

IRRIGATION WATER USE EFFICIENCY OF AGROCENOSES AT LEFT BANK OF LOWER VOLGA RIVER

EFFICACITÉ DE L'UTILISATION DE L'EAU D'IRRIGATION DES AGROCÉNOSES SUR LA RIVE GAUCHE DE LA BASSE VOLGA

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ABSTRACT

In this study, MOD16A2 geodata sets were used to estimate actual evapotranspiration (ET_{av}) during the 2003–2017 growing seasons for irrigated and non-irrigated agrocnoses in the Pryvolgskaya and Komsomolskaya irrigation systems (Marksovsky District, Saratov Region, Russian Federation). For the spatial and temporal analysis of annual ET_{av} layers and the assessment of irrigation water use efficiency by agrocnoses, a geodatabase was created. It included land-use layers, arable land boundaries, irrigation infrastructure, and volumes of irrigation water supplied to agricultural enterprises for irrigating agrocnoses. For the annual division of the territory occupied by arable land into those occupied by irrigated and non-irrigated agrocnoses, Landsat 7-9 data were used. The analysis of ET_{av} flows corresponding to irrigated and non-irrigated agrocnoses allowed us to identify periods associated with fluctuations in weather conditions, as well as a number of external drivers. Comparison of irrigation water volumes with ET_{av} estimates of irrigated and non-irrigated agrocnoses yielded regional average water-use efficiency coefficients ranging from 0.35 to 0.72.

Keywords: irrigation water; irrigation infrastructure; geodatabase; water-use efficiency coefficients.

RESUME

Dans cette étude, des ensembles de données géographiques MOD16A2 ont été utilisés pour estimer l'évapotranspiration réelle (ET_{av}) au cours des saisons de croissance 2003-2017 pour les agrocnoses irrigués et non irrigués dans les périmètres irrigués de Pryvolgskaya et Komsomolskaya (périmètre de Marksovsky, région de Saratov, Fédération de Russie). Pour l'analyse spatiale et temporelle des couches annuelles d'ET_{av} et l'évaluation de l'efficacité de l'utilisation de l'eau d'irrigation par les agrocnoses, une base de données géographique a été créée. Cette base de données intégrait les couches d'usages du sol, les limites des terres arables, les infrastructures d'irrigation et les volumes d'eau d'irrigation fournis aux exploitations agricoles pour irriguer les agrocnoses. Des données issues des satellites Landsat 7 à 9 ont été utilisées pour distinguer, chaque année, le territoire occupé par les terres arables en ceux occupés par les agrocnoses irriguées et non irriguées. L'analyse des flux d'ET_{av} correspondant aux agrocnoses irrigués et non irrigués nous a permis d'identifier les périodes associées aux fluctuations des conditions météorologiques, ainsi qu'un certain nombre de facteurs externes. La comparaison entre les volumes d'eau d'irrigation et les estimations ET_{av} des agrocnoses irriguées et non irriguées a établi des coefficients moyens régionaux d'efficacité de l'utilisation de l'eau allant de 0,35 à 0,72.

Mots clés : Eau d'irrigation; Infrastructure d'irrigation; Base de données géographique; Coefficients d'efficacité de l'utilisation de l'eau.

