Multilevel river classification as the methodological basis for analysis of maximum runoff values in different geographical regions

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Abstract This paper presents a methodology for analysis of river runoff hydrometric and hydrographic data obtained in different geographical regions. The purpose of the analysis is the investigation and classification of the effect of different climates on maximum river runoff. The difficulties of analysis of river runoff at the global scale include the diversity in climatic conditions (continental, semi-arid, tropical, equatorial climates) and geographic environmental conditions (tundra, forests, steppes, savanna), as well as heterogeneity of regional environmental conditions (permafrost, bogs, karst, etc.). The methodology presented proposes river classification in terms of runoff types such as transitional, local, zonal and intrazonal runoff types. It is shown that only the rivers with zonal type of runoff can be used to estimate climatic effects on maximum runoff values.

Key words multilevel river classification; climate; maximum river runoff; transitional runoff; local runoff; intrazonal runoff; zonal runoff

INTRODUCTION

Currently, the problems of the possible effects of future climate warming are being discussed widely. Change of river regimes is one of the problems. To predict future changes, the effects of current climate conditions on river runoff in different geographical regions need to be revealed.

Global-scale investigations of peak runoff data need to take into account: (1) the effect of climate; (2) the effect of geographic environment; (3) the effect of regional environmental conditions; and (4) the effect of the hydrographic parameters of the river catchment. Climate types change from very cold to very hot. Global environmental diversity is expressed by geographical zonality (tundra, forests, steppes, savanna). Regional conditions may include such local phenomena as permafrost, lakes, bogs, karst, etc. Important hydrographic parameters of river catchments are area, height, surface gradient, river network density, and shape. How can the climatic influence on maximum runoff be estimated in areas characterized by a combination of such variously heterogeneous information?

The methodology presented in this paper was developed to compare the parameters of maximum runoff formed in different geographical regions under influence of different climates. Cases of the maximum runoff of plain rivers are used to demonstrate the approach.

THEORETICAL PREREQUISITES OF THE METHODOLOGY

The proposed methodology is based on natural climatic zonality which was described first by Humboldt (1851) and formulated as an environmental law by Dokuchaev (1898). The meteorologist Voyeykov (1884) noted that “rivers can be considered as products of climate”, and he prepared the first classification of rivers from the climatic conditions of their catchments.

Thereafter, numerous attempts were made to estimate the effect of climatic and environmental zonality, including individual characteristics of river catchments, on runoff parameters. Let us consider only some results. Based on the geographical zonality, mapping of hydrological zones by the water regime of rivers was performed (Kuzin & Babkin, 1979). Spatial diversity of runoff parameters was analysed on the basis of climatic zonality, environmental zones and components of regional water balance (Olivry, 1986). Cosandey & Oliveira (1996) found different effects of river catchment relief on maximum runoff formation. Empirical formulae were proposed for estimation of maximum discharges in different climates (Meigh *et al*., 1997). Regionalization of river catchments by prevailing losses of precipitation (accumulation, evaporation, transpiration, infiltration) was made by Asabina (1998). Lohmann *et al.* (1998) showed the great importance of vegetation and infiltration capacity of soils in precipitation losses at the catchment scale.

Analysis of these and many other publications has shown that it is hard to determine the influence of single factors on runoff parameters. Therefore another methodological approach is proposed here which is based on the following notions:

– maximum runoff value depends mainly on climatic and environmental zonality;
– water discharge in a control section of river represents the averaged runoff from the whole river catchment and its value reflects the influence of all environmental factors;
– no single river can be representative for estimation of climate effects on runoff, because some rivers cross several climatic zones and others are greatly influenced by the individual peculiarities of their catchments.

Based on these notions, the methodology proposes a multilevel river classification based on uniform climatic conditions, uniform environmental conditions, and uniform types of river runoff. The first level divides a territory into large regions that are uniform with respect to climatic conditions. The second level separates catchments by more specialized properties such as physical geographic conditions. The third level of regionalization reveals the rivers from their local or transitional runoff. The fourth level details the local runoff that can be zonal or intrazonal. The core of the approach is the creation of hydrological maps for each of the regions. The maps reflect rivers with runoff of different types, i.e. transitional, local, zonal, and intrazonal types. The runoff type reveals the representative rivers for estimation of the climatic effect on peak runoff.

