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ESTIMATION OF THE IMPACT OF CLIMATIC AND ANTHROPOGENIC FACTORS ON THE FORMATION OF THE EXTREME LOW-FLOW PERIOD IN THE DON RIVER BASIN DURING 2007-2016

ABSTRACT. The Don River is the largest river in the southwestern part of European Russia and the second largest river system in European Russia. The Don River basin is one of the most water deficient regions in Russia and the long term average water usage in the basin amounts to 45%. The period 2007-2016 was the longest long-term low-flow period observed, with an estimated total water resources deficit of 40.4 km^3 over 8 years. The main reason for this deficit were anomalously warm winters (2-4 degrees over average) with a low degree of soil frost penetration. This resulted in low spring flood volume (37% of the average) due to heavy seepage losses combined with thin snow cover. A similar low-flow situation was observed in 2014, when the drought caused great damage to ecosystem of Tsimlianskoye water reservoir and the River Don. Most of the fish breeding grounds had dried up by May 2014. This caused the number of round fish whitebait to drop 5-10 times below the 2002-2014 average. Inland shipping and hydropower industry also sustained losses of 42 million euro (according to interview from State Shipping company) due to low water level. This study shows that the main reasons for the 2007-2016 extreme hydrological drought are exceptional hydro-climatic conditions and anthropogenic transformations in the watershed, such as urbanisation growth and afforestation. The analysis shows that the main cause in water deficit is associated with the left tributaries of Don – Khoper and Medveditsa, while the flow in Upper Don remained more or less normal. The results can be interpreted as a "warning sign" to reduce water consumption in these sub-basins to avoid similar drought situations in future.

KEY WORDS: low-flow period, hydrological hazards, hydrological droughts, Don River, climatic factors, anthropogenic factors, runoff formation

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INTRODUCTION

The clustering of years of a high and low water discharge in a river are a distinctive feature of fluctuations in the river runoff characteristics, especially during the low-flow period of the year. The term "low-flow" is determined by characteristics of a period with low discharges, accompanied by various types of social, economic and environmental damage (Alekseevskiy and Frolova 2011). The concept of "low-flow" used in this study is closely connected to the concept of "hydrological drought" (Hydrometeorological Risks 2008), which differs from the atmospheric, soil, agricultural and water use drought (Bolgov et al. 2005).

For the Don River basin located in the southern European part of Russia the clustering of floods and low water levels is particularly clear (Shiklomanov 1979; Dzhamalov 2013). The observed increase in the occurrence frequency of such extreme events is related to climatic changes (Semenov 2009; Semenov et al. 2015). However, while the duration of floods rarely exceeds several months, low-flow periods can last for several years (Dmitrieva 2011). In addition, since the 1950s, the high needs for water availability, driven by the population growth, have led to a sharp increase in the human impact (runoff regulation, water withdrawal, water transfer to neighbouring basins) on the hydrological regime of the rivers in the Don basin. Thus, I.A. Shiklomanov noted (Shiklomanov 1979) that in 1975 the irretrievable water consumption was 8-10 km3 per year, which is approximately equal to one third of the annual runoff of the Don River in its estuary. In terms of runoff losses, the additional evaporation from the water surface of ponds and reservoirs and the water abstraction for municipal and domestic water supply and agriculture (Alekseevskiy and Frolova 2011) are important factors. For example, the area of irrigated land increased from 35.000 ha in the 1940s and 1950s to 511.000 ha in 1975. Similar conclusions about unconstrained water use in the Don River basin in 1970s -1980s were obtained other studies (Koronkevich et al. 1990; Scheme of complex... 2013). Thus, according to most of the past studies performed during the Late Soviet period (1980s-1990s) the industry and agriculture was expected to grow continue growing at the same rate. These projections would have led to twice as much water abstractions by the beginning of the twenty-first century. However, the collapse of the Soviet Union led to a reduced growth of water management activities and these projections were not confirmed. Nevertheless, the Don basin is currently one of the most water-stressed regions in Russia (Alekseevskiy 2013). In addition, significant changes in seasonal runoff in the Don basin were observed, which also have an impact on the low-flow periods (Kireeva et al. 2015; Dmitrieva 2013, 2014).

The increased occurrence of low water levels in recent years has been observed in many European countries and around the world (Van Lenen et al. 2016; Bordi et al. 2009). For example, the summer of 2015 was extremely dry in Europe and at the same time an extreme low-flow period was also observed in the Don basin, which has similar hydro-climatic conditions as the countries of south-east Europe (Van Lenen et al. 2016).

To gain more insights into the characteristics of extreme low-flow periods, this paper presents a comprehensive analysis of the 2007-2016 low-flow in the Don basin.

MATERIALS AND METHODS

ERA Interim reanalysis data (V2) was used in this paper, to study the contribution of climatic variability to the formation of low-flow period. ERA Interim is a third-generation reanalysis created by the European Centre for Medium-Range Weather Forecasts (ECMWF official website [online]). The reanalysis data is publicly available and include series from 1979 to the present. The data is available in grid format with a spatial resolution of 0.75° x 0.75°, which covers the surface of the entire planet (Mouat and Lancaster 2008).

