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THE ROLE OF METEOROLOGICAL DROUGHTS IN LOW FLOW PERIOD ON THE RIVERS OF THE NORTH-WEST BLACK SEA REGION IN PRESENT AND FUTURE (BY THE CLIMATE SCENARIOS DATA)

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Abstract. Changes of climate aridity in the North-west Black Sea Region are analyzed by retrospective and scenario (A1B and RCP4.5) meteorological data using Standardized Precipitation Evaporation Index (SPEI). It is concluded that in recent decades the number and severity of meteorological droughts has increased. According to scenarios, drought intensity is projected to increase by 2050.
The main factors of low flow formation based on factor analysis are revealed. Multiple stepwise linear regression shows that SPEI can be successfully used as predictors in constructing of dependencies for calculation and prediction of low-flow characteristics.
Keywords: North-West Black Sea Region, drought, indices of aridity, index SPEI, low-flow prediction.

Introduction. Ukraine has signed an association agreement with the European Union and its Member States. The implementation of EU environmental legislation is regulated by 29 EU sources of law - Directives to which the State of Ukraine must adapt its legislation (http: //minjust/gov.ua/45875). Among these Directives is

Directive №24 “River basin management in the conditions of climate change”. It foresees the adaptation of the country to the effects of global warming. One of the manifestations of climate change in Ukraine is the increase of the number of extreme weather events, including those as dangerous as droughts. Droughts are one of the main natural causes of social, economic and environmental damage [1].

The area of the Northwest Black Sea is located in a zone of low humidity. Rivers are characterized by low runoff. 89% of the Black Sea Rivers are medium-sized with a catchment area of 100-1000 km^2 (according to the European Union Water Framework Directive). Only three rivers have a catchment area of 1000-10000 km^2 [2]. Water deficit was offset by a flow of large rivers (Danube, Dniester, Southern Bug) (Fig. 1). In the times of the USSR, powerful melioration systems operated here, on which surface water was diverted. Many rivers were part of these systems. At present, the melioration network has been reduced. The ponds created for intra-annual regulation of runoff have turned into artificial evaporators. It greatly reduces the rivers runoff of the study area [3]. At the beginning of the XXI century water resources has degraded because of rising air temperatures on the background of a slight change in precipitations. This caused drying up of rivers with unstable underground river recharge. This also led to a decrease in low water period for rivers, which drain the main aquifers of the zone of active underground water exchange.

Fig. 1. Geographical location of North-Western Black Sea Region

Meteorological drought is period with long-term (multi-day, multi-month, multi-year) dry weather with often elevated air temperature and no or very low precipitation, which leads to depletion of water (moisture) in the soil and a sharp decrease in relative humidity [1].

Meteorological droughts create unfavourable conditions for the river runoff formation. As a result, there is a shortage of water consumption. From an environmental point of view, the effects of drought are crop failures, degradation of meadows, reduced wood growth, livestock loss, and sharp fluctuations in the number of microorganisms. There are different approaches to drought classification. Droughts, which are considered as a manifestation of climatic variability, are divided into the following categories: meteorological, agricultural, hydrological, socio-economic [4]. Hydrological drought occurs as a result of prolonged meteorological drought with some shift in time and an indicator of water resources depletion [5]. For rivers with a sustainable underground supply, the hydrological drought characteristic can be the number of days when the water runoff in a river is below a certain critical value. If the river dries even in natural conditions, the hydrological drought may be the number of days (in each month and in the whole year) during which the river has dried up.

Most scientists believe that climate changes are the one of the main factor of increasing the number of droughts, its duration and intensity. This is confirmed by the results of a studies of the Intergovernmental Panel on Climate Change [6].

Methods. One of the most common approaches to drought analysis is based on the use of special indices. These indices should reflect meteorological phenomena and conditions conducive to the occurrence of agricultural or hydrological drought. Almost all existing drought indices are based on a comparison of existing water supplies (in which precipitation is the main component) with water losses from evaporation from the land surface. The latter are determined by the influx to the earth's surface of solar radiation. The components of the radiation balance are measured only at actinometrical stations, so air temperature is often used to characterize the inflow of heat to the earth's surface. The most known in the literature drought index α was proposed by De Martonne [7].

The α index is determined over a multi-year observation period and is calculated as:

$$\alpha = \frac{X}{10+T} \quad , \qquad (1)$$

where X - average long-term precipitation, mm; T - average long-term value of air temperature, ºC.

If the value α <15, then the study area is classified as arid.

In the modern estimates of aridity indicators are more commonly use data about precipitation and maximum possible evaporation (also called potential evaporation or potential evapotranspiration *PET*). This characteristic is considered as the maximum amount of water that could evaporate from the vegetation-covered land surface in these climatic conditions, provided sufficient moisture supply. According to the formula of Thornthwaite [8], it is calculated as a function of sums of temperatures for 12 months. If the average annual precipitation is less than PET, then the study area is classified as semi-arid zone.

