Proceedings of FRIEND-Water 2014, Montpellier, France, October 2014 (IAHS Publ. 363, 2014).

Present-day surface and subsurface water resources of European Russia: conditions, use and forecast

R. DZHAMALOV[1], N. FROLOVA[2], M. KIREEVA[2] & E. RETS[1]
1 Water Problems Institute, Russian Academy of Sciences, ul. Gubkina 3, Moscow, 119333 Russia
dzhamal@aqua.laser.ru
2 Department of Hydrology, Lomonosov Moscow State University, 119899, Leninskiye Gory, Moscow, Russia

Abstract Climate change-derived variations in the characteristics of the annual, dry-season, and minimal monthly runoff in rivers of European Russia were estimated and analysed. The current changes in runoff characteristics were studied for different river basins, and their major causes were identified. Regional regularities in the hydrological and geohydrological processes were identified. The natural resources of surface and subsurface waters over 1970–2005 were re-estimated with the construction of appropriate maps. Water availability and demand on water resources were analysed.

Key words natural groundwater resources; surface water resources; groundwater runoff; river runoff; runoff regime

INTRODUCTION

An urgent current problem is to re-estimate the renewable water resources (natural resources of sub-surface and surface waters) in the context of changing climatic characteristics, which affect the formation of water balance elements in river basins. Studying the current features of the formation of river runoff components makes it possible to describe the distribution of total water resources in European Russia (ER) and their dynamics under the effect of non stationary climate.

MATERIALS AND METHODS

The input data for the analysis were materials from the State Water Cadastre and Russian and international hydrometric and climatic databases collected for approximately 300 watersheds in ER. Calculations for each gauge were carried out for three periods: the entire observational period, 1940–1969, and 1970–2005. The year 1970 was taken as a threshold because it is associated with the beginning of changes in climate conditions in the major portion of ER (Vodnyeresursy, 2008). The characteristics evaluated for the chosen observation periods included the mean, minimal, and maximal values of mean-square deviations. Spearman's nonparametric trend tests, Fisher's test, and Student's test were used to check the statistical homogeneity of the examined series. Additionally, data in the series of annual and seasonal precipitation and surface air temperature were analysed for more than 200 weather stations in ER.

The subsurface component of river runoff was characterized by dry-season runoff, evaluated as the mean monthly water discharges over dry months.

CLIMATIC FEATURES OF SURFACE AND SUBSURFACE WATER FORMATION

A considerable increase in surface air temperature has been recorded in ER since the late 1970s. The average annual temperature increase rate for the considered territory is 0.53°C/10 years, which is mostly due to the mean cold season temperatures (0.45—0.6°C/10 years).

In the last 50 years, a higher moistening level has been recorded in ER areas north of 50°N, where the share of liquid precipitation in the cold season has also increased. This is largely due to the more intense circulation processes in the North Atlantic, which affect the transfer of cyclones into central regions of Russia (Kislov *et al.*, 2008). Although the total percentage of precipitation of Atlantic origin in ER averages less than 50%, the analysis for large basins in ER showed that almost 80% of Volga runoff variations, 30% of those in the Dnieper, almost 40% of those in the Don and the Neva, 35% of those in the northern Dvina, and 25% of those in the Pechora are due to changes in the paths of cyclones of Atlantic origin and their corresponding precipitation (Vodnyeresursy, 2008).

FACTORS AND CHARACTER OF RIVER RUNOFF VARIATIONS AND WATER RESOURCES FORMATION

The main feature of the current changes in the river regime in ER is the redistribution of runoff within the year; the mean annual water discharges remaining relatively constant. An increase in the temperature and a slight increase in precipitation in the cold period have resulted in more frequent winter thaws and shallower seasonal freezing of rocks in the aeration zone. Therefore, a considerable portion of flow from snowmelt participates in the increase in rock moisture content in the aeration zone and groundwater recharge, which jointly lead to a considerable increase in the dry-season river runoff. Snowmelt runoff losses due to infiltration increase resulted in positive trends in groundwater levels observed at different sites in ER (Dmitrieva, 2012; Kalyuzhnyi & Lavrov, 2012). Almost all gauges show a decrease in the share of flood runoff in total annual runoff. The redistribution of runoff between the flood and dry seasons radically changes the shape and the general pattern of the runoff hydrograph. As a result, the recent climate situation is generally favourable for the water resources formation conditions.