Different versions of the reanalysis data have different errors in the air temperature and the precipitation magnitudes. Typically, reanalysis temperature data has a smooth field structure and a high degree of spatial correlation of adjacent values. Due to this, for example, when comparing air temperature data obtained from the Lipetsk weather station and the data obtained reanalysis (here – ERA-Interim V2), the square of the coefficient of determination (R^2) is 0.99 (Fig. 1A). In the case of total precipitation, the R^2 is reduced to 0.53 (Fig. 1B). These differences are likely due to the large distance (about 40 km) between

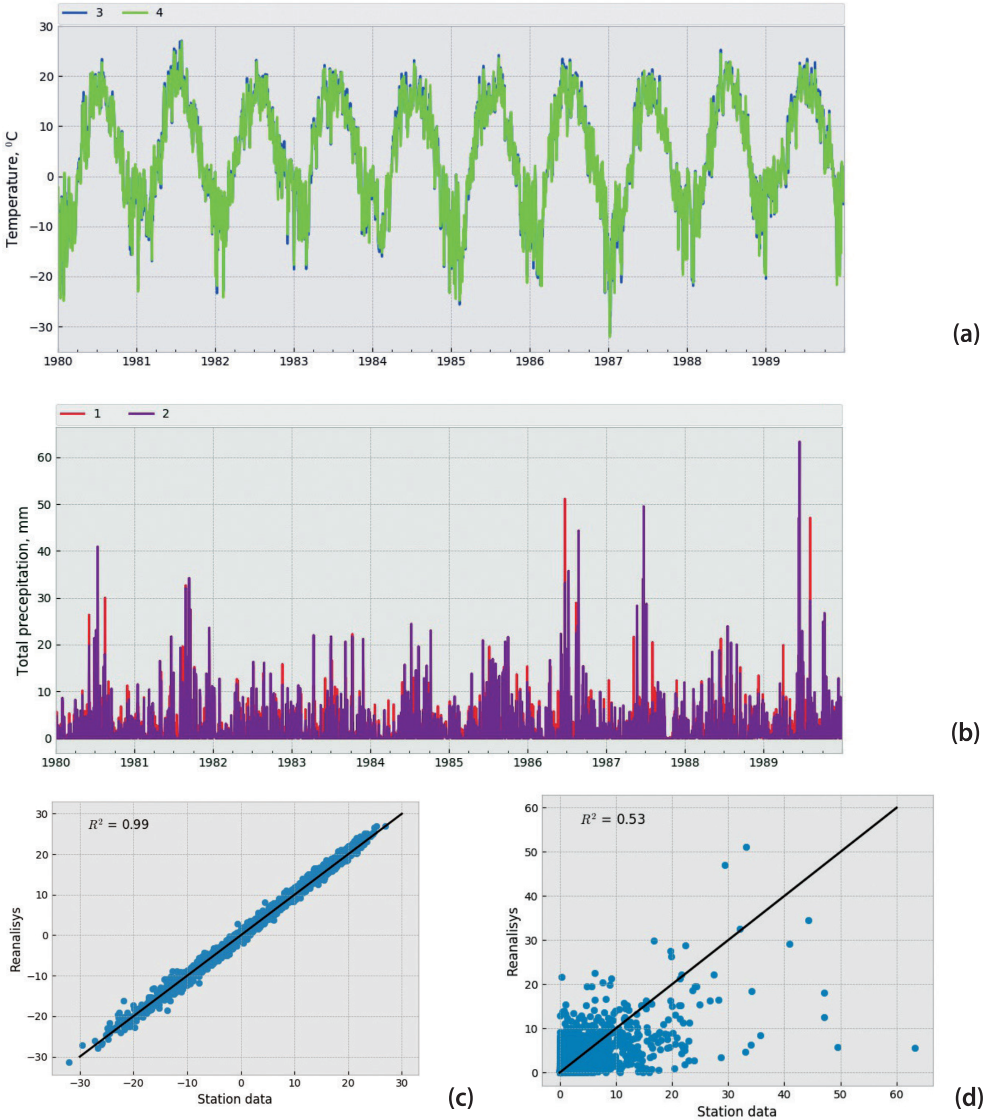

Fig. 1. Comparison between the observation data of temperature (A, C) and precipitation (B, D) at the Lipetsk meteorological station and the reanalysis data for the period from 1980 to 1990. Blue (3) and red (1) indicates data obtained from the weather stations; green (4) and violet (2) indicate reanalysis data

the weather station and the nearest grid point of the reanalysis grid and the uneven distribution of precipitation at small scales. When averaging over larger areas errors cancel each other. Thus, we consider the analyses of the tendencies in precipitation characteristics calculated from reanalyze data as a good approximation, as the data show shows the main pattern and differences between sub-regions clearly.

In this study, daily records of precipitation and air temperature were taken from the model, available in the NetCDF format from 1979 to 2016 (ERA-Interim 2005; ERA-40 2005). The coarse reanalysis data (0.75° x 0.75°) were interpolated to a 0.125″x 0.125″ grid (Official site CDO [online]), using the CDO (Climate Data Operators [online]) utility developed at the Max Planck Institute for Meteorology.

The data was then divided into two periods: 1979-2006 and 2007-2016. The former period is used as a reference period. The latter period was chosen, as it is representative of the extreme low-flow period in the Don basin. Based on the reanalysis data for the catchment area of the Don River and its tributaries the key meteorological indicators that are suspected to have affected the runoff formation in the catchment were chosen. Then the anomalies compared to the reference period, were calculated (Table 1).

