Regional characteristics of water use in conditions of water scarcity in steppe transboundary river basins (the Ural River basin as a case study)

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Abstract. The regional features of water use within the steppe biome and in conditions of water scarcity is analysed. It has established a steady trend of increasing summer temperature extremes and identified a trend in the seasonal distribution of precipitation. Rivers of the Ural River basin are found to be characterized by a decline in the percentage of spring flood runoff and an increase in the percentage of low-water seasonal runoff. This transformation of intra-annual flow is even more significant for rivers with a regulated regime. The paper defines also regional specific features concerning the use of water resources in the Ural River basin. In the Russian regions, the main portion of water resources is spent on industrial and utilities needs, and the minimum portion spent on the needs of agriculture. Another specific is a high portion of recycled water in the Russian regions, which confirms the rather efficient use of water resources in various economy sectors. The structure of water consumption in Kazakhstan regions is characterized by predominance of water use for industrial and utilities needs and preservation of a significant portion of water for agricultural supply. The results obtained show that an ambiguous and poorly predicted situation with water resources emerges in the transboundary basin of the Ural River. In this context, the priority task is to ensure the cost-effective and environmentally safe use of water resources in regions of the studied basin.

1. Introduction

The guaranteed provision of water resources to the economy and the population is one of the most important sustainable development challenges facing individual regions and countries. Against the backdrop of changing climate, this problem is especially relevant for regions with insufficient and unstable moisture [1, 2, 3]. According to the report prepared by the Intergovernmental Group of Experts, climate warming is an indisputable fact and is most significantly observed over the past 30–40 years. The rate of warming within the Russian Federation is more than 0.45°C per 10 years and it varies across the country [4]. The observed long-term climate changes lead to an increase in the spatial and temporal variability of river runoff, which significantly reduces the reliability of forecasts. Therefore, problems of efficient use of water resources are most relevant for water deficient regions [5]. These include the transboundary basin of the Ural River with its significant portion of drainage area being located within the Southern Urals steppe and the Pre-Caspian area. Climatic conditions of the steppe biome define a significant spatial and temporal heterogeneity of river runoff in long-term and seasonal aspects.
2. Materials and methods
To identify regional patterns of climatic changes and their direction, the linear trend coefficient was calculated. Deviations of average annual air temperatures from the norm for 1961-1990 were also calculated. To study the dynamics of water availability, the Hydrothermal Coefficient of Selyaninov (HTC) was calculated and analysed. This coefficient is widely used in meteorological research and characterizes the ratio of precipitation for a period of at least a month (Σpr) to the sum of average daily temperatures over 10°C for the same period (ΣT) (HTC = Σpr/10ΣT) [6].

When characterizing the natural moisture content, an average long-term value (norm) of the annual atmospheric precipitation (Pavr) was calculated, subject to standard deviation (2σ) and number of years of observations. Accordingly, low-water precipitation years are those with precipitation of less than Pavr-2σ. Further, the range corresponding to low-water precipitation years was defined by the probability curve of annual precipitation anomalies.

Data on the use and protection of water resources in the regions of the Russian Federation and the Republic of Kazakhstan we accepted as the initial data for studying regional characteristics of water use [7, 8]. We made water resource assessments by comparing the volume of water resources: a) with the volume of water used (water use efficiency coefficient – Cused); b) with population size – potential water availability (thousand cubic meters per person); c) subject to actual water content conditions in a particular period – real water availability (thousand cubic meters per person), i.e. the ratio of average annual water resources for a three-year low-water period, irrevocable water consumption and population size [9]; d) with the area of the region – normalized natural water resource availability (thousand cubic meters/year per km²).

3. Results and discussion
The observed climatic transformation is accompanied by a change in the frequency of extreme weather and climate events. According to multi-model estimates, the annual temperature in the Ural River basin is expected to increase by 1.6°C by 2030 compared to the baseline period (1980-2000) [10].

