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RECENT CHANGES OF ANNUAL FLOW DISTRIBUTION OF THE VOLGA BASIN RIVERS

ABSTRACT. Modern features of the annual flow distribution of the Volga Basin were analyzed. Statistical analysis of the annual flow data for the spring, summer-autumn, and winter seasons were carried out to study the changes of the water regime of the Volga Basin Rivers in 1946–2010, 1946–1977, and 1978–2010 observation years. Using the data of 207 stations, new maps of seasonal flow were created and changes in the natural river flow regulation were shown. In recent decades, the water regime of the rivers in European Russia and their annual flow distribution has changed greatly.
A statistically significant decrease in the river flow irregularity after 1946 has been revealed for the most of the Volga Basin Rivers. It resulted in the increase in the natural regulation index φ, change of the seasonal flow, primarily in low-water period, and especially in winter. The increase in the φ index during the last 30 years is approximately 30%, compared to the similar previous period. Such a change of the φ value took place due to the reduction of the spring flood flow and the increased significance of the groundwater flow.
In the second half of the 1970s, the rivers of the Volga Basin were characterized as "snow-feeding"; at the end of the XXth century, they became the rivers with "mixed feeding" or even "mixed feeding with prevailing groundwater feeding" according to B.D. Zaikov's river classification. This has resulted in the significant increase in the natural flow regulation comparable to the effect of seasonal storage reservoirs.

KEYWORDS: river flow distribution, climate change, seasonal river flow.

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INTRODUCTION

The study of rivers' flow distribution is an important scientific and practical problem in the field of economically effective and ecologically safe water management. A range of issues, relating to this subject, is of interest both from the scientific knowledge view and for a variety of applications. On the one hand, this statement finds ample evidence in fundamental hydrological investigations creating a theoretical basis for the further activity in this area [for example, Andreyanov, 1960; Yevstigneev, 1990 et al.]; on the other hand – in the regulation documents specifying strict calculation algorithms of the annual flow distribution for further application in different fields of economy [SP 33-101-2003, 2004]. Water management options, such as a guaranteed water return, power generation, and controlled storage of annual flow variability, often arise in ecological management of small and medium-size rivers and optimization of the usage of their water resources. The water resources management system also needs to be adapted to seasonal flow variations under climate change. The most recent comprehensive studies were carried out in Russia in the early 1970s when "Surface water resources of the USSR" was published. Since that time, the annual flow regime of the European rivers of Russia has changed significantly making the development of new correlations and calculation models and the creation of modern maps of seasonal flow distribution are the urgent scientific tasks. The purpose of this work is to study modern annual flow distribution of the rivers of the Volga River basin and to calculate new characteristics of their seasonal flow.

BACKGROUND INFORMATION

The Volga River basin is one of the key points to understanding river runoff transformation on the European part of Russia. The basin is influenced by spatiotemporal variation of flow closely connected with natural and anthropogenic factors [Georgiadi et al., 2016]. In this paper, natural component of flow was calculated by empirical correlation with the flow of the non-transformed watersheds. It appears that during the XXth century, a few phases of high and low flow occurred. These phases are well visible in seasonal flow dynamics, while they are washed out in annual flow. The difference between annual flow of Volga and Don Rivers and mean average for the period of observation is now more then 10%. Until the 1970s-1980s, the phase of higher flow was observed. Spring flood runoff increased by 10%, winter low flow – by 50%, and summer-autumn flow – by 25%. According to Georgiadi A.G., Milyukova I.P. [2006)], based on scenarios calculation, in the XXI, increase in both annual and spring flood runoff can bee expected. More detailed analyses were done in the further publication of the authors [Georgiadi et al., 2016]. It was shown that expected changes in the Volga and Don annual river runoff and its intra-annual distribution in the first third of this century can be relatively small, while changes in water use characteristics may be extremely negative in some scenarios, especially in the Don River basin.