The absolute changes of characteristics (ΔC_{abs}) were obtained by subtracting the long-term average of the reference period $\overline{P}_1$ (1979 – 2006) from the long term average value of the low-flow period $\overline{P}_2$ (2007 – 2016) (Eq. 1)

$$\Delta C_{abc} = \overline{P}_2 - \overline{P}_1 \qquad (1)$$

The relative changes of the characteristics (ΔC_{rel}) in percents (%) were calculated as the difference between the low-flow period ($\overline{P}_2$) and the reference period ($\overline{P}_1$), relative to the average value of the reference period ($\overline{P}_1$), multiplied by 100 (Eq. 2):

$$\Delta C_{rel} = \frac{\overline{P}_2 - \overline{P}_1}{\overline{P}_1} \qquad (2)$$

The statistical significance of the detected changes was assessed at the 95% confidence level using a Student's t-test.

Table 1. Meteorological indicators used in the analysis

Meteorological indicator	Reference period	Low-flow period
number of days with negative air temperature	1979 – 2006	2007 – 2016
total sum of negative air temperatures in 'degree' values	1979 – 2006	2007 – 2016
duration of the winter period* in days	1979 – 2006	2007 – 2016
average air temperature during the winter period*	1979 – 2006	2007 – 2016
number of thaw episodes during the winter period**	1979 – 2006	2007 – 2016
total solid precipitation for the winter period*	1979 – 2006	2007 – 2016
total liquid precipitation for the winter period*	1979 – 2006	2007 – 2016
total liquid precipitation for the summer period***	1979 – 2006	2007 – 2016

**winter period = the time interval from the moment of the first transition of air temperature through 0°C to the moment of the last transition of air temperature through 0°C*
*** number of thaw = the number of temperature transitions through 0°C*
****summer period = the time interval between two winter periods*

The hydrological characteristics in this study were estimated at 14 representative hydrological stations located at the main tributaries of the Don River (Fig. 2).

One of the most important characteristics of low-flow period is the water deficit. Usually it can be calculated as difference between mean value of the annual runoff volume (averaged for all years of low-flow period) and runoff of 50% occurrence (for the all period of observation). In this work we also decided to use normalized values of deficit to make them comparable with each other.

To analyze the spatio-temporal distribution of this deficit, equation (3) was used:

$$D_{lfp} = \frac{\overline{W}_{lfp} \cdot - W_{50\%}}{W_{50\%}} \quad (3)$$

where D_{lfp} is the runoff deficit for the low-flow period, $\overline{W}_{lfp}$. is the average annual runoff for the low-flow period and W50% is the runoff of 50% occurrence (for all the period of observation).

The anthropogenic influences can also contribute significantly to changes in river runoff. During extreme low-flow periods, an increasing water use can be

Fig. 2. Location of the hydrological stations selected for the analysis. Gauges with extra data include two watersheds, which used for analyzes of land cover transformation

observed, for example, in agriculture (Koronkevich 1990). This increases the water abstractions, which can further exacerbate the water supply deficit. In addition, the transformation of the catchment area surface can have an indirect impact on the formation of low-flow periods. One of the most popular methods for the catchment land cover estimation is processing remote sensing data of the Earth (Mouat and Lancaster 2008; Sheeja et al. 2011). In this study, the data on land cover transformation, water withdraw, and sewage were used from the past studies (Kireeva et al. 2017; State water kadastre 1990-2013) to analyze the direct anthropogenic impact, and the results of processing the composition of satellite images LANDSAT for the selected time periods of 1985, 1995, 2005 and 2015 were used to estimate the indirect anthropogenic impact.

RESULTS

The low-flow period of 2007-2016 is characterized by fewer days with negative air temperatures during the cold period, i.e. more days with positive air temperatures when compared to the reference period 1979-2006 (Fig. 3). The warmest winter in the region occurred in 2007 and 2013-2014. In the eastern and southern parts of the Don basin, there are ~10 to 15 days less compared to the reference period 1979-2006. The greatest changes are found in the western part of the basin, with 15 - 30 more days with positive air temperatures, which accounts to about 20 - 25% (Fig. 3 B). For the whole basin, except the south-east territory, the change is statistically significant.

Apart from the decrease in the number of days with negative temperatures described above, there was also a decrease in the total sum of negative temperatures compared with the reference period (not shown). In the western part of the basin, the relative decrease of this parameter accounts to 20-25%, while in the north-east part to 5-10%.