RESULTS OF INVESTIGATION

Studied territory and data

The studied rivers are located (Fig. 1) in the territory of Asia (Ob River) and Africa (rivers Niger, Chari, Sanaga, Niyong and Sangha) within an area delimited by latitude

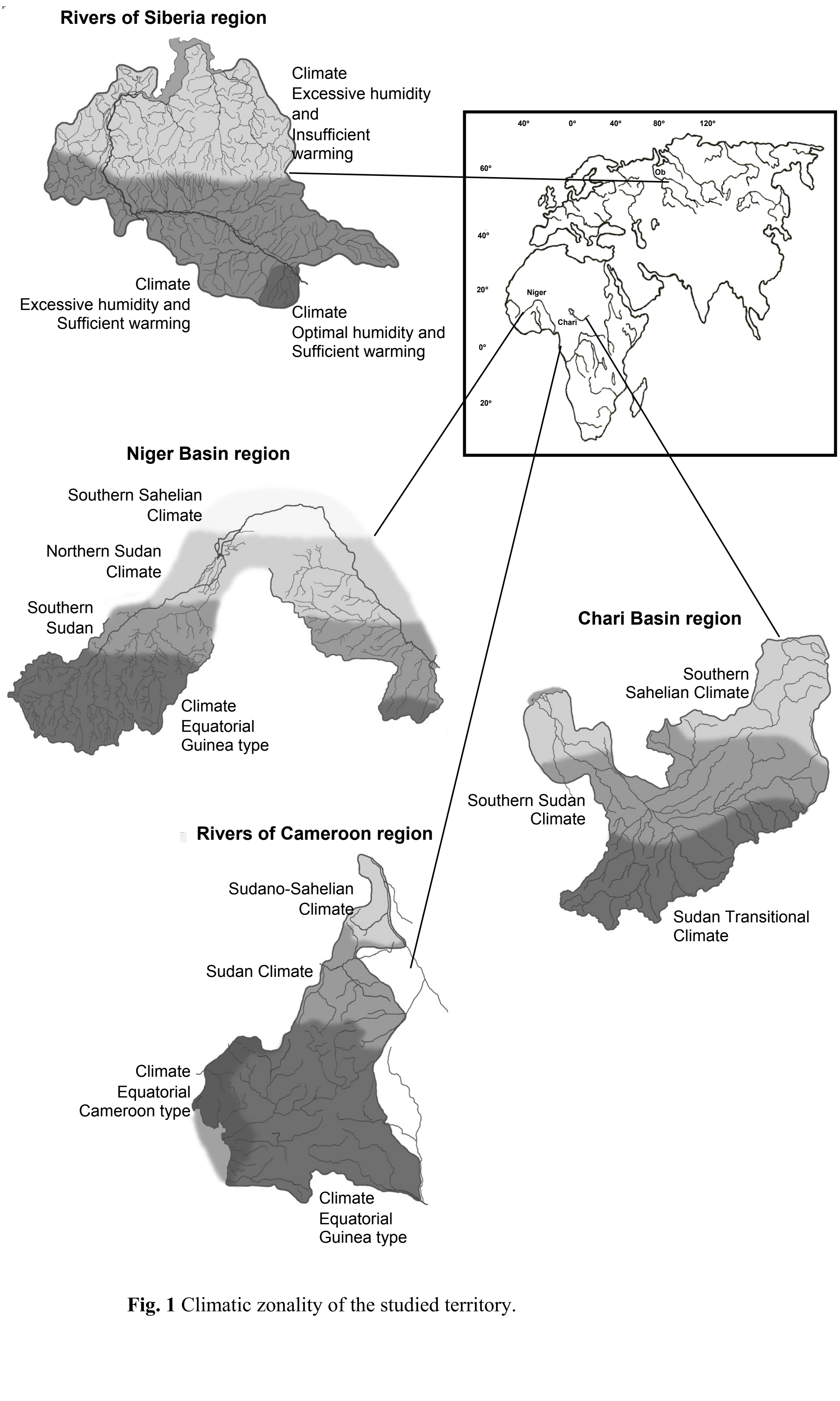

Fig. 1 Climatic zonality of the studied territory.

