = 0.550	0.840	0.462
February-April	27/40 = 0.675	0.694	0.468
January-April	32/40 = 0.800	0.562	0.450
December-April	34/40 = 0.850	0.444	0.377
November-April	35/40 = 0.875	0.340	0.298

Scandinavia occurs during the late spring. It is observed on the rivers of Western Finland and in the whole region from Southern Norway to Eastern Sweden.

The timing of the first maximum of mean monthly flows is stable or relatively stable on the rivers of other European regions. The first stable maximum occurs during the winter (December-February) or winter-spring (December-March, January-April) months on the rivers of Western Europe. In Central Europe, and the Balkan Peninsula, *1stmax* is observed during different periods of time: winter-spring (February-April) in Central Poland, spring in Eastern Poland (March-April) and the Balkans (April-May), spring-summer (April-une) in the southern and eastern parts of the Carpathian Mountains, and winter (December-February) in Dalmatia. A relatively stable first maximum of the mean monthly flows is recorded in the winter-spring period (January-April) on the rivers of Southern Sweden, Northern Poland and Eastern Germany. *1st max* is observed mainly during the spring-summer period (April-July) in the Sudetes and Carpathian Mountains in Poland, and during the winter or winter-spring period (December-March) in the French Massif Central, Scotland and the Balkans.

A highly stable second maximum of monthly flows (*2ndmax*) is observed in the same regions as the first maximum, however, the second maximum is more

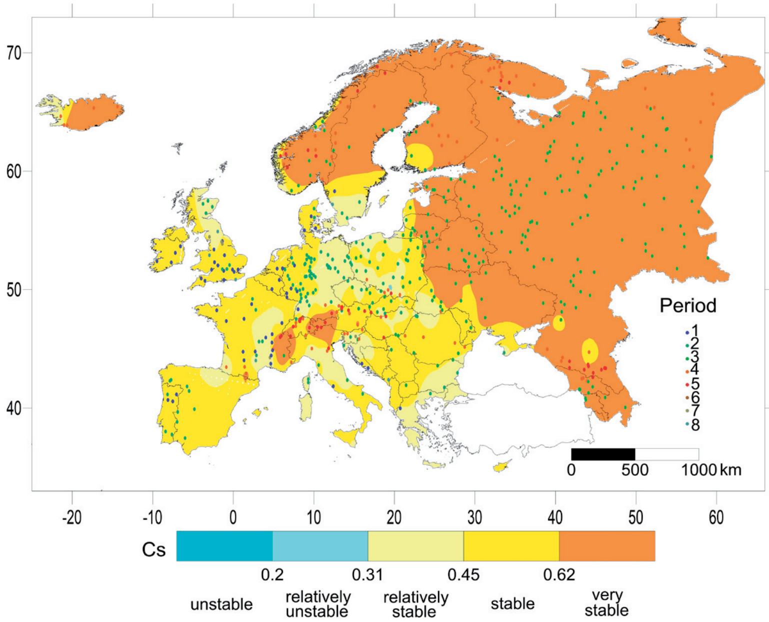

Fig. 2. Stability of the 1st maximum of monthly flows
Cs – coefficient of stability; period of occurrence of the 1st maximum: 1 – winter, 2 – winter/spring, 3 – spring, 4 – spring/summer, 5 – summer, 6 – summer/autumn, 7 – autumn, 8 – autumn/winter