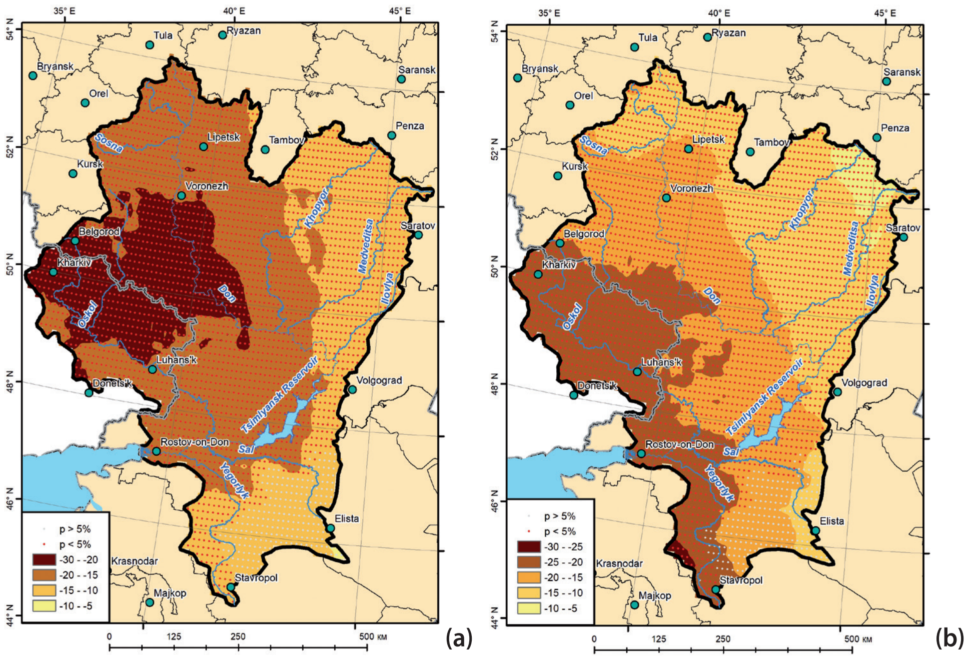

Fig. 3. Difference in the number of days with negative temperatures. Absolute difference (ΔC_{abs}) in days (A) and relative difference (ΔC_{rel}) in percent (B). Dots denote change above the 95% confidence level (t-test)

Fig. 4 shows the decrease in the duration of the winter period. In most parts of the basin, the absolute reduction ranged from 10 to 15 days, which accounts to an approximate 5-10% decrease relative to the reference period. The smallest changes of 0-5 days (up to 5%) are found in the northern and southern parts of the basin. The highest changes are located in the northwestern part of the basin in the vicinity of Lipetsk, Voronezh and Belgorod. In these regions, the duration of the winter period decreased between 15 to 20 days, i.e. about 10-15%. Most of the central part of the watershed shows statistical significant changes, while on the north and south-east part the changes between the periods are non-significant. The average air temperature for the winter period increased throughout the entire basin (not shown). The increase ranged between 0.25-1.5 °C over the entire period 2007-2016, with some extreme years (2011, 2014, 2015), in which the temperature anomalies reached up to 3-4 °C in winter.

The recorded warming during the winter period had also an impact on the amount of solid precipitation. In general, solid precipitation decreased throughout the basin over the years 2007-2016 (Fig. 5A). The smallest changes are found in the eastern and southern parts of the basin. The amount of solid precipitation decreased by 10-20% in these regions during the winter period. In the north-eastern part, the changes amount to 0-10%. The greatest changes are observed in the central and western parts, where the amount of solid precipitation decreased by (20-50 mm), which is about 20-35%. Simultaneously, the total amount of liquid precipitation also changed, for example, only 40-60 mm per year were recorded throughout the basin in 2014 and 2015 (not shown).

The decrease in the amount of solid precipitation was partially compensated by an increase in the amount of liquid precipitation (Fig. 5 B) in some regions during the winter period. Liquid precipitation increased by 10-40% (10-40 mm) in the northern part of the

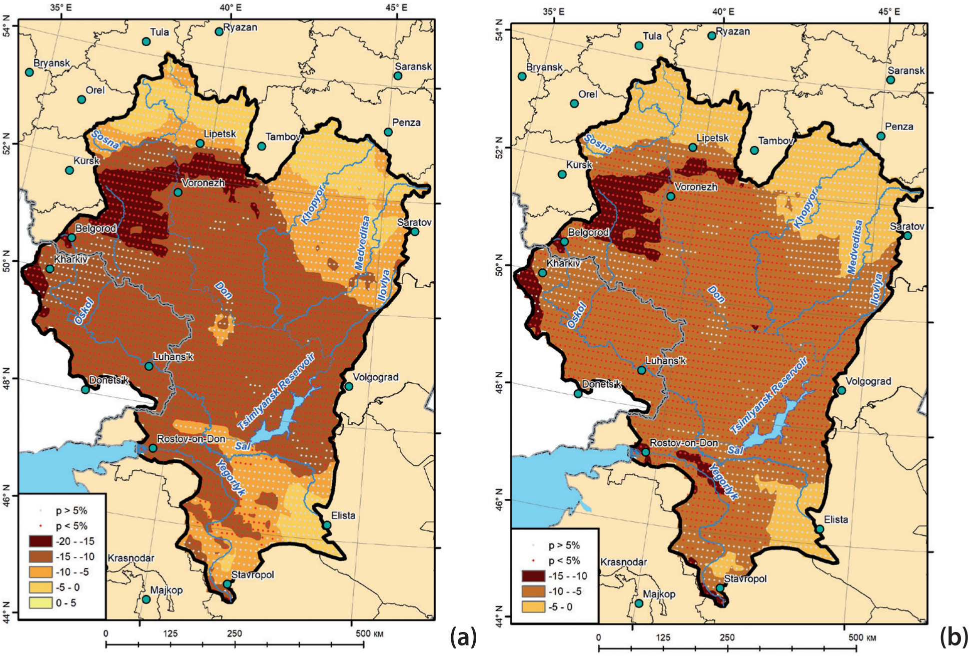

Fig. 4. Difference in the length of the winter period (see Table 1). Absolute difference (ΔC_{abs}) in days (A) and relative difference (ΔC_{rel}) in percent (B). Dots denote change above the 95% confidence level (t-test)

