Scenarios of long-term river runoff changes within Russian large river basins

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Global and regional climate changes and anthropogenic impacts are the leading factors determining the future state of large river basin water systems which play an important role in the economic development of Russia. That is why it is necessary to create integrated scenarios of river runoff changes within large river basins. The creation of such scenarios should become one of the main principles for ecologically safe management of water systems in the future.

Scenarios include the following components:
(a) Scenarios of global climate change and methods of their assimilation.
(b) Scenarios of hydrological consequences caused by climate changes.
(c) Scenarios of hydrological consequences of socio-economic development, including changes in the water management complexes.
Modules of construction of integrated scenarios of the state of river basin water system

Present-day State of Water System

- Module of description of the present-day state of water system and its conditions
- Module of analysis of the present-day state of water system and its conditions
- Module of transformation of data of the present-day state of water system and its conditions (downscaling, etc.)

Methods of Construction of Scenarios

- Module of construction of scenarios of change of water management complex
- Module of hydrological models for construction of scenarios of the state of natural components of water system
- Module of methods of construction of scenarios of natural conditions changes (climate, permafrost conditions, etc.)

Future State of Water System

- Module of description of scenario changes of the state of water management complex
- Module of description of scenarios changes of the state of natural components of water system and their conditions
- Module of analysis of scenarios states of water system and its conditions

Geographical information system and data bases control system

- Module of graphic and table support and visualization of data on present-day and scenarios state of water system
- Data bases characterizing present-day and scenarios state of water system
Results for development of integrated scenarios are submitted by the examples for the largest river basins of Russian plain (Volga, Don river basins) for the first third of the XXI century.
Representative river basins, used for preparation of digital fields for monthly river runoff within large river basins.

The Volga

The Don
RESEARCH METHODOLOGY

The methodology allows to create long-term scenario forecasts of:

(a) changes in river runoff resources in large river basins as a result of global and regional climate change and
(b) water management complex transformation caused by social and economic changes in Russia and their impacts on the river runoff resources characteristics.

Scenarios of changes, probable at consecutive stages of global climate warming and socio-economic development for transboundary large river basins for the Russian plain and Siberia in the XXI century are under construction on the basis of: (a) results of modeling of climate changes and methods of their assimilation; (b) the hydrological model adapted to conditions of above mentioned regions; (c) method of water use scenarios caused by socio-economic changes; (d) geographical information systems and databases.
Monthly water balance model

The initial versions of the model, and its application to the largest river basins of the Russian plain are considered in detail in publications of authors (Georgiadi & Milyukova, 2002; 2006a; 2006b). In the model the basic processes of a hydrological cycle are described: infiltration and moisture accumulation in soil, evaporation (on the basis of modified Thornthwaite's method (Willmott et al., 1985), accumulation of water in a snow cover and snow melting (on the basis of V.D.Komarov's method (Manual ..., 1989), formation of surface, subsurface and groundwater flow in the rivers and full river runoff. The model can take into account macroscale heterogeneity of hydrometeorological fields and other territory characteristics, allowing a degree of reliability in the modeling of the river runoff changes. In the model of monthly water balance the changes of the river runoff and other water balance elements are estimated in units of a regular grid, which facilitates the coupling of the model with climate model simulations. Blocks for calculations of seasonal soil grounds freezing/ thawing have been arranged (Pavlov, 1979; Belchikov & Koren, 1979).
The model is based on a conservation equation of average long-term monthly water balance of river catchments. In general it can be written down for each cell of a regular grid in the following way:

\[
Q_s(t) + Q_{gr}(t) = P(t) - E(t) - I_d(t) - \frac{dW}{dt}
\]

where \(Q_s(t)\) is the total surface and subsurface (seasonal active layer) flow (mm); \(Q_{gr}(t)\) is groundwater flow (mm). The sum of \(Q_s(t)\) and \(Q_{gr}(t)\) makes a full river runoff. \(P(t)\) is atmospheric precipitation (mm); \(E(t)\) is evaporation (mm); \(I_d(t)\) is infiltration of water to deep horizons of underground water outside of active water exchange zone (mm), \(\frac{dW}{dt}\) is the change of water amount in active water exchange zone of the river basin for the time interval \(dt\).
The model parameters were optimized by the H. Rosenbrok optimization procedure (Rosenbrock & Story, 1968). The parameters were partly selected in an empirical manner.
Active layer

