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CONTENTS

APPLICATION OF THE «CLIMATE-RUNOFF» MODEL TO THE ASSESSMENT OF THE DUNABE RIVER BASIN WATER RESOURCES IN THE XXI CENTURY ACCORDING TO THE CLIMATE SCENARIOS (A1B)

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ABSTRACT

The results of calculations of possible state of water resources within The Danube River in the XXI century were shown. This estimation was based on the model «climate-runoff», developed in Odessa State Environmental University. As the input to model data of climate scenario A1B (model REMO) were used. Average long-term annual flow values using meteorological data (air temperature and precipitation) from the scenario for different climatic periods of XXI century were calculated. 32 points (grid nodes) which were uniformly distributed over the catchment area of The Danube River were studied. Projection of changes in water resources was given by comparing the calculation results in the past (before 1989) and in the future (1990-2030, 2031-2070, 2071-2100).

The major trends in climatic factors of the flow formation and water resources were established. It is shown that the climatic conditions in the XXI century on the Danube River catchment is unfavorable for the formation of runoff. The positive component of the water balance (precipitation) remains unchanged and the negative component (evaporation) increases. Isolines of norms of climatic annual flow within the whole basin were constructed. It is established that by 2030 a significant reduction of water resources will not occur; during the 2031-2070 diminution will be 17,9%; during the 2071-2100 – 22,0%.

Thus, in the XXI century, changes in the water resources of the Danube will not be destructive and irreversible.

Keywords: water resources, climate change scenarios, the model «climate-runoff»', forecast of Danube water resources change

INTRODUCTION

Water resources are the most valuable natural resource. It is determine the success of economic and social development of the countries. The task of assessing of climate change effects, especially in terms of redistribution of water resources in time and in space, is especially problematic [20]. The river flow is formed, first of all, by climatic factors that determine its zoning. Recently, in the world there is an increase in the number of dangerous hydrological phenomena – catastrophic floods and the reduction of water resources of vast territories [18]. Climate change affects not only quantitative but also qualitative characteristics of river runoff [24]. It requires adaptation measures for all sectors of the economy, population and ecosystems [27]. Ukraine belongs to the countries of the Danube basin [31]. It is located in the mouth of the river and uses significant amounts of water for economic and drinking needs [4]. Prospects for changing the state of the Danube water resources should determine the water strategy of our country in the Northwest part of the Black Sea in the XXI century [14].

The purpose of the work is the forecast of future changes in water resources in the Danube basin based on global scenario data. The object of the study is the water resources of the Danube River. The subject is the quantitative characteristics of the annual runoff of this river, obtained by the «climate-runoff» model [28], using the meteorological data of the A1B climate scenario.

The peculiarity of the study is that the runoff of the Danube River at its mouth is determined by the hydrometeorological processes of its formation zone, which is located in the mountainous parts of the basin. Thus, determining the state of the Danube water resources by meteorological data requires, first of all, the study of climatic factors.

Content of the work is in line with the European Union Strategy for the Danube Region, approved by the EU Council on 24 June 2011, the work of the Coordination Center related to the participation of Ukraine in the implementation of the European Union Strategy for the Danube Region (21 September 2011), the Danube Transnational Program 2014-2020.

LITERATURE REVIEW

Most of the joint international scientific research on Danube water resources relates to their quantitative assessments. Usually they are performed on the basis of observation data [31-33] with the assessment of the natural conditions of the runoff formation and the levels of water management in time and space (mainly along the length of the river). Calculations of the state of the water resources under the scenarios of climate change were carried out by Ukrainian scientists for the part of the Danube basin, which is located in the Ukrainian Carpathians [9, 15]. To calculate the changes in water resources of the transboundary influx of the Danube, the development of scientists from neighboring countries [25] was used. In 1994-1997 the Slovak Republic participated in the second round of the American Research Program, which was conducted with the participation of the American Department of Environmental Protection. From CSMT, Slovakia received five general circulation models, three of which were selected for regionalization (CCCM, GISS, GFDL).

The results of calculations obtained in the Odessa State Environmental University (OSEU) for the territory of Transcarpathia according to the projected scenario data adapted for Slovakia and Ukraine, showed, basically, their satisfactory compliance. The exception was the GISS scenario. According to it in Ukrainian scientists the increase of precipitation will occur 1,06 times (in case of doubling of CO_2 concentration), and according to Slovak scientists - in 1,14 times. As a result of calculations under the GISS scenario, according to Ukrainian scientists, water resources are reduced by 25-31 %, and according to Slovak scientists - by 1-6 % [13]. This discrepancy was due to the insufficient resolution of the CCCM, GISS, and GFDL scenarios that were developed at the end of the last century.