36° and longitude 55°. The total area is 3.88 million km^2. The territory consists of four large geographical regions which are represented by: (a) the rivers of Siberia (catchment of middle and lower Ob River); (b) the Niger basin (catchment of upstream and middle Niger River); (c) the Chari basin (whole catchment of Chari River), and (d) the rivers of Cameroon (catchments of all the rivers located in the state of Cameroon).

In order to create hydrological maps of runoff types, maximum runoff records on 225 gauge stations were used. The total duration of the record series is 4081 years. There is one hydrological station for each 17 200 km^2, whereas worldwide there is one station for each 26 500 km^2 of catchment territory (World Water Balance, 1974). Runoff within the selected territory is generally poorly studied.

Registration of influence heterogeneity of climatic and environmental conditions on maximum runoff values

The studied territories are influenced by four types of climate: continental, semi-arid, tropical, and equatorial (Fig. 1). Mean annual precipitation varies from 350 mm to 6000 mm and mean annual air temperature varies from –9.0 to +28.5°C. Each of the climates forms typical environmental zones such as forest tundra, forests, steppes and savannas. The locations of geographical regions in different climatic and environmental zones and subzones are presented in Table 1.

First and second levels of classification The first level of classification is intended to detect the catchments with uniform climatic conditions. Climatic zonal borders were determined a long time ago (Mezentsev & Karnatsevich, 1969; Billon *et al.*, 1974; Brunet-Moret *et al.*, 1986; Olivry, 1986). The main factor in their determination is mean annual precipitation which is mapped using isolines. The second level of classification intends to detect the catchments with uniform geographic environmental conditions in the given region. The zonal borders of these conditions are well known too. The zones are detected by types of dominant vegetation.

Different stages of runoff type determination for the rivers of the Siberia region are illustrated in Fig. 2. First and second levels of classification were performed in the following order: (1) borders of climatic zones within the studied territory were marked by existing maps (Fig. 2(a)); (2) borders of geographic environmental zones within the studied territory were marked by existing maps (Fig. 2(b)); (3) watershed lines of all the rivers within the studied territory were marked; (4) partial catchments of gauge stations were detected; (5) the maps were superposed; (6) the catchments located in similar climatic and environmental zones were detected. Classification in the three other regions was performed similarly.

Third level of classification The third level was performed on the basis of the first and second ones. This level is determined by hydrological classification. It is intended to detect homogeneous types of river runoff. Runoff type is ascertained by the location of the river catchment in different climatic zones. If a river crosses several climatic and environmental zones, it is characterized as having a transitional type of runoff. Rivers of catchments located within individual climatic and environmental zone are characterized as having local runoff.