*Tt < T_{kp} - calculation of active layer freezing*

*T >= T_{kp} - calculation of active layer thawing*

*T >= T_{kp} - calculation of soil moisture reserve changes in thawing soil layer*

Horizon of underground water. Calculation of water filtration into deeper horizon of underground water

Surface and Subsurface flow

Flow from underground horizon

River runoff

Principal scheme of monthly water budget estimation in river basin

**EVAPORATION**

**PRECIPITATION**

*T < T_{kp} - water accumulation in snow cover*

*Tt >= T_{kp} - snow cover melting, receipt of melting and rain water on land surface*
The model of monthly water balance numerically evaluated the changes of river runoff and other water balance elements in large river basins in the cells of a regular grid, which facilitates of coupling with the data of numerical experiments with climate models.
As the climate scenario is used a range of possible climate change, which is calculated based on the results of numerical estimates for deviations of climatic elements from their recent values carried out on ensemble of 10 global climate models, originating from two contrasting scenarios of globally averaged air temperature changes (A2 and B1) included in the program of last experiment 20C3M-20th Century Climate in Coupled Models, held in the framework of the Intergovernmental Panel on Climate Change (IPCC) and selected on the basis of comparison of observed and model present-day climate (Kislov et al., 2008).
<table>
<thead>
<tr>
<th>Climate Model</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCSM3</td>
<td>USA</td>
</tr>
<tr>
<td>CNRM-CM3</td>
<td>France</td>
</tr>
<tr>
<td>CSIRO-Mk3.0</td>
<td>Australia</td>
</tr>
<tr>
<td>ECHAM5/MPI-OM</td>
<td>Germany</td>
</tr>
<tr>
<td>GFDL-CM2.0</td>
<td>USA</td>
</tr>
<tr>
<td>GFDL-CM2.1</td>
<td>USA</td>
</tr>
<tr>
<td>INM-CV3.0</td>
<td>Russia</td>
</tr>
<tr>
<td>MIROC3.2</td>
<td>Japan</td>
</tr>
<tr>
<td>MRI-CGCM2.3.2a</td>
<td>Japan</td>
</tr>
<tr>
<td>PCM</td>
<td>USA</td>
</tr>
</tbody>
</table>
Method for assimilation of climatic scenario modeling based on GIS
Methodology for assess the impact of socio-economic changes on the resources of river runoff based on assumption of different rates for socio-economic development of the country and its regions and scenarios for development of different technologies of water use and protection of water systems.

The major water users (domestic, industrial, agriculture including irrigation) are considered.

Scenario changes for household water consumption carried out taking into account the dynamics of population, including urban and rural.

Among the major scenarios are considered: accelerated scenario (based on innovation, 4-5% per year) moderate and minimal (2-3% per year) and social economic development.

Considered scenarios, based on existing specific water consumption and its maximum, average and minimum reduction.

In addition, it was taken into account the change of evaporation from the water reservoirs and the impact of agricultural activities.
**General algorithm of scenario development**

**Pre-forecast stage:**
- the general orientation of the method development;
- the analysis of environment and spatial-temporal regularities of water resources distribution and their natural quality;
- the analysis of economic activities and their influence on water systems;
- the analysis of the dynamics of water systems condition;
- the choice of operational units.