Investigation of the impact of changes in the Danube water resources as a result of global warming on the hydrological, hydrochemical and hydroecological state of the Northwest of the Black Sea is being carried in OSEU. It was done within the framework of the research work «Investigation of the influence of climatic fluctuations on the hydrological and hydrochemical regimes of the Northwest of the Black Sea» in 2010-2011 on order of the Ministry of Education of Ukraine.

Annual runoff calculations were performed using data from global warming scenarios. It was established that while simultaneously doubling the CO_2 concentration in the atmosphere Danube water resources would decrease by 30-42% under the CCCM and GISS scenarios and by 30-37% under the GFDL and UKMO.

It was determined that with the gradual increase of carbon dioxide concentration in the non-stationary GFDL scenario in 2000-2010, the reduction of water resources of the Danube River became 8%, and according to observation data for the period 2000 - 2004 – 1 %. It was found that under this scenario the reduction of water resources in the Danube River will pass a critical limit of 50 % by 2080 [12, 14].

In these calculations, data from the forecast of changes in climatic factors in different climatic zones of Ukraine were used [21]. For the transition from the conditions of the steppe zone (the mouth part in Ukraine) to other climatic zones of the Danube gradients of changes of precipitation and air temperatures with height were established. Modern scenarios of climate change, including A1B, describe the study area in more detail and are available in electronic resources [8]. This made it possible to estimate changes in the water resources of the Danube River with greater accuracy.

METHODS AND DATA

The Danube River belongs to the Black Sea basins and is the largest river in Central and Southeastern Europe. The total catchment area is 817000 km^2, and the length is 2857 km. The Danube River crosses various landscape zones with a pronounced diversity of natural conditions. Most of the Danube river basin is in the mixed forest zone, the bottom reaches the forest-steppe and steppe zones. The orographically, the watershed of the Danube River is very heterogeneous and includes both mountainous and plain areas (Table 1). According to the data [26], the difference between the highest and lowest points of relief is 3651 m. Mountain areas with a height of more than 500 m include 31% of the total catchment area.

Table 1. Distribution of the catchment area of the Danube River in high altitudes

Altitude zone, m	Average height of altitude zone, m	Area of high-altitude zone, %
<100	50	18
100-500	150	51
501-1000	750	23
1001-2000	1500	6,5
>2000	2500	1,5

According to the complex of physico-geographical and geological features, the Danube River is divided into three parts: Upper, Middle, and Lower Danube [31, 32] (Fig. 1). Such a distribution is confirmed by the results of factor analysis [16, 22], which we used to estimate the synchronization of annual precipitation variations (Fig. 2).

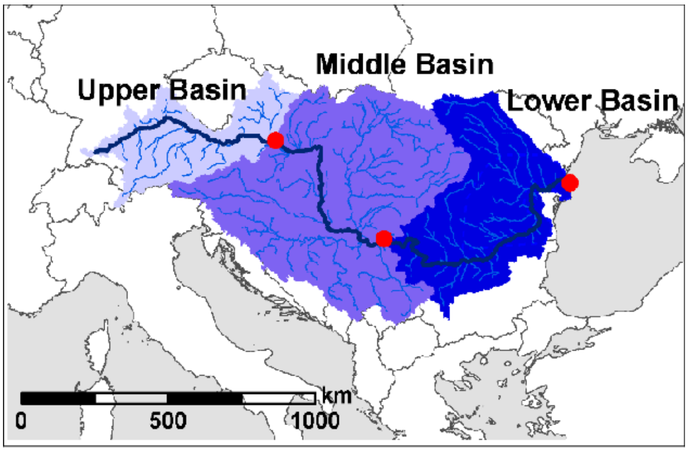

Fig. 1. Main parts of the Danube river basin [27]