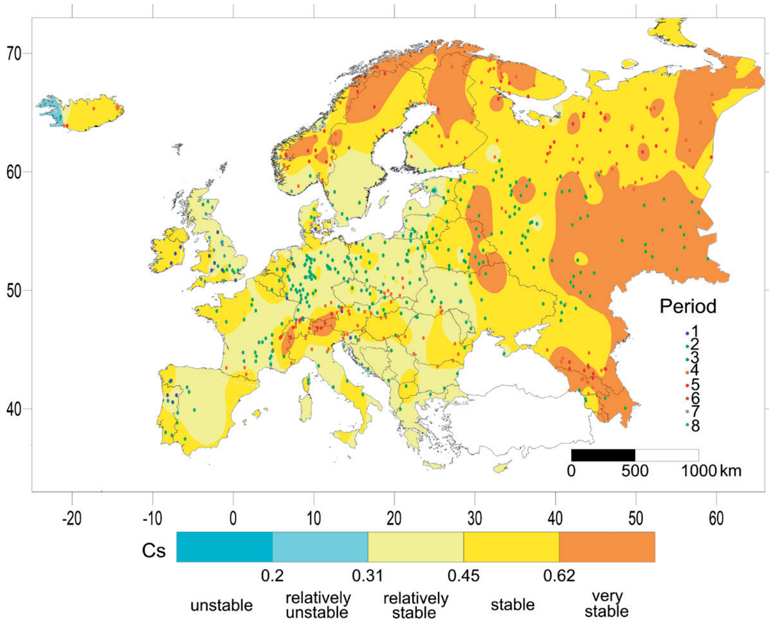

Fig. 3. Stability of the 2nd maximum of monthly flows, legend as in Fig. 2

disperse (Fig. 3). The highest stability of the $2^{nd}max$ in the eastern parts of the continent can be observed on rivers of the Oka-Don Lowland, Ural and north-eastern areas of European Russia. Rivers of the highest Scandinavian Mountain ranges in Norway, as well as the rivers in Northern Finland, the Alps and Caucasus Mountains are also characterised by a highly stable second maximum. It usually occurs later than the first one. This occurrence is especially apparent when analysing Russian rivers located north of the 60°N circle of latitude. On these rivers, the $2^{nd}max$ is recorded in the spring-summer period (April-June). The latest $2^{nd}max$ is detected in north-eastern areas of European Russia (May-July). Other rivers of the East European Plain and Scandinavia are characterised by a stable second maximum of monthly flows. However, it is relatively stable for the rivers of Western Ukraine, the Baltic states, and the southern parts of Finland, Sweden and Norway. In other regions of the continent, areas with a relatively stable second maximum of monthly flows are significantly larger than that of the $1^{st}max$.

The stability of the third maximum of monthly flows ($3^{rd}max$) is even lower. The most stable period of the $3^{rd}max$ occurrence is characteristic solely for the rivers of the Caucasus region (June-July) and the Ural River catchment (April-May) – Fig. 4. A stable $3^{rd}max$ is observed on the rivers of the Scandinavian Mountains, the Alps, Northern Sweden and Finland, the Kola Peninsula, as well as in the north-eastern and south-eastern parts of European Russia. The third maximum is relatively stable for the remaining regions, with the exception of the rivers of the western part of Eastern Europe, e.g. the Belarusian Ridge (Neman, Neris, Daugava, Dnieper), Central Ukraine and Northern Moldavia (Riv, Southern Bug, Tikych, Răut) where the date of occurrence of the $3^{rd}max$ period is relatively unstable.

Stability of minimum flows

The area of highly stable flows is much smaller for the period of low water – Fig. 5 than for the period of high water – Fig. 2. In the cooler climate zone, this area covers the same regions – the northern and north-eastern part of European Russia, northern parts of Norway, Sweden and Finland, as well as the Caucasus. The first and second minimum of monthly flows are observed during the colder part of the year, when river feeding is limited. The $1^{st}min$ occurs during the winter-spring period (February-March) or spring (March and March-April), and as for the Caucasus rivers – mainly during winter (January-February) or winter-spring (February-March).

The time of the $2^{nd}min$ is usually earlier and occurs during the winter-spring period (February-March and February-April) – Fig. 6. Highly stable minimum flows are also observed on rivers in Southern Europe. On the rivers of the north-western part of the Iberian Peninsula, rivers of Corsica, as well as on some

Apennine and Balkan rivers, the first minimum occurs during the summer-autumn period (August-September). In other regions, the *1st min* is observed in summer (July-September). The area with a highly stable second minimum (*2nd min*) is smaller. A highly stable summer (July-August) or summer-autumn (August-September) *2nd min* is only recorded on the rivers of the Italian Peninsula and the western parts of the Balkans.

The stability of minimum flows (*1st min, 2nd min* as well as *3rd min* of monthly flows) in the Eastern European Plain clearly decreases from the north-east, where the flows are the most stable, towards the south and south-west. On the northern, left tributaries of the Volga River stable minima are observed in the winter-spring months (February-March), however on the eastern tributaries – the Sok and Samara, and on the Ural River *1st max* occurs earlier – in the winter period (December-February). The second minimum is recorded on these rivers in the winter-spring months (January-March). The Volga constitutes a border between stable and relatively stable minima of monthly flows, with the latter observed south-west of the river. The timing of the low water periods on rivers is exceptionally diverse. In the northern parts of the Central Russian Upland (in the Oka and Don catchments), and in the catchment of the Dnieper (Desna, Sozh, Pripyat) it occurs during winter (January-February).

The eastern parts of the upland, the Don catchment (e.g. Vorona, Voronezh), and the west (Neman, Lovat) are characterised by a summer-autumn (July-September) period of low water. On many rivers, mainly in the Dnieper catchment, the timing of the *2nd min* is relatively unstable. Furthermore, the area of the relatively unstable *3rd min* is even larger (Fig. 7). It expands to the north, encompassing the rivers located in the eastern parts of the Baltic states (Daugava, Emajõgi), Western Russia (Dolga, Narva, Lovat) and the Finnish Lakeland (Kallavesi). The area also extends to the south as far as Ukraine (Southern Bug, Riv, Tikych).