The questions of risk management and floods disaster management due to the climate change are variously discussed in the CABRI – Volga reports [http://www.cabri-volga.org/publications.html]. Estimation of the river annual flow distribution is strictly regulated and performed according to a number of standardized documents [SP 33-101-2003, etc.]. The main technique of summarizing data on river flow distribution is identification of regional patterns of seasonal distribution in high, low, and medium water flow years. Seasonal flow distribution is expressed in proportions of annual and seasonal flow distribution – in proportions of the appropriate season flow. In this paper, the estimation of annual flow distribution is performed using the average flow distribution in high, low, and medium water flow years.

Initially, the idea of water regime transformation (the main types and geographic movement of their borders) was expressed in general by Georgievskiy [Georgievskiy et al., 1996]. In the electronic issue [Main hydrological characteristics …, 2015], main hydrological characteristics of the Volga runoff for modern periods were calculated. In this paper, the calculation has evolved; the authors provided quantitative assessment of changes for different types of water regime in the Volga basin.

MATERIALS AND METHODS

Monthly averaged water discharges for selected representative stations were used to calculate the annual flow distribution of rivers: the Lower Volga (37 stations), the Kama (68 stations), the Upper Volga basins (102 stations – Fig. 1) in 1946-1977, 1978-2010, and for the whole period of 1946-2010. The gaps in the time-series of the runoff were filled by using regression equations due to the runoff of the other rivers. However, they were characterized by coefficients of pair correlation of 0.8 or higher.

The choice of the calculation periods is based on the results of earlier analysis of long-term monthly flow fluctuations and our own research [Water Resources of Russia, 2008; Frolova et al., 2013]. Selection of the representative period is also supported by the results of the analysis of long-term (20 years or more) phases of growing and reduced runoff, coupled with the respective phases of cooling and warming [Georgiadi et al, 2014; Georgiadi et al, 2016]. In this paper, we assess the changes carried out on the basis of representative selection periods. Periods of relatively undisturbed natural conditions of the river basins (1945–1977) and periods of high intensity of human impacts and climate change (1978–2010) were identified. All the rivers for annual, winter, summer-autumn, and spring flood have clearly visible phase of runoff increase, the beginning of which can be attributed to the end of the 1970s – early 1980s. All these data refer to the rivers with natural water regime (not disturbed by economic activity) with a range of catchment area from 2,000 to 15,000 km^2.

The study of seasonal river flow required identification of the defined and constant dates of the beginning and the end of seasons for local rivers. The division of hydrological year into seasons depends on the type of annual flow regime. Spring, summer-autumn, and winter were taken as the main seasons for the rivers with spring flood. Depending on the type of the river flow regime and the prevailing type of its use, the hydrological year was divided into the limiting (low flow) and non-limiting (high water) periods, and the limiting period was divided into limiting and non-limiting seasons accordingly. The boundaries of the seasons were defined for the Volga basin in the 1950s [Andreyanov, 1960] under the available limited hydrometric information. At present, there are many stations with long periods of river flow observations. The change of climate conditions observed in the recent decades also required updating and refining relevant characteristics, assumed for calculating the annual river flow distribution. As a result of analysis of hydrographs for more than 200 rivers in 1946-2010, the following periods were selected for further calculations (Table 1).

SPATIOTEMPORAL VARIABILITY OF THE ANNUAL FLOW DISTRIBUTION

Hydrological and meteorological conditions on the Russian plain in 1975–2000 were characterized by high moistening of the territory and an increase in regional river flow. The change of circulation and other