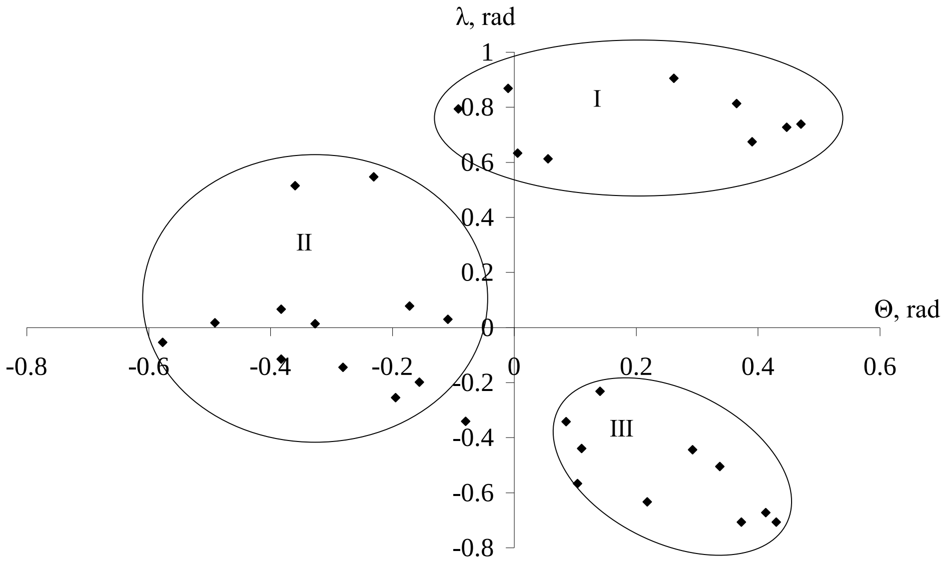

Fig. 2. Allocation of groups with synchronous quantities of precipitation based on three

factors (I - the region of the Supreme Danube, II - the region of the Middle Danube, III - the Lower Danube area)

Most often, in the assessment of the impact of climate change on water resources of territories with a not dense network of hydrometeorological observations, balance models are used.

To be more precise, it is models of water and water-thermal balance, which combine both the water balance of the catchment and the thermal balance of the underlying surface. The fact is that the equations of water and heat balances contain a common component - evaporation from the surface of the land. This allows the use of heat balance components to calculate evaporation.

In Odessa State Environmental University over the past three decades for assessment of water resources of Ukraine using meteorological data model «climate-runoff» was used. It was developed by prof. E.D. Gopchenko and prof. N.S. Loboda [5]. The development of such a model was relevant in the second half of the twentieth century because of the lack of data of runoff observations in both natural and disturbed water management. Since the 1980s, relevance, theoretical and practical significance of the model has increased as a result of the addition of climate change [6]. The model has been calibrated and verified on the materials of river flow of different geographical zones of Ukraine. It is sensitive to modern changes of climatic factors. This model allows to estimate with satisfactory accuracy the zonal runoff and influence of the underlying surface, including water management transformations [11]. The developed method of calculating the characteristics of annual runoff has become a component of the State Building Norms of the Republic of Moldova [17] and is included in the new edition of the State Building Norms of Ukraine [7].

The «climate-runoff» model consists of two parts. The first part allows estimation of natural annual runoff on the basis of meteorological data, the second - the estimation of domestic (transformed by water management) runoff. At the entrance to the first part of the model meteorological data are used, in the second - the natural (undisturbed water management) annual runoff and quantitative indicators of water management transformations.

To estimate the changes in water resources at the Danube catchment area, the first part of the model was used. The theoretical basis of it is the equation of water-heat balance of the catchment area. For a long period, it looks like

$$\bar{Y}_K^{'} = \bar{X}^{'} - \bar{E}_m^{'}\left[1+\left(\frac{\bar{X}^{'}}{\bar{E}_m^{'}}\right)^{-n}\right]^{-\frac{1}{n}}, \qquad \textbf{(1)}$$

where $\bar{Y}_K'$ is the average long-term value of annual climatic runoff in terms of climate change, mm; $\bar{E}_m^{'}$ - average long-term value of the maximum possible evaporation in the terms of climate change, mm; $\bar{X}^{'}$ - the average long-term value of annual precipitation in terms of climate change, mm.

It is established that the norms of annual climatic runoff correspond to the norms of zonal runoff of rivers in natural conditions of its formation [10]. The accuracy of determining the statistical parameters of annual runoff using the «climate-runoff» model is within the accuracy of calculations (±10,0% for the average long-term value of annual runoff). The structure of the water-heat balance equation (1) allows it to be used to calculate runoff with meteorological data of climate scenarios.