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INTRODUCTION

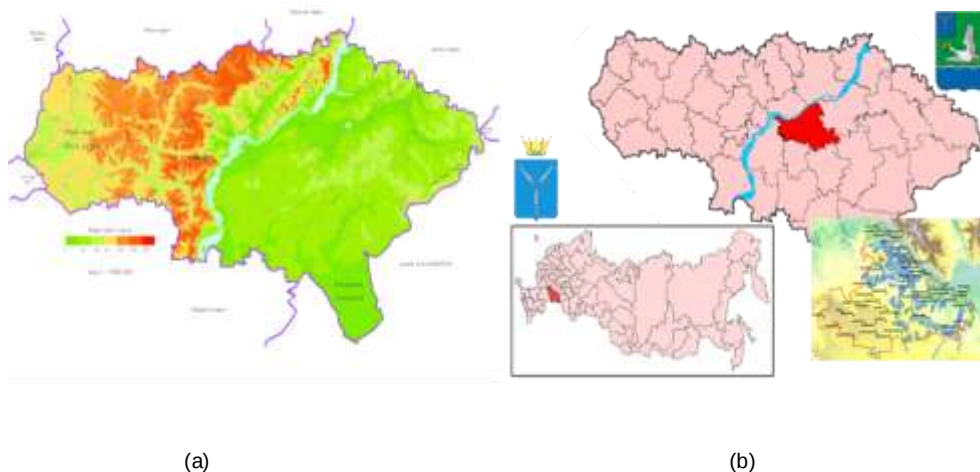
Sustainable management of freshwater resources is a global challenge driven by increasing climate variability, growing food demand, and rapid urbanization. As a result, competition for water resources intensifies among industry, households, and agriculture. At the same time, agricultural irrigation, which is vital for food security, is often the least water-efficient sector because large volumes of freshwater are lost during transport and field application. Among the priorities for assessing irrigation water use efficiency (IWUE) by agroecosystems are the development of modern technologies for objective and independent monitoring of efficiency-related parameters. Such technologies are needed to support water accounting, evaluate consumed water resources, and estimate irrigation withdrawals and atmospheric return using remote sensing. Obtaining high-quality information on the effectiveness of irrigated agriculture is a difficult task, especially from the point of view of quantifying the volume of irrigation water used for irrigation of agroecosystems. This publication uses ground-based and space-based monitoring datasets that have been used to map and quantify the use of irrigation water for irrigation of agroecosystems.

RESEARCH AREA

The study area was the Marksovsky District of the Saratov Region, Russian Federation, where the Pryvolgskaya and Komsomolskaya irrigation systems (PIS and KIS, respectively) are located. Favorable soil, climatic, and hydrogeological conditions, together with access to the Volga River water resources, created the basis for irrigated agriculture in the area. Its beginning was laid by the commissioning of the PIS and KIS in 1974.

The territory of the research area is characterized by high spatial and temporal variability of weather and soil parameters, as well as a variety of vegetation cover and anthropogenic impact. Analysis of time series of precipitation rates of vegetation periods (May-August) for the period 2003-2017. revealed: a) increase in May at an average rate of 0.16 mm/year; b) decrease in June at an average rate of 0.08 mm/year; c) decrease in July at an average rate of 0.79 mm/year; d) decrease in August at an average rate of 0.25 mm/year. A similar analysis of the time series of the sums of the daily air temperatures of the growing seasons for the same period revealed an increase in these amounts for these four months.

At the same time, the largest of them occur in July and August (0.73 and 0.80 degrees/year), and the smallest in May and June (0.38 and 0.03 degrees/year). A joint assessment of the effect of changes in these parameters on evaporation from the water surface (evaporation rate) in May-August showed an increase from 520 mm to 600 mm. A similar assessment of the Selyaninov' hydrothermal coefficient (SHTC) revealed a shift in the hydrothermal conditions of July and August from the dry farming zone ($0.5 < \text{SHTC} < 0.7$) to the irrigation zone ($\text{SHTC} < 0.5$).



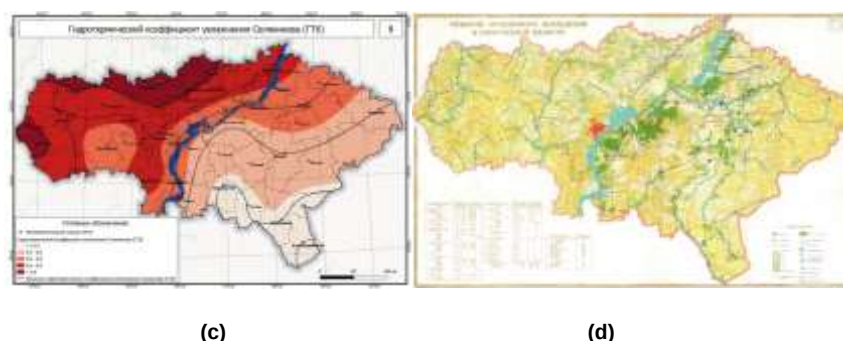


Figure 1. Cartograms: a) the location of the research area; b) the elevation of the Saratov region; c) the location of irrigation systems; d) isolines of the Selyaninov' hydrothermal coefficient