Until the late 1970s, the ER rivers considered in the study, due to their snowmelt component and within-year runoff distribution, were categorised as rivers with predominantly snow nourishment. In the late 20th century, their nourishment became mixed or even mixed with the predominance of that through seepage. The result was a considerable increase in the natural runoff regulation, comparable to the effect of reservoirs with seasonal regulation (Vodnyeresursy, 2008). A statistically significant ascending trend in φ coefficient (the base to annual runoff ratio), which can be used to characterise natural regulation of runoff, was established in most rivers of ER. The value of φ in the rivers of Moksha, Oka, Khoper, and others increased from 0.4 (1935–1969) to 0.6–0.7 (1970–2005) (Dzhamalov *et al*., 2010).

The within-year runoff distribution shows a steady drop in maximal discharges and the flattening of spring flood peak, accompanied by a gradual increase in the dry-season runoff, which is especially significant in the 2000s. The single-peak hydrographs with distinct spring peaks, which were typical of the regime of East European rivers in the 1970s, are replaced by modern hydrographs with comb-like segments in the phase of higher water abundance (Fig. 1). In this case, the excess ratio of maximal spring water discharges over mean dry-season values decreases from 10–15 to 3–5 times. Analysis of field data over the past 100 years shows no such changes in the past, since both high-water and low-water phases before the 1970s were determined by the runoff value during spring flood. The isolation of spring flood as an individual phase of river water regime becomes a difficult problem, since the increase in the number of thaws also increases the uncertainty in the identification of the start of spring flood (Fig. 1).

The changes in the river spring-flood runoff in the southern slope of ER can be most clearly seen in the dynamics of maximal water discharges, where decreases in the Don basin average 40–60%. Changes in the maximum water discharges of the Oka and its tributaries are 20–40%, and those for the rivers of the Lower Volga are 40–70%.

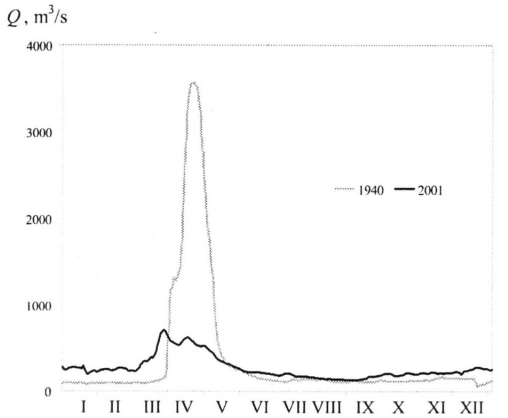

Fig. 1 Typical shape of runoff hydrographs (Don basin, Kazanskaya gauge).

At almost all gauges at the heads of large rivers and in basins of medium rivers, a statistically significant shift of the dates of the flood beginning and maximum water discharge to earlier time was observed. The general trend in the current runoff regime is also a shift of the dates of spring flood end to later time. In this context, the duration of spring flood increases with a statistically significant trend, by practically 10–20 days, depending on the size of the river and the latitude of its basin location (Kislov *et al*., 2008).

A response of annual runoff to climate changes in the last quarter of the 20th century was the higher water abundance in rivers in the territory of the Upper and Middle Volga. The largest changes in the annual runoff (by 15–30%) were recorded in ER rivers flowing approximately between 56 and 60°N (the left tributaries of the Volga in its upper and middle reaches, part of Kama basin) (Fig. 3(a)). The long-term variations in annual runoff for one of the Volga's tributaries − the Oka River – are given in Fig 2. About the same increase took place in Volga tributaries in the forest–steppe zone. North and south from this area, the increase in river water volumes was less (Fig. 3).

