Ecological status estimation for the Kalaus river in the Stavropolskii region

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Abstract. The Kalaus is the river in the Stavropol region of Russia being an important source of water. Water use has caused water decrease, water depletion and water deterioration. Therefore water shortages exceed natural river flow by 100%. The water quality category is estimated as "very dirty". The main source of river water pollution is diffuse runoff from agricultural lands. Estimations of both the environmental river flow and the efficiency of water protection measures are given in this paper. It considers the impact of the lands on the flow volume and quality of the river water, and also estimates the impact of global climate change on water scarcity. To improve the ecological status of the river up to "satisfactory" it is necessary to save the volume of environmentally friendly flow without its with drawing. To improve the water quality up to "moderately polluted" it is necessary integrated water protection measures.

1. Introduction
In the steppe zone most rivers have the following main hydrologic characteristics: low discharge (flow rate varies within 0.5 ... 2 l/s per square kilometer), high both annual variation of flow (Cv=0.5...1) and intra-annual variability (spring flow equals 60...100%). The density of the river network is about 0.21 km/km$^2$. Steppe region of Russia is very important for economy of the country. Up to 25% of agricultural production is produced in the region. Intensive agricultural activity resulted in significant anthropogenic impact on the rivers, which are the main sources of water. Thus, water consumption reaches 40 .. 100% of the available water resource in low-water and acutely low-water year respectively. Up to 70% of the water consumed is required for irrigation purposes. Farming land occupy up to 90% of the catchment area, which leads to river flow decrease in the range of 20 ... 40%. The quality of river water in the steppe region corresponds to the "dirty" class as the result of agricultural land influence [1, 2]. The above mentioned issues are typical for the rivers in the steppe zone both in Russia [3, 4] and in the foreign countries [5, 6].

The Kalaus River is an important source of water in the Stavropol Territory of Russia (river length - 436 km, watershed - area 9700 km$^2$). Water management as well as ecological situation being caused by runoff formation and human activity requires river stream regulation by the hydraulic structures. Serious changes in the flow, deterioration of water and changes in the ecological status of the water body occurs as the result. The Kalaus is the dirtiest river in the Stavropol Territory now. This situation is also influenced by the global climate changes. In the southern regions of Russia (including Stavropol) decrease in water resources by 10-20% was observed in 2015. The frequency of low-water...
years has increased, while the annual water supply has decreased and equals 1.0-1.5 thousand m³/capita, which is lower than the international standard of 1.7 thousand m³/capita. Nowadays water scarcity constrains the economic growth of the Stavropol region [1]. Environmental risks and danger estimation of the above mentioned processes for the water system of the Kalaus as well as forecast challenges to the water supply system are considered in the paper.

The goal of the research is to estimate the impact of water management, activity within river catchment and global climate change processes on the water quality and ecological status of the river Kalaus, as well as to recommend water protection measures.

2. Models and Methods

Estimation of the forecast changes in the water management was carried out based on water balance calculations. The calculated hydrological characteristics of the natural flow of the river were determined using the method "In the absence of observational data" and refined by relationship of hydrological characteristics identifying which are obtained for the rivers in the Stavropol region. This approach is used because of the slow developed monitoring net of water bodies in the Stavropol region.

The water economic balance equation (WEB) was used as the following:

\[ WEB = W_r + W_{gw} + W_{redis} + \Delta W_{ret} - \Delta W - W_{exh} - W_{env} - W_{agr} - W_{clim} \]

where: \( W_r \) - the river stream volume; \( W_{gw} \) - water intakes from underground water; \( W_{ret} \) - return waters; \( W_{redis} \) - water territorial redistribution; \( W_{exh} \) - river flow exhaustion caused by underground water intake; \( W \) - water consumption; \( W_{env} \) - environmental friendly river flow; \( W_{agr} \) - changes in the river flow caused by agricultural activities in the catchment area (it is determined as the difference between the total evaporation for the crops and natural meadows, taking into account the structure of crop rotation [2]); \( W_{clim} \) - change in the river flow caused by global climate change (it is determined as a proportion of natural river flow to the forecast river flow data).

Water quality and ecological status are estimated using the integrated coefficient of marginal pollution [3]. Polluted waste and return waters coming from water users (their impact is determined in accordance with the structure of water use in the region), diffuse runoff coming from the rainfed and irrigated lands being taken into account too. Both the required efficiency and the set of the water protection measures (WPM) are determined by the comparison of the actual water quality for the Kalaus river with the natural background of water quality (which is devoted to the "moderately polluted") in it.

The ecological status of the river water quality was estimated as the degree of the water eco-system preservation [4], which is determined as the probability of the actual water quality corresponding to the target level of it.

Permissible water withdrawal from the river is determined as the difference between natural flow of the river and the volume of environmentally friendly flow. The latter is estimated using the "Universal method" [5], which proposed taking into account the following parameters:

- the economic use of a water body, including river flow regulation;
- the existing river ecosystem preservation (the "satisfactory" ecological status corresponds to ecosystem preservation in the range of \( \Delta P=60 \ldots 80\% \) [3]).

The developed approach makes it possible to estimate the impact of water management activities on the water bodies, as well as to make water quality forecasts to determine the ecological status of the rivers.

3. Results and Discussion

To determine the environmentally friendly river flow different water withdrawals \( \Delta W_i \) were considered. The actual river flow \( W_{fi} \) was determined, and histograms of both natural river flow distribution \( f(W_{fi}) \) and actual river flow distribution \( f(W_{fi}) \) were plotted. The natural river flow conservation index was determined as the overlap area of the relative histograms of the natural and actual river flow distribution (figure 1).
Figure 1. Comparison of relative histograms of natural river flow and actual river flow distribution (the latter - taking into account 20% water consumption).

