Spatial and temporal correlation between severe droughts and extreme low flow on rivers in the Russian Plain

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Abstract. Extreme low flow on rivers (when water flow was less than or equal to the value of 75 and 90\% exceedance probability), observed in years with severe meteorological and agricultural droughts in the Russian Plain (1972, 1975, 1981, 1995, 1998, 1999, and 2010) were studied. In 1972 and 1975, the exceptional low flow was recorded in the largest area, including the basins of the largest rivers (the Volga, Don, and Dnieper) and even the outlet, as well as in their tributaries. One of the heaviest droughts (2010) accompanied the abnormally low flow only in the Lower Volga and its tributaries in the eastern part of its basin. In other years with severe meteorological and agricultural droughts, their occurrence areas in the Russian Plain were much less. In 1975, extreme low flow was recorded in the rivers of the Volga, Don, and Dnieper basins in the main hydrological seasons (during summer–autumn low-water season and snow-melt flood), as well as all the year round, including their outlet (in their lower reaches in the general case and in the middle reaches in the case of the Dnieper). However, in these seasons in 1972, extreme low flow was recorded in rivers in the basins of the Don and Dnieper (while in the Volga, it took place only during summer–autumn low-water season), and in 2010, it formed only in the Volga basin. Abnormally low flow in years with severe droughts were recorded mostly in rivers of the forest–steppe and steppe zones, as well as the southern part of the forest zone.

1. Introduction

The present-day global warming, which began in the 1970s–1980s, has been accompanied by higher air temperature and, to a lesser extent, atmospheric precipitation higher than that in the previous colder period; this resulted in long-term changes in different components of the water cycle, in particular, river flow. In the majority of rivers in the steppe, forest-steppe zones and the southern and western parts of the forest zones of the Russian Plain within the basins of the Volga, Don, and Dnieper, a long phase of decreased snow-melt flood runoff and increased runoff of summer–autumn and winter low-water seasons was observed in this epoch [1-3]. The character of changes in the annual runoff was more complicated. Note that in many rivers of this region, a passage to the opposite long phase seemed to begin in the mid-2000s. A long phase of higher soil moisture content was also observed in this region in this period [4]. Note that long-term changes in the runoff coincided in time with an appreciable decrease in the volumes of water withdrawal and wastewater discharge [5].

Low flow on rivers of different intensity formed in rivers against the background of long-term changes in the hydrometeorological characteristics. They often manifested themselves in considerable...
areas, especially, in years with severe meteorological and agricultural droughts [6, 7], mostly in the steppe, forest-steppe, and the southern part of the forest zone. The most severe among them (the strong and vast droughts according to [6]) were observed in the Russian Plain in 1972, 1975, 1981, 1995, 1998, 1999, and 2010. Overall, the geographic position of the occurrence areas of severe droughts is relatively stable and associated with the basins of the Volga, Don, Dnieper, and Ural, see figure 1.

| 1972 | 1981 |
|------|------|
| ![Map 1972](image1) | ![Map 1981](image2) |

| 1998 | 2010 |
|------|------|
| ![Map 1998](image3) | ![Map 2010](image4) |

**Figure 1.** Anomalies of spring wheat yield decrease during extreme droughts in 1972, 1981, 1998, and 2010 in modular coefficients relative to "normal" conditions.

Exceptional low river flows receive lesser attention in the studies than severe droughts and their spatial and temporal correlation/conjugation [8-10]. The article gives the analysis of the characteristics of extreme low flow on rivers of the region in years with severe droughts in the period of current global warming.

2. **Materials and Methods**

Unlike the severest droughts, which commonly took place in summer, extreme low water flow on rivers in these years occurred in different hydrological seasons or in a year as a whole. The criteria for the extremeness of the low water flow on rivers were the areas affected and whether the seasons or the year as a whole were involved; another criterion was the degree of water flow abnormality. The extreme low water flow years were assumed to be those in which the mean monthly, mean seasonal (for summer–autumn low-water season and the snow-melt flood), and the mean annual flow was less than or equal to the streamflow corresponding to 75% and 90% probability of exceeding. The boundaries of the seasons were determined using long-term data on the mean monthly water discharges and were assumed constant for the entire observation period.
The analysis of low flow in the main hydrological seasons and the year as a whole for the Volga at Volgograd and the Don at Razdorskaya was based on long-term series of their naturalized seasonal and annual flow. This was made with the use of the method of rivers–indicators to the climate conditions (tributaries and the upper reaches of the main river), which are known to feature relatively low anthropogenic disturbances of their water regime [1, 11].