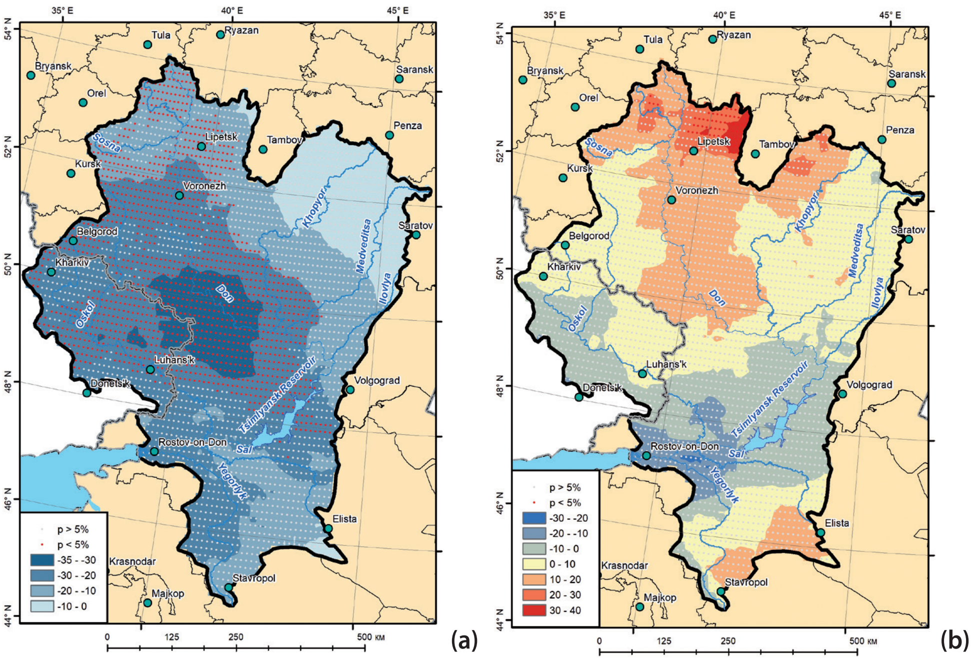

Fig. 5. Relative difference (ΔC_{rel}) in percent in the amount of solid (A) and liquid (B) precipitation for the winter period. Dots denote change above the 95% confidence level (t-test)

basin and 10-20% (10-20 mm) in the southern part. In the central part of the basin (near the Tsimlyansk Reservoir), the relative decrease of liquid precipitation ranges between 10 and 20% (up to 20 30 mm).

A change in the amount of liquid precipitation during the summer period was the most noticeable change over the past 10 years (Fig. 6). The largest changes can be found in the northern and in parts of the central region of the basin, where the precipitation amount has decreased by 20-25% (-80-120 mm). Here the changes are statistical significant. The northeastern region (Medveditsa river basin) exhibits similar changes. Here liquid precipitation for the summer period decreased by 80-100 mm, but the relative change amounts to more than 25 %. The smallest changes are found in the vicinity of the Tsimlyansk Reservoir and at the mouth of the Medveditsa River with a decrease of 20-60 mm (i.e. 5-10%).

In the previous sections the changes of the meteorological indicator were analysed to identify possible influences on the runoff formation in the catchment. However, transformations of the catchment surface area (e.g. land use changes) and the economic use of the water resources might have exacerbated the low-flow situation. Therefore, an analysis of economic activity in the "pilot" basins at the Khopyor River at the gauging section of Novokhopyorsk and the Don River at Liski was carried out.

In the Khopyor basin, an increase in forest cover from 10.0% to 16.8% and a slight increase in urban areas was observed between 1985 and 2015 (Fig. 7A). The increasing area of water bodies (including artificial reservoirs and rivers) in the 1980s and 1990s was followed by a decline in the early 2000s. From 2007 to 2014 the area decreased almost twice as much (from 0.90 to 0.49%). The direct water abstraction (equals water withdraw minus sewage) from the river system does not seem to play an important role in the formation of a wa-