Taking into account the permissible water ecosystem conservation index $\Delta P_{perm}=60\%$ (which corresponds to the "satisfactory" status of the water ecosystem), the dependence curve $\Delta P=f(\Delta W_i)$ determines the share of environmentally acceptable flow in the natural flow of the river, which equals $100-48=52\%$ (figure 2): $W_{env}=0.52 \times W_r$.

Figure 2. Water ecosystem conservation index depending on the share of the water consumption (river flow variation coefficient $C_v=0.55$, skewness coefficient $C_s=2C_v$).

The results of the research shows, that it is impossible to supply water to the consumers without both river flow transfer and its regulation in time for the Kalaus river basin. The above mentioned results are confirmed by the calculations of the water management balance for the year of 75% river flow availability (table 1, 2). Water shortage ranges from $125.4\%$ in a low-water year to $151.54\%$ in an acutely low-water year.
Table 1. Components of the monthly water management balance for the Kalaus River in a low-water year (P=75%) and in an acutely low-water year (P=95%), million m$^3$.

| $P,\%$ | $W_r$ | $W_{gw}$ | $W_{ret}$ | $W$ | $W_{exh}$ | $W_{env}$ | $WEB$ |
|-------|-------|----------|-----------|-----|-----------|-----------|-------|
| 75    | 64.25 | 12.14    | 235.83    | 404.51 | 1.21      | 31.90     | -125.40 |
| 95    | 18.97 | 12.14    | 235.83    | 404.51 | 1.21      | 12.76     | -151.54 |

Table 2. Useful capacity of the reservoir ($V_{\text{useful}}$) and irrigation capacity: unregulated flow ($F_{\text{unreg}}$), regulated flow taking into account transfer and full annual regulation ($F_{\text{reg}}$). Weighted average irrigation rate of 3000 m$^3$/ha, irrigation system efficiency 0.85.

| $V_{\text{useful}},\text{mlnm}^3$ | Irrigation capacity,hectare |
|-------------------------------|-----------------------------|
|                               | $F_{\text{unreg}}$ | $F_{\text{reg}}$ |
|                               | 41.77                     | 3366             | 32090 |

Transfer and river flow regulation will decrease water shortages (figure 3). However, decrease in water flow as a result of global warming leads to an increase in water shortages.

Figure 3. Monthly water management balances without ($W_{\text{clim}}=0$) and taking into account global climate changes ($W_{\text{clim}}=10\%$ and $W_{\text{clim}}=20\%$).

River water pollution is estimated at the average level of 12MPC (MPC - maximum permissible concentration) for various pollutants. The main source of pollution is defusing runoff from agricultural land, the next one being agricultural water use (table 3). The required efficiency of water protection measures is estimated as not less than 92%, which can be achieved by application of the suggested set of measures to reduce both waste water discharge and diffuse runoff dumping to the river (table 4).

Diffuse runoff coming from agricultural land influences the river flow quality indirectly changing the conditions of flow formation. Agricultural land occupies 87% areas in the Stavropol region, 60% being arable land therefore diffuse flow influence is significant. Flow decrease due to area ploughing was calculated according to the famous method [2], and it is estimated as 42 and 77%, respectively for 75% and 95% river flow probability of exceeding (figure 4).
Table 3. Sources of pollution average concentration of pollutants in river water ($n \times$MPC) and required efficiency of water protection measures.

| Sources of pollution, % | Municipal waste water | Industrial waste water | Irrigation | Rural water use | Other | Diffuse runoff | Rainfed land | Rainfed land | River water pollution, $\mathcal{E}_{\text{rpm}}$, $n \times$ MPC |
|-------------------------|-----------------------|------------------------|------------|----------------|-------|---------------|-------------|-------------|--------------------------------------------------|
|                         |                       |                        |            |                |       |               |             |             |                                                  |
| Municipal waste water   | 3                     | 15                     | 10         | 28             | 3     | 10            | 31          | 12          | 92                                               |

Table 4. Water protection measures and their efficiency.

| Water protection measures | Efficiency, % | Sources of pollution |
|---------------------------|---------------|----------------------|
| Water protection areas    | 70            | Agricultural land. agricultural water supply systems |
| Forest belts              | 40            | Agricultural lands and water supply systems |
| Agrotechnical measures    | 30            | Agricultural lands   |
| Snow retention            | 10            | Agricultural lands   |
| Wastewater treatment      | 98            | Municipal and industrial waste water |
| Constructed wetlands      | 40            | Irrigated lands      |
| Water cycling             | 90            | Industry             |

Figure 4. River flow decrease for the Kalaus River depending on the availability of the year as a proportion of the natural flow of the river (ploughed area - 60% of the watershed).

4. Conclusions
- The current water management leads to water shortages which are accounted as more than 100% of the natural river flow.
- River water quality corresponds to "very dirty", average concentration of main pollutants reaches 12 MPC.
- The main source of pollution is agriculture, which causes 79% of the total amount of pollution coming to the river.
The share of the diffuse runoff from agricultural land reaches up to 41%.

The required efficiency of water protection measures is not less than 92%.

The indirect effect of the catchment area ploughing on the river flow reduction is estimated as 42 and 77% of the natural flow in low-water and acute low-water years correspondently.

The forecast decrease in the river flow which can be caused by the climate change is estimated as 20%, leading to water scarcity at about 1 million m³.

To improve the ecological status of the river up to "satisfactory", it is necessary:

- to observe the volume of environmentally friendly flow which must equal not less than 52% of the natural flow;
- to apply a complex of water protection measures at the recommended efficiency of 92% to achieve "moderately polluted" water quality.

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