Hydrological regime of the Black and Azov Seas catchment under the global warming

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Abstract. Estimates of probable change in water balance parameters of the Black and Azov Seas drainage basin under the global warming by 1°C were obtained. A steady-state hydrological model has been developed for evaluation of river runoff and evaporation. The paleoclimatic reconstruction for global warming on 1°C has been used as an empirical scenario. This scale of climate change corresponds to the warm epoch of the past, considered as an analogue of the future climate: the Holocene Thermal Maximum (7-6 ka BP). The estimates indicate possible increase in the total river inflow into the Black and Azov Seas by about 17 km³ per year and increase of the mean annual evaporation by 27 mm per year relative to the period of 1961-1990 years. Estimation was made notwithstanding water consumption.

1. Introduction

Anthropogenic impacts on the environment such as the construction of hydraulic structures, river regulation, etc. amplified by the current climate change have already led to significant changes in the hydrological regime of the inland seas. For the last 30-50 years, the Black and Azov Seas have been under the substantial anthropogenic pressure.

Unique hydrometric characteristics of the Azov Sea raise a particular interest in studying its hydrological regime. The Azov Sea is one of the shallowest seas in the world, which makes it very sensitive to climate fluctuations. Two main sources of water and salt balance change are fresh water coming in from the rivers and water exchange with the Black Sea via the Kerch Strait. In fact, river inflow water accounts for about 12% of the Azov Sea total water volume, is one of the most extreme share for the seas all over the World.

Study on the current status of the seas under the global warming is of great importance [1 – 3]. At the same time, there is no consensus in the scientific community on the reliability of estimates of hydrological parameters change in the future. Considerable uncertainty of water resources forecasts and anthropogenic impact on the sea drainage basin along with contradictory forecasts for temperature, precipitation and river runoff do not allow one to perform reliable long-term estimation.

2. Method and Data
There are two independent approaches to climate and hydrological cycle forecasting: a theoretical approach, which is based on climate models’ output, and an empirical one which uses both the data on the current large-scale trends and paleoclimatic reconstructions for warm geological epochs of the past. The empirical approach is an independent method. Application of various future climate scenarios including paleoclimate-based allows one to estimate a possible water balance parameters variation over the catchment of the Black and Azov Seas, and to predict its marine ecosystem response.

In the geological past of the Earth, there were warm epochs during which the global temperature anomalies had values close to those expected in the nearest future according to Global Climate Models (GCMs) simulations [2]. The paleoclimatic reconstruction of winter and summer air temperature and annual precipitation patterns can be used as an analogue and possible scenario of climatic conditions in the 21st century [4]. Paleoclimatic reconstructions are mainly based on multiple proxy data such as pollen charts, paleontological, geological materials, sediments and lake levels, etc. [5 – 7]. The Holocene Thermal Maximum (7-6 ka BP) is characterized by the global mean annual surface air temperature anomaly of 1°C relative to the 1961–1990 period. Nowadays the global temperature is close to 0.77 °C above the pre-industrial level as defined by IPCC [2]. The 1°C rise of the global temperature is expected under scenario of RCP2.6 by 2046-2065 [2].

During Holocene Thermal Maximum (7-6 ka BP) winter and summer air temperatures over the Black and Azov Seas basin are assumed to be higher by 1.0-1.5°C and 0.3-0.9°C respectively and annual precipitation amounts was from -20 mm to 80 mm in comparison to 1961-1990 [6]. The region-scaled mean annual precipitation for the catchment area was 28 mm higher than the mean value for 1961-1990 (figure 1).

**Figure 1.** Deviation of the annual precipitation (mm) from the 1961-1990 mean value for the Holocene Thermal Maximum over the basin of the Black & Azov Seas.

A stationary hydrological model has been developed to evaluate the climate and hydrological parameters of the Sea of Azov with the progress of the global warming. The model is based on the energy and water balance method and on the paleoclimate-based scenario of the global warming by 1°C. The calculations are performed using the data on deviations of annual precipitation amounts, winter and summer air temperatures between the Holocene Thermal Maximum and the current climate values.

Budyko’s «combined method» for estimation of land surface evaporation [4] was adapted to compute energy and water budget of the sea drainage basin. This method is based on a combined solution of energy and water balance equations and two semi-empirical parameterizations of surface evaporation and runoff represented by equations (1) and (2):

1. The evaporation rate is considered to be a function of soil moisture content

   \[
   E = \begin{cases} 
   E_0, & \text{if } W \geq W_0 \\
   E_0 \left( \frac{W}{W_0} \right), & \text{if } W < W_0 
   \end{cases}
   \]  

   (1)

   where \( W \) – soil moisture content, \( E_0 \) – potential evaporation, \( E \) – evaporation, \( W_0 \) – limit value of soil moisture.

2. Surface runoff is considered to be a function of precipitation and soil moisture:
\[ F = \frac{uPW}{W_k} \quad \text{if} \quad P < E_0 \]
\[ F = P\left(\frac{W}{W_k} \sqrt{u^2 - (1 - E_u P^{-1})^2} \right) + (1 - E_u P^{-1}) \quad \text{if} \quad P \geq E_0 \]

where \( E_0 \) – potential evaporation, \( E \) – evaporation, \( W \) – soil moisture content, \( W_k \) – the field capacity, \( u \) – index depending on the intensity of precipitation, \( F \) – runoff, \( P \) – precipitation.