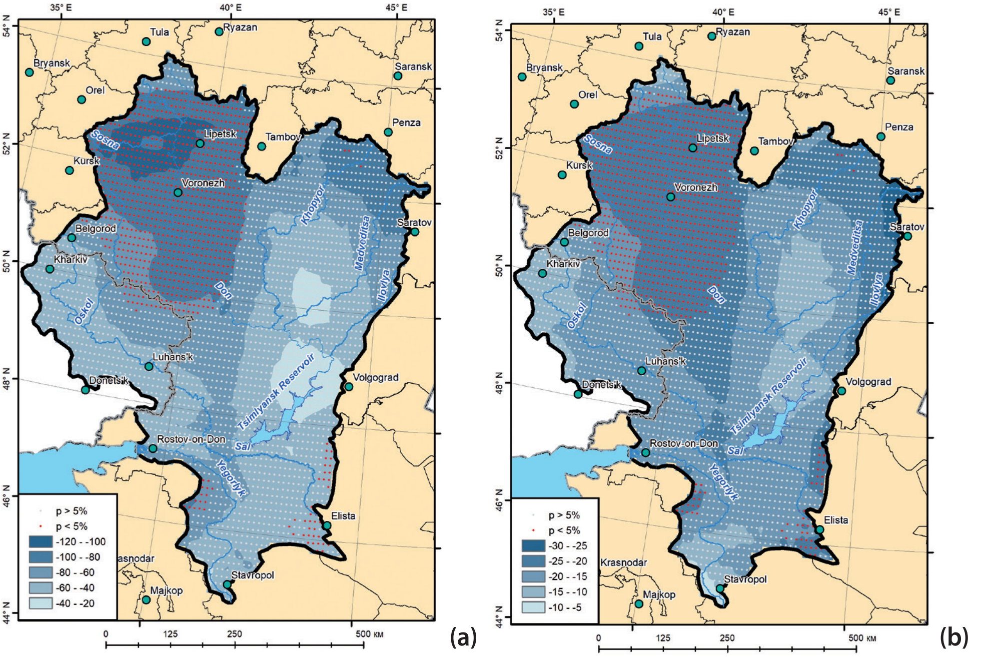

Fig. 6. Difference in liquid precipitation for the summer period (see Table 1). Absolute difference (ΔC_{abs}) in mm (A) and relative difference (ΔC_{rel}) in percent (B). Dots denote change above the 95% confidence level

ter deficit. Even in 1992, when runoff of 90% occurrence (less than 2 km^3) was observed, and the water abstraction volume was much higher than now, the water abstraction volume was just 6 % from total runoff (Fig. 7A). During last 20 years, the water abstractions fluctuate around 0.6-0.8% of total runoff (Fig. 7A).

Even for the shorter analyzing intervals (for the satellite images) of the Liski station (1998 to 2014), an increase in the forest cover is evident from 1.2 to 5.2% of the total catchment area (i.e. 870 km^2 to 3580 km^2), which accounts to a 4-fold increase (Fig. 7B). This increase is due to a reduction in cultivated agricultural land and, as a consequence, overgrowing of fields and natural reforestation. In addition to forest cover, the area of urban land also increased (from 5.3% to 7.8%). This is caused by the expansion of the private sector and the growth of industry since the mid-1990s. The direct water abstraction (equals water withdraw minus sewage) from the runoff at the Liski gauging section, ranges from -5 to +3.5%. An interesting detail is that at the Liski gauging station, the observed runoff is above the naturalised runoff (calculated natural runoff, without any anthropogenic influence, derived through regression analysis by the State Water Cadastre (1990-2016 yy.). This higher observed flow is due to the additional discharges from sewage withdrawn from wastewater plants, including that from the underground sources, into the river system.

During the historical period of observations (1930-2015), from 3 to 5 prolonged low-flow periods were reported in different parts of the Don basin (Fig. 8). The most extreme low water levels on the Don river at Razdorskaya were observed in the early 1950s, mid-1970s and mid-2000s (Table 2).

The low-flow period of 2007-2016 has the longest duration. Due to the extended period, the runoff deficit volume for the entire low-flow period totals to 55.0 km^3, which is approximately twice the annual volume of the river runoff of the Don River at the Razdorskaya

Fig. 7. Percent of catchment area covered by water bodies (1), urban area (2) and forest (3). Percent of water abstractions from the total runoff (4) and the annual volume of runoff (W, km³) (5) for the catchment area of the Khopyor River - Novokhopyorsk (A) and the Don River - Liski (B)

gauging station (at the river mouth). The low-flow period in the early 1970s is characterized by slightly lower deficit volumes - 42.0 km³. However, the deviation of runoff from the average annual value during the low-flow period of 2007-2016 is only 6.1 km³, which is 1.5 times less than the similar indicator for the low water levels of the 1950s and 1970s. Thus, in terms of the average annual volume and annual deficit these two periods are harsher.

Table 2. Characteristics of the 4 most extreme low-water periods for the gauging station Razdorskaya (at the mouth of the Don River)

Low water period	Duration, years	Average annual volume of runoff for the low water period, km³	Deviation from the average runoff, km³	Runoff deficit for the low water period, km³
1938-1940	2	16.0	4.9	9.8
1949-1951	2	12.7	8.2	16.4
1972-1977	5	12.5	8.4	42.0
2007-2016	9	14.8	6.1	55.0

The occurrence and severity of low-flow periods in the Don Basin are highly spatial heterogenic. The spatio-temporal distribution of the runoff deficit is shown in Fig. 8. Note that some stations in Fig. 8 have an incomplete record. For rivers like the Khopyor and Medvyeditsa River which flow in the eastern part of the Don basin (i.e. left tributaries in flow direction), the most important low-flow period with duration of 5-6 years, occurred in the 1930s. During this period, the runoff deficit on the Medvyeditsa River was higher than that on the Hopyor River (48% and 40% respectively). During the same period, there was a high water deficit on the Chir River (42%) as well.

The low-flow periods in 1938 (according to Fig. 8 for some rivers 1935) - 1940 and 1949-1951 was short at Razdorskaya station (only 2 years), but nevertheless very important in terms of the annual runoff volume accounts 16.0 and 12.7 km^3. The low-flow period from 1972 to 1977 have the same to 1949-1951 averaged annual runoff value (12.5 km^3), but the doubled duration (5 years). Extreme low water levels were observed at all the stations (Fig. 8).