**Forecast stage:**
- take into consideration expected natural hydroclimatic situation;
- take into consideration forecast of population and economy development;
- estimation of possible changes of water use technology;
- take into consideration anthropogenous and natural-climatic factors;
- verification of scenarios on water-economic balances.
Selected results
SCENARIO CHANGES OF REGIONAL CLIMATE AND RIVER RUNOFF
In Volga and Don river basins in the first third of the century under both scenarios (A2 and B1), we can expect very similar increases of annual air temperature that can be in the range 1.5-1.6 °C.

Annual sum of atmospheric precipitation can be increased, however, it will be within a few percent.

It is expected that for both scenarios the maximum increase in precipitation in both basins will be occur in the cold season. During the summer months it can be even decreased. Intraannual distribution of positive changes in air temperature is characterized by two comparable winter and summer "peaks". In the basin of the Don (scenario B1), the "peak" of summer temperature increase may exceed the winter one.
Hydrological changes.

To obtain the scenario assessment of changes of river flow, possibly in the first third of the XXI century, on the basis of the above climate scenarios were calculated on the model of a monthly water balance of the Institute of Geography RAS.

Calculations showed that in the case of the scenarios A2 and B1 in the first third of this century we can expect not so noticeable increase of annual runoff in Volga basin (within 3-5%) and its more substantial growth in Don basin (9-12%).

Climate warming in the first third of the century, may cause the compact transformation of flood wave for Volga river basin and flood peak here will be shifted to earlier dates. Flood peak monthly discharge for Don river will be increased too.
SCENARIO CHANGES FOR CHARACTERISTICS OF WATER MANAGEMENT COMPLEX
### Existing water use indices in Russia, Don* and Volga river basins, 2000-2005, cub. km/year

<table>
<thead>
<tr>
<th>Indices</th>
<th>Russia</th>
<th>Don</th>
<th>Volga</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water abstraction</td>
<td>85,9**</td>
<td>7,2</td>
<td>25,3</td>
</tr>
<tr>
<td>Fresh water use</td>
<td>66,9</td>
<td>6,3</td>
<td>21,4</td>
</tr>
<tr>
<td>including domestic use</td>
<td>13,6</td>
<td>0,9</td>
<td>6,5</td>
</tr>
<tr>
<td>industry</td>
<td>38,7</td>
<td>3,6</td>
<td>11,8</td>
</tr>
<tr>
<td>irrigation and watering</td>
<td>9,3</td>
<td>1,1</td>
<td>1,6</td>
</tr>
<tr>
<td>agricultural water supply</td>
<td>1,4</td>
<td>0,3</td>
<td>0,4</td>
</tr>
<tr>
<td>other needs</td>
<td>3,9</td>
<td>0,4</td>
<td>1,1</td>
</tr>
<tr>
<td>Recycling and reuse water</td>
<td>133,5</td>
<td>9,3</td>
<td>50,9</td>
</tr>
<tr>
<td>Total water use</td>
<td>200,4</td>
<td>15,6</td>
<td>72,3</td>
</tr>
<tr>
<td>Water disposal</td>
<td>57,3</td>
<td>4,7</td>
<td>18,0</td>
</tr>
<tr>
<td>including surface water bodies</td>
<td>55,6</td>
<td>4,5</td>
<td>17,4</td>
</tr>
<tr>
<td>including polluted water</td>
<td>20,3</td>
<td>0,8</td>
<td>8,4</td>
</tr>
<tr>
<td>Consumptive water use</td>
<td>30,3***</td>
<td>2,7</td>
<td>8,5</td>
</tr>
<tr>
<td>Losses on the additional evaporation from the surface water reservoirs and ponds</td>
<td>-</td>
<td>1,7</td>
<td>4,5</td>
</tr>
<tr>
<td>Detention of runoff by agro-technical measures</td>
<td>-</td>
<td>1,3</td>
<td>2,0</td>
</tr>
<tr>
<td>Consumptive water withdrawals</td>
<td>-</td>
<td>5,7</td>
<td>15,0</td>
</tr>
</tbody>
</table>