The study used the international ENSEMBLES project database, which can be accessed on the Internet at http://ensemblesrt3.dmi.dk. The A1B scenario (REMO model) was chosen for the calculations, which is characterized by the highest correspondence of observed and simulated meteorological series for the retrospective period in Europe.

The A1B climate change scenario is implemented in the REMO regional climate model developed at the Max Planck Institute for Meteorology in Hamburg, Germany. REMO integrates the former numerical EUROPA-MODEL weather forecast model for the calculation of thermodynamic characteristics and the ECHAM5 global climate model unit [29].

For the study of changes in the main climatic factors of runoff and water resources formation within the Danube catchment area 32 points were considered. It is point-nodes of the 25 km grid of scenario data with different physical and geographical conditions.

To estimate changes in the basic hydrometeorological characteristics (average values of annual precipitation, maximum possible evaporation, climatic runoff), a comparison of the calculated values obtained for different climatic periods in the 21st century was performed. Periods 1990-2030, 2031-2070, 2071-2100 were compared with relevant characteristics of the base period (1951-1989), in which the manifestation of changes in air temperatures was not yet statistically significant in either Ukraine or Europe [3, 23].

Trends in meteorological fluctuations were detected by meteorological stations located at the Danube catchment area in different parts of it. The type of trend equations and correlation coefficients were determined on the basis of regression analysis [30].

RESULTS AND DISCUSSION

The analysis of time series of the annual air temperature (scenario A1B) showed the existence of trends to their growth for all 32 weather stations. For example, at the point corresponding to the meteorological station Innsbruck, the conditional mathematical expectation of annual air temperatures will increase from 2.3 °C in 1951 to 6.9 °C at the end of the XXI century (Fig. 3), in Belgrade - from 12.0 °C to 16,5 ºC, and in the Danube Delta (Izmail) this characteristic will increase from 11,8 ºC to 16,3 ºC. By the end of the XXI century, as compared with the middle of the last century (1951), the annual air temperature increase would be on average about 4.0 ºC. And compared to 1989 (year with a statistically significant increase of air temperature in Ukraine) will be 3-3,5 ºC.

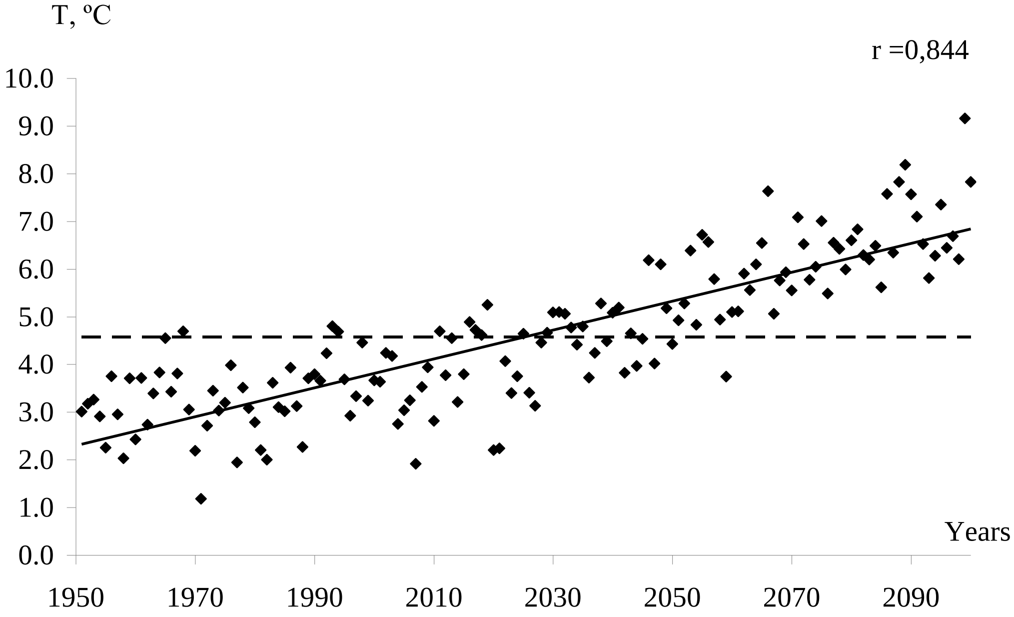

Fig. 3. Time series of the annual air temperature, scenario A1B, Innsbruck (---- average long-term value, —— trend line)

It has been established that average temperatures of warm (IV-X) and cold (XI-III) periods will also increase in all studied meteorological stations. The increase in the air temperatures of the cold period in the upper Danube will occur not so intensively, as at the mouth. However, the transition of the average temperatures of the cold period from the negative values to positive in the 30 years of the XXI century (Fig. 4) is well marked. This transition during the cold period means changing the conditions of the formation of the spring runoff. The contribution of thawed water to the formation of the runoff will decrease, and the role of rain floods and underground river recharge will increase.