The most extreme and wide-spread low-flow period in the Don basin occurred between 1972 to 1977 with all stations experiencing, to some extent, low runoff values. The most pronounced low-flow period in terms of duration and total deficit was observed on the Krasivaya Mecha River, at the gauging station Don-Kazanskaya and also on the Severskiy Donets River (both right side tributaries). The low-flow situation was slightly better on the left side tributaries of the Don River; namely at the Khoper, Medvyeditsa and Ilovlya. On these rivers, the years experiencing low-flow alternated with years of a medium and high annual runoff. At the same time, the occurrences of the runoff (for all the period of observation) for the extreme low-flow years (1972, 1975, 1976) were much higher (more than 95 %) compared with the others (50 – 80

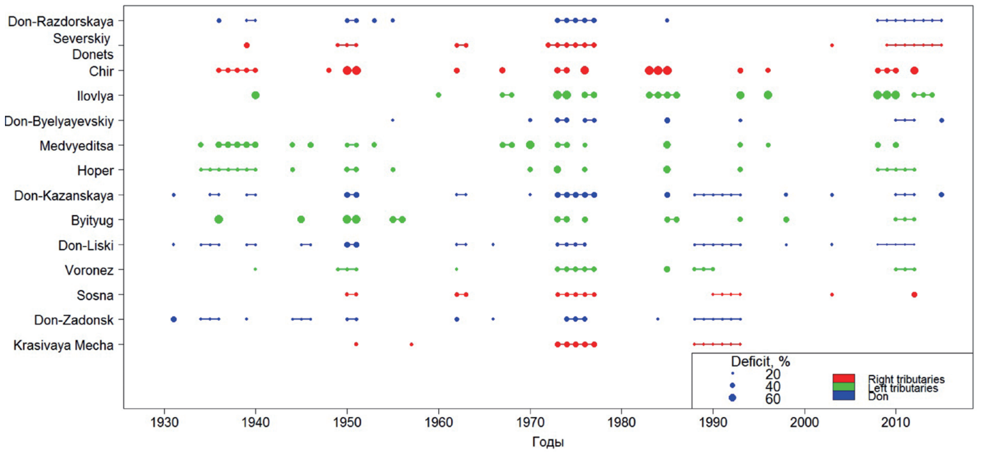

Fig. 8. Volume deficits in the Don basin for the period 1930-2015. Hydrological stations placed at regular intervals on the ordinate in the order from the source (1 – Krasivaya Mecha at Efremov; 2 – Don at Zadonsk; 3 – Sosna at Elets; 4 – Voronezh – at Lipetsk; 5 – Don at Liski; 6 – Bitug at Bobrov; 7 – Don at Kazanskaya; 8 – Khoper at Besplemyanovskiy; 9 – Medvyeditsa at Archedinskaya; 10 – Don at Belyaevskiy; 11 – Ilovlya at Aleksandrovka; 12 – Chir at Oblivskaya; 13 – Seveskiy Donets at Belaya Kalitva; 14 – Don at Razdorskaya) to the mouth , years are on the abscissa, the point size shows the magnitude of the runoff deficit, averaged over each period (the points associated with one period are connected with the line): the larger an icon, the greater was the deficit averaged over that period. Colours indicated the spatial location of the gauging station (Updated from [9])

%). The same alteration was noted for Chir River, one of the largest tributaries to the Tsimlyansk Reservoir. The runoff in 1976 was 67% less than average annual runoff on this river. In general, the runoff of Chir is characterized by high deficit volumes, during low-flow years, with 9 out of 22 low-flow years having less than 50% of the average runoff (occurrences from 80 to 95 %).

In the upper reaches of the Don basin, the period of 1988-1993 was the longest low-flow period observed so far. This low-flow period was especially pronounced on the Krasivaya Mecha River and on the Don River above the station of Khutor Belyaevsky (the gauging stations of Zadonsk, Liski and the Kazanskaya station). There is no long-term low-flow period below the above-mentioned stations during 1988-1993, although the annual runoff in 1993 had very high occurrence (more than 80%) on the rivers Khopyor, Medvyeditsa, Ilovlya and Chir.

The situation in the basin during the most recent low-flow period, is the spatial reverse of the period 1988-1993. In the lower reaches, 2007 can be defined as the beginning of a low-flow period. At the same year, in the upper reaches, a phase of a higher annual flow (with low runoff occurrence 5-10%) is apparent. However, along the Don River, starting from the Liski gauging station and below, there is a continuous water deficit for more than 8 years. At the same time during the whole period 2007-2016, the annual (averaged within low-flow period) deficit is not so high in comparison to the period 1950-1951 and 1972-1977 for the same river (Medvyeditsa, Bityug). The years with low annual flow alternate with years of high annual flow, due to that total deficit of the period is not so high. However, in the lower reaches of the basin, on the Seversky Donets River and the Don River at the gauging station of Razdorskaya, the period 2007-2016 is only characterized by high (more than 90%) annual runoff occurrence values. In some years (2007, 2009), extreme low-flow values observed just for the eastern rivers (i.e. left tributaries), and there is a phase of an increased water content on the western rivers (i.e. right tributaries), which compensates the water deficit in the main river Don.