The exceedance probability of the flow was evaluated using empirical curves of exceedance probability constructed based on long-term series of monthly, mean seasonal, and mean annual river water discharges in the basins of the Volga (10 rivers, including the Volga at the Volgograd), the Don (11 rivers, including the Don at Razdorskaya), the Dnieper (6 rivers, including the Dnieper at Rechitsa gage), and the Ural at Kizil’skoe. Low flow in the downstream gages of the Dnieper and Ural were not considered because the flow at them was considerable changed by anthropogenic impact (table 1). The rivers under consideration in the large river basins are uniformly distributed over their territories, and their area varies from 3.47 to 121 thou. km². Their major portion (table 1) lies in the steppe and forest-steppe zones.

Table 1. Characteristics of river basins.

| № | River-gage | Basin area, thou. km² | Natural zone | № | River-gage | Basin area, thou. km² | Natural zone |
|---|------------|----------------------|--------------|---|------------|----------------------|--------------|
| 1 | Unzha-Makar’ev | 18.5 | Taiga | 14 | Seim-Ryl’sk | 18.1 | FS, MBF |
| 2 | Vyatka-Kirov | 48.3 | Taiga | 15 | Desna-Bryansk | 12.4 | FS |
| 3 | Volga-Staritsa | 21.1 | MBFa | 16 | Don-Liski | 69.1 | FS |
| 4 | Oka-Kaluga | 54.9 | MBF | 17 | Sosna-Elets | 16.3 | FS, MBF |
| 5 | Belaya-Birsk | 121 | FSb | 18 | Voronezh-Lipetsk | 15.3 | FS |
| 6 | Samara-Elshanka | 22.8 | MBF | 19 | Vorona-Borisoglebsk | 13.2 | FS |
| 7 | Dema-Bochkareva | 12.5 | FS | 20 | Bityug-Bobrov | 7.65 | FS |
| 8 | Sok-Surgut | 4.73 | FS | 21 | Khoper-Besplemyanovski | 44.9 | FS |
| 9 | Bol’shói Karaman-Sovetskoe | 3.47 | steppe | 22 | Kalitva-Pogorelov | 10.5 | Steppe |
| 10 | Dnieper-Rechitsa | 58.2 | MBF | 23 | Medveditsa-Archedinskaya | 33.7 | Steppe |
| 11 | Pripyat-Mozyr’ | 97.2 | MBF | 24 | Ilovlya-Aleksandrovka | 6.52 | Steppe |
| 12 | Sozh-Gomel’ | 38.9 | MBF | 25 | Chir-Oblivskaya | 8.54 | Steppe |
| 13 | Berezina-Bobruisk | 20.2 | MBF | 26 | Ural-Kizil’skoe | 17.2 | FS |

aMBF-mixed and broad-leaved forest
bFS-forest-steppe

3. Results and Discussion

The largest area with exceptional low flow was recorded in 1975, when it contained the basins of largest rivers (Volga, Don, and Dnieper), including even their outlet sections, see figure 2. Dnieper water flow was analyzed at Rechitsa gage (middle reaches of the river), because as mentioned above there were no data on the water regime in its lower reaches not disturbed by anthropogenic impact.
However, the conclusions derived for this gage seemed to be applicable to the downstream section of the river as well. This can be seen from the analysis of the flow of tributaries of the Dnieper at its gages located downstream (given below). In the lower reaches of the rivers mentioned above, the abnormal low flow in 1975 can be seen not only in the summer–autumn low-water season (the period when the severest droughts were observed), but it can also be seen during snow-melt flood and the year as a whole. In the Volga at Volgograd and the Don at Razdorskaya, the flow in these periods was extremely low, corresponding to 93–99% exceedance probability, while the flow in the Dnieper at Rechitsa was higher (75–80% exceedance probability). In the Ural at Kizil’skoe, the runoff exceedance probability was 83–87%.

![Figure 2](image_url)

**Figure 2.** Low flow at the downstream gages of the Volga (a), Don (b), and Dnieper at Rechitsa (c). P, % - exceedance probability. The horizontal blue lines show low flow at 75% and 90% exceedance probability.