To assess the response of vegetation and soil cover on arable land to weather fluctuations, ETa data and additional geodata describing irrigation infrastructure were used. To systematize the characteristics of the irrigated area, a geodatabase (GDB) was created. It includes weather layers, technical and operational characteristics of both irrigation systems, and ETav layers for the 2003–2017 growing seasons. To do this, layers of corresponding geo objects were created in the ArcGIS Pro 2.8 software, formed based on data from various sources. A single UTM38N projection was used for their spatial consistency.

Geodata database creation

When generating the layers, OpenStreetMap data were used for administrative boundaries, settlements, and water bodies. The axial lines of the main channels of the PIS and KIS, as well as the boundaries of land plots served by sprinkler pivot irrigation machines (SPIM), were delineated using Landsat 7-9 imagery. Raster data with a spatial resolution of 150 m were used for the main types of land use, created at the International Institute for Applied Systems Research IIASA (Vienna, Austria); Geodata tiles ETa8 of the MOD16A2 product were used for ETa streams, generated based on the results of surveys from the MODIS platform using the thermal balance inversion method using the SEBS model.

To ensure uniformity of the results of the ETa8 analysis, a single time interval was chosen from 145 calendar days (May 25) to 241 (September 2) calendar years, corresponding to the average annual start and end dates on both irrigation systems. As a result, 180 ETa8 raster layers were created, structured as a space-time cube, which included 12 ETa8 layers with 19,837 pixels for each of the 15 years of the studied time interval from 2003 to 2017. The total number of entries in BGD was 3,570,660. The corresponding cartograms of these layers, displayed using a single color palette, are shown in Figure 2. formed by the results of the survey from the MODIS platform using the thermal balance inversion method using the SEBS model.

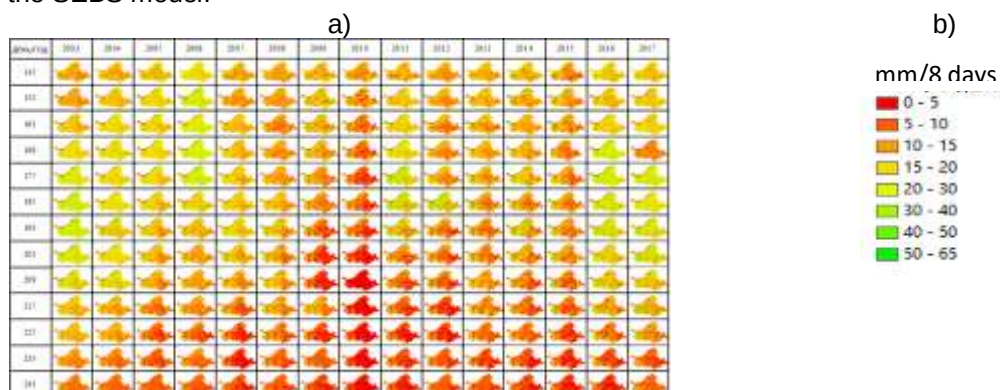


Figure 2. Mosaic cartographic representation of a set of ETa8 BGD-MR geodata layers: a) ETa8 cartograms; b) legend

Marking of arable lands into irrigated and non-irrigated arable lands In order to mark the layers of the ETav GDB corresponding to the type of "arable land", they belong to one of two subspecies.: 1) "irrigated arable land" (IAL); 2) "non-irrigated arable land" (NIAL) in the ArcGIS Pro 2.8 software, a computer code was developed, as a result of which time series for 404 SPIM contours were obtained. The analysis of these series made it possible to identify cases in which irrigation was not carried out on individual SPIM contours for various reasons. The most common were replacement or repair of SPIM units and emergency situations at pumping stations and water-supply pipelines. A number of such cases, recorded during field research in 2006-2009 on the territory of the KOS, served as the basis for testing the developed methodology, which showed satisfactory results.

