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Up-to-date climate forced seasonal flood changes (the case study for the European part of Russia)

NATALIA FROLOVA, MARIA KIREEVA, DMITRY NESTERENKO, SVETLANA AGAFONOVA & PAVEL TERSKY

Department of Hydrology, Lomonosov Moscow State University, 119899, Leninskiye Gory, Moscow, Russia
frolova_nl@mail.ru

Abstract The analysis of hydrological information for the observation period (1946–2010) based on data from more than 200 hydrological stations enabled the evaluation of changes in characteristics of a spring flood in the rivers of the European territory of Russia and the determination of flood characteristic factors. In addition, changes of climatic characteristics such as the increase in number of winter thaws and the precipitation total in the cold season have been related to features of spatial and temporal variability of the beginning and end dates of the spring flood, maximum water discharges and shapes of hydrographs, and volume of runoff during a spring high-water period.

Key words flood; water regime; climate change; European part of Russia

INTRODUCTION

Spring flood as a phase of the water regime plays an important role in the formation of river runoff in the European territory of Russia (ETR). It determines potential water supply during the summer–autumn low water period and the character of rain-fed flash floods. The main reason for change of river runoff in different seasons of the year lies in the change of climate resulting in changes of atmospheric circulation in the study region. The atmospheric circulation change leads to changes of climate in winter, resulting changes in precipitation and length of warm and cold periods. The increase of air temperature in the cold period, the increase in number, duration and "severity" of winter thaws, and the decrease of cold period length are prerequisites for the changes in the river water regime. Changes of water regime result in a significant decrease of river runoff during the spring flood and increase of natural runoff regulation. However, the degree of changes due to climate depends on the characteristics of a particular drainage basin, natural and anthropogenic runoff regulation capacity and economic development. The main objective of the current study is to estimate contemporary features of the spring flood on rivers in the plains part of the ETR and to account for this information in runoff forecasts and calculations. Achievement of the research objective needed creation of databases and GIS-projects; statistical analysis of data series and research of regularities of spring flood characteristics for the main drainage basins in the ETR for the period up to 2010; the research of interconnections of spring flood characteristics with characteristics of other phases of water regime; and the creation of maps.

DATA AND METHODS

In the current study long-term data with the period of observation up to 2010 from the Russian State water cadastre on more than 200 non-regulated middle-sized river basins was used. Meteorological data used in the research includes average daily air temperatures and precipitation rates measured at meteorological stations located in the ETR. Two periods were used for analysis: 1946–1977 during which changes in the rivers' water regime were not found, and 1978–2010 during which spring river runoff has decreased and low water runoff has increased. Assessment of the homogeneity of annual, seasonal and monthly river runoff data has been carried out according to Student and Fisher criteria. For assessment of homogeneity of dispersions and average values, the data series was divided in two periods: 1946–1977 and 1978–2010. Assessment of the homogeneity was conducted at a level of statistical significance equal to 5%.

CHANGE OF CLIMATE FEATURES IN THE EUROPEAN TERRITORY OF RUSSIA

In the European territory, an increase of mid-annual air temperature is the most intensive (0.43°C/10 years during the period from 1977 to 2011), more than twice as high compared with global temperature and statistically significant in comparison with other regions of Russia (Frolova *et al.*, 2011). The increase in average temperature of air for the cold season (from November to March) is distinctly affected in the whole European territory of Russia. The rise of air temperature in the cold season resulted in more frequent winter thaws, a decrease in the depth of seasonal soil frost, and a decrease of snowmelt from winter thaws that feed the groundwater. In this study factors affecting snow accumulation (the main factor of spring flood) in the ETR were taken into account. The increase in the sum of positive temperatures led to an increase in liquid precipitation (rainfall) and a non-significant decrease in solid precipitation (snow) for the cold period. However, the amount of snow supply in the longer term is not changing significantly because of low air temperatures, leading to smoothing of warming impacts and boosting the interception of liquid precipitation into the snow layer. Significant long-term trends in changes of decreasing period and intensity of snow supply melting were not revealed. The increase in total duration of winter thaws can lead to an increase in the intensity of snowmelt in winter, and to an increase in low-period water runoff. Due to the increased warming process the soil thaws were more intense during the snowmelt periods which lead to an increased transition of surface snowmelt runoff to underground waters. As a result, in recent decades in central and southern parts of the ETR there has been a significant change of water runoff characteristics.