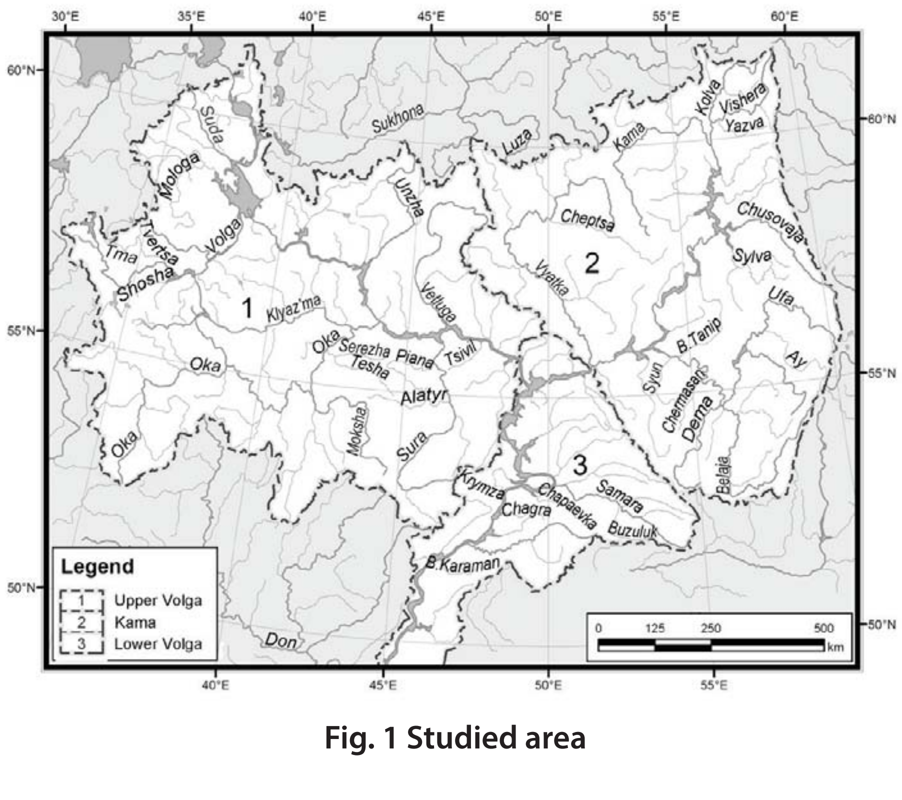

Fig. 1 Studied area

Table. 1. The terms of hydrological seasons for the Volga Basin Rivers

Region	Season		
	Spring	Summer-autumn	Winter
Upper Oka	III-V	VI-XI	XII-II
Lower Volga	III-V	VI-XI	XII-II
Upper Volga (right bank tributaries)	III-V	VI-XI	XII-II
Upper Volga (left bank tributaries)	IV-VI	VII-XI	XII-III
Kama	IV-VI	VII-X	XI-III

related climate-forming processes led to favorable conditions of river flow formation on the East European Plain. Recent climate change in the Volga basin undoubtedly affected the water regime of the rivers and the volume of their annual and low water flow and the volume and height of the spring flood [Water Resources of Russia, 2008; Alexeevsky et al., 2013].

Long-term increase in surface air temperature within the Volga basin occurred mainly due to winter temperature increase. Precipitation changes were significant only in the north-west of the territory. As a result, the long-term changes in snow storage and duration of the snow season were also insignificant. The long-term increase in thaws and, respectively, liquid precipitation, led apparently to the increased snowmelt during the snow season and the inflow of melt water to the rivers. The winter low flow increased, whereas the maximum discharges, typical of the end of the snowmelt period, decreased. Warming also affected the period of intense snowmelt: thawing of the ground accelerated, which brought the surface melt water into the underground component of the water balance; as a result, the maximum (spring) river discharges decreased even further [Kireeva et al., 2015; Dzhamalov et al., 2014].

The statistical processing of annual flow data for the spring, summer-autumn, and winter seasons has been carried out to study the changes of the water regime of the Volga basin rivers.