The analysed statistical parameters of the July surface temperature extremes in Orenburg and Aktobe indicate the following. The general changes are generally the same and are characterized by a distinct trend of increasing temperature extremes, especially in the period 1991-2017. A steady increase in the average temperature in summer months is accompanied by an increase in the daily amplitude and the number of sunny days, which indirectly indicates predominance of the anticyclonic type of weather. The results obtained correspond to the current trends of increasing the number of days with abnormally high temperatures for most European Russia (with the exception of winter) [11]. In addition, there is a stable tendency to increase the intra-annual redistribution of precipitation in the Ural River basin. Similar transformations of the modern climate are observed in the European area of Russia.

Analysis of the distribution of annual precipitation anomalies in the Ural River basin over a 76-year period revealed a long 12-year low-water period subject to conditions of natural moisture, between 1948 and 1960. During this period, only a few individual years exceeded the long-term average. The extremity of this period is confirmed by probability curves of annual precipitation anomalies, and according to them, the anomalies of annual precipitation were in the range from 70 to 99% for half of the studied period. Similar groups of low-water years were identified in the Volga River basin [12]. Later on, since 1961, the tendency to group a significant number of years subject to conditions of natural moisture content has not been revealed – the alternation of short high-water and low-water periods prevails.

According to calculated HTC values, greater portion of the Ural River drainage area belongs to the ”very dry” area (table 1). HTC values naturally decline in the southern direction. Zilair weather station occupies an elevated position, which is why it is characterized by increased atmospheric humidity and, according to HTC description, corresponds to the ‘dry area’. Barrier functions of the Southern Urals Mountains against to prevailing western air mass transport contribute to a much more stable distribution of HTC values in a long-term series of observations.
The influence of climate on the state and formation of water resources has a zonal character and is related to the latitudinal-zonal and geomorphological heterogeneity of landscapes. Despite the latitudinal variations in precipitation and temperature, the climate conditions in the studied region (Urals region) are relatively stable according to the climatic parameters for the considered weather stations.

Assessment of the relationship strength between data series for the considered weather stations indicates that moisture conditions are characterized by common macro-regional weather and climate processes. Despite the latitudinal-zonal and geomorphological heterogeneity of landscapes in the Ural River basin, differences in the pair correlation coefficients do not exceed 0.11, and the values themselves vary between 0.58 and 0.69.

In a long-term period of time, individual hydrographic areas of the studied basin experience multidirectional trends. The most visible is a decrease in the values of HTC characteristic for the main collecting areas, primarily subject to changes in cyclonic activity. They include low mountains of the Southern Ural (Zilair weather station) and plains of the Southern Trans-Urals (Bredy). The identified decrease is due to both an increase in temperatures during the warm period and a decline in precipitation. The Pre-Urals region (Orenburg and Aktobe weather stations) is relatively stable according to the analysed climatic parameters, and a slight increase in the values of HTC is recorded only within the western periphery of the studied basin (Uralsk).

The influence of climate on the state and formation of water resources has a zonal character. The role of this factor increases from north to south and from west to east for European Russia, as natural moisture declines [7]. There was no doubt that characteristic spatial and temporal heterogeneity of climatic conditions in the steppe biome is the main reason for significant variability in distribution of water resources (table 2).

### Table 1. Main HTC statistics for 1936-2015.

| Weather station | Average value | Coefficient of variation | Linear trend value |
|-----------------|---------------|--------------------------|--------------------|
| Zilair          | 0.91          | 0.41                     | -0.158             |
| Bredy           | 0.67          | 0.44                     | -0.158             |
| Orenburg        | 0.55          | 0.45                     | -0.047             |
| Uralsk          | 0.49          | 0.44                     | 0.087              |
| Aktobe          | 0.43          | 0.47                     | 0.032              |