Rivers of Central Europe are characterised by a stable or relatively stable timing of the low water characteristics – *1st min* and *2nd min*. These periods occur during the summer (June-August) and the summer-autumn (July-September) seasons respectively. Mountain rivers are an exception since their minima are observed in the winter (January-February) or the autumn-winter period (November-January). Moreover, the *2nd min* on those rivers can also be observed in autumn (September-November). In the area located west of Germany, minima are stable and occur in the summer-autumn period (August-October). Earlier, i.e. spring-summer and summer, first minima are recorded on the rivers of Scotland, Ireland, and Northern England (May-July), but also on the rivers of Denmark and Southern Sweden (June-August). The second and third minima on these rivers occur at a similar time or are shifted to the summer-autumn period (June-September). The timing of the *1st max* and the *2nd max* on Alpine rivers is also stable. The first minimum is observed in the winter (December-February) (Rhone, Ticino, Inn, Mura, Sava) or the autumn-winter period (October-

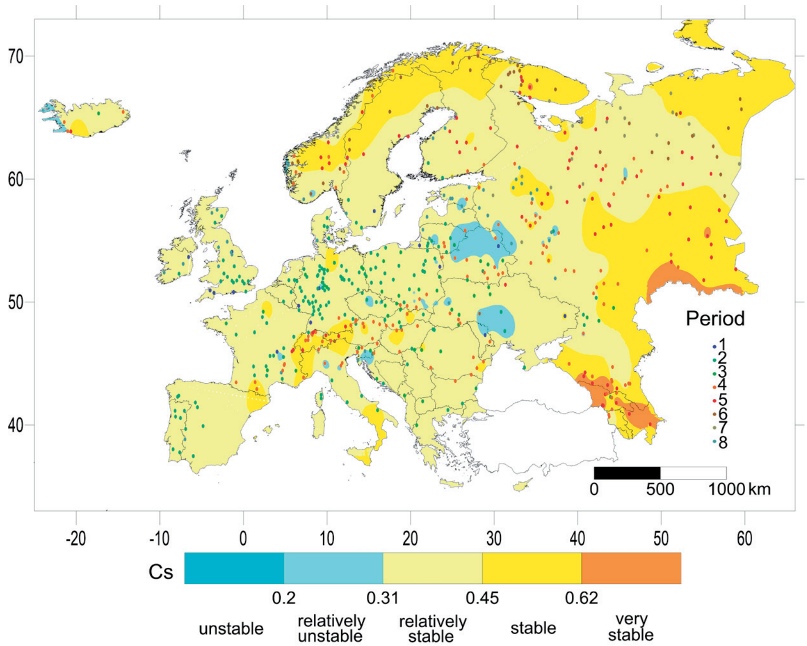

Fig. 4. Stability of the 3rd maximum of monthly flows, legend as in Fig. 2

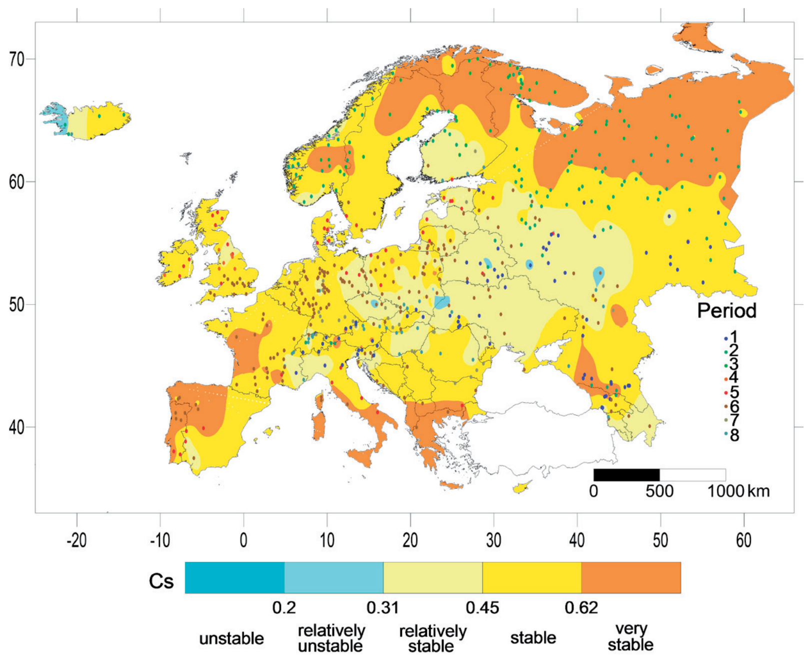

Fig. 5. Stability of the 1st minimum of monthly flows, legend as in Fig. 2

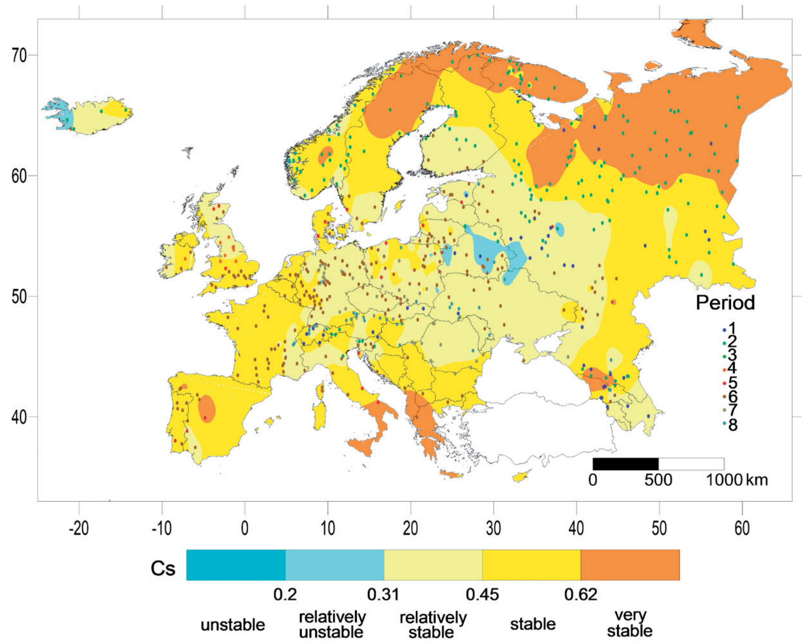

Fig. 6. Stability of the 2nd minimum of monthly flows, legend as in Fig. 2

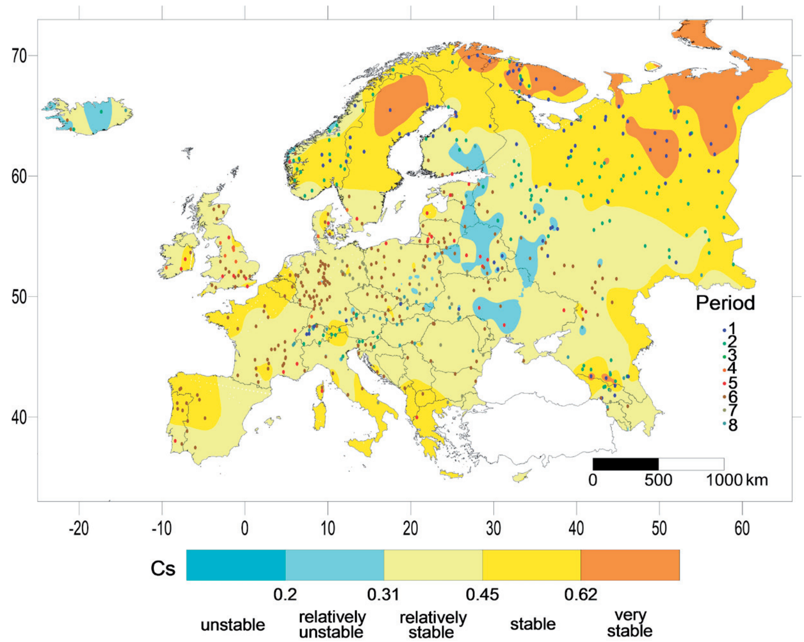

Fig. 7. Stability of the 3rd minimum of monthly flows, legend as in Fig. 2