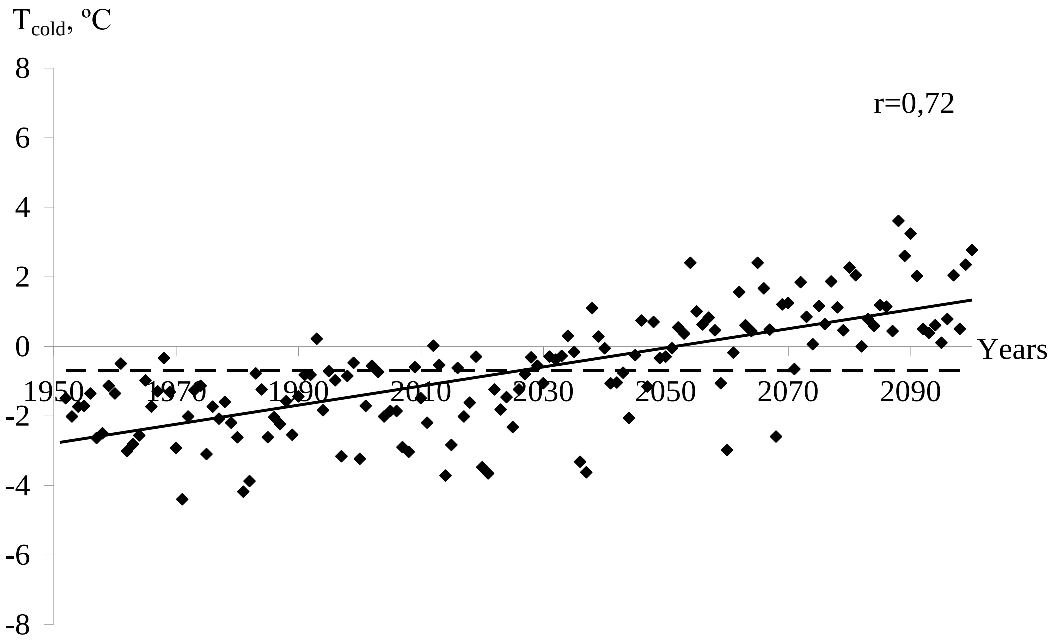

Fig. 4. Time series of the air temperature of the cold (XI-III) period, Murau, 1951-2100 (---- average long-term value, —— trend line)

An analysis of the time series of annual precipitation amounts as well as precipitation amounts of warm and cold periods showed that it was not possible to detect statistically significant trends in their fluctuations during the period 1951-2100 on all 32 stations (Fig. 5).