### Table 2. Surface runoff characteristics for rivers in the Ural River transboundary basin.

| River – cross-section | S, km² | W, km³ | Waterflow rate, m³/sec, endowment % | Cv |
|-----------------------|--------|--------|-----------------------------------|----|
| Ural – Orenburg       | 82.3   | 2.02   | 269.7 122.0 31.9 0.73             |
| Ural– Kushum          | 188.0  | 8.01   | 655.0 251.1 112.0 0.64             |
| Ilek– Vesely          | 17.2   | 0.07   | 46.0 17.2 5.1 0.77                |
| Or– Istemes           | 13.0   | 0.04   | 15.0 5.1 0.4 0.73                |

Analysis of long-term data identified phases of different water discharges for rivers of the studied basin. As established earlier [13], synchronous changes are predominant in river run-off. At the same time, a similar direction and significance of changes is evident for most watercourses, irrespective of the drainage area size and physical and geographical conditions of runoff formation. It was found that in some cases (for some rivers) time limits of cycles can be shifted relative to the prevailing ones by 2-3 years. In-phase character of long-term runoff fluctuations of the Ural, Sakmara, and Ilek rivers are illustrated by modular coefficients dynamics (figure 1). For instance, we recorded 5 low-water periods, different in duration and stability for a long series of observations (1927-2018). The longest period of low water discharges was observed in the period 1950-1977 (years with 75-90% of water availability prevailed), which was due not only to decreased natural moisture, but also to the significant volumes of water intake for various needs.
It should be noted that water discharges to steppe rivers (for annual and long-term periods) is largely determined by specifics of the runoff intra-annual distribution. One of the most important factors of river discharges is conditions and parameters of the river runoff during the period of active snowmelt and spring flood.

Rivers of the studied basin was found to be characterized by a decline in the portion of spring runoff and an increase in low-water period runoff [14]. This transformation of intra-annual runoff is even more significant for rivers with a regulated regime. For example, the spring flood portion of the Ilek River (Vesely settlement) declined from 77% (1950-1977) to 56% (modern period), and the portion of summer-autumn runoff increased from 12 to 24%. One of the reasons for such changes (in addition to climatic factor) was regulation of the Ilek River runoff by Aktyubinsk reservoir, commissioned in 1988.

The main reason for this trend was proved to be a significant long-term increase in surface air temperature during the cold period, accompanied by an increase in the frequency and duration of thaws and, consequently, consumption in winter low water period. In addition, an increase in the minimum runoff during winter period is attributable to an increased portion of the basic, groundwater inflow [15]. This identified tendency is of great practical importance, as winter runoff is the main limiting factor in the use of water resources.

Modern changes in the water regime of rivers in the transboundary basin of the Ural River undoubtedly affect the spatial and temporal specific distribution of water resources. Besides, the amounts of water available is directly related to such social and economic indicators as water consumption patterns, population dynamics, technological innovations in production, etc. Assessment of water resources available in regions of the studied basin conducted on the basis of various methods indicates the presence of significant regional differences (table 3).

Table 3. Regional water availability in transboundary basin of the Ural River.

| Region            | $C_{med.}$, % | Potential availability, thousands m³/person | Normalized natural availability, thousands m³/km² | River runoff, km³/year |
|-------------------|--------------|---------------------------------------------|-----------------------------------------------|------------------------|
| Orenburg          | 13.9         | 4.75                                        | 76.0                                          | 9.4                    |
| Chelyabinsk       | 6.3          | 2.62                                        | 103.9                                         | 9.2                    |
| West Kazakhstan   | 3.9          | 13.81                                       | 57.7                                          | 12.0                   |
| Aktyubinsk        | 9.8          | 3.89                                        | 10.9                                          | 3.2                    |
| Atyrau            | 3.2          | 11.35                                       | 58.2                                          | 6.5                    |
The comparison of population and average annual renewable water resources defines the amount of water scarcity. This criterion is used to compare different regions in terms of potential water availability, and therefore we will be able to judge the state of water resources in natural conditions of their formation [9]. Minimum potential water availability is observed in the Orenburg and Chelyabinsk regions, which is associated with an insufficient renewable river runoff against the backdrop of significant water intake for industrial and municipal needs. In Kazakhstan, the most difficult situation with provision of water resources is recorded in the Aktobe region.

