Monitoring and Evaluation of Water Availability of the South of Ukraine and Russian Federation with Usage of the Standardized Precipitation Index

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Abstract **– The methodology of the Standardized Precipitation Index (SPI) usage for evaluation of the level of water availability of the territory for the estimated period in comparison with long-term precipitation rate is given in this paper. Using the methodology of normalized parameters assessment gives possibility to make it comparable for different territories and regions as well as for different time scale, enable to conduct a retrospective analysis, evaluate the current situation or study the influence of probable climate change scenarios. Examples of water availability evaluation mapping of the South of Ukraine and Russia by SPI on the base of processing of the long-term precipitation records and weather data of spring 2014 with GIS tools using are given. Recommendations on the Standardized Precipitation Index application for the evaluation of agricultural and hydrological droughts and potential risk for waterworks objects have been proposed.**

Keywords – Water availability; monitoring; evaluation; Standardized Precipitation Index; mapping; Ukraine; Russia

I. INTRODUCTION

The Standardized Precipitation Index usage becomes more and more popular methodology of current state of water availability estimation in comparison with average, typical for local area conditions. Although the possibility of normalized values of precipitation for different time scales can be used both for the analysis of retrospective data and probable scenarios (related with climate change), but it received the widest expansion due to the monitoring of current situation related with risk evaluation of meteorological and agricultural drought [1, 2, 3], especially in arid regions.

II. STUDY AREA AND ACTUALITY

The Sought of Ukraine and Russian Federation (RF) belong to the regions of risk agriculture with a high probability of the drought appearance of different duration and intensity. Precipitation rate has ranged from 250 – 350 mm in Astrakhan (RF) and steppe zone of Crimea to 350-450 mm per year in the northern parts of Odessa, Nikolayev and other parts of the South of Ukraine, and in the south of Volgograd, the north of Rostov region, Stavropol and Krasnodar Territories of RF.

To obtain integrated indicators of water availability of the territory in addition to geophysical and meteorological parameters, indices of state of waterworks infrastructure are often used. It gives the possibility to take into consideration the local conditions, but creates certain limitations for indicators comparison. Presence of these limitations and the necessity of getting considerable quantity of additional parameters narrow the field of application of integrated composite indices and in many cases experts have to return back to some simplified ones, introduce in their usage new understanding, new possibilities of visualization, space and time analysis. The Standardized Precipitation Index, developed near 20 years ago, is a striking example thereof. SPI has acquired new perception due to modern technologies of its application not only for the monitoring of the current situation of the territory aridity, but for the visualization of these processes at the level of the regions and countries integrally, and for the mutual influence of drought periods on waterworks functioning.

III. METHODOLOGY

Long-term precipitation data (monthly sum) are used to calculate SPI – at least 30 years recommended. Time step can vary from 1 to 48 months depending on the analysis goal. Shorter periods (1-3 months) are used for monitoring of meteorological and agricultural drought appearance, and longer periods (usually multiple 3 months) used for analysis of hydrological drought appearance, waterworks conditions functioning and other tasks.

Methodology of SPI calculation and idea of its application for the territory of the United States were developed more than 20 years ago [4]. Value of the index is dimensionless. Taking into account its normalization, i.e. transformation of distribution law of stochastic variable to normal, and for data set of certain meteorological station it is described as

$$SPI = \frac{x_i - \bar{x}}{\sigma} \qquad (1)$$

where, x_i - sum of precipitation for *i* year and taken time scale, mm;

x - mean of sum of precipitation for taken time scale, mm;

σ - standard deviation of sum of precipitation for data set and taken time scale, mm.

Actually this index represents a central deviation expressed by number of standard deviations [5]. Although curve of density of the distribution of normal law of probability theoretically is not limited from the left and right side, from practical point of view, SPI is said to be able to vary from +4 to -4, but even out of +3 and -3 boundaries there are events that may appear less than once per 1000 years (if we are talking about the analysis of monthly sum of precipitation).

Taking into consideration wide spreading of gamma probability distribution for precipitation analysis, SPI developers used this statistical function, frequency distribution of which is described as [6]

$$f_x(x) = (\lambda^{\alpha} x^{\alpha-1} e^{-\lambda x}) / \Gamma(\alpha) \text{ for } x > 0, \quad (2)$$

where, α, λ – shape and scale parameters;
Γ(α) – Euler's gamma function, expressed as

$$\Gamma(\alpha) = \int_0^{\infty} x^{\alpha-1} e^{-x} dx \quad (3)$$

Moments matching or maximum likelihood estimation methods are most frequently used for determining of α and λ parameters. Gamma function has not been defined for zero data values. That's why for such periods (without precipitation or when precipitation is equal to zero) cumulative probability is defined as a sum of the probability of appearance of such periods and value of probability integral of gamma density function.