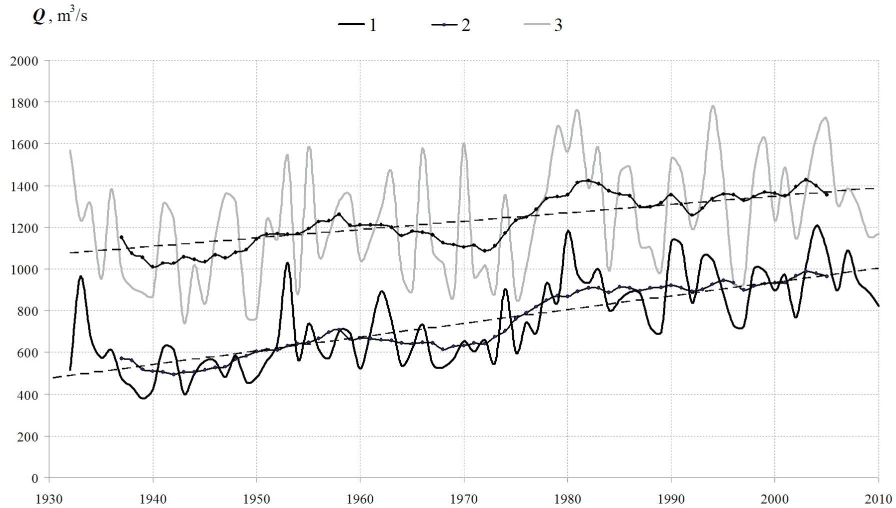

Fig. 2 Variations in natural groundwater resources (1) and mean annual runoff (3) for the Oka River − Gorbatov gauge, where (2) is 10-year sliding average.

Changes in natural groundwater resources (dry-season runoff) are observed in the majority of ER rivers (Fig. 3(b)). The maximum increase in the runoff in winter and summer–autumn season is typical of the southern parts of the forest and forest-steppe zones. The largest changes in the dry-season runoff (more than 70%) are typical of the upper Oka and the Ural rivers. The long-term variations in annual runoff for Oka River, Gorbatov gauge, are given in Fig. 2. In the rivers of the Volga basin (except for the Kama), the increase in the winter dry-season runoff is 45–70%. About the same value is typical of variations in dry-season runoff in the Upper Don. However, in the northern ER and on the south of the Tsimlyansk Reservoir, there is a statistically insignificant drop or increase in the observed mean dry-season runoff (Fig. 3(b)).

On the northern slope of the Caucasus (the basins of the Terek and Kuban), the long-term fluctuations of mean annual discharge and minimum monthly discharge have a weak spatial correlation. Four principal types of long-term fluctuations of these characteristics can be distinguished in Terek river basin (Rets & Kireeva, 2010). While homogeneous series are typical of the upstream of Terek and Malka rivers, some of the mountainous tributaries of the Terek and the Sounzha rivers showed an increase in the value (by 15–45%) and variance (by >100%) since the middle–late 1970s in the inter stream mountainous area of the Terek and Baksan rivers. The latter region is also characteristic for its high value of the autocorrelation coefficient of mean annual and minimum monthly discharges (r(1) > 0.7−0.8 in some cases). This indicates a high degree of natural runoff regulation which is caused by the specifics of the geological structure of the river basins. The long-term fluctuations of annual discharge and minimum monthly discharge in the foothills' river basins have shown a constant increase in the mean value, and variance for the whole observation period. Against the background of the constant rise, well-defined cycles of relatively low and high-flow periods are observed, which are in phase with respective cycles in annual precipitation fluctuations, but with several-years delay due to strong natural regulation facilities of the basins, which is indicated by the high value of the autocorrelation coefficient ($r(1) > 0.75-0.85$). A decrease in the mean annual discharge was detected for the lower stream of the largest rivers in the Terek River basin. It was caused by losses of river flow through economic activity in the basin. Maximum water levels tend to increase at more stations in the lower stream of the largest rivers in the Terek River basin, which is mostly due to sediment accumulation, detected by comparison of the dependencies between water level and water discharge for different time periods in the selected sites.