According to UNESCO recommendations [9], the degree of aridity is determined depending on the ratio of moisture and heat resources:

$X / PET < 0{,}03$ – hyperarid zone;

$$0{,}03 \le X / PET < 0{,}20 - \text{ arid zone;} \qquad (2)$$

$0{,}20 \le X / PET < 0{,}50$ – semi-arid zone,

where X - average annual precipitation; PET - potential evaporation.

On the territory of Ukraine, the model of water-heat balance was used to determine the aridity index. Model introduces the concept of maximum possible evaporation or heat-energy equivalent E_m [10], which is close in content to *PET*. The value of E_m is interpreted as the maximum possible evaporation from the land surface, which would occur if all the revenue components of the land heat balance were spent on the evaporation process. A similar approach was proposed by the L. Turk [11]. Turk's research was later developed by polish hydrologist Z. Kaczmarek [12] during his work in the Working Group of the Intergovernmental Panel on Climate Change [13]. On the basis of the water-heat balance, by analogy with (2), the degree of aridity of the territory of Ukraine was determined as the ratio between moisture resources $\overline{X}$ and heat $\overline{E}_m$. This ratio is denoted as $\beta_X = \frac{\overline{X}}{\overline{E}_m}$. Depending on the ratio, different areas of aridity or moisture were determined

$\beta_X \geq 1{,}0$ – the zone of excessive moistur;

$$0{,}8 \leq \beta_X < 1{,}0 \text{ – the zone of sufficient moisture;} \quad (3)$$

$$0{,}5 \leq \beta_X < 0{,}8 \text{ – the zone of low moisture;}$$

$0{,}2 \leq \beta_X < 0{,}5$ – the semi-arid zone.

It should be noted that by the end of the 90-ies of the XX century the semi-arid zone occupied a narrow coastal strip.

In the last decades, standardized precipitation index (SPI) has been widely used, which can be calculated for any place using a long series of precipitation observations and is based on the notion of standardized precipitation [14]. Standardized precipitation means the deviation of their value over a period of time from the average value, divided by the standard deviation. That is, the normalized values are used. This index was further modified by the inclusion of the concept of total potential evaporation *PE* [15]. So calculated index was called the Standardized Precipitation and Evaporation Index (SPEI).

SPEI indices are calculated using the method presented in [15].

The resulting equation looks like this

$$SPEI = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3}, \quad (4)$$

$W = \sqrt{-2\ln(P)}$, for $P \leq 0{,}5$, (5)

P - is the probability of exceeding a determined value, where $P = 1 - F(x)$; C_0, C_1, C_2, d_1, d_2, d_3 - constants.

The average SPEI value is 0 and the standard deviation is 1. SPEI is a standardized variable and can be compared to other SPEI values in time and space.

The drought classifications is determined according to SPEI value (Table 1).

Table 1

Classification of SPEI [14]

SPEI values	Category period	Категорія посухи
SPEI ≥ 2,00	Extremely moist	
1,50 ≤ SPEI ≤ 1,99	Very wet	
1,00 ≤ SPEI ≤ 1,49	Moderately moist	
0 ≤ SPEI ≤ 0,99	Close to normal	
0 ≥ SPEI ≥ -0,99	Close to normal	Mild drought
-1,00 ≥ SPEI ≥ -1,49	Moderately dry	Moderate drought
-1,50 ≥ SPEI ≥ -1,99	Very dry	Severe drought
SPEI ≤ −2,00	Extremely dry	Extreme drought

The SPEI determination procedure is based on the calculation of monthly average differences between precipitation and potential cumulative evaporation and has been implemented internationally since 2009. The presence and intensity of drought are determined according to the SPEI values from the Table 1.

Results. SPEI indices were calculated using special computer software for meteorological stations located in the North-West Black Sea Region. The input file contained information on average monthly air temperatures, precipitation amounts and weather station coordinates [15].

Between 17 and 38 cases of droughts of varying duration and intensity were recorded at the meteorological stations. After 1989 (this year was recorded as a turning point, after which statistically significant changes in air temperatures began in Ukraine), the frequency of light and extreme droughts increased throughout the North-West Black Sea Region. When considering the entire observation period, it was found that weak droughts last the longest. The occurrence of monthly SPEI≤0,00 indices after 1989 increased by 20%.

In order to identify the main factors that determine the low-water runoff characteristics in summer and autumn seasons, the investigation of the relationship between minimum runoff characteristics and indecies of aridity was made [16].