DISCUSSION

Based on the results obtained in this study, we conclude that the main reason of the extreme low-flow period 2007-2016 in the Don River basin was the combination of several, meteorological conditions. The higher than usual air temperatures that were observed during winter period (plus ~2-4°C) favoured increasing runoff losses in the winter and the pre-spring period from 2007 to 2016. The higher air temperature during winter and the shorter duration of winter had also direct influence on the depth of soil freeze. These three parameters are widely use in forecasting schemes of seasonal and occasional flood wave as well as in modelling (Koren 1988). Warmer conditions in winter lead to shallower frozen soil layer, and additionally, smaller precipitation amounts during fall result in low soil humidity and empty pore space in the soil (Barabanov et al. 2018). Finally, the humidity of soil is small, pore space is filed by the air, and the water inside the soil isn't frozen. In this case the watershed during spring works as a "sponge" and cut significant part of melt water to the infiltration. The same effects widely discussed by Barabanov et al. (2018) for different geographical zones. Small amounts of solid precipitation in winter resulted in thin snow pack and additionally, several transitions through zero °C- dropped the snow thickness to very low values. This mechanism results in increased infiltration and higher groundwater levels (Dzhamalov et al. 2013; Barabanov et al. 2018). This causes the winter discharge in the rivers to increase (Dzhamalov 2013) and the main phase of hydrological year (flood wave by snow melt) to disappear. This lead to infiltration dominating the other runoff processes. Another, untypical for this natural conditions, process of runoff formation starts to realize (Koren 1988). Small amounts of precipitation during summer and earlier start of the dry season (Dmitreva 2014) resulted in a longer duration and a higher volume of the water deficit.

According to Kireeva (2017), in the Don basin, the evaporative losses from the surface of ponds and reservoirs at the time of the low-flow period in 2007-2016 were about 4-5% of the annual runoff, whereas they reached 13% in the early 1990s. In addition, an increase in the forest cover leads to an increase in water losses through evapotranspiration. Therefore, we can conclude that the input component of the water balance equation is the main reason for the low-flow period.

The low flow periods in the Don basin have several important implications. First, the period 2007-2016 was considered a critical situation and was widely discussed in mass media. The topic was of importance, because the proportion of cultivated agricultural land in the southern part of the catchment is higher than in the north part of the Don basin (Kireeva 2017) and the amount of precipitation is lower during summer as well as snow during winter, which consequently increases the demand for water. The second important factor is the role of the lower reach of the Don River for providing various branches of the water sector: shipping, recreation and industry. Lack of water and falling water levels can cause significant problems for water transport, impede navigation or lead to under load of ships. The third reason for the fact that the long-term low-flow period 2007-2016 in the Don mouth can bring more problems to the population than the same in 1972-1977 in the upper reaches is the largest city (Rostov-on-Don) with one million of inhabitants located in the lower part of the Don basin. The Don river is the main water source for the city and low water levels can lead to interruptions in the water.

SUMMARY AND CONCLUSION

The results of this study show that the low-flow period of 2007-2016 was the highest on record in terms of the duration and the water deficit volume in the Lower Don. Generally, the formation of distinct periods of extreme low-flow is not unusual and can be considered a common feature of the rivers of the Don basin located in the arid climate zone in the southern part of the European Russia. Depending on the part of the basion, four to five long-term low-flow periods were revealed during the period of hydrometric observations (1899-2016).

The most severe periods occurred in the early 1950s and mid-1970s in terms of deviation of the annual runoff volume, during which, the deviation reached 8 km^3, which is equal one third of the total annual runoff. However, the low-flow period of 2007-2016 had the highest water deficit volume. At the gauging section Razdorskaya, the total deficit for the 8-year period was 44.3 km^3, which is equivalent to twice the annual runoff volume of the entire basin. The analysis shows that the tributaries that make the main contribution to the runoff deficit measured at the gauging section Razdorskaya, are varying from year to year. Sometimes the water deficit is more pronounced in the upper reaches, and sometimes in the lower reaches. The long duration of the 2007-2016 low-flow period is the consequence of the combination and superposition of several low-flow periods in different parts of the basin.

According to the analysis performed in this study, the main contribution to low-flow formation was made by unfavourable hydroclimatic conditions due to a combination of several factors during the period 2007-2016. On one hand, at the beginning of the low-flow period, anomalously warm winters were recorded for the region. This contributed to increasing losses of spring runoff due to low soil freezing and higher infiltration of the melt water, finally, leading to the formation of extremely low spring floods. An increase of days with "thawing conditions" of more than one week lead to a decrease in the amount of solid precipitation, due to spells with positive air temperatures during winter. Solid precipitation decreased by 10-35% throughout the entire basin compared to the reference period (1979-2006). The decrease in the amount of solid precipitation during winter was partially compensated by a higher amount of liquid precipitation during the winter period by 10-30%. The great change for the past 10 years was detected in the amount of liquid precipitation in summer, which decreased by 20-25% (60-120 mm) compared to the reference period. At the same time, the total annual amount of precipitation changed: for example, the precipitation recorded throughout the basin was only 40-60 mm during 2014-2015.

The estimates of the contribution of the transformation of the catchment surface area that were performed for the "pilot" basins of the Khopyor River at Novokhopyorsk and the Don River at Liski showed that the anthropogenic changes in runoff, both the direct (water withdrawal) and the indirect ones (urban growth, reforestation, decrease in field's area) related to the redistribution of land categories, ploughing and reforestation, made a minor contribution to the formation of the low-flow period.

The research presented in this paper gives and overview over the spatial and temporal characteristics of the low-flow periods in the Don Basin over the available record length. The detailed assessment of the 2007-2016 period allowed investigating the meteorological factors contributing to the most recent low situation together with some preliminary assessment of possible human contributions. The results obtained here already provide some important insights in the low-flow characteristics of the region and can aid to inform water management and the development of a low-flow forecasting system. Future studies will perform research beyond these pilot regions, to obtain additional results and test further hypotheses with additional data to gain further insights.

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