(a) (b)

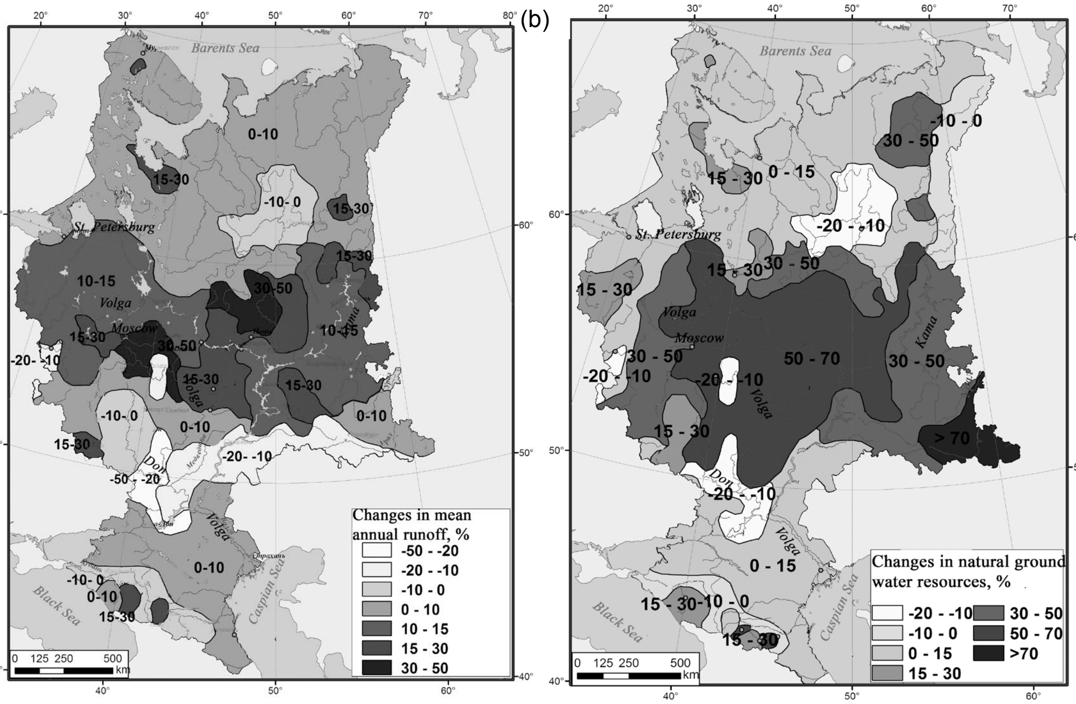

Fig. 3 Changes in (a) mean annual runoff and (b) natural groundwater resources in ER relative period 1940–1969.

THE AVAILABILITY OF WATER RESOURCES IN EUROPEAN RUSSIA AND THEIR USE

The population of European Russia is 80% of that of the country, but it only has 21% of the country's total water resources. The data on current water resources, their components, distribution and use are given in Tables 1 and 2. The mean annual resources of river runoff and their use in the basins of large rivers of ER are given in Table 3.

The decrease in water withdrawal that began in the 1990s continued in 2009 in accordance with the general decrease in economic activity in those years in almost all branches of the country's economy. The volume of water withdrawal and use decreased almost 1.6 times relative to 1990. The total annual water withdrawal from all natural sources, according to State Water Cadastre data was 79.5 km^3 in 2005, 80.3 in 2008, and 75.4 km^3 in 2009. The shares of individual water use in the total volume of water use also changed considerably: the share of industry is 66%, that of housing and utilities infrastructure is 20%, that of irrigation is 12%, and that of agricultural water use is 2% (Vodnye Resursy, 2008; Shiklomanov, 2009; Shiklomanov *et al*., 2011).