In 1972, extreme low flow during periods of snow-melt flood, summer–autumn low-water season, and the year as a whole were observed in the outlet sections of the Don (the runoff at which
corresponded to 99% exceedance probability), the Dnieper (the runoff with the exceedance probability of 86–97%), and the Ural at Kizil’skoe gage (the runoff with 89–97% exceedance probability).

One of the most severe droughts of 2010 correlated with the abnormal low flow in the lower reaches of the single river - the Volga. It was observed in all considered periods of the annual cycle and also was extremely low (corresponding to 85–91% exceedance probability).

In other years with the severest droughts, extreme low flow were observed in some seasons in the Lower Don (during summer–autumn low-water season in 1981 and during snow-melt flood in 1999) and, probably, in the Dnieper (in 1991 during snow-melt flood).

The abnormally low flow during summer–autumn low-water season of 1975 and the year as a whole was recorded in all examined rivers in the Volga basin (except for the snow-melt flood in the Volga at Staritsa), the Don, and the Dnieper (except for the Berezina). The mean flow in these periods in rivers in these large basins commonly varied from 80 to 99% exceedance probability. In 1972, extreme low flow were recorded in all rivers in the Don basin in all periods mentioned above, and their mean flow in most cases was below the flow of 90% exceedance probability. On the other hand, extreme low flow in the Volga basin were observed mostly in summer and autumn. It is only in the Volga at Staritsa that it took place also during snow-melt flood and in the year as a whole, while it was completely absent in the Sok river. In the Dnieper basin, the rivers in this year showed extreme low flow mostly during snow-melt flood and the year as a whole (the exceedance probability of flow in these periods was mostly above 85%). It is only in the Desna at Bryansk that low flow was also observed during summer–autumn low-water season and its mean flow had 75% exceedance probability. In the Ural at Kizil’skaya in 1972 and 1975, the extreme low flow covered all seasons under consideration and their flow exceedance probability reached 83–97%.

In 2010, exceptional low flow extended over all periods under consideration only in the rivers in the northeastern and eastern Volga basin (the rivers of the Vyatka and Belaya). The exceedance probability of their flow varied within 81–93%. In the Don basin, it formed in its tributaries and in its middle reaches (the Voronezh and Vorona) during spring flood and the year as a whole, while in the Khoper, it was observed only during snow-melt flood. The exceedance probability of the flow in these periods was 76–85%.

In other years with the severest meteorological and agricultural droughts, abnormally low flow were observed in much lesser areas. Thus, in the period of drought of 1981 in the Volga basin, extreme low flow was observed only in summer and autumn in taiga (the Unzha and the Vyatka) and steppe (the Samara and the Bol’shoy Karaman) rivers, and the exceedance probability of their mean flow was 75–79%. In 1991, extreme low flow was recorded only in the Unzha (during summer–autumn low-water season), and in 1995, only in the Volga at Staritsa in the same season. In 1999, it was observed in the Volga at Staritsa (during summer–autumn season) and in the Bol’shoy Karaman (during spring flood and in the year as a whole). The exceedance probability of flow in these periods was about 75%, and it is only in 1999 in the Bol’shoy Karaman that it reached 90%. In rivers in the Don basin, extreme low flow in years with severe droughts were regularly observed (in 1991, 1995, 1998, and 1999) only on the Don at Liski and only during snow-melt flood. The exceedance probability of low flow during snow-melt flood in these years was about 75%. Extreme low flow formed also in the period of snow-melt flood and in a year as a whole in the Sosna in 1991 and 1995, in the Medveditsa in 1995, and in the Ilovlya in 1995 and 1998. In the Ilovlya, the exceedance probability of flow in these periods was about 90%, while in other cases, it was about 75%. Abnormally low flow in summer and autumn were observed only in two rivers – in the Chir in 1995 (with flow exceedance probability of 75%) and in the Ilovlya in 1998 (the exceedance probability of the flow was more than 98%). In the Dnieper basin in 1980–1990s years with severe droughts, abnormally low flow were observed only once (in 1991) and in the only one river (the Desna at Bryansk) during snow-melt flood.

In the summer (in the period when the severest droughts are most frequent) of 1975, extreme low flow was observed in all months in nearly all rivers considered in the Volga basin, a half of rivers in the Don basin, and in two rivers in Dnieper basin (the Pripyat and Desna), and in the Ural. The flow
was very low in these months (its exceedance probability varied from 90 to 99%). In some rivers in the Don basin, extreme low flow was observed in June and July (the Bityug and the Ilovlya) or only in June (the Voronezh), and it also showed very low flow with the exceedance probability of more than 90%. A similar picture was observed in some rivers in the Dnieper basin. The extreme low flow period here shifted to July–August (the Sozh and Seim) and in August (the Dnieper at Rechitsa and the Berezina). The exceedance probability of the mean monthly flow in forest rivers was much less (about 75%) than in forest–steppe rivers (the Seim), where it approaches 90%.