The spring flood is the main phase and the hallmark of water regime of the Volga basin rivers. The major part of the annual flow of rivers is formed in the spring season. The flow depth in spring in the Volga basin increased from south to north, reaching the highest values in the basins of the Wishera, Yazva, and Colva Rivers. In the basin of the Belaya River, the flow depth value varied considerably, depending on the altitude, from 150-200 mm in the upper reaches to 80-90 mm in the Dema, Chermasan and Syun River basins. In the Samara River basin, this value was 45-60 mm. The spring season flow was 65-70%. Over the last 30 years, the spring flow for the greater part of the Kama basin has decreased by 10%; in the lower reaches of the Belaya River, the decrease ranged from 10 to 20%. In the considered northernmost rivers (the Kolva, Vishera), the increase in the spring river flow was even smaller (5%). In all rivers of the Lower Volga, the decrease in spring river flow and annual flow from 5% in the south to 15-20% in the rest of the basin, was observed. In the Upper Volga basin, the spring flow value increased from 50% in the west (headwater of theVolga, Tvertsa, Shosha, Tma) to 70% or greater in the east (the Tesha and Serezha Rivers and the left-bank tributaries of the Sura River – Piana, Alatyr). In the upper reaches of the Oka River, the spring flood flow was 50-60% of the annual flow, and within the rest of the Upper Volga basin – 60-65%. A decrease in spring flood flow and its share in annual river flow were observed from 5-10% (north) to 20% (south) of all rivers of the territory (Fig. 1). The decrease in the maximum spring flood discharges was typical of the whole period of observations (1946-2010) for the rivers of the Oka basin and the Lower Volga basin. For these rivers, the spring flood started 5-10 days earlier and, consequently, flood duration was longer (Fig. 2).

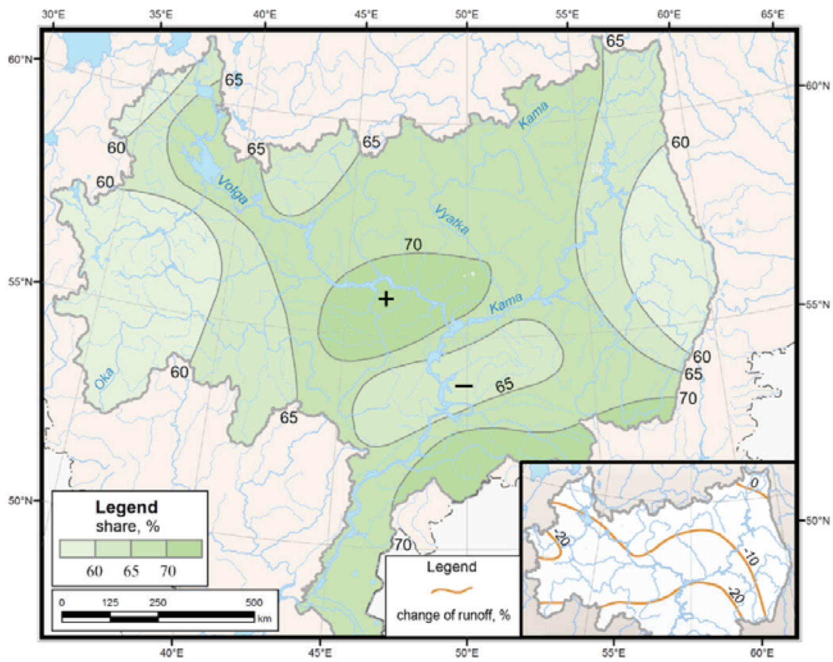

Fig. 2. The value of spring river flow (in % of the annual) in 1978-2010 and its change in 1978-2010 compared with 1946-1977 (%) (the insert map)

For the Oka River and its tributaries, the change of the maximum discharges was 20-40%; for the Lower Volga tributaries, it was 40-70%. This trend was due to an increase in the winter air temperature accompanied by an increase in the number and duration of thaws and, hence, a decrease in pre-spring water reserves and the maximum discharges of the spring flood (Fig. 3).

The spring flood was followed by the summer-autumn low-water period when the rivers are fed by groundwater and drawdown of lakes located in the catchment