CONTEMPORARY FEATURES OF SPRING FLOOD IN THE ETR RIVERS

Contemporary climate changes affect features of the spring flood passage in the ETR rivers in different ways. Research of the specific character of this process in different natural conditions in the European territory of Russia was conducted using case studies for drainage basins of northern rivers in the ETR, the Volga, Ural and Don basins. In the drainage basins of northern rivers in the presence of frequent and prolonged winter thaws, even with large values of sums of winter precipitation rates, water shortages can sometimes occur, leading to relatively low water discharges during the spring flood. However, the relationship between the number of winter thaws, maximum water discharges of spring flood and volume of flood river runoff could not be found due to complexity and multiple-factors of the runoff formation process. In the period of the most intensive climate change (1978–2010) in the rivers of the north of the ETR, maximum day discharges did not change significantly. Annual dates of the flood beginning changed to earlier dates, but not significantly. The volume and depth of runoff did not change (Fig. 1(b)). The coefficient of natural runoff regulation φ, the ratio of a hydrograph area, located lower than a line of average annual discharge (base runoff), to total area of the hydrograph (annual runoff) (Fig. 1(a)) had some small changes.

The spring flood is the main phase and feature of the water regime of rivers in the Volga drainage basin. For the period concerned (1946–2010) a decrease of the maximum discharges of the spring flood in the Oka and Lower Volga drainage basins is typical. For the rivers concerned the beginning of the spring flood in the Volga and Don basins has shifted by 10–15 days to earlier dates, corresponding to increases in duration of the spring flood. For the Oka basin, the maximum water discharge has decreased by 20–40%, and for the Lower Volga basin by 40–70% (Fig. 1(c)).

In the last three decades this regularity is typical for oscillations of maximum runoff for rivers of the Upper Volga (rivers Chagodoshcha, Unzha, Suda, Lid’, Kerzhenets, Vetluga) and Kama drainage basins. It can be explained by a character of change of the cold period precipitation rates which increased in the territories considered. For rivers in the northwestern part of the Volga basin located in the south of the taiga zone, a non-significant positive trend of maximum discharges is found (River Vetluga) or the trend is not present (River Vyatka). A significant increase of maximum discharges is traced only on rivers in the northern and northeastern parts of the taiga zone with severe climate where an increase of winter precipitation has been marked (rivers Unzha and Kama). On rivers located in the forest-steppe and steppe zones there has been a decreasing trend of maximum flood discharges. In the mixed forests zone a decreasing trend is less noticeable (River Kostroma), but is more noticeable for rivers flowing partly or fully in semi-arid zones (rivers Oka and Bolshaya Kinel'). The change of spring flood features has had an impact on its share in annual runoff. Before 1977 the contribution changed from 60% (Kama and Upper Volga drainage basins) up to 70–80% and more (left tributaries in the Lower Volga basin). In the last few decades the share has decreased by approx. 10%.