To transfer from gamma to normal probability distribution approximation equations can be used (see [7], for example).

Simplified rational approximation [8] was used for transformation gamma distribution probability into curve of normal distribution (with error < $3\text{x}10^{-3}$, taking into account 30 years precipitation minimal data set usage).

If cumulative probability denoted as p and introducing additional parameter Z, rational approximation ([7, 8], has been modified) and SPI calculation can be made with the next relations

$$Z = (2.30753+0.27061\, t) / (1+0.99229\, t+0.04481\, t^2) \quad (4)$$

where, for $p \leq 0.5$

$$t = (\ln (p^{-2}))^{0.5}, \quad (5)$$

$$\text{SPI} = Z - t, \quad (6)$$

for $p > 0.5$

$$t = (\ln (1 - p)^{-2})^{0.5}, \quad (7)$$

$$\text{SPI} = t - Z \quad (8)$$

Though it is easier to realize calculation algorithm of gamma distribution transformation to the normal probability distribution, however Pearson III type, incomplete beta distribution or others can be used as initial distribution as well (taking into account local regional specific conditions). It is necessary to underline that in a number of cases (for Crimean steppe zone meteorological stations, for example) there is practically small difference between results of SPI estimation, received with Pearson III type or gamma distribution usage.

It is accepted that essential lack of soil moisture and drought phenomenon begin at SPI value less "-1". Conditional boundaries of drought severity or wet conditions suggested by authors of methodology [4, 9] differ from the ones accepted in Ukraine and RF. For example, "-1" SPI value complies with accepted boundary of "average dry" conditions with probability of occurrence less precipitation value for the time period near once per 6 years, and even less value of aridity (once per 4 years or SPI = - 0.674) frequently used for designing of some of water infrastructure. Therefore, boundaries offered in table can be considered as referenced only.

TABLE I. EVALUATION OF WATER AVAILABILITY FOR THE SPECIFIC PERIOD ACCORDING TO SPI VALUE

SPI	Rating*	Probability, %	
		Exceeding	*Less value*
> 3.00	EW	< 0.13	> 99.87
2.50	EW	0.62	99.38
2.00	EW	2.28	97.72
1.645	VW	5.00	95.00
1.50	VW	6.68	93.32
1.282	WE	10.00	90.00
1.00	WE	15.87	84.13
0.674	AW	25.00	75.00
0.524	MW	30.00	70.00
0.50	NN	30.85	69.15
0.00	AV	50.00	50.00
-0.50	NN	69.15	30.85
-0.524	MD	70.00	30.00
-0.674	AD	75.00	25.00
-1.00	DR	84.13	15.87
-1.282	DR	90.00	10.00
-1.50	VD	93.32	6.68
-1.645	VD	95.00	5.00
-2.00	ED	97.72	2.28
-2.50	ED	99.38	0.62
< - 3.00	ED	> 99.87	< 0.13

*EW - extremely wet; VW – very wet; WE – wet; AW – average wet; MW – moderately wet; NN – near normal; AV – average or normal; MD – moderately dry; AD - average dry; DR – dry; VD – very dry; ED – extremely dry.

Below there are the examples of SPI usage for the estimation of availability level of precipitations (or water resources deficit / drought severity) for the territory of the South of Ukraine and RF, and its interrelation with dynamics of groundwater level and changing of the volume of reservoirs.

IV. Results and Discussion

Water availability of the territory can be split on two components - natural and additional, which are formed due to the inflow additional water resources in the territory under study from its boundaries in the form of river flow or by the network of sufficient canals or pipelines (including possible additional feeding of deep aquifer with waters formed in other territories).

Natural water availability is determined, first of all, with available local water resources and can be characterized by ratio of precipitation and evapotranspiration, stream frequency or flow rate from the territory. However, incoming energy flux on the territory for the specific period, which determines level of potential evapotranspiration, has more sustainable value. Therefore, current state of the water resources availability (without taking into consideration soil moisture changing) depends above all on the sum of precipitation for a span (for short as well as medium-term periods that is especially important for agricultural drought monitoring).