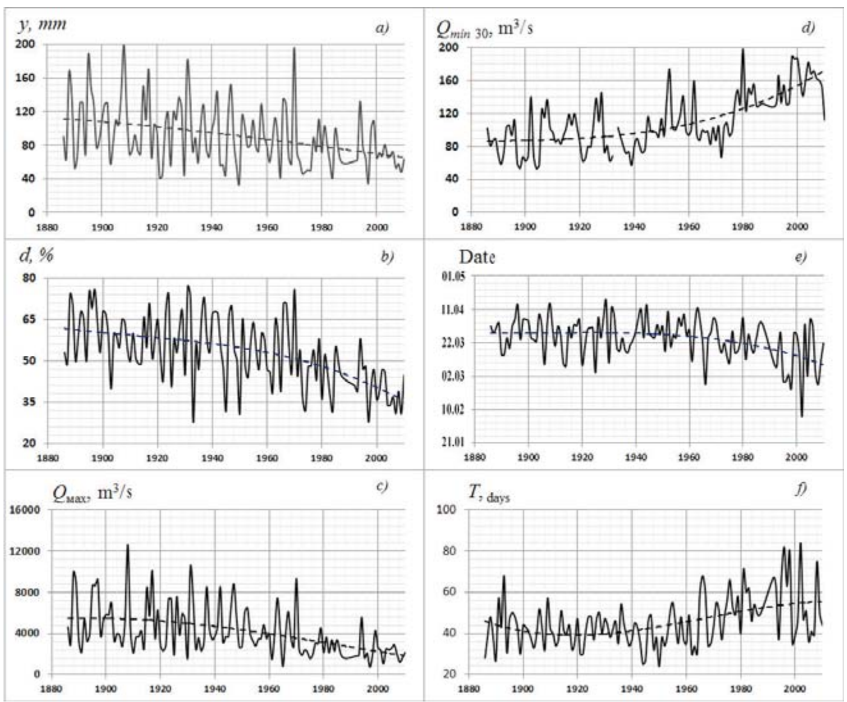

Fig. 3. The change in the spring flow depth (y, mm) (a), in the value of the flood flow (d,%) (b), in the maximum discharges of the spring flood Qmax (m3/s) (c), the minimum 30-day discharges during the open channel period Qmin 30 (m3/s) (d), the date of the spring flood beginning (e), its duration T (days) (f), (the Oka River – Kaluga) (the dotted line shows the trend as a polynomial of the third degree)

area. River flow depth in low-water period also increased regularly from south to north and north-east from 20 to 200 mm. A relatively large river depth is typical of the mountainous part of the basin and the upper reaches of the Kama River. The river flow value in the low water period changed slightly in the territory and was 30-35% for the most territory, and slightly greater than 40% for the basins of the Chusovaya, the Ufa, and other rivers with karst-prone catchments and the rivers of the upper reaches of the Volga and the Oka. The value of low-water flow also varied from west to east, averaging 40-45% in the west, where the flood flow value was high, up to 30-35% in the east. The change of the river flow value in recent decades has been quite significant – from and reached its maximum (40-50 mm) in the karst-prone region (the basins of the Ufa, Bystriy Tanip, Sylva and other rivers). For the rivers of the Lower Volga basin, the river flow depth was between 3-5 mm in the south and 10-15 mm in the north. The winter flow depth for the rivers of the Upper Volga basin varied from 10-15 mm in the south-east (the Sura basin) to 35-40 mm in the north-west. The share of winter river flow in the annual value ranged from 5% in the south of the territory up to 10-15% in the north-west and north-east (Fig. 4). It was the greatest for the Upper Oka (up to 16-18%) and decreased in the north-east direction to 5-10% in the Upper Vetluga Rivers. The increase in the winter flow value for the last thirty years has been almost the same as for the low-water