As already mentioned, formation of water resources occurs in non-stationary conditions. Hence, assessment of water availability is more indicative, based on the analysis of real water resources and volume of their irrevocable withdrawal [9]. The real water availability is calculated for the Russian regions, subject to average values for the three-year low-water period of 2009-2011. This assessment illustrates the difference in values of real and potential water availability: in Chelyabinsk region they total 1.21 and 2.63 thousand m³/person; in Orenburg region 4.0 and 4.8 thousand m³/person, accordingly.

The development of the complex water management situation caused by a shortage of water resources also depends on the specifics of regional water consumption. The following indicators are of key importance in the structure of water consumption: percentage of recycled water use in the total volume, volume of water losses during transportation, percentage of irrevocable withdrawal of water resources, volume of river runoff regulation, etc. In general, the current structure of water consumption has regional differences throughout the Ural River transboundary basin (table 4).

### Table 4. Structure of regional water consumption in the Ural River transboundary basin

| Region          | W<sub>wc</sub>, mln m³ | W<sub>rec</sub>, % | W<sub>sw</sub>, mln m³ | Including for needs of, % |
|-----------------|------------------------|-------------------|------------------------|--------------------------|
| Orenburg        | 2710                   | 64                | 979                    | 88                       |
| Chelyabinsk     | 7359                   | 92                | 567                    | 54                       |
| West Kazakhstan | 627                    | 1                 | 623                    | 12                       |
| Aktobe          | 749                    | 4                 | 717                    | 13                       |
| Atyrau          | 419                    | 47                | 222                    | 41                       |

W<sub>wc</sub> – total water consumption volume; W<sub>rec</sub> – percentage of recycled water; W<sub>sw</sub> – source (fresh) water volume; P – production sector; U – utilities; A/C – agriculture

In the Russian section of the basin, the main percentage of water resources is spent on industrial and utilities needs, and the minimum spent on the needs of agriculture. Interestingly, the percentage of recycled water in the Russian regions is very high – 60-90%, which confirms the rather efficient use of water resources in various sectors of the economy. In addition, water savings were achieved by a significant reduction in the volume of water withdrawals for agricultural purposes, especially in the period 1990-2015. In recent years, we also recorded some stabilization and even some growth in the use of water resources for irrigation and agricultural water supply in several regions of the transboundary basin (figure 2).

The structure of water consumption in Kazakhstan’s regions is characterized by predominance of water use for industrial and utilities needs. The exception is the Atyrau region where the structure of water consumption is described by significant percentage of water intake for the needs of agriculture (31%). A number of regions illustrate the negative dynamics in terms of fresh water savings. In particular, in the Aktobe region, the percentage of recycled and reused water supply has decreased by more than 20% in recent years.
Furthermore, the percentage of water use for irrigation needs within the Kazakh regions is traditionally high, which affects significantly the preservation of irretrievable water consumption. For example, in the 1980s, along the lower course of the Ural River for 800 km, there were 50 water intake channels, including an irrigation system from the Kushum Canal with a total water intake of 35.7 m³/sec [16]. In the 20th century, to reduce levels of water stress in the agricultural sector, in circumstances of extremely uneven distribution of water resources, hydro-reclamation works were actively carried out within the study region, aimed at improving humid conditions in local areas. In particular, in southern steppe and semi-desert areas throughout the transboundary basin, inundative (liman) irrigation experiments were carried out, i.e. the accumulation of snowmelt water through a system of dams, for bringing water to pastures and hayfields. Most of inundative irrigation lands are located in floodplains of the Ilek River, Or River and their tributaries, along the main axes of resettlement. Systems of watered fluvial limans have contributed to a significant improvement in the forage quality of pastures and development of the cattle-breeding sector. In the structure of drainage areas, such sites occupy a small portion. For instance, in the basin of the Or River (18.5 thousand km²) the total area of 10 inundative irrigation sites is 205.9 km², or about 1% of the drainage area.