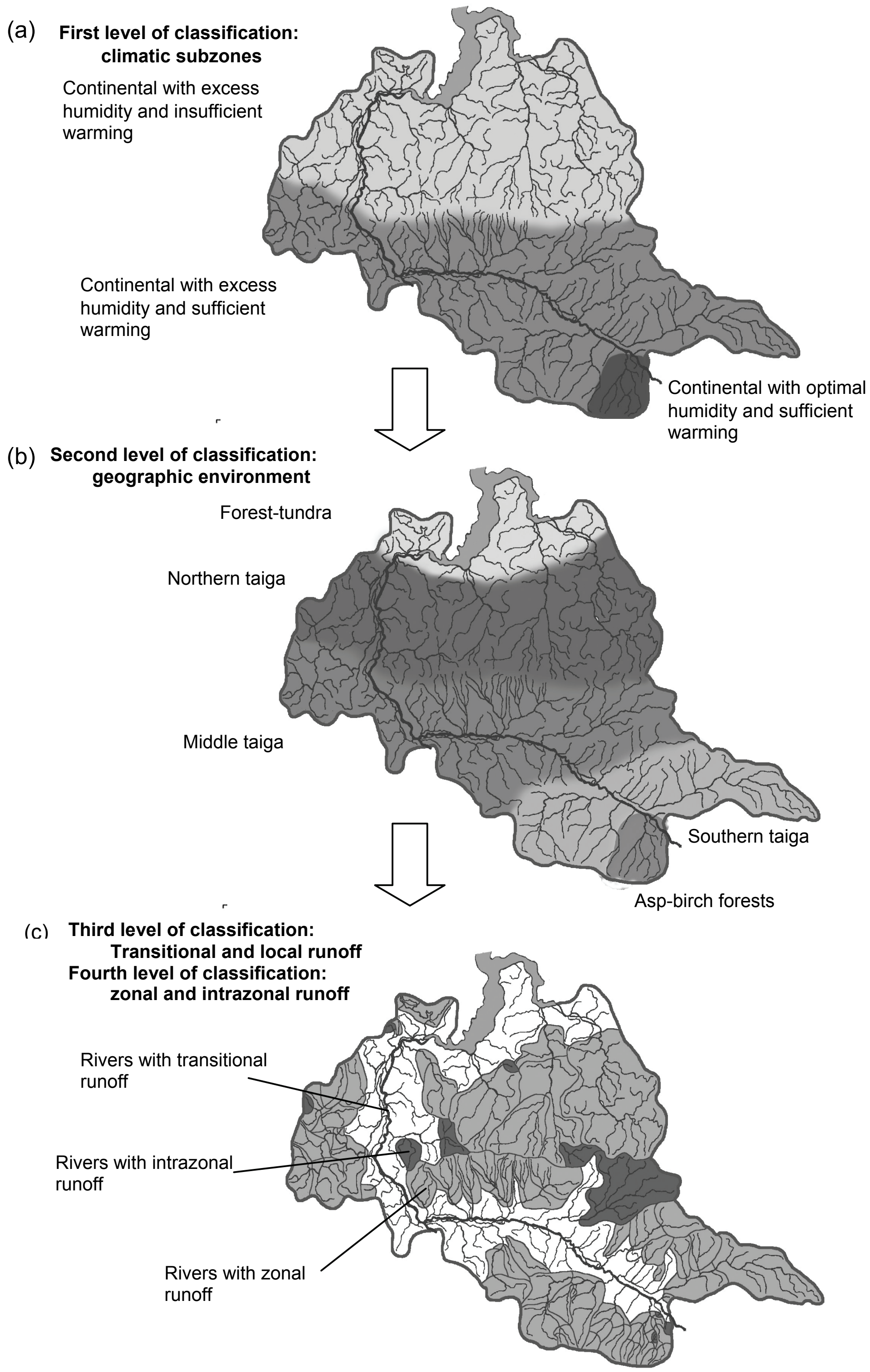

Fig. 2 River classification in terms of: (a) climate zones, (b) geographic environmental zones, and (c) runoff types for the rivers of the Siberia region.

Table 1 Main characteristics of climatic and environmental subzones within the studied territory.