The present-day load on groundwater resources in constituent entities in ER, as a limiting factor of water availability, is presented in Table 1. The highest anthropogenic load on water resources and water bodies in Russian Federation territory was recorded in the Moscow region and nearby territories of the Central FD, as well as in many regions of the Southern and North Caucasian districts.

Table 1 Water resources availability in ER and their distribution and use.

ER Federal entity	Area, $km^2 \times 10^3$	Population (as of 2010), million	Natural resources, km^3/year		Natural water resources availability per capita, thous. km^3/year	
			Mean annual river runoff	Groundwater	Mean annual river runoff	Groundwater
Northwestern	1686.9	13.6	592.7	203.5	43.7	15
Central	650.3	38.4	116.8	55.4	3	1.4
Privolzhskii	1036.9	29.9	191.8	75.7	6.4	2.5
N-Caucasian	591.4	23.4	59.9	34.3	2.6	1.5
Total	3965.5	105.3	961.2	368.9	9.1	3.5

Table 2 Water resources use in ER.

ER Federal entity	Water withdrawal km^3/year (after 2000)	Load on natural water resources, %	
		Annual river	Groundwater
Northwestern	12.18	2	6
Central	13.26	11	24
Privolzhskii	11.38	6	15
N-Caucasian	24.62	41	72
Total	61.44	6	17

Table 3 Resources of surface and subsurface waters and their use in the basins of major rivers of ER.

River basin	Area, $km^2 \times 10^3$	Natural resources, km^3/year/ changes relative to 1940–1969 (%)		Water withdrawal	The ratio of water withdrawal volume to natural resources (%)	
		Mean annual river runoff	Groundwater	km^3/year, after the 2000s	Mean annual river runoff	Groundwater
Northern Dvina	360.0	100.1/1	37.9/1	0.29	0.2	1
Mezen	79.65	19.9/–1	6.6/5	0.04	0.2	1
Pechora	322	147.2/17	40.2/–12	0.28	0.2	1
Volga	1380	260.1/7	192.2/15	2.44	1	1.3
Oka	245.0	41.1/16	25.0/63	0.65	1.6	2.6
Don	422.44	21.2/–14	18.1/27	1.75	8	10
Khoper	61.1	4.0/23	2.2/150	0.01	0.3	0.5
Kuban	57.9	14.3/3	10.5/7	4.58	32	44
Terek	37.42	7.2/–8	4.6/7	3.91	54	85

Notwithstanding an increase in the natural resources of surface and subsurface waters in ER, the economically developed regions in the Central and the agricultural areas of the Privolzhskii, Southern, and North Caucasian federal districts have practically no potential for further increase in water resources use, unless a realistic program of water saving and water quality rehabilitation is introduced.

A factor that hampers the development of domestic water supply is drinking water deficiency in some constituent entities in ER, which is associated primarily with the irrational use of limited water resources. Water availability is low in some entities in the Central, Povolzhshkii, Southern, and North Caucasian federal districts. Water supply to the population of those areas is often not continuous within the day but follows a delivery schedule or is taken from open sources without proper treatment or processing.

In recent years, water quality at the sites of water withdrawal from both subsurface and surface sources of centralized water supply is poor. In Russia, ~40% of surface water and 17% of subsurface sources of drinking water supply fail to meet sanitary standards. Nearly half the Russian population use water that does not meet hygienic standards and is hazardous to human health. The situation with the quality of drinking water supply is especially tense in rural areas. In the structure of discharge of polluted wastewater, municipal wastes dominate (almost 90%).

In planning water supply to large urban areas, two independent sources need to be considered. In the case of pollution of the vulnerable surface source, the alternative, better protected subsurface source should ensure water supply to the population with the adequate rates throughout the entire period of quarantine. In this case, the admissible environmental load on water bodies should be taken into account, and the requirements of the RF Water Code on the reservation of sources of drinking and domestic water supply should be fulfilled.