The results of the analysis of the parameters of the central measures and the distribution of geodatasets of the ETav flow corresponding to the IAL and NIAL (respectively $ETav^{IAL}$ and $ETav^{NIAL}$) are presented in Figure 3 in the form of scattering diagrams.

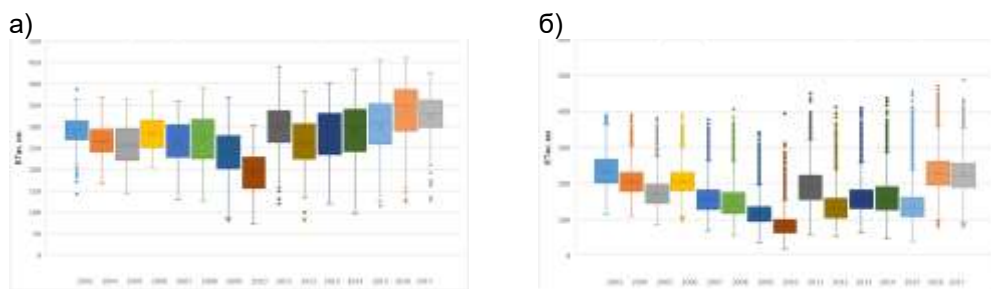


Figure 3. ETav flow scattering diagrams for : a) IAL; b) NIAL

The results of calculations of the total volume of evaporation from the surface of irrigated and non-irrigated arable land (respectively $vETav_j^{IAL}$ and $vETav_j^{NIAL}$), as well as averaged ETav (respectively $\overline{ETav}_j^{IAL}$ и $\overline{ETav}_j^{NIAL}$) is presented in figure 4.

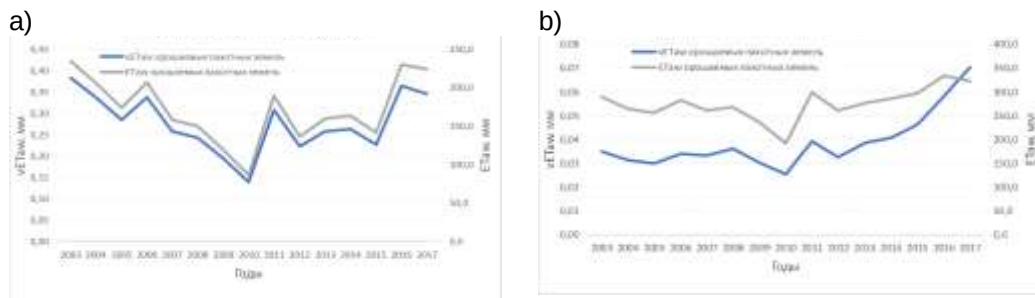


Figure 4. Diagrams of the time series of the volume of $vETav$ and the average evaporation $\overline{ETav}$, corresponding to: a) NIAL; b) IAL

The time series of both NIAL and IAL characteristics shown in Figure 4 have a number of significant features. For example, in the case of NUAL (Figure 4a), the profiles of both time series in the 2003-2010 half-period have a sawtooth shape with a general negative trend and a gradual convergence as we approach 2010. In the second half-period of 2010-2017, these profiles have a similar synchronicity with a more pronounced sawtooth pattern and a steady positive trend. These features seem to be a reflection of technological practices that have developed in non-irrigated agriculture, the effectiveness of which almost entirely depends on weather conditions.