Climatic zone	Climatic subzone	North latitude (°)	Mean annual precipitation (mm)	Mean annual temperature (°C)	Region	Natural zone and subzone
Continental	*EHIW*	68 – 64	350 – 600	–4.0 to –9.0	Rivers of Siberia	Forest tundra Northern taiga
	EHSW	64 – 58	400 – 500	–4.0 to +2.5	Rivers of Siberia	Middle taiga Southern taiga
	OHSW	58	400	+1.0 to +3.0	Rivers of Siberia	Aspen-birch forests
Sudan-Sahelian (semi arid)	*SSah*	17 – 16	150 – 300	+29.1	Niger basin	Steppe
	NSud	16 – 13	300 – 700	+28.6	Niger basin	Slightly wooded savanna
	SSah	14 – 10	400 – 800	+29.0	Chari basin	Steppe
	SudSah	12 – 10	400 – 900	+28.0	Rivers of Cameroon	Steppe Soudano-Guinean wooded savanna
Sudan (tropical)	*NSud*	13 – 11	700 – 1200	+28.5	Niger basin	Slight wooded savanna
	NSud	10 – 8	800 – 1200	+26.5	Chari basin	Soudano-Guinean wooded savanna
	SudHum	10 – 7	900 – 1500	+28.0	Rivers of Cameroon	Bush savanna and wooded savanna
	SudTr	8 – 6	1200 – 1600	+25.8	Chari basin	Dry forest
Equatorial	*EGt*	11 – 9	1200 – 2000	+26.9	Niger basin	Wooded savanna of Guinean type
	EGt	7 – 2	1500 – 2000	+25.0	Rivers of Cameroon	Semi-deciduous forests Congo forests
	ECt	6 – 2	2000 – 6000	+26.0	Rivers of Cameroon	Atlantic forests

EHIW: Excessive humidity with insufficient warming; *EHSW*: Excessive humidity with sufficient warming; *OHSW*: Optimal humidity with sufficient warming. *SSah*: Southern Sahelian; *SudSah*: Sudano-Sahelian; *NSud*: Northern Sudan; *SSud*: Southern Sudan; *SudHum*: Sudan Humidity; *SudTr*: Sudan Transitional. *EGt*: Equatorial Guinea type; *ECt*: Equatorial Cameroon type.

Common analysis of several maps (climatic, environmental zonality, catchments, hydrological observations network, partial catchments) by their superposition allows identification of the rivers with transitional and local runoff (Fig. 2(c)). Plain rivers with transitional runoff have the greatest specific discharges varying from 7 up to 588 L s^{-1} km^{-2} (Table 2). It is seen that the maximum runoff of the local river types (Table 3) differs by a factor of 10 from the maximum runoff of transitional river types. Such significant differences in values of maximum runoff illustrate the validity of river dividing by homogeneous runoff in relation to climatic and environmental zones.

Registration of runoff variations in relation to regional environmental conditions and hydrographic parameters

Climate forms not only environmental zones but influences also the diversity of environmental conditions in each of a region. All the rivers of the Siberia region, being

Table 2 Observed maximum runoff of transitional runoff types within different climatic zones.

Climatic zone	Climatic sub-zone of gauging station location	Climatic subzone of river flow	Region	*Num*	*T* (year)	Highest maximum *Q* ($m^3\ s^{-1}$)	*M* ($L\ s^{-1}\ km^{-2}$)
Continental	*EHIW*	*EHIW, EHSW, OHSW*	Rivers of Siberia	1	43	44 800	15.2
	EHSW	*EHSW, OHSW*	Rivers of Siberia	2	62	22 400	30 4
	OHSW	*EHSW, OHSW*	Rivers of Siberia	1	61	29 800	61.3
Sudan-Sahelian (semiarid)	*SSah*	*EGt, SSud, NSud, SSah*	Niger basin	1	13	2 640	7.3
	NSud	*EGt, SSud, NSud, SSah*	Niger basin	1	20	477	12.3
	SSah	*SudTr, SSud, SSah*	Chari basin	3	55	5 160	8.6
	SudSah	*EGt, SudHum*	Rivers of Cameroon	1	29	2 740	37.0
Sudan (tropical)	*SSud*	*EGt, SSud, Nsud, SSah*	Niger basin	7	210	7 219	102
	SSud	*SudTr, SSud, SSah*	Chari basin	6	80	3 670	46.0
	SudHum	*EGt, SudHum*	Rivers of Cameroon	4	65	1 880	588
Equatorial	*EGt*	*EGt, ECt*	Rivers of Cameroon	6	146	220	191

T: total observation period; *Q*: discharge; *M*: specific discharge.

located in continental climatic conditions, have ice cover for 3–8 months annually. Some of them freeze up completely. Also, permafrost occurs in this region with depths of seasonal thawing of 1–2 metres. There is no river ice cover and no permafrost in the other climate zones. On the other hand, drying takes place in the semiarid climatic zones of the Niger and the Chari basins. Thus, hydrological conditions are very different.