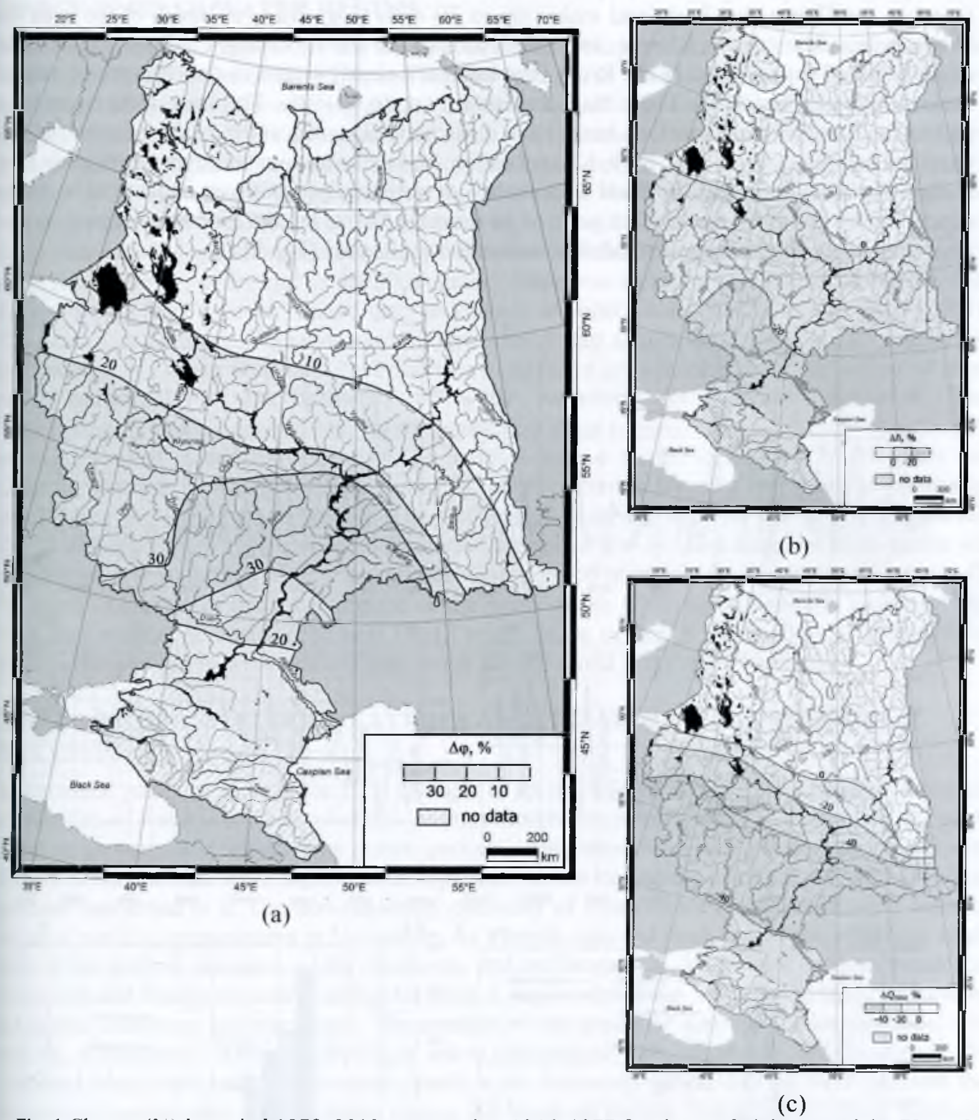

Fig. 1 Change (%) in period 1978–2010 compared to 1946–1977 for rivers of plain part of the ETR of: (a) the coefficient of natural runoff regulation φ, (b) depth of runoff of spring flood h (mm), (c) maximum river discharges of spring flood (Q_{max}, m^3/s).

For south of the ETR changes of spring flood river runoff are particularly significant. Flood as a phase of water regime annually defines total water supply in drainage basins of Don, Ural, Kuban and Terek rivers, and in the Lower Volga basin. Climate changes taking place have led to significant degradation of the spring flood as a phase of water regime on the rivers in the Don basin (Fig. 2).

Statistical analysis of depth of runoff data series (Fig. 2(a)) has shown that for 60% of hydrological stations statistically significant decreases of average values is found, and for 50% a statistically significant increase of dispersion. Even separation of the spring flood as a phase of water regime using hydrographs has become an exceptionally complex task in recent years. The increase in number of winter thaws leads to "smearing" of the beginning of the flood. More frequently than before, flash floods are occurring with the spring flood wave (Fig. 2(e),(f)). In the whole Don basin the depth of runoff has decreased by 10–30%. The most significant decrease of depth of runoff is found in the Upper Don basin and makes up to 30–40% (Fig. 2(a)), in basins of the main River Don's tributaries (rivers Khoper and Medveditsa), 10–20%. Changes of spring runoff and degradation of spring flood in the River Don basin are clearly traced in the dynamic of maximum water discharges (Fig. 2(b)). These have decreased by up to 40–60%. The dates of the beginning and end of the flood in the River Don basin have also changed significantly: in the western part of the basin the beginning has shifted by 9–12 days earlier, and in the eastern part by approximately a week earlier. The total impact of the flood shift leads to a statistically significant increase of its duration: depending on the river size and its position in drainage basin, the duration can increase by 10–20 days (Fig. 2(c)). Natural runoff regulation increases significantly (Fig. 2(d)).