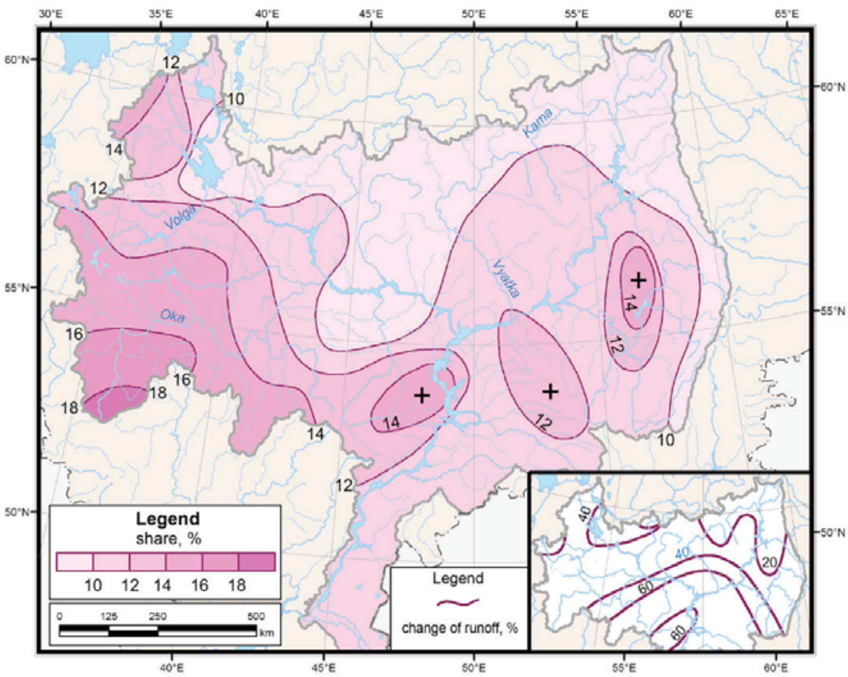

Fig. 4 Value of winter flow (November-March) (in % of annual) in 1978-2010 and its variation in 1978-2010 compared to 1946-1977(%) (the insert map)

zero in the north-east (the Vishera and Yazva Rivers) to 40-60% or more for the Oka and the Upper Volga basin Rivers.

The lowest river flow was observed in winter, when the rivers are mostly fed by groundwater. The winter flow of all the rivers of the region was less than the summer-autumn one. In small streams, winter flow was often almost absent. The flow depth in winter varied from 15 to 25 mm in the flat part of the Kama basin and in the Upper Belaya and Chusovaya Rivers, period on the whole and reached 40-60% or greater, especially for the south-eastern part of the territory.

It is definitely possible to say that the variability of winter flow in the Volga basin was influenced by two main factors: autumn precipitation (autumn river flow) and air temperature in winter (frosts, thaws). For the parts of the basin with relatively low depth of soil freezing (less than 40 cm) and relatively high groundwater table (less than 2 m), the prevailing factor influencing the increase in the winter flow was the rise of winter air temperatures. Conversely, for the areas with a significant depth of freezing (more than 60 cm) and the groundwater depth of 3 m, precipitation growth and an autumn flow in particular played the main role in the winter flow increase. Basically, the combination of both factors should be taken into account to assess the variability of winter flow.

According to [Lavrov, Kalyuzhny, 2012] for the whole Volga basin, the contribution of each of the considered factors (autumn precipitation, frosts, thaws) to the increase in winter flow was approximately the same. Fig. 5 presents the annual river flow changes of the Oka River near Kaluga.

river flow volume. We applied smoothing and separation rules to the recorded hydrographs from which we compared mean daily flow data with its average annual value. In each case, if mean daily flow data were more than the average annual water flow, the latter was the ordinate of the baseflow line. Otherwise, the mean daily flow data were the ordinate of the baseflow line. We continued this procedure until all data have been analyzed and we provided the derived set of baseflow ordinates. The separated hydrograph indicated the base river flow. The index φ was calculated as the ratio of the volume under the baseflow line (volume of a separated hydrograph) to the volume under the total hydrograph.

