Modern hydrological changes in the Don River basin, caused by economic activities in the watersheds and climatic factors, and their consequences

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Abstract. An assessment of the current hydrological changes in the Don River basin, the largest river in Russia located in the forest-steppe and steppe zones, is given on the basis of the geographic-hydrological method. Particular attention is paid to identifying the hydrological role of economic activity in catchments on the background of ongoing climatic changes. The contribution of flow from various lands to the spring surface slope runoff was determined. The anthropogenic and climatic changes of the surface slope runoff and infiltration into the soil on arable lands, as well as river runoff, its surface and underground components are calculated. It was found that due to the increase in air temperature, a significant reduction in the river runoff surface component and an increase in its underground component has become a characteristic feature of the river flow formation. It is shown that hydrological changes in the Don River basin have ambiguous after effects and along with negative there are also take place positive consequences. The identified hydrological changes are of a sustainable nature, and it is advisable to take them into account when predicting the state of water resources in the near future.

1. Introduction

The nature of the Don River basin, which is located almost entirely in the forest-steppe and steppe zones, is very sensitive, especially on watersheds, to anthropogenic impact and climatic changes. The current state of the water resources of the Don River basin is largely conditioned by the landscape transformation and climatic factors. A lot of works has been devoted to the hydrological role of the economic activity on catchments, but most of them were completed quite a long time ago and do not reflect the current situation.

The article is devoted to the study of the combined effect by economic activities taking place on the catchment and modern climate changes on the Don river flow.

Particular attention is paid to water balance changes on arable lands in spring, first of all to such components as the surface slope runoff and infiltration of precipitation, as well as to the changes in the river runoff, its surface and underground components, to the consequences of the changes that have occurred, which are important for assessing the future water management development, for making optimal management decisions and effective water protection measures.
2. Materials and Methods
The research was carried out on the basis of the geographic-hydrological method. To identify the modern features of runoff formation, data from water balance stations [1] were used. This made it possible to determine the zonal values of the components of the water balance as of 1980 and for the conditionally modern period – from the 1981 to the present.

The surface slope runoff calculations took into account the characteristics of the following hydrologically most important elements of the Don River basin landscape structure (lands):
- land plowed in autumn for spring sowing and black fallow land;
- non-plowed lands with compacted soil by spring (winter crops, perennial grasses, fallow lands, pastures);
- urbanized areas (settlements and road network);
- area of the hydrographic network (areas located below the edge of river valleys, gullies, small ravines, hollows);
- slopes (total area minus the area occupied by the hydrographic network);
- forest (half of its area is referred to slopes, half - to the area occupied by the hydrographic network).

The assessment of the hydrological characteristics of the Don basin as a whole was carried out by summarizing the calculation results for each of its administrative units, taking into account the unit’s participation in the Don River runoff formation. In case the territory of a unit is not completely within the natural boundaries of the Don basin the total area of different landscapes in this unit is taken into account. The size of different landscapes in the Ukrainian part of the Don basin and actually in the basin of the Seversky Donets River, we estimated to be the same as in the neighboring Russian regions.

The data of Russian meteorological service on long-term observations of river runoff, atmospheric precipitation and air temperature, as well as the data of the Novosilsky, Volgogradsky and Povolzhsky water balance stations of the Federal Research Center of Agroecology RAS [2, 3] and the Nizhneveditsky water balance station served as the initial information. To identify the modern features of the Don basin landscape structure, we analyzed the official statistics from Federal State Statistics Service and Federal Service for State Registration on the landscape structure and land use in administrative units.

3. Results and Discussion

3.1. Transformation of economic activities on watersheds
Hydrological changes prior to the early 1980s were largely due to the widespread use of fall plowing. The spring surface runoff from the fall-plowed fields is much less (1.5 and more times in the forest-steppe zone and up to 4–5 times in the steppe zone) than from the fields that were not plowed by the beginning of the flood [1].

At the level of 1940, the area of the fall-plowing in the Don River basin was 25%. In 1960-1970 it increased to 50%, and became the main factor of the spring surface slope runoff decrease (figure 1). Compared to the flow rate calculating period with relatively stable climatic conditions, it decreased by 20% in the northern part of the forest-steppe, by 1.5 times in the central forest-steppe, and in the steppe zone by 6 times. As a result, the river runoff in the Don River basin has decreased by 10% [4].