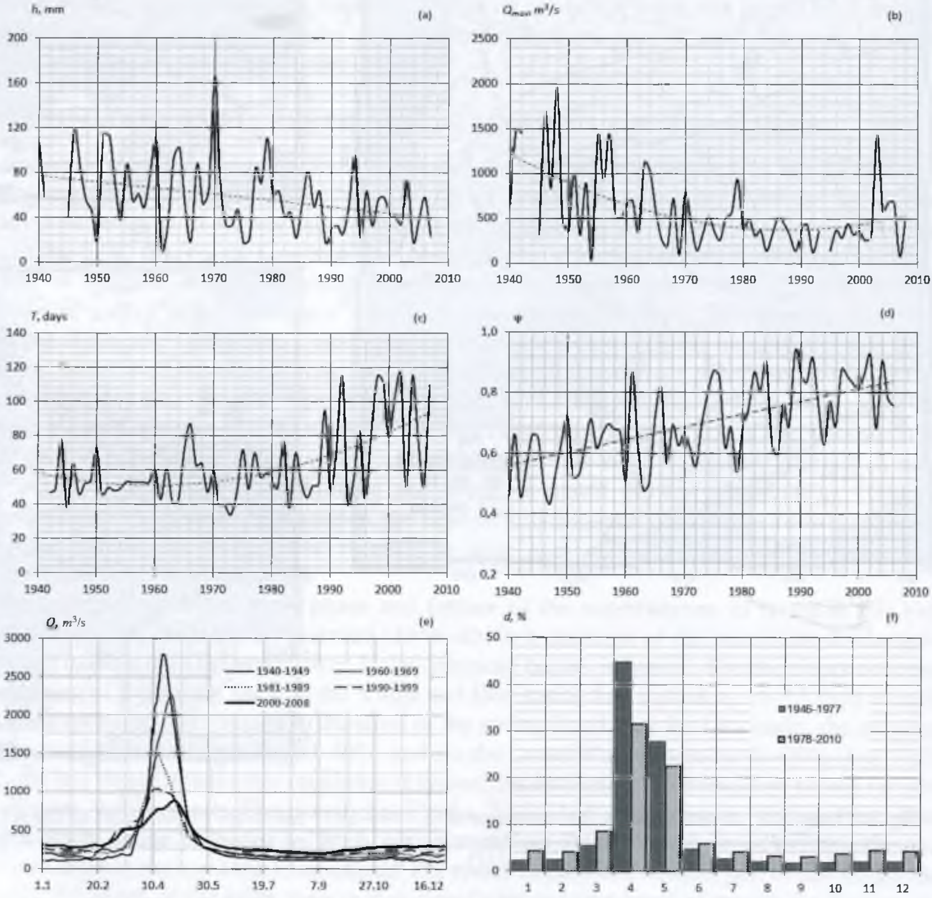

Fig. 2 Change in: (a) spring flood depth of runoff (h, mm) for the River Sosna in Elets; (b) the maximum discharge (Q_{max}, m^3/s) for the River Medveditsa in Archedinskaya, (c) duration of spring flood (T, days) for the River Don in Liski, days; (d) the coefficient of natural runoff regulation φ for the River Don in Zadonks; (e) average hydrographs for different periods for the River Don in Kazanskaya, (f) share of monthly water discharge of annual discharge d (%) in 1946–1977 and 1978–2010 for the River Khoper in Bespleyannovsky.

A similar, but less noticeable pattern of changes of flood characteristics, is found in the River Ural basin. Analysis of maximum discharge data series on homogeneity has revealed a statistically reliable decrease of their average values. The negative trend is traced along almost all the length of rivers Ural and Ilek and makes up to 20–70%. Changes of spring flood dates in the River Ural basin, as opposed to the River Don basin, are multidirectional. Significant changes of spring runoff in the plains part of the drainage basins of the rivers Kuban, Kuma and Terek were not found.