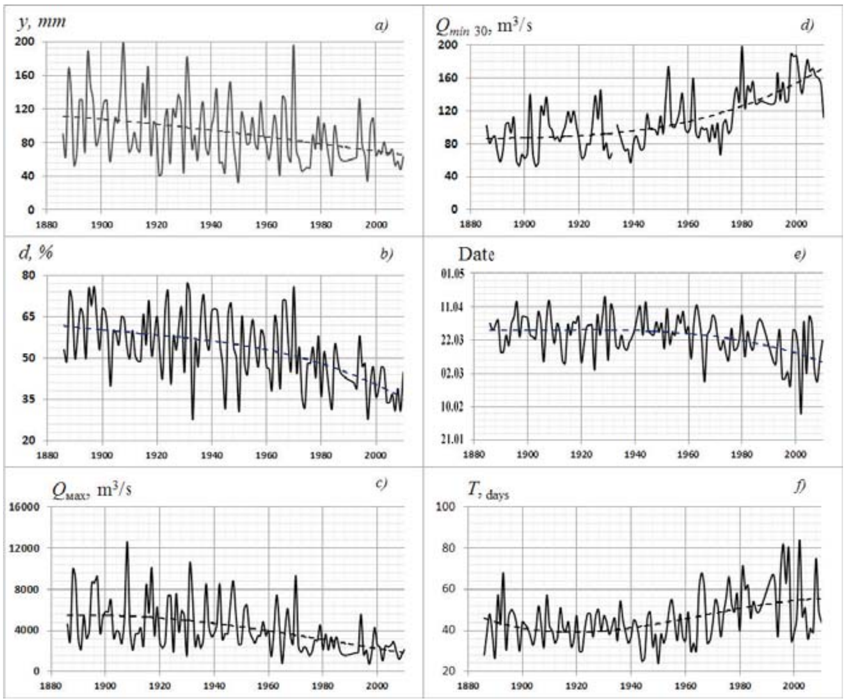

Fig.5 Hydrographs of the Oka River – Kaluga, averaged over different decades

Therefore, seasonal river flow distribution over the territory and its variation for the last decades, in general, followed the geographical zoning; however, the influence of local azonal factors (number of lakes, karst, sandy soils, etc.) often violated this pattern.

THE NATURAL REGULATION OF THE VOLGA BASIN RIVERS.

The irregularity of annual water flow distribution was characterized by natural regulation index φ which corresponds to the share of the "base" flow in annual

The baseflow reflects the natural regulation of the catchment area and its accumulation capacity, so the value of φ index decreases with the decrease in percent lake area, and from the forest to semi-arid zone as well. This index is mainly used for the comparison of different rivers or areas with respect to the value of the most stable ("base",) water resources. For a particular river, the φ value varies from year to year, depending on water regime features, mainly its high-water phase [Andreyanov, 1960]. The spring flood share, in fact, determines its annual irregularity (correlation coefficient R between the spring flood and the annual flow is more than 0.95). The lower the flood flow is the weaker the correlation between the natural regulation φ and the maximum spring discharges. At the same time, φ is affected by groundwater flow which determines the baseflow.

The general feature of natural regulation index in Russia were studied in [Frolova et al., 2010]. For the Upper Volga basin, the φ value, calculated for the period of 1978-2010, increased gradually from 0.55 in the north to 0.8 in the south (the upper reaches of the Oka and the Moksha rivers), and in the west (the upper reaches of the Volga river) (Fig. 6). The average value of φ was approximately 0.65. In 25% of cases, there was a statistically significant trend of index φ increase in 1946-2010. It was most evident in the Moksha and the Sura basins (over 30%), the upper reaches of the Oka and the Volga Rivers (20-30%), and, to a smaller degree, in the Mologa basin, middle and lower reaches of the Vetluga and the Unzha Rivers (10-20%), and almost imperceptible in the northern part of the basin. These changes happened due to the reduction of the snow melt flow value and a significant increase in the underground component. The greatest changes occurred in the southern part of the basin (Fig. 6). All the trends for the entire observation period were statistically significant for the rivers of the Lower Volga Basin, except for one station on the Chapaevka River (Podyom-Mikhajlovka village). The increase in the φ index during the last 30 years was about 30%, compared to the similar previous period. This trend was accompanied by a decrease in the spring flood flow value. For some stations (the Tsivil River – village Tuvsi, the B. Karaman River – village Sovietskoye, the Krymza River – Syzran city and some others), it was over 40%. Analysis of the spring flood and groundwater flow showed that such a change of the φ value took place due to the reduction of the spring flood flow and the increased significance of the groundwater flow [Frolova et al., 2014]. Over the last 30 years, the flood flow value has decreased for the studied rivers by approximately 15%.