At the same time variable calculation interval gives the possibility to perform monitoring of different processes simultaneously, such as estimation of availability of water resources or soil moisture for agricultural crops (or level of the deficit), changes of inflow into the reservoir or dynamics of effective reservoir capacity, as well as changing of groundwater level.

There are the results of SPI calculation carried out for the territory of the South of Ukraine and Russian Federation for 3-month time scale in Figure 1 with the results visualization by means of open GIS (QGIS 2.0 [10]) for spring period of 2014. Calculation results show significant deviation from precipitation rate in the territory of Crimean peninsula that can lead to shortage of agricultural production compared to mean value of this territory for the previous years.

Meteorological parameters database has been formed from the data banks of the external sources of information [11] and current weather databases, supported by some of the weather informers.

Qualitative assessment and analysis of water availability of the territory with visualization of the SPI values are carry out with taking into account thresholds given in the table.

As mentioned before, 1…3 months' SPI values are actively used for agricultural drought monitoring and have been recommended by World Meteorological Organization for implementation as standard monitoring procedure in all countries [9]. This methodology can be used especially effectively at the zone of risky agriculture (including essential part of the territory of the steppes of the South of Ukraine and Russian Federation).

Mapped SPI values have been shown in Figure 1, calculated with special procedures usage created for database support and maintenance at Visual FoxPro environment, and analytical possibilities of VBA, built in Microsoft Excel on the base of methodological aspects and relationships, described at the beginning of the article. However, ready program procedures can be used to simplify calculation procedures, including procedures, created with the usage of open free software ideology, such as, for example, software, developed by The National Drought Mitigation Center [12] in the USA (spi_sl_6.exe procedure, with additional files, which have been included at the SPI package).

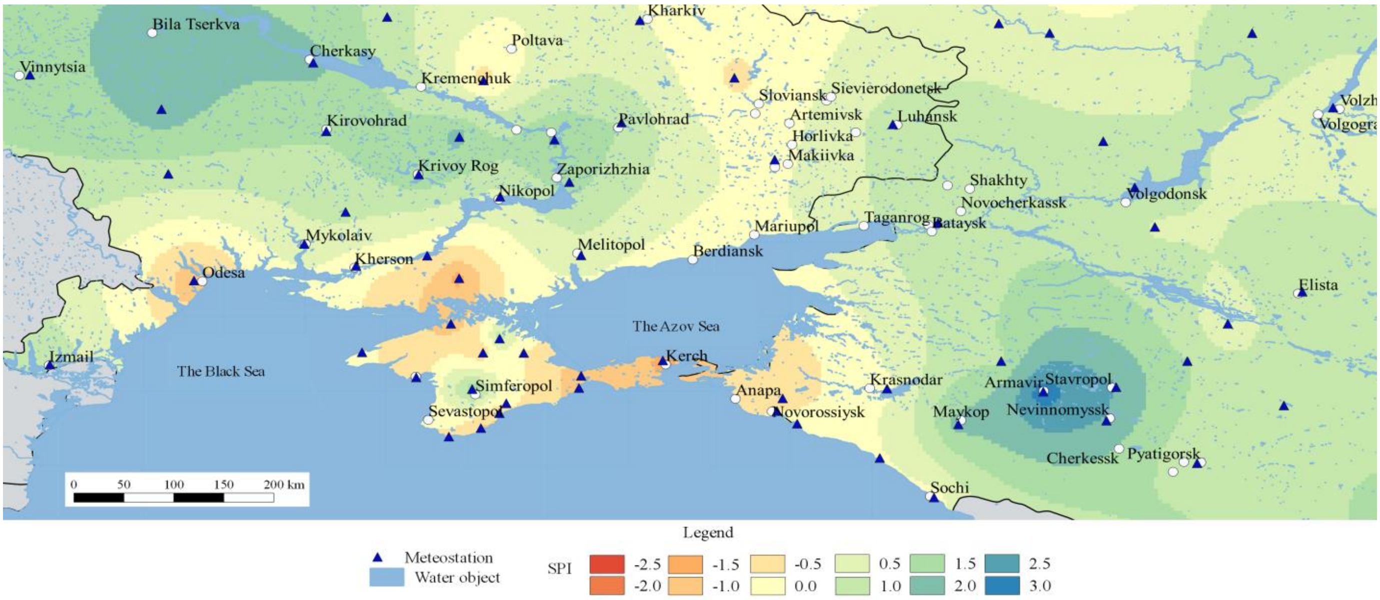

Fig. 1. The spatial distribution of evaluation (monitoring) precipitation availability for the South of Ukraine and Russian Federation by SPI during spring (March-May) 2014