CHANGE IN RIVER WATER REGIME

The change in climatic conditions has led to considerable changes in all the characteristics of the water regime of the rivers of the ETR, and thereby changes in annual and seasonal runoff. For the majority of the considered rivers, significant trends of runoff increase in the winter and summer–autumn low water periods are apparent. The degree of increase in low runoff rises from northern areas to southern areas. So over the last 30 years low runoff in the Northern Dvina basin has increased by 20–30%, in the Volga basin by 50–70%, and in the Don basin by 40–60%. Before the second half of the 1970s, according to M.I. Lvovich's classification, the rivers of the ETR were, due to their runoff generation sources and within-year variation of runoff, considered as "mainly snow" fed. However, at the end of the 20th century there was a category transition of the rivers to the type "mixed feed" or even "mixed with prevalence of underground feed" (Shiklomanov, 2008). This means that the share of groundwater in river runoff had significantly increased by the end of the 20th century. These processes have led to a significant growth of natural regulation of river runoff, comparable to the influence of water reservoirs on seasonal regulation. The "synchronization" of changes of low runoff over these large regions and the scale of the changes are unprecedented in the 20th century. The increase in low runoff in the last 25–30 years has caused an increase in water resources, even in the river basins where there was a reduction in runoff during the spring flood season. The analysis of observed data for the last 100 years has allowed the conclusion that such a situation has developed for the first time, because earlier all considerable low water and high water phases were defined primarily by the spring flood runoff. The trends of change of the water regime of the rivers of the ETR, noted from the middle of the 1970s, may remain, at least for the next 10–15 years. In the centre, in the northwest, and south of the ETR, the increase in winter runoff may reach 60–90%, and in summer 20–50%.

CHANGE OF SPRING FLOOD FEATURES AND HAZARDOUS HYDROLOGICAL PROCESSES

In central and southern parts of the ETR changes of spring flood features have a beneficial impact on reliability of water use. The probability of large floods due to snowmelt decreases and the water runoff in summer and winter low water periods increases. However, for the northern rivers changes of climate and water regime have an impact on the ice regime of rivers and the hazardous processes connected to it. The non-stationary character of temperature change in autumn leads to returns of positive temperatures in November. As a result, rain-fed flash floods are occurring. High water in this period promotes a later freeze-up, and an increase in duration of autumn period, of floating ice and sludge ice and resulting ice jams. Long winter thaws lead to winter ice break-ups, and related hazardous ice blockages. The number of ice jams and ice hummocks increases. For example, in December 2006, ice blockages led to catastrophic water level rise and flooding in the Northern Dvina River basin. High water levels in the freeze-up period and ice jams promote the formation of catastrophic ice blockages during the break-up period (Spring 2007, River Northern Dvina). The increase in the amount of winter precipitation falling on the upper layer of snow accelerates melting of snow cover and increases the risk of floods. The processes described are most intensively developed in the northern and northwestern regions of Russia in the last 50 years.

CONCLUSIONS

The statistical analysis of changes of meteorological characteristics has shown the increase of the average air temperatures during the cold season for all of European Russia. As a result of the rise in temperature of air in the cold season, winter thaws have become more frequent and the depth of the seasonal frost in the unsaturated zone of soils has decreased. The increase in wetness of an active layer of soils and an increase in groundwater recharge are connected with the snowmelt runoff during winter thaws. Climate changes observed in recent decades in the mid-latitudes of the European territory of Russia have considerably affected and changed the characteristics of water regimes, spring flood river runoff, the quantities of surface water, and groundwater resources.

The impact of contemporary climate changes on spring flood runoff of the biggest rivers in European Russia is multidirectional and has different consequences. For the northern rivers in the ETR relative stability of flood characteristics is typical, despite the growth of winter precipitation and increase in number of winter thaws. In the River Volga basin changes of water regime have become apparent in the decrease of maximum water discharges for the Oka and Lower Volga drainage basins by 20–70% and in a decrease of depth of runoff up to 20%. At the same time, for the rivers Kama and Unzha basins a significant increase of maximum discharges was found. In the River Don basin degradation of a spring flood as a phase of water regime has become apparent. The share of spring flood in annual runoff has decreased by 20–40%, reaching 50% of the total annual runoff. The decrease of maximum discharges is general and reaches 20–60%. For the majority of the ETR rivers considered, there are significant (at a significance value of 95%) positive trends of increase in winter and summer–autumnal low-water runoff. Changes in the genesis of the runoff to the rivers, caused by reduction of the spring runoff and the increase of low-water runoff, have led to significant growth of natural regulation of runoff.

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