Hydrographic parameters of river catchments are very different too. Catchment areas vary from 120 to 2 950 000 km^2. The mean altitude of the catchments is from 70 to 900 m. The catchments of the Siberian rivers region are lowest and those of the rivers of Cameroon are highest. Mean river gradients vary from 0.5 to 7.6‰.

Fourth level of classification The recorded discharge value reflects the summarized conditions of maximum runoff formation of individual catchments. Local runoff values formed within individual climatic and environmental zones reflect the influence of regional environmental conditions. It is known, however, that runoff values of neighbouring rivers may differ greatly because of the different hydrographic parameters of each catchment. Therefore, it is incorrect to analyse climate effects on runoff taking into account local runoff river types only. That is why the local type of runoff was divided into zonal and intrazonal subtypes. The rivers with homogeneous type of runoff – zonal or intrazonal – were detected in the fourth level of classification (Fig. 2(c)). In spite of the formation of intrazonal runoff within the same climatic and environmental zone, the runoff is changed because of hydrographic peculiarities

Table 3 Observed maximum runoff of local runoff types within different climatic zones.

Climatic zone	Climatic subzone	Region	*Num*	*T* (year)	Intrazonal runoff Highest maximum *Q* ($m^3 s^{-1}$)	*M* ($L s^{-1} km^{-2}$)	Zonal runoff Highest maximum *Q* ($m^3 s^{-1}$)	*M* ($L s^{-1} km^{-2}$)
Continental	*EHIW*	Rivers of Siberia	4/13	66/305	451	376	530	316
	EHSW	Rivers of Siberia	1/42	31/1063	3440	61.0	21.7	224
	OHSW	Rivers of Siberia	4/9	48/269	8.0	136	27.7	129
Sudan-Sahelian	*NSud*	Niger basin	2/2	34/39	86.9	32.0	224	29.9
Sudan	*SSud*	Niger basin	1/6	14/123	52.2	9.8	690	84.0
	SSud:	Chari basin	4/5	13/35	10.0	111	15.0	58.0
	SudHum	Rivers of Cameroon	1/2	22/75	1554	62.0	3428	112
	SudTr	Chari basin	1/4	12/42	185	42.0	3680	54.0
Equatorial	*EGt*	Niger basin	6/27	97/403	385	389	1963	154
	EGt	Rivers of Cameroon	3/16	64/309	114	66.0	43.2	98.0
	ECt	Rivers of Cameroon	–/2	–/41	–	–	564	245

4/13: intrazonal/zonal runoff; – no gauging stations.

of certain catchments. Maximum specific discharges of zonal runoff differ by 1.5–2.0 times from those of intrazonal runoff in all climatic zones (Table 3). In this case, 128 stations gauged zonal runoff whereas only 27 recorded runoff from intrazonal rivers. The rivers with zonal and intrazonal runoff were separated by their maximum specific discharge values. The separation was checked by calculating the mean quadratic deviation and correlation coefficient values. If differences do not exceed the mean quadratic deviation, the runoff is zonal. Otherwise, the runoff is intrazonal.

CONCLUSIONS

Transitional runoff reflects the integrated effects of several climatic and environmental zones, and intrazonal runoff reflects the effects of hydrographic characteristics of different catchments. The rivers with zonal type runoff only should be the subject of analysis for estimation of the climate effect on maximum runoff. Because the zonal runoff is being formed within individual climatic and environmental zones, the influence of the individual properties of different catchments is not significant in these rivers. Zonal types of runoff mostly reflect the steady long-term relation between maximum runoff values and climatic characteristics such as precipitation, air temperature and evaporation.

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