A somewhat different pattern is observed for IAL time series (Figure 4b). Compared with NIAL, they are smoother in both subperiods, show lower trend rates in the first subperiod, and display a loss of synchronicity in the second subperiod. At the same time, if the first two of the noted differences are explained in the stabilizing role of irrigation during fluctuations in weather conditions during the growing

season, then the explanation for the third may be due to the presence, in addition to the positive precipitation trend in the 2010-2017 half-year, of one or more drivers contributing to an increase in ETav flows. One of these drivers was the progressive growth of agricultural land areas, which in 2012 accounted for about 4% of the area of arable land, and in 2017 increased 1.5 times, reaching about 6%. However, a simple increase in these areas due to the installation of additional SPIM could not by itself without the presence of the other driver to lead to a higher rate of increase in regional $\overline{ETav}_j^{IAL}$ in comparison with the rate of increase in the volume of regional $vETav_j^{NIAL}$. Apparently, this kind of driver could be a change in irrigation management methods, which made it possible to create a more efficient water regime for the root-habitable layer of the soil cover of irrigated agrocenoses. Regional characteristics ETav of irrigated $ETav_j^{IAL}$ and non-irrigated $ETav_j^{NIAL}$ is shown in figure 5.

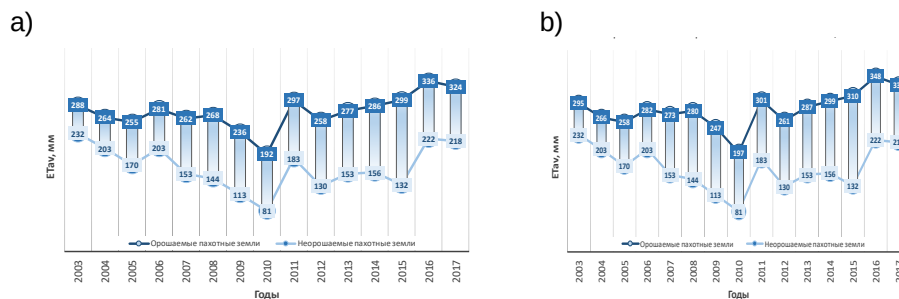


Figure 5. Time series of average and median values of the datasets of $ETav_j^{IAL}$ and $ETav_j^{NIAL}$

Presented in figure 5 time series plots of average and median values of regional $ETav_j^{IAL}$ and $ETav_j^{NIAL}$ of the period under study, 2003-2017, indicate a significant excess of the corresponding flows from the SPIM over similar flows from the NIAL. This rather natural result is associated with the replenishment of available for crop soil moisture reserves as a result of irrigation. At the same time, we note that the noted excess of the values of the time series of both central measures of the regional flow $ETav_j^{IAL}$ over the values of similar series of the regional flow of $ETav_j^{NIAL}$ has a slightly more significant difference in the case of median values (Figure 5b). At the same time, it is also important to note that in the exceptionally dry year of 2010, when there was practically no precipitation during the irrigation period and almost all crops burned out on non-irrigated agrocenoses, and the harvest was written off, although it was possible to obtain a low, but extremely necessary harvest on irrigated agrocenoses.

Characterizing the dynamics of the regional flow $ETav_j^{NIAL}$ during the first half-period, it is also necessary to note the negative impact of not only weather conditions, but also the difficult economic situation of irrigated agriculture due to high prices for water supply, as well as the imperfection and deterioration of sprinkler equipment used in those years. This led, on the one hand, to a reduction in irrigation standards against the recommended ones, as well as to large losses of irrigation water [250] as a result of groundwater discharge resulting from irrigation with high standards.