Availability of local water resources, as mentioned, is determined (in average) with the relation of the precipitation volume and evapotranspiration, and their variation depends, first of all, on the dynamics of precipitation falling out. At the same time project stochastic values are defined by long-term dynamics of precipitation data, local flows and evaporation (if such data are available, otherwise calculation methods and hydrologic analog approaches are used). Groundwater replenishment or lowering is determined with solution of water balance equation of the territory and in the framework of groundwater levels monitoring by observation wells. To receive target parameters outside the values, which were observed or under insufficiency of observation data theoretical distribution curves are used with the further interpolation of the values over the territory. Interesting additional possibilities of analysis of groundwater dynamics and estimation of conditions of some of the waterworks objects operation can be received by means of SPI usage. An example of groundwater dynamics and SPI coherence for the territory of one of the Crimean districts has been shown in Figure 2.

Data shown in the Figure 2 are the evidence of close interrelation of dynamics of 6 and 12-month time scale trends of SPI with averaged fluctuation of groundwater level data on the plots without drainage at Dzhankoy district (conditions of steppe part of Crimea, territory of Pobednoe village council). Presence of such relation gives the possibility to use simplified indices to select “critical” periods for the analysis and modeling of waterworks objects operation conditions both on the base of retrospective data and taking into consideration probable influence of climate change, especially taking into account that monthly precipitation data are one of the main output parameters of global climate change models.

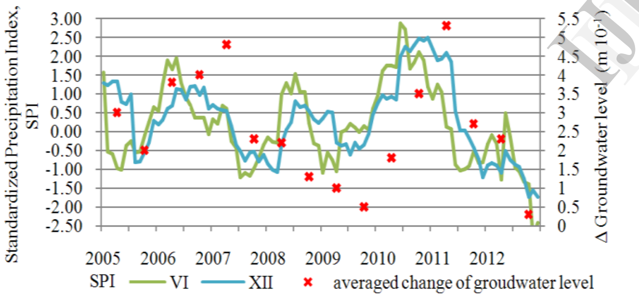

Fig. 2. The dynamics comparison of groundwater level and SPI for Dzhankoy district of Crimea for 2005-2012 (groundwater levels taken on the base of Crimean Hydrogeological and Land Reclamation Expedition data)

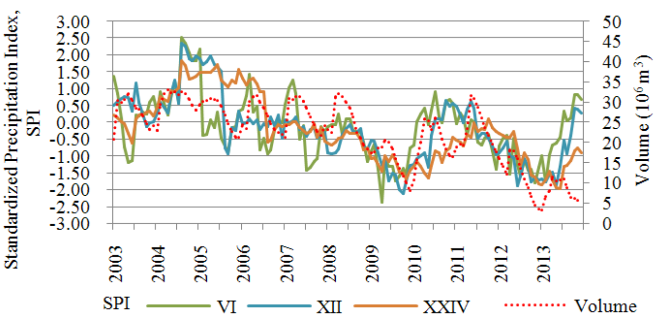

Fig. 3. The dynamics comparison of Partizan reservoir volume and SPI for 6, 12 and 24-month time scales

There is an example of SPI usage in Figure 3 for the analysis of Partizan reservoir operation, situated at the head of Alma river within submountain part of Crimea.

As for Simferopol reservoir (situated at similar hydrologic conditions) as for Partizan reservoir 6, 12 and 24-month time scales are the most suitable for the analysis of the dynamics of reservoir volumes. At the same time in Figure 3 (the right part of the figure) lag of hydrological and water-resources drought or prolonged drought with comparison to meteorological drought is clearly tracked (Return to the period of increasing of precipitation that has been shown by positive values of SPI at the end of 2013 doesn’t mean the end of the lack of water resources period in waterworks meaning.). Besides, there are clear distinguished periods of deficit of water resources even for the waterworks objects with over-year regulation.

V. Conclusions

Estimation of water availability of the territory with the usage of the Standardized Precipitation Index and visualization (mapping) of the values of this parameter for different time scales allows to receive numerical characteristics of deviation scope from the rate and it can be useful both for estimation of possible losses, for example, yield shortage, and for risk level estimation of waterworks facilities functioning as well (reservoirs, drainage systems etc.).

At the same time during the analysis of water resources shortage it is necessary take into account features of the persistence or temporal lag under agricultural drought estimation or water infrastructure operation related with adjusting influence of soil field capacity and other processes.

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