RESEARCH PAPER

MULTIYEAR VARIATIONS OF SOIL MOISTURE AVAILABILITY IN THE EAST EUROPEAN PLAIN

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ABSTRACT. This study aims to examine the impact of climate change on the water storage across the East European Plain, utilizing archived digital materials from several remote sensing satellites, including the Terra/Aqua (MODIS), the Global Precipitation Climatology Project, GRACE, and GRACE FO satellites, as well as data from digital maps of Selyaninov hydrothermal coefficients. The spatial resolution of the analyzed data ranged from 1x1 km to 250x250 km. Aiming to enhance the spatial resolution of Selyaninov coefficient maps, a new version of the Selyaninov hydrothermal coefficient was suggested, leveraging satellite remote sensing data. Both visual and computer analyses of these materials reveal a consistent reduction in water storage in the southern regions of the East European Plain, accompanied by a slight increase in the Novgorod Oblast. This information suggests that the non-chernozem region of the East European Plain will play a crucial role in supplying agricultural products to the population in the next decades. The observed stable water storage in the northern part of the East European Plain, encompassing the Komi Republic and the Novgorod Oblast, hints at the potential of increased agricultural production in these areas. However, achieving sustainable growth in agricultural production in these regions necessitates a focused investment policy.

KEYWORDS: East European Plain, climate change, water storage, satellite, remote sensing, digital maps, processing, trends, forecast

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INTRODUCTION

Agricultural production heavily relies on meteorological factors, particularly temperature and precipitation, which are highly variable and dictate moisture levels and water storage in the region. Consequently, crop yields fluctuate from year to year due to the strong dependence on weather conditions (Gulyanov 2022, Javadinejad et al. 2021). In recent decades, climate change has significantly impacted the water storage of various regions worldwide (Tretii otsenochnyi doklad… 2022).

In Russia, the hydrothermal coefficient (K_{Sel}), developed by G.T. Selyaninov, is commonly used to assess regional water storage (Selyaninov 1928, Svoboda et al. 2016, Cherenkova, Zolotokrylin 2016). K_{Sel} is calculated using the formula $K_{Sel}= R_M\cdot 10/\Sigma t$, where R_M represents the total precipitation measured by an weather station in millimeters during the period with temperatures exceeding +10°C, and Σt denotes the total of daily average temperatures in Celsius during the same period. K_{Sel} values ranging from 1.0 to 1.3 indicate sufficient moisture, while values between 0.7 and 1.0 signify arid farming zones, and values between 0.5 and 0.7 correspond to dryland farming zones. However, K_{Sel} has limitations, as it does not consider differences in evaporation and surface runoff of areas and relies on meteorological data with low spatial resolution. In contrast, satellite monitoring systems, such as Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (FO), enable multi-year monitoring of water storage over large areas, automatically accounting for differences in evaporation, humidity, and surface runoff. However, these systems have a low spatial resolution of 250x250 km. Monthly values of the equivalent water thickness layer (EWTL)[1] are deduced from the detected variations of the terrestrial gravitation field. The benefit of using this method to monitor regional water storage lies in its ability to automatically account for evaporation and surface runoff, as well as its consistent observation network. Prior research has demonstrated the reliability of GRACE data in tracking soil moisture and water storage in watersheds (Kiselev et al. 2015, Kiselev et al. 2016, Velicogna et al. 2015, Sun 2013, Longuevergne et al. 2013, Cesanelli 2011, Strassberg et al. 2007, Pat et al. 2006).

The aim of this study is to assess changes in water storage within the Eastern European Plain over a 20-year period. We utilized satellite digital maps of land surface temperature and precipitation, along with GRACE and GRACE FO satellite data, and time series of meteorological station observations of air temperature and precipitation. To enhance the spatial resolution of soil moisture availability maps, the paper suggests creating a novel hydrothermal moistening criterion: K_{RS}, or Selyaninov's hydrothermal coefficient. This new criterion will rely on satellite remote sensing precipitation and land surface temperature measurements.

The study seeks to objectively assess how climate change affects water storage in various territories. Additionally, it aims to predict the economic significance of agricultural land in different zones of the East European Plain.

[1]The equivalent water thickness layer refers to the thickness of an infinite, plane-parallel layer of water situated on the surface of a geoid, whose gravitation force at the orbital level is equivalent to the gravitation field change observed by the satellite.

Data and Methods

The research utilized the following satellite data:

- infrared thermal spectral bands imagery materials from Terra/Aqua satellites (MODIS instrument), with a spatial resolution of 1x1 km, a standard product for land surface analysis. Daily maps of the Earth's surface temperature were generated four times per day (MOD11A1[2] and MYD11A1[3]) from 2003 to 2022.

- Global Precipitation Climatology Project version 3 (Huffman et al. 2022) precipitation maps with a spatial resolution of 0.5°x0.5° (~50x50 km), displaying daily precipitation totals for the period from 2002 to 2020.