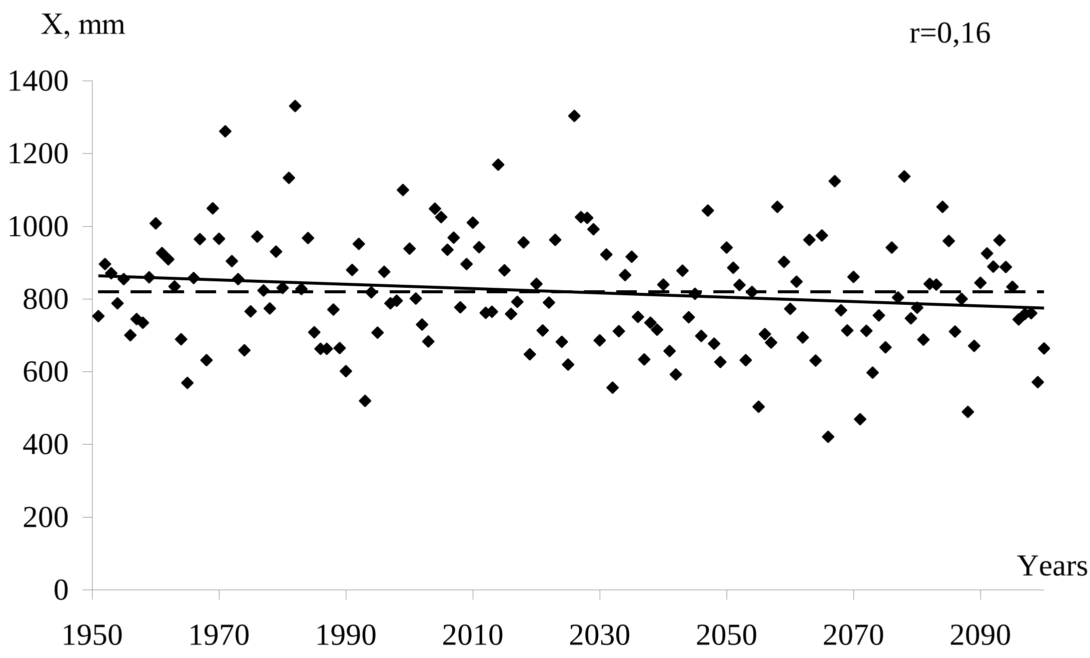

Fig. 5. Time series of the annual precipitation, scenario A1B, Bihac (---- average long-term value, —— trend line)

The results of the study of the trend existence in the fluctuations of climatic factors correspond to those obtained by the authors for the Northwest Black Sea: air temperatures are projected to increase at the background of almost unchanged precipitations [2, 3]. Such climatic conditions are unfavorable for the formation of runoff, since the growth of air temperatures leads to an increase in evaporation from the surface of the land.

Comparison of the average long-term precipitation before and after 1989 showed that during the period 1990-2030 the amount of precipitation at individual points-meteorological stations will grow and decrease. Compared with the scenario data until 1989, these changes will be within ± 10 %. The average relative deviation of the average values $\overline{X}$ for the estimated climatic period (1990-2030) from the corresponding value for the basic climatic period (1951-1989) will be ± 2,7 %. During the estimated period 2031-2070, changes in the humidity resources compared with the base period will be ± 4,0 %, and in the period 2071-2100 - ± 4,2 %.

The maximum possible evaporation (heat equivalent) will increase throughout the catchment area by increasing air temperatures. Compared to the base climate period (1951-1989), the increase of $\overline{E}_m$ will be + 6,9 % in 1990-2030; 22,4 % - in 2031-2070; 39,9 % - in 2071-2100.

The peculiarity of the «climate-runoff» model is that the meteorological data are calculated at points that correspond to the position of the grid stations. An analysis of the climate runoff values $\overline{Y}_K$ for each point showed that during the 1990-2030 the largest changes of $\overline{Y}_K$ would not exceed «minus» 15 %. The average relative deviation of the compared values would be ±11,2 %. Destructive effects of global warming under the A1B scenario will start from 2030. From this year the increasing of air temperatures will become more intense. In 2031-2070, averaged reduction in annual climate runoff will reach «minus» 32 %, and in 2071-2100 - «minus» 40 %.

However, simply averaging the climate runoff values for each point-node does not give a complete picture of the average long-term runoff from the Danube catchment. The weight coefitient of each point may be different. To identify possible changes in the Danube water resources in the 21st century, maps of isolines of the annual climate runoff norms were constructed for each of the calculated climatic periods. An average annual value of annual runoff from the catchment was also established by the method of «weighing» by area [19]. This average long-term annual runoff of the Danube River for the basic climatic period (1951-1989) is 246 mm, which corresponds to the actual data [1,31]. The differences are within ± 5.0 %. The distribution of the isolines of the annual climate runoff norms is in accordance with the developed maps of the runoff norms of the annual runoff given in professional editions [32].

According to the A1B scenario, the water resources of the Danube catchment area will decrease over time (Table 2).

Table 2. Changes of average long-term annual climatic runoff of Danube River, determined by weighing in different time intervals (at comparison with the data before 1989)

Characteristic	The climate period			
	1951-1989	1990-2030	2031-2070	2071-2100
Average long-term values of annual climatic runoff $\overline{Y}_K$, mm	246	231	202	192
Changes of $\overline{Y}_K$ in comparison to the baseline climatic period 1951-1989, %		-6.1%	-17.9%	-22.0%

A more complete picture of the change in the Danube water resources is given by the isolines of relative deviations δ

$$\delta = \frac{\overline{Y_K}' - \overline{Y_K}}{\overline{Y_K}}, \qquad (2)$$

where $\overline{Y_K}'$ is the average annual value of annual climatic runoff, calculated according to scenario data, mm; $\overline{Y_K}$ - the average annual value of the annual climatic runoff, calculated for the basic climatic period.