January) (Aara), whereas the second minimum is observed in the winter-spring period (January-March). The stability of the minima on rivers in Iceland is diverse. These minima usually occur in the winter-spring period (January-March) and are stable in the eastern part of the island. Minima in the western part are relatively unstable.

CONCLUSION

The stability of the river flow regime was determined on the basis of the regularity of high waters and low waters during a year. Six descriptors served as the regime characteristics: the *1*st, *2*nd, and *3*rd maximum (for high flow periods), and the *1*st, *2*nd, and *3*rd minimum (for low flow periods) of mean monthly flows. In order to assess their regularity, the coefficient of stability was calculated. The period of time when the coefficient reached its maximum value was also established.

After analysing the regional changeability of the stability coefficient during high and low waters, it was concluded that the stability of flow is considerably higher during the high water periods relative to the low water periods. This is particularly apparent when analysing the *1*st*max*. Rivers of Northern and Eastern Europe, as well as many mountain rivers, are characterised by a very stable timing of the *1*st*max*, *2*nd*max* and *3*rd*max*. The most stable timing of the *1*st*min* is observed on the rivers of Northern and Southern Europe. Simultaneously, the minimum flows on rivers located in the Central and Eastern parts of the continent are the least stable.

The coefficient of stability used in the analysis enables an extension of classical hydrological regime analysis, e.g. by Lvovich (1979). The proposed approach allows not only to establish the term of high and low flow periods of the river, but it also shows the regularity (stability) of their occurrence.

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