In 1972, extreme low flow periods in all summer months were observed in practically all rivers in the Don basin, as well as in the Samara in the Volga basin. As well as the low flow in 1975, this one affected mostly forest-steppe and steppe rivers. In other rivers of this basin, the low flow lasted for two months (except for the Vyatka, where only one low flow month took place, and the Sok River, where no low-water periods were recorded in this year). The occurrence probability of flow in low-water months varied widely (75–90%). In the Dnieper basin, low flow was observed during one or two summer months (except for the Berezina, where there were no extreme low flow), the exceedance probability in which varied from 75% (the Sozh, forest zone) to 95% (the Desna, forest steppe). In the Ural, low flow was observed in July and August at an exceedance probability of 78–90%.

A extreme low flow summer period ranking third in terms of the affected territory was observed in 2010. However, unlike such periods in 1975 and 1972, this one was recorded only in four forest-steppe and steppe rivers, two of which (Belaya and Dema) belonged to the Volga basin and the basins of the Dnieper and the Don, each containing one such river (the Seim and the Medveditsa, respectively). It was observed for two months in the Vyatka (the Volga basin), the Khoper (the Don basin), and the Desna (the Dnieper basin). One low flow month was recorded in the Don at Liski and the Voronezh (the Don basin), the Sok river (the Volga basin), and in the Ural river.

In other years with the severest droughts, extreme low flow in summer involved much lesser territory, embraced individual parts of the considered large river basins, and lasted mostly for one summer month (in 1981, in the Unzha, the Vyatka, the Sosna, the Voronezh, and the Ilovlya; in 1991, in the Belaya; in 1995, in the Berezina; and in 1999, in the Vyatka) and rarely for two months (in 1981, in the Samara; in 1991, in the Kalitva and the Medveditsa; and in 1995, in the Chir) or three months (in 1991, in the Unzha, and in 1995 and 1998, in the Ilovlya). The flow in these extreme low flow months varied widely and had 75–95% exceedance probability. In this case, low flow summer months were observed mostly in steppe and forest-steppe rivers.

4. Conclusions

Abnormally low flow in the rivers of the steppe, forest-steppe, and the southern and western parts of forest zones are closely correlated with the most severe meteorological and agricultural droughts in the Russian Plain in the 1970s–2000s in the period of global warming.

The extreme low flow involved the largest territory during the severest droughts of 1975, 1972, and 2010. In 1975, the zone of low flow included the basins of largest rivers (the Volga, the Don, the Dnieper, and the Ural), and it manifested itself even in their outlet sections. In 1972, exceptional low flow was observed in the outlet section of the Don, Dnieper, and Ural, while in 2010, it was observed only in the Lower Volga. In this case, in 1975, 1972, and 2010, in the outlet sections of these rivers, it was observed not only in the summer–autumn low-water season (a period when the severest droughts occur), but also in the period of snow-melt flood and in the year as a whole. The flow in this period of the annual cycle was very low and its exceedance probability commonly varied from 80 to 99%.

Extreme low flow of 1975 during the summer–autumn low-water season, the snow-melt flood, and the year as a whole were recorded in almost all rivers considered in the basins of the Volga, Don, and Dnieper. Whereas, in 1972, only in the Don basin, low flow was observed in all rivers in all seasons of the year, while in 2010, it extended over all considered periods only in the rivers of the northeastern and eastern parts of the Volga basin. In this case, the exceedance probability of the seasonal and annual flow was 75–97%.
In 1975 extreme low flow was observed throughout the summer in almost all rivers considered in the Volga basin, a half of rivers in the Don basin, in two rivers in the Dnieper basin, and in the Ural, while in 1972, it was observed throughout the summer in nearly all rivers of the Don basin only. In 2010, unlike the low flow of 1975 and 1972, it was recorded all over the three summer months only in four rivers of the region. The exceedance probability of the flow of extreme low flow months varied within wide limits (75–90%).

In other years with the severest droughts, extreme low flow was observed in much lesser areas, in individual periods, and, in summer, only in some months.

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