- GRACE and GRACE-FO satellite gravimetric survey data covering the period from 2002 to 2022 as a standard product in the form of monthly maps that display the EWTL and changes in the terrestrial gravitation field. The maps have a spatial resolution of approximately 250 km (Swenson and Wahr 2006). A total of 168 scenes were analyzed.

The Selyaninov hydrothermal coefficient was calculated by using satellite data as $K_{RS}=R_{RS}\cdot 10/\Sigma t_{RS}$, where R_{RS} denotes the total precipitation in millimeters during the period with temperatures above +10°C. Σt_{RS} refers to the total daily average surface temperatures in Celsius during the same period, also based on the satellite data. K_{Sel} values ranging from 1.0 to 1.3 indicate sufficient moisture, while values between 0.7 and 1.0 signify arid farming zones, and values between 0.5 and 0.7 correspond to dryland farming zones. Daily average temperatures were calculated using every four scenes of the daily Terra/Aqua (MODIS) satellite imagery, while the data on precipitation were sourced from the Global Precipitation Climatology Project. For each surface element, a time series of daily average surface temperatures was created, and every year in which the daily average temperature exceeded +10°C was identified within that series. At the same time, the K_{RS} formula was implemented to calculate the overall amounts of temperature and precipitation. To compare the hydrothermal coefficient K_{RS} calculated from the remote sensing data with the traditional K_{Sel}, we used the Agroecological Atlas of Russia (Afonin et al. 2006). K_{Sel} was calculated in the atlas using the abovementioned formula, with two notable differences. Firstly, the atlas (Afonin et al. 2006) determined the growing season for average daily air temperatures exceeding +5°C. Secondly, in our case for K_{RS} calculation, land surface temperature was used instead of a daily air temperature at a 2 m height, which is used for K_{Sel}. In order for agrometeorologists to better understand the idea, it was necessary to further calibrate the K_{RS} with respect to the K_{Sel} map shown in Figure 1. Figure 2C shows the calibrated digital K_{RS} map.

Further analysis involved creating digital maps displaying trends in K_{RS}, EWTL, *p*-values, and *Var*, or coefficients of variation, between 2003 and 2022. The reliability of trend determination was judged using *p*-values, with trends having $p>0.05$ being considered unreliable. Additionally, coefficients of variation assessed the consistency of the factors in effect and were determined by dividing the standard deviation by the sample mean: $Var=\sigma V/(\bar{V})$, with $(\bar{V})$ being the sample mean.

Results and Discussion

The primary outcome of this study is a compilation of annual digital maps of the East European Plain, developed using metrologically-supported satellite measurement systems. These maps delineate fluctuations in moisture content on a subcontinental scale over a multi-year period (Fig. 2).

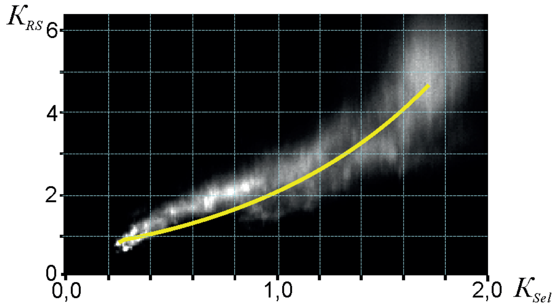

Fig. 1. Approximation of K_{RS} by the exponential function $K_{RS}=0.8\cdot exp(K_{Sel})$ of a two-dimensional distribution

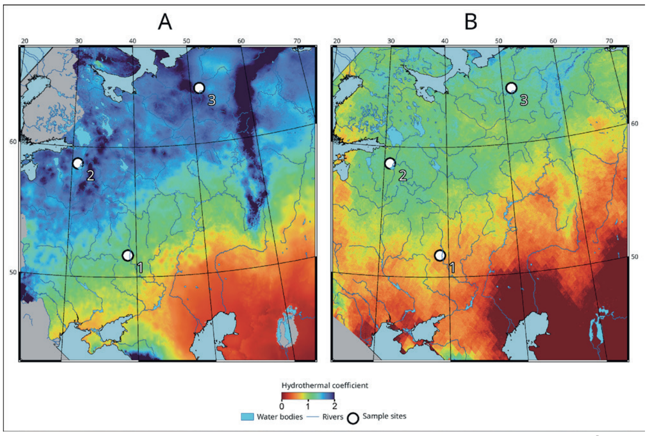

Fig. 2. Digital maps of the East European Plain. A) K_{Sel} - according to observations of air temperature and precipitation at weather stations, averaged over the period from 1965 to 1974. The initial spatial resolution is 0.25x0.25 (~250x250 km) degrees of the geographic grid, increased by reanalysis to 10x10 km (Afonin et al. 2006). B) K_{RS}, built up for 2003 according to satellite monitoring data. Spatial resolution 10x10 km

[2]Daily per-pixel Land Surface Temperature and Emissivity Product MOD11A1v006, DOI:10.5067/MODIS/MOD11A1.006, https://lpdaac.usgs.gov/products/mod11a1v006/

[3]Daily per-pixel Land Surface Temperature and Emissivity Product MYD11A1v006, DOI:10.5067/MODIS/MYD11A1.006, https://lpdaac.usgs.gov/products/myd11a1v006/

Over the last two decades, the region with low hydrothermal coefficient values in the East European Plain has exhibited a clear northward trend. Simultaneously, the southern areas of the East European Plain have become a part of the irrigated agricultural zone.