During the 1978-2013 period the fall-plowing area decreased on average to 36% and became 5% less than the area of land with compacted soil by the beginning of the flood (table 1), and in the most recent years it decreased to 25–28%.

Significant surface runoff is observed in urbanized areas. The area under buildings and roads has increased 1.5–2 times in recent years. The share of urbanized territories in the entire area of the Don River basin has reached 3.6% over the last years, exceeding a little the share of forested areas (3.1%), the surface runoff from which is close to zero. The runoff from urbanized areas is currently comparable to that from agricultural land.
The area of the hydrographic network (16% of the Don River basin) remains unchanged over time. Large snow reserves accumulated here contribute to the increasing surface runoff. The generalization of the results of flow calculation for individual land plots made it possible to determine the current structure of the surface slope runoff during the spring flood phase (table 2).

![Slope runoff (mm)](image)

**Figure 1.** Surface slope runoff from agricultural land in different periods in the southern part of the Russian Plain (taking into account the mechanical composition of soils and the structure of land). 1 - northern forest-steppe; 2 - central and southern forest-steppe; 3 - steppe zone.

**Table 1.** Modern structure of the Don River basin lands (%).

| Region                  | Urbanized territories | Forest | Fall-plowing | Not tilled fields by spring | Area of the hydrographic network |
|-------------------------|-----------------------|--------|--------------|-----------------------------|----------------------------------|
| Russian part            | 3.4                   | 3.3    | 37.2         | 41.1                        | 15                               |
| Ukrainian part          | 4.8                   | 4.7    | 32.0         | 38.5                        | 20                               |
| The Don River basin     | 3.6                   | 3.1    | 36.5         | 40.8                        | 16                               |

**Table 2.** Flow contribution of various lands to the surface runoff in the Don River basin in 1978-2013 (mm).

| Region                  | Urbanized territories | Forest | Fall-plowing | Not tilled fields by spring | Total  |
|-------------------------|-----------------------|--------|--------------|-----------------------------|--------|
| Russian part            | 2.5                   | 0      | 1.8          | 4.5                         | 8.8    |
| Ukrainian part          | 3.5                   | 0      | 0.6          | 3.1                         | 7.2    |
| The Don River basin     | 2.5                   | 0      | 1.7          | 4.4                         | 8.6    |

Climatic changes that have taken place in recent decades have begun to play a particularly significant role in the runoff changes. Calculations have shown that in modern times the climatic factor has several times greater influence on the surface slope runoff change as compared to the anthropogenic landscape transformation of the territory under consideration. Over the past decades (since 1981) the contribution of the climatic component to the total runoff change in the Don River basin is 75–85%, and that of the anthropogenic (mainly due to the reduction of the fall-plowing area) is only 15–25% [3].
3.2. Changes in climatic factors

Although the urbanized territories have spread and the fall-plowing areas shrunk, a 1.9°C rise of air temperature during the cold season (from November to March) in the 1981-2007 period was the main reason of the fact that the surface slope runoff and river runoff during the spring flood phase decreased.

This rise made thaws more frequent and provided less depth of ground freezing in the aeration zone. As a result, in spring there took place a sharp decrease in the surface slope runoff (by 40–74% on compacted arable land and 33–83% on fall-plowing lands) and an increase in precipitation infiltration into the soil (by 24–32% and 22–41%, respectively). Moreover, in the most recent years, the surface slope runoff has become close to zero.

The air temperature increase is also clearly expressed in the warm season (from April to October). During the 1981-2007 period in comparison with the norm it increased by 0.7°C and contributing to evaporation growth.

The revealed tendencies in the long-term course of air temperature are quite sustainable. In the last decade, the temperature rise has become even more pronounced. In the cold period the rise was going on and has exceeded the norm by 3°C but quite significantly it has raised in the warm period and exceeded the norm by 2.2°C leading to the evaporation growth, including the evaporation of shallow ground water, and to a river flow decrease in the low-water period. This air temperature rise has become one of the main reasons for groundwater levels lowering since 2007 in the Kamennaya Steppe region.

Changes in atmospheric precipitation have not played as noticeable role as the air temperature changers have in the river runoff decrease that has occurred over the past 40 years in the Don River basin. Calculations showed that, annual precipitation has exceeded the norm on average over the territory under consideration by only 3.6%. The amount of precipitation has increased predominantly during the warm period (by 5.8%), providing mainly evaporation, and not the runoff formation.