The isolines maps were constructed. According to them the decrease in the annual climatic runoff is well traced in the direction from northwest and north to south (Fig. 6, Fig. 7).

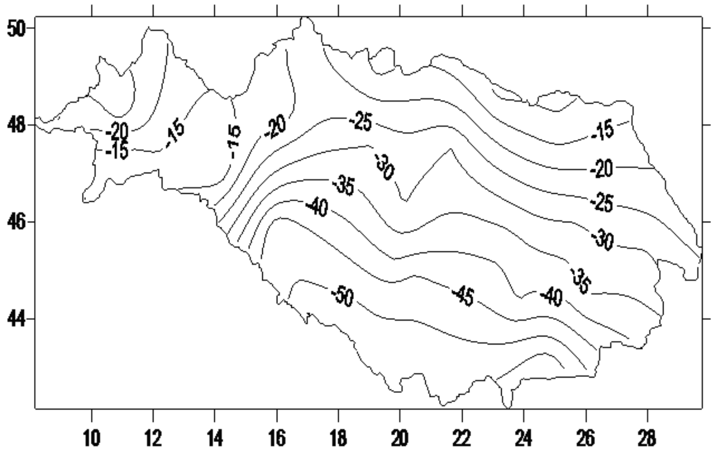

Fig. 6. Spatial distribution of relative deviations (%) of annual climate runoff in the Danube basin according to the A1B scenario (REMO model) for the period 2031-2070 compared to 1989

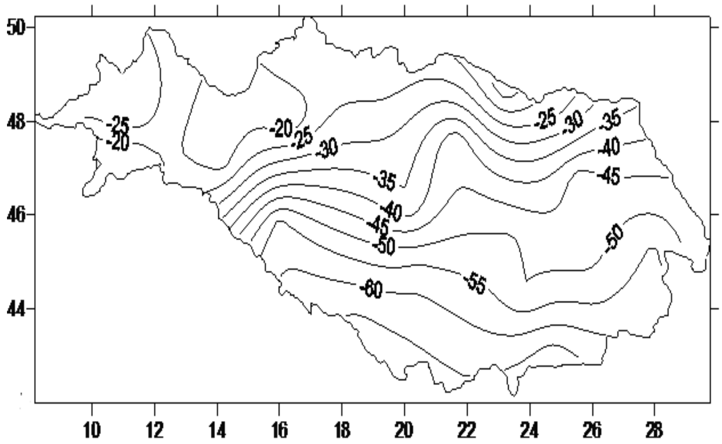

Fig. 7. Spatial distribution of relative deviations (%) of annual climate runoff in the Danube basin according to the A1B scenario (REMO model) for the period 2071-2100 compared to 1989

In the period 2031-2070, the interval of changes is within the «minus» 15-20% in the northwest and north to «minus» 50% in the south. In the period 2071-2100, the decrease in annual climate runoff is 20-25% in the north and northwest (if compared to the base period) and reaches 70% in the south. The obtained results of the calculations of water resources by the «climate-runoff» model make it possible to conclude that a significant reduction of water resources of the Danube River will occur after 2030. The least affected by climate change will be the areas of the sufficient humidity. The plains and the southern part of the Danube catchment, which belong to the area of insufficient moisture, will be the most hit.

CONCLUSIONS

The climatic conditions of the 21st century by the A1B scenario at the Danube catchment are unfavorable for runoff formation. The positive component of the water balance (precipitation) remains unchanged and the negative component (evaporation) increases. The water resources of the area will decrease under such climatic conditions.

Changes in water resources will occur in different parts of the Danube catchment area. They will be the smallest in the northwest and north of the catchment area and will increase in the southeast. In the period 2031-2070, the reduction of water resources by the A1B scenario will reach 50 % in the south, and in the period 2071-2100 – 70 %.

The total annual runoff from the catchment of the Danube River was determined by «weighing» the values of runoff in areas by parts. It was established that the river water resources will decrease very gradually: in the period 1990-2030 – by 6,1 % (decreasing will not be statistically significant), in the period 2031-2070 – by 17,9 %, in the period 2071-2100 – by 22,0 %. This result is ensured by the high water content of the Danube mountainous zones, which are the areas of runoff formation. In mountainous areas that climate change will be least affected.

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