* within Russia, ** including +5,4 for using, *** including 19,8 at transportation and using
Water use indices in the Volga (numerator) and Don (denominator) river basins in 2025-2030 at existing climate and specific water consumption (cub. km/year)

<table>
<thead>
<tr>
<th>Indices</th>
<th>moderate</th>
<th>maximal</th>
<th>minimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water abstraction</td>
<td>56.4/17</td>
<td>71.3/21.8</td>
<td>44.7/13.2</td>
</tr>
<tr>
<td>Fresh water use</td>
<td>46.5/14.9</td>
<td>58.7/19.1</td>
<td>36.9/11.6</td>
</tr>
<tr>
<td>Water disposal</td>
<td>38.7/11.2</td>
<td>48.9/14.3</td>
<td>30.8/8.7</td>
</tr>
<tr>
<td>Consumptive water withdrawal</td>
<td>26.9/5.8</td>
<td>33.2/7.5</td>
<td>21.9/4.5</td>
</tr>
</tbody>
</table>
Water use indices in the Volga (numerator) and Don (denominator) river basins in 2025-2030 at present-day climate and at different scenarios of economic development with regard for the change in specific water consumption (cub. km/year)

<table>
<thead>
<tr>
<th>Water use indices</th>
<th>Scenario of economic development</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>moderate</td>
<td>minimal</td>
<td>moderate</td>
<td>minimal</td>
<td>moderate</td>
<td>minimal</td>
</tr>
<tr>
<td></td>
<td>Decrease of specific water consumption</td>
<td>minimal</td>
<td>moderate</td>
<td>minimal</td>
<td>moderate</td>
<td>minimal</td>
</tr>
<tr>
<td>Water abstraction</td>
<td>45,2/13,8</td>
<td>35,7/11</td>
<td>28,3/8,8</td>
<td>36,2/7</td>
<td>28,7/5.3</td>
<td>22,8/4,2</td>
</tr>
<tr>
<td>Fresh water use</td>
<td>37,8/12,1</td>
<td>30,9/9.9</td>
<td>26,3/8,3</td>
<td>30,1/9,3</td>
<td>24,8/7,8</td>
<td>21,2/6,5</td>
</tr>
<tr>
<td>Water disposal</td>
<td>30,7/8,9</td>
<td>24,6/7</td>
<td>21,2/6</td>
<td>24,7/4,7</td>
<td>20,0/5,5</td>
<td>17,2/6,9</td>
</tr>
<tr>
<td>Consumptive water</td>
<td>23,7/9,7</td>
<td>20,3/8,8</td>
<td>16,3/7,6</td>
<td>19,4/7,8</td>
<td>16,7/7,1</td>
<td>13,5/6,2</td>
</tr>
<tr>
<td>withdrawal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparison of recent and scenario water use indices (km³)

Volga river basin

- Modern period
- Moderate economic development and maximum reduction of specific water consumption
- Minimal economic development and maximal reduction of specific water consumption

Don river basin

- Total water abstraction
- Water use
- Water disposal
- Consumptive water use
- Water withdrawals
The obtained scenario estimates show that expected changes in river runoff in the Volga and Don river basins in the first third of this century can be relatively small as for annual river runoff and as for its intraannual distribution, while changes in the characteristics of water management complex may be in some scenarios for its development extremely negative.

Thus, conservation and continue the existing norms of specific water consumption is unacceptable, especially for Don and Volga river basins because in all variants of creating excessive load on the water element of the environment.

Reduction of the specific water consumption based on the known technological solutions, primarily for decreasing the unnecessary loss of water, while allowing a higher level of welfare to significantly reduce the basic indicators of water use, and even achieve anthropogenic pressures on water resources less than or about equal to that that we have now. The foregoing quantitative recommendations for individual components of scenarios should be considered as indicative, requiring adjustments as further development of scenarios.