The method is universal as it was tested for various climate conditions. An important advantage of using this method is that the coefficients of the equations are zoned for all climatic and landscape belts and seasons of the year, which allowed us to calculate the water budget for different conditions.

The calculation algorithm consists of a several consecutive steps:

1. Mean monthly values of the heat and water balances of the land surface are calculated using meteorological data on surface air temperature, relative humidity, air moisture deficit, total cloudiness, surface albedo, total solar radiation, precipitation, the dates of formation and melting of permanent snow cover over the catchments’ area of the Black and Azov Seas for 1961-1990.

GIS for the basin of the Black and Azov seas was developed to perform basin-scale calculations. Meteorological stations over study area are shown on the figure 2. In order to verify the method, mean values of calculated potential evaporation and evaporation (monthly, seasonal, annual), river runoff (annual) were compared with the observational data. The comparison showed their good agreement. Calculation accuracy of the annual evaporation estimation was 8%, whereas the annual runoff accuracy was 9% [8].

2. Computation of the energy and water balances of the land surface is carried out for the global warming of 1°C. Monthly air temperature and precipitation changes for the Holocene Thermal Maximum are introduced into the 1961-1990 mean values for each meteorological station.

3. Differences between the values of potential evaporation, runoff and evaporation for a paleoclimate analogue and their values for the baseline (1961–1990) were calculated.

3. Results and discussion

As a result, changes in runoff and evaporation for the study area under the global warming by 1°C have been obtained. Annual runoff values were also obtained over the territory of watersheds of the main rivers flowing into the Black and Azov Seas (the Don, the Kuban, the Dnieper, the Danube, and the Dniester). This was done using mathematical methods of spatial interpolation implemented in the GIS. Figure 3 depicts spatial changes in annual river runoff according to the Holocene Thermal Maximum paleoclimate scenario.

Figure 2. Network of meteorological stations of the Black &Azov Seas basin.

Figure 3. Modeled change in annual river runoff (mm) based on paleoclimatic scenario.

Modeled changes in the annual runoff for the paleoclimate scenario corresponds mainly to the pattern of changes in precipitation. The annual runoff will increase by 10-25 mm in the downstream region of inflowing rivers and will decrease in their upstream regions by 0-15 mm.

The basin-average runoff depth change of all rivers of the Azov and Black Seas catchment is estimated to be +7 mm per year. Hence, according to the calculation performed under the empirical scenario the upcoming global warming by 1°C is expected to increase the total river inflow into the Azov and Black Seas by the volume of about 17 km³ per year. Estimation was accomplished notwithstanding water consumption. The mean annual evaporation will increase over water basin by about 27 mm per year.
Effects of increased precipitation and runoff over the basin of the Azov Sea are of great interest because of the Sea's shallowness and dominating role of the river inflow in its seawater balance. Precipitation increment over the river catchments is estimated to be 30 mm/year for the Don and 65 mm/year for the Kuban. The River Don’s runoff assumed to be higher by 5 mm per year and for the Kuban River runoff – by 24 mm/year. As a result, the total river inflow into the Azov Sea will increase by about 3 km³ per year. As for evaporation, the results point out that mean annual evaporation will increase by 20 mm/year.

Comparison of estimated runoff and evaporation changes with the GCM results showed their significant difference. This difference can be mainly explained by the high variation in GCMs estimations of air temperature and precipitation trends. Later in [9], combining GCMs output with hydrological modelling have been done to estimate future changes in the Don and Dnieper Rivers runoff. Surface runoff was calculated based on the water balance equation and evaporation rate by the equation proposed by V.S. Mezentsev. The results indicated a decrease in the annual runoff by about 25% by the middle of the 21st century. Differences in GCMs data on precipitation and in runoff calculation methods were concluded to evoke substantial bias in prognostic estimation. The paleoclimatic scenario of the Holocene Thermal Maximum as an empirical tool for estimation of the river flow change was also tested in [8]. Projected change in the annual river runoff for the Black Sea basin was evaluated to have values within the wide range from -10 mm to +20 mm. Runoff change estimated in the present study falls within the mentioned range.

4. Conclusions
Methods of paleogeography usually use seawater level as a natural indicator reflecting both short-term and long-term variations in environment and moisture regime for different epochs in the past. In the present study, we apply the paleoclimate analogue for prospecting the hydrological regime over the Black and Azov Seas catchments under the global climate change. Projected change of the total inflow to the seas can be used for the Black Sea and Azov Sea water levels assessment (for the 21st century) along with general circulation models output. For example, substantial Azov Sea level rise can be provided by calculated increase of the river inflow of 3 km³/year which is only 8% of its long-term mean value. It should be noted that present estimates are related to the climate-driven tendency. Irretrievable water consumption, in its turn, should be additionally estimated by using forecasts of economic development or by fixing its present value.

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