In general, despite the positive dynamics of certain water saving indicators, the problem of effective use of water resources remains relevant today in most regions of the trans-boundary river basin of the Ural River.

Water availability equally depends not only on the quantitative characteristics of water resources, but also on their qualitative state. Individual sections of the Ural River and major tributaries are characterized by a significant technogenic metamorphosis in the river water chemical structure. The maximum variety of pollutants (copper, zinc, sulphates, nitrite nitrogen, phosphates, etc.) is typical for the upper sections of the studied basin.

One of the typical examples of long-term and permanent surface water pollution as a result of mining is the basin of the Tanalyk River, the right tributary of the Ural River (the Iriklinsky Reservoir) (figure 3).
Practically fresh water in the upper reaches of the Tanalyk River contains no obvious traces of heavy metals. Entering into the technogenic zone (industrial enterprises of Baymak, Buribay and Akyar, active deposits), the water is quickly saturated with salts and heavy metal ions. The most persistent pollutants along the entire river profile include copper, manganese, total iron, and zinc. A similar situation is observed on many tributaries of the Ural River (Khudolaz, Urtazymka, Dzhusa, Kumak, etc.).

In the middle sections of the studied basin, the most complex environmental and hydrochemical situation is observed in the area of large industrial hubs – Orsk-Novotroitsk, Aktobe and Orenburg. The main pollutants typical for this hydrographic area include heavy metals (copper); ammonium nitrogen, nitrite and nitrate; petroleum products; organochlorine pesticides, etc. Within the Aktobe industrial hub (the upper reaches of the Ilek River), the traditional problem is the high concentration of hexavalent chromium and boron. According to some reports [8], boron concentrations exceeding the MAC was 15.8, and hexavalent chromium was 4.9 for in 2018.

Thus, the current environmental; and hydrochemical situation in rivers of the Ural River basin remains difficult. It has started to form since the second half of the 18th century, but the most negative consequences appeared in the 1930s with discovering and developing mineral resources of the Southern Trans-Urals. A certain improvement in water quality occurs in low-flow conditions of the Iriklinsky Reservoir on the Ural River, where pollutants are transformed and partially neutralized. In the middle
and lower sections of the Ural River basin, reduction in the content of pollutants is mainly due to dilution with large volumes of relatively clean water.

Summarizing the results obtained, we can state an ambiguous and poorly predicted situation with the provision of water resources in the transboundary basin of the Ural River. On the one hand, water consumption has decreased somewhat due to decline of certain industries and agriculture since the 1980s and 1990s. On the other hand, we have seen the consequences of the low-water runoff phase and associated problems of water use in the last 10-15 years. It is obvious to consider changes in climate and river runoff, and to adapt the water consumption system to modern conditions.

4. Conclusions

Guaranteed provision of water resources remains an urgent problem for steppe regions. The main reasons are as follows:

- spatial and temporal specifics of river runoff, and this specific increase against the backdrop of observed changes in regional climate;
- the difficulty of forecasting river runoff parameters for regions with sub-arid climatic conditions;
- a need to regulate local runoff almost everywhere, which reduces the volume of water inflow into the main river and increases the intra-annual transformation of its runoff;
- technogenic metamorphosis in quality of river waters;
- significant irrevocable consumption of water resources for agricultural and industrial purposes.

The problems of water supply are particularly relevant in the context of transboundary location of watercourses and river basins. Accordingly, one of the priorities for the sustainable development of transboundary regions is to ensure the cost-effective and environmentally safe use of water resources.

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