The matrix of correlations between different factors of low-water flow formation was investigated by factor analysis. 19 catchments located in Ukraine and Moldova has been considered. It was established that the correlation matrix is described by 4 factors. The first factor accounts for 29,8% of the variance of the raw data, the second – 28,0%, the third – 24,1%, the fourth – 6,07%. The total contribution of the first three factors is 81,9%, of the four – 88,0%. Studies of the factor weights on each of the considered factors have allowed to establish that the first factor indicates the existence of statistically significant relationships between the low water and the underground river recharge. The second factor reflects the role of the catchment area in the formation of the discharges of low flow period. The third factor can be interpreted as describing the indicators of climate aridity. The fourth factor reflects the physical process associated with the impact of forest cover on the duration of the low water period.

The application of the regression analysis method to construct prognostic dependencies on the factors of low-water flow formation has shown that the SPEI aridity index can be used to predict the characteristics of the average monthly minimum runoff with duration of 1 and 2 months.

The general view of the developed prognostic dependencies is:

$$Q_{m,i} = a_0 + a_1 Q_{m,i-1} + a_2 SPEI_{i-1}; \tag{6}$$

$$Q_{\min d,i} = b_0 + b_1 Q_{\min d,i-1} + b_2 SPEI_{i-1}; \tag{7}$$

$$t_{Q<Q_P,i} = c_0 - c_1 Q_{m,i-1} - c_2 SPEI_{i-1}, \tag{8}$$

where Q_m – the average monthly water discharge, m^3/s; $Q_{\min,d}$ – minimum daily water discharge, m^3/s; $t_{Q<Q_P}$ – duration of period when the water discharges were lower than the discharges of P-% probability, days; *SPEI* – index of aridity; i - the number of a calendar month.

Drought indices estimates for different scenarios, such as Special Report In Emissions Scenarios SRES [17] and Representative Concentration Pathways - RCP [18], showed that by all scenarios, most of the North-West Black Sea Region territory by 2050 will transform into the semi-arid zone with $0{,}2 \le \beta_X < 0{,}5$ [19, 20].

Calculations of SPEI indices by the data of global warming scenarios have shown that by mid-21st century, according to the A1B scenario, from 11 to 15 droughts of varying intensity and duration will be possible in the North-West Black Sea Region (fig.2). The amount of intense and extreme droughts will increase compared to retrospective data. The longest will be mild droughts.

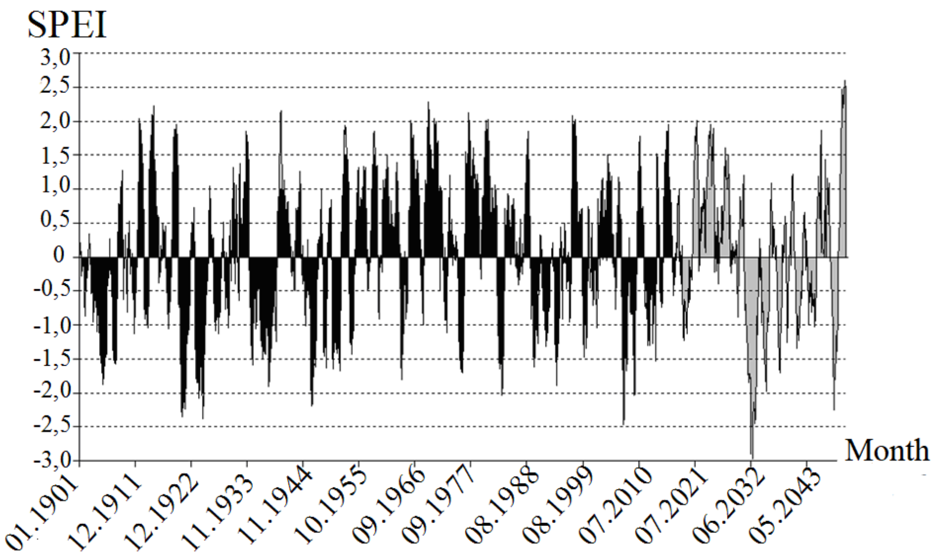

Fig. 2. Chronological course of SPEI indices, Odesa, 1901-2013 (black – by the retrospective data), 2014-2050 pp. (gray - by the A1B scenario)

Conclusion. Climate change analysis using the SPEI standardized index shows that in the beginning of the 21st century, the number and severity of meteorological droughts is increasing across the North-West Black Sea Region.

Climate change scenarios A1B and RCP4.5 have been considered in order to predict the possibility of drought formation in the future. An analysis of the SPEI index calculated from climate scenarios has shown that by 2050 there will be an increase in the number of intense and extreme droughts. The greatest duration will be characterized by weak droughts. According to the indicator β_X, which represents the ratio of moisture resources to heat resources, the transition from the zone of insufficient humidity to the zone of semi-humid climate is projected. It is shown that monthly drought indices (SPEI) can be used as predictors in constructing of dependencies for calculation and prediction of the characteristics of the average monthly minimum runoff.

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