3.3. Changes in the river flow structure

The most detailed assessment of runoff changes over the past decades (1998–2017) was made for the Devitsa River with the catchment area of 1490 km² and being representative for the most part of the Don River basin. In consequence of the climatic conditions changes a very significant increase in the underground runoff component (by 30%) and a considerable reduction in its surface component (by 75%) has become a characteristic feature in the Devitsa annual river runoff formation. The share of underground runoff in the total annual flow has increased from 39 to 80% as compared to the 1960 flow rate. The annual total river runoff has significantly decreased – by 35%. Its surface component began to form mainly not due to the surface slope runoff, but due to the runoff from the hydrographic network area. Moreover, a temporary perched water (verhovodka) forms a significant part of the surface runoff component.

In the last decade (2008-2017), the reduction in the Devitsa total annual runoff was going on and amounted to 13 mm. The surface runoff from the catchment area has decreased especially noticeably – from 6 mm to zero. Due to the increased evaporation of moisture reserves in the aeration zone and of ground water during the warm period of the year, the underground runoff component also began to decrease. Moreover, a decrease in groundwater runoff is observed in the Upper Don both in the warm (April – October) and cold (November – March) periods of the year. The same situation is also observed on the Middle Don tributaries. So, the dynamics of the minimum 30-day runoff of the river Chir at Oblivskaya village (the catchment area is of 8470 km²) shows a 45% underground flow decrease in relation to that during the 1981–2007 period, and of the river Ilovlya at Borovki village (8730 km² catchment area) – a 55% decrease.

In the table 3 is given the seasonal distribution of the surface, underground and total flow in the Devitsa River catchment. As it is seen the flood runoff during the 1998–2017 period on average was relatively small amounting about 25% of the total runoff for a hydrological year (the surface component made 14% and 11% did underground). The share of surface runoff from the catchment
area significantly decreases in the summer-autumn and autumn-winter periods and is less than 4%. At the same time, the share of underground runoff in the total flow increases, comprising, respectively, 36–40% and 27–30%.

Table 3. Seasonal distribution of the Devitsa River runoff components at Devitsa village (1998-2017).

| Flow component | Years       | Hydrological year (October this year – November next year) | Summer-autumn period (from the end of flood till October) | Autumn-winter period (from November till the flood beginning) |
|----------------|-------------|------------------------------------------------------------|--------------------------------------------------------|---------------------------------------------------------------|
|                |             | mm             | %              | mm          | %              | mm          | %              | mm          | %              |
| Surface runoff | 1998–2007   | 20.1           | 20             | 13.2        | 13.3           | 3.6         | 3.7            | 3.3         | 3.3            |
|                | 2008–2017   | 21.8           | 25             | 13.7        | 15.9           | 3.7         | 4.2            | 4.4         | 5.1            |
| Underground runoff | 1998–2007 | 79.2           | 80             | 10.4        | 10.4           | 39.5        | 39.8           | 29.3        | 29.5           |
|                | 2008–2017   | 64.6           | 75             | 9.7         | 11.2           | 31.5        | 36.5           | 23.4        | 27.1           |
| Total flow     | 1998–2007   | 99.3           | 100            | 23.5        | 23.7           | 43.2        | 43.5           | 32.6        | 32.8           |
|                | 2008–2017   | 86.4           | 100            | 23.5        | 27.2           | 35.2        | 40.7           | 27.8        | 32.2           |

3.4. Consequences of the flow change

Hydrological changes in the Don River basin, which occurred as a result of the anthropogenic activity transformation and climate warming, have ambiguous consequences.

The growth of snowmelt-water infiltration brought along the soil moisture reserves increase before the vegetative cycle and crop improvement. The probability of extremely high inundations forming during the spring flood has decreased. A significant surface slope runoff reduction lowered the intensity of erosion and the quantity of pollutants drained into rivers from catchments during the spring flood.

One of the meaningful negative after-effects of the flow change is a decrease in water resources, especially during the flood season, which is observed mainly in April – May. These months in 1981-2006 the Don's runoff significantly decreased (by 30–40%) as related to the 1882–1980 annual normal flow (figure 2). Moreover, in the most recent years (2007–2016), the decrease in flood runoff accelerated and reached 40–60%. As a result, there were difficulties in filling reservoirs and ponds up to the design levels, low water levels complicated navigation, and the quality of water resources decreased. Low spring flood runoff has reduced the efficiency of river channels flushing and worsened the conditions of floodplain spawning areas for fish natural reproduction.