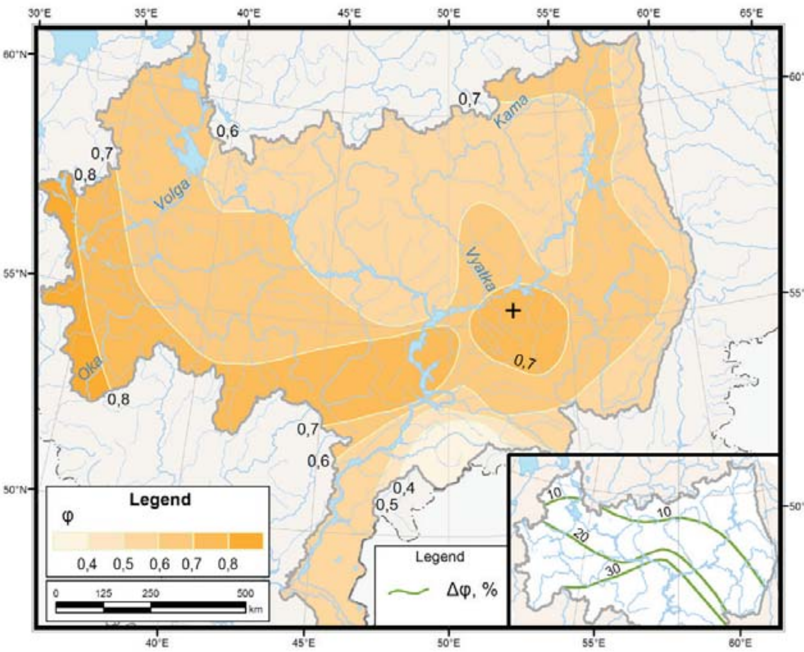

Fig. 6. The average value of the φ index in 1978-2010 and its change in 1978-2010 compared to 1946-1977(%) (the insert map)

The largest values of φ (0.7–0.8) were associated with the uplands with a large erosion depth – the Volga Upland and the Bugulma-Belebey Upland. These areas are characterized by the karst occurrence and increased groundwater feeding. The lowest values of φ (0.3-0.4) were noted for the southernmost of the territory – the Bolshoi Irgiz, the Chagra, and the Chapaevka River Basins. The largest spring flood value (70–80%) was also noted in these areas. In contrast to the Lower and Upper Volga, the statistically significant increasing trends in the Kama Basin were only observed in isolated cases (1946–2010) (the Ay, the Belaya, the Vyatka and the Dema Rivers) due to the slight changes in water regime and the constancy of the flood flow share. For the studied Kama Basin Rivers, the φ value varied within 0.55-0.7, reaching its maximum values in the karst areas (see Fig. 6).

CONCLUSIONS

The annual river flow distribution of the Volga Basin Rivers varied considerably along the territory in accordance with both latitudinal and altitudinal climate change. Besides the climate factors, local characteristics of river basins (the hydrogeological conditions and related karst phenomena, percent lake area, waterlogging, and physical properties of soils) had a great influence on the flow distribution within the year. A statistically significant decrease in the river flow irregularity after 1946 has been revealed for the most of the Volga Basin Rivers. It resulted in the increase in the φ index and change of the seasonal flow, primarily in low-water period, and especially in winter.

Traditionally, the rivers of the European part of Russia had the East European type of water regime, according to B.D. Zaikov's classification [Zaikov, 1944]. This type refers to the first group of rivers with conspicuous spring flood which provides the largest part of the annual river flow. According to "Surface water resources of the USSR" (1972), this value varies between 50 and 100% and 25-50% in the west of the territory. The rivers of the East European type are characterized by a single peak spring flood, starting in March-April and caused by the snow melting, which is, on average, 10 times the maximum discharges of the low-water period. In the autumn, the floods are frequently observed on such rivers. In winter, the low-water period prevails practically across the territory (except for the western and south-western margins with unstable frosty period). A low-water period with varying stability is typical of most of the territory in the summer-autumn period. In recent decades, the water regime of the rivers in European Russia and their annual flow distribution has changed significantly, whereas in the second half of the 1970s, the rivers were characterized as "snow-feeding." By the end of the XXth century, they transitioned to the type of the rivers with "mixed feeding" or even "mixed feeding with prevailing groundwater feeding." This has resulted in the significant increase in the natural flow regulation comparable to the affect of seasonal storage reservoirs.

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