DISCUSSION AND CONCLUSION

The positive changes in the mean annual and, especially, winter air temperatures, as well as precipitation have a considerable effect on river water volumes and their runoff regime.

In a considerable portion of the middle-latitude part of ER, river runoff in recent decades was in excess of the mean for 1940–1969. However, north and south from this area, the variations in annual runoff do not go beyond their natural limits.

Most rivers of ER show changes in their runoff regime and nourishment source. Since the late 20th century, many rivers' nourishment structure has changed from the predominance of springtime snow melt to a mixed type, with the predominance of groundwater recharge in some cases. This has led to a considerable increase in the natural regulation of runoff, whose extent is comparable with the effect of "seasonal regulation reservoirs."

The main feature of the current water regime is a considerable change in the within-year regime with higher dry-season runoff, especially in winter. In large regions, for most rivers under consideration, significant positive trends (with significance level of 95%) were identified in the runoff of the winter and summer–autumn dry seasons. The increase in dry-season runoff in the last 25–30 years has caused an increase in natural groundwater resources even in the basins of rivers where spring flood runoff has dropped. Such a situation is quite new, since previously the major low-water and high-water phases were determined by the spring flood runoff.

The specific water availability in the major portion of Russian territory is expected to increase by 10−25%. Only some administrative areas in the Central, Povolzhskii, Southern, and North Caucasian federal districts will have low water availability.

REFERENCES

Dmitrieva, V. A. (2012) Geographic-Geohydrological Assessment of Water Resources in a Constituent Entity of Russian Federation under Changing Climate and Economic Activity, Extended Abstract of Doctoral (Geogr.) Dissertation, Voronezh.

Dzhamalov, R. G., Frolova, N. L., Kireeva, M. B. & Safronova, T. I. (2010) Climate-induced changes in groundwater runoff in Don Basin, *Water Resour.* 37(5), 733–742.

Gosudarstvennyi doklad "O sostoyani i ispol'zovaniivodnykh resursov Rossiiskoi Federatsii v 2009 godu"(2010) (State Report "On the State and Use of Water Resources in the Russian Federation in 2009), Moscow, NIA-Priroda.

Kalyuzhnyi, I. L. & Lavrov, S. A. (2012) Major physical processes and regularities in the formation of winter and spring river runoff under warming climate. *Gidrol. Meteorol.* 1, 68–81.

Kislov, A. V., Evstigneev, V. M., Malkhazova, S. M., *et al.* (2008) *PrognozklimaticheskoiresursoobespechennostiVostochno-Evropeiskoiravniny v usloviyakhpotepleniya XXI veka* (Forecast of Climate Resource Availability in East European Plain under Warming in the XXI Century). MAKS Press, Moscow.

Rets, E. & Kireeva, M. (2010) Hazardous hydrological processes in mountainous areas under the impact of recent climate change: case study of Terek River basin. In: *Global Change: Facing Risks and Threats to Water Resources* (ed. by E. Servat *et al.*). Proc. of the Sixth World FRIEND Conference. IAHS Publ. 340, 126−134. IAHS Press, Wallingford, UK.

Vodnyi kadastr Rossiiskoi Federatsii. Resursy poverkhnostnykh I podzemnykh vod, ikh ispol'zovanie i kachestvo. (2010)(Water Cadaster of the Russian Federation. Surface and Subsurface Water Resources, Their Use and Quality), St. Petersburg: ART-Xpress.

Shiklomanov, I. A. (ed.) *Vodnye resursy Rossii I ikh ispol'zovanie* (Water Resources of Russia and Their Use), St. Petersburg: GGI, 2008.

Shiklomanov, I. A., Babkin, V. I. & Balonishnikova, Zh. A. (2011) Water resources, their use, and water availability in Russia: current estimates and forecasts.*Water Resour.* 38(2), 139–148.