In contrast, the second half-period is characterized by a positive trend in both the median and mean values of regional $ETav_j^{IAL}$ and $ETav_j^{NIAL}$. This is due, on the one hand, to an increase in summer precipitation rates, and on the other, to an overall improvement in the economic situation, as well as the technical re-equipment of irrigated agriculture. So, if in the first half of the second half-period the differences between the values of both regional flows ranged from 110 to 120 mm, which was already higher than the same indicator in the second half of the first half-period, then starting in 2014, this difference began to grow, reaching 130 mm and 150 mm in 2014 and 2015, respectively. At the same time, it should also be noted that, judging by the magnitude of the regional flow of $ETav_j^{NIAL}$ in 2015, this year was considered a dry one, which was reflected in a decrease in this flow compared to the previous one. However, despite this, there was an increase in the regional flow of $ETav_j^{IAL}$ which was reflected in the synchronicity misalignment noted above. The increase of the difference between the

values of regional flows $ETav_j^{IAL}$ and $ETav_j^{NIAL}$ stabilized during the relatively favorable summer precipitation periods of 2016 and 2017, reaching values of about 120-130 mm.

Another important result of the analysis of the increase of the difference between the regional $ETav_j^{IAL}$ and $ETav_j^{NIAL}$, which began to manifest itself, starting in 2007, which caused the need for increased irrigation rates. At the same time, the period following the most unfavorable one in 2010, when the minimum summer precipitation rate for the study period was recorded, coincided with the beginning of the reconstruction of irrigation systems. As a result of this reconstruction, on the one hand, the morally and technically obsolete irrigation systems were replaced with new ones, and on the other, new irrigation systems were installed in areas where irrigation had been discontinued in previous years. Obviously, both of these factors have manifested themselves as a result of the launch of the Federal Target Program "Development of agricultural Land Reclamation in Russia for 2014-2020". Thus, the modernization of the SPIM could contribute to a more efficient use of irrigation water by agroecosystems, which was reflected in a decrease in its flows to soil and groundwater layers located below the root layer, which was reflected in an increase in the regional $ETav_j^{IAL}$. Thus, the results of the analysis of time series of regional $ETav_j^{IAL}$ and $ETav_j^{NIAL}$ in the second half-period are closely related to the extensive and intensive development of irrigated agriculture and the technical renovation of sprinkler equipment that occurred as a result of the implementation of the aforementioned federal target program.

DISCUSSION

Within the framework of Agenda 2030, remote sensing is considered a reliable source of data for monitoring Sustainable Development Goal indicator 6.4.1, which concerns water-use efficiency and is intended for near-real-time assessment. The IWUE assessment based on remote sensing data is characterized by a number of uncertainties that are gradually being overcome with the development and improvement of relevant technologies and methods. According to the classification based on this parameter, surface irrigation with values in the range of 40-60% is considered the least water-efficient). Next, in ascending order of IWUE, sprinkling and micro-drip irrigation follow with values of 70-90% and 85-95%. The differences between IWUE within these three groups largely depend on irrigation management methods. Thus, in our studies in the Saratov Trans-Volga region, on alfalfa, soybean, and corn crops irrigated with SPIM, the IWUE values ranged from 30-70%. In this study, the use of water supply data for 2005-2009 resulted in similar results with IWUE values in the range of 0.35-0.72. Such a wide range under nearly identical external conditions is largely explained by differences in irrigation management across years with different weather parameters, farming technologies, sprinkler equipment characteristics, and the quality of applied irrigation water supply regimes. Thus, among the anthropogenic factors affecting irrigation water losses during irrigation of agroecosystems, the main factors are related to the use of obsolete methods for monitoring the needs of agroecosystems in irrigation water, which leads to the groundwater discharge and a heterogeneous distribution of the flow of ETa irrigation water over the space of the irrigated agroecosystem.

CONCLUSIONS

The analysis of regional ETav values showed that weather conditions play the leading role in shaping flows in both irrigated and non-irrigated agroecosystems. In the case of irrigated agroecosystems, a driver related to irrigation management and its economic efficiency is added to these factors. This driver played a significant role in the second part of the time interval under study, especially after the extremely dry year of 2010, which was associated with the modernization of sprinkler equipment supported by the state Federal target program. This was likely caused by changes in the irrigation regime and improved irrigation efficiency through reduced water losses to surface runoff and deep percolation. This often forces farmers to reduce irrigation standards, which leads to lower yields and economic efficiency.

Acknowledgments

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