Figure 2. The Don’s average monthly runoff at Kazanskaya village over the past decades relative to the 1882-1980 annual normal flow.
Another negative consequence is the pollution of ground waters due to the increased filtration of snow-melt and rain waters in aeration zone during the cold period. The rise of air and water temperature during the warm period does not improve the hydrological situation. It promotes water quality deterioration, often leads to the massive development of higher aquatic vegetation and algae (including blue-green), water bloom and the oxygen concentration decrease in it.

The development of some kinds of anthropogenic activity in the latest years such as the landscape urbanization, road transport network extension, as well as the crop area enlargement and heavy fertilizing, is an important reason for the water quality deterioration.

The subjective anthropogenic factor also has a significant negative impact. This concerns environmental and water protection authorities whose work cannot be called effective in pollution abatement by various household waste, garbage, etc. of coastal river sections (especially within settlements and in their vicinity). There is practically no ecological control over agricultural activities in numerous private farm households located near rivers in the area of the hydrographic network, the hydrological role of which has increased in recent years. The diffuse pollution of rivers, as much as nitrogen and phosphorus, remains uncontrolled by the environmental authorities. According to [5], the Don waters are characterized as “polluted” and “extremely dirty”, and diffuse pollution from the catchment area plays a significant role in the Don waters contamination. Calculations have shown [6] that the removal of nitrogen with diffuse runoff during the spring flood is 14 times higher than its removal with wastewater, and phosphorus removal is 19 times higher (table 4). In fact, due to the process of self-purification taking place in small rivers and reservoirs, only a part of the diffuse nutrients flow gets into large rivers and reservoirs. To find out what this part is, to determine the total annual nutrients removal and not only from farmland, but also from urbanized territories, are further research challengers.

Table 4. Nitrogen and phosphorus content in diffuse flow and wastewater discharges during the spring flood in the Don River basin (Kt).

| Diffuse flow | Wastewater discharge |
|--------------|----------------------|
| mean annual  | 2012-2015            | 2012-2015 | 2000, 2005, 2008, 2009 |
| mineral nitrogen | total nitrogen | total phosphorus | mineral nitrogen | total nitrogen | total phosphorus |
| 22.8         | 45.6                | 1.9       | 5.7           | 1.6           | 3.3       |
| 0.1          | 0.3                 |           |               |              |

4. Conclusion
Hydrological changes prior to the early 1980s were largely due to the widespread use of autumn plowing (up to 50% of the entire Don basin area was plowed in the 1970s), contributing to spring surface and river runoff decrease. Subsequently, the fall-plowing area began to decrease and in the most recent years it does not exceed 25–28%. Along with the developing urbanization, this did not lead the slope runoff rise, since climate changes began to play a more significant role in the flow changes. The cardinal changes in the Don basin river flow mainly due to climate warming began in the late 1970s – early 1980s. These changes have no analogues for the entire period of instrumental observations.

The main factor in the river runoff reduction in the Don basin was the air temperature increase in the cold season (on the background of practically unchanged atmospheric precipitation), which has led to a freezing depth decrease in the aeration zone, to frequent thaws, to rising infiltration and to a decrease in surface slope runoff, up to its absence in some years. In the result, the river runoff during the spring flood has sharply decreased and in the most recent years (2007–2016) amounted 40-60% near Kazanskaya village as compared to the 1927–1980 annual normal flow. However, since the underground runoff during the low-water period has raised, the total annual river runoff decreased much lesser (by 17%).
Hydrological changes that have taken place in the Don River basin have ambiguous consequences. Along with negative after effects (a decrease in water resources, especially during floods, increased migration of pollutants (nitrogen and phosphorus), to ground water and underground runoff, water quality deterioration in rivers in the summer-autumn low-water season caused by the rise of water temperature, etc.) there are also positive ones. The latter include a decrease in erosion and in the volume of pollutants flowing into rivers with the surface slope runoff, an increase in soil moisture reserves and crop yields, etc.

It seems highly probable that the identified hydrological changes in the Don River basin will sustain in the future. To study them more detailed, it is extremely important to reanimate the network of water balance stations in the river catchments.

Acknowledgements
The article was prepared within the framework of the State assignment no. 0148-2019-0007 (assessment of changes in the landscape structure, and climatic and anthropogenic runoff factors) and with the financial support of the Russian Science Foundation project no. 20-17-00209 (the surface and underground runoff components changes evaluation, the environmental consequences of these changes).

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