To illustrate the northward shift of the dry zone, a digital map of the K_{RS} trend from 2003 to 2020 was created (Fig. 3D). This map quantitatively confirms by the trend (Fig. 4C). Meanwhile, the non-chernozem region of the East European Plain maintains adequate moisture. The northern part of the East European Plain displays a trend of water availability (Fig. 3A) with high values of both p-value (Fig. 3B) and Var coefficient (Fig. 3C). This suggests a lack of a significant, permanent factor affecting the K_{RS} in this region.

An analysis of meteorological data for Novgorod Oblast over the past 60 years indicates a consistent increase in annual precipitation and annual average temperature. Precipitation has increased by 28 mm, and the annual temperature has risen by 0.5ºC per decade (Table). Furthermore, the sum of effective temperatures (above +10ºC), which determines the heat storage of major crops, is increasing at a rate of +54ºC per decade, while precipitation is increasing by 10 mm over the same period. Over the 60-year period, the moisture availability K_{Sel} in Novgorod Oblast has not displayed a clear dependence on time. However, during the last 30 years, there has been a consistent rise in the moisture content in the area: K_{Sel} has increased from 1.28 to 1.45 units.

Based on the analysis of K_{Sel} and K_{RS} trends, we assume that there will be no significant changes in moisture availability in the non-chernozem regions over the next decade, despite the situation in the southern regions of the East European Plain. However, a further decrease in soil moisture availability is expected in those southern regions.

The map depicting the EWTL trend across the East European Plain (Fig. 3A) provides a clearer picture. In Novgorod Oblast, there has been a slight increase in water storage over the past two decades, albeit an insignificant one (Fig. 3A, Fig. 4 A, B). Conversely, the areas south of Novgorod Oblast have experienced a decline in overall water storage in the soil, groundwater, and atmosphere.

Simultaneously, Figure 3B demonstrates a highly reliable trend estimation, while the Var coefficient map (Fig. 3C) displays a consistent factor in the southern areas of the East European Plain. Moreover, the EWTL graph (Fig.

Table 1. Meteorological indicators for the Novgorod Oblast

Period, years	Indicators				
	Annual amount of precipitation, mm	Average annual temperature, ºC	Precipitation at temperatures above +10ºC, mm	Sum of temperatures above 10ºC	K_{Sel}
1960-1969	525	3,6	280	2091	1,36
1970-1979	538	4,3	284	2141	1,34
1980-1989	577	4,6	336	2193	1,55
1990-1999	562	5,3	281	2212	1,28
2000-2009	604	5,7	316	2271	1,40
2010-2019	683	6,3	343	2389	1,45
Dependence of the indicator (y) on time (x)	y = 2,78x - 4937	y = 0,053x - 99	y = 1,017x - 1712	y = 5,43x - 8554	y = 0,001x - 0,645
Correlation coefficient	0,91	0,99	0,66	0,97	0,20

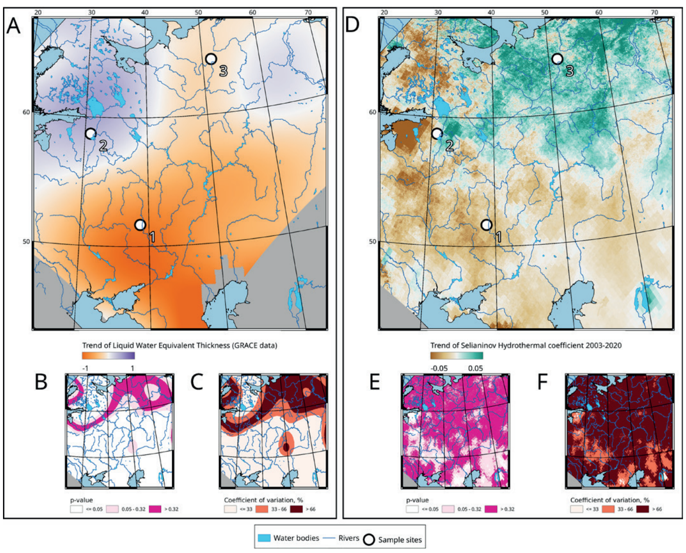

Fig. 3. Digital maps of the East European Plain.
A) EWTL trend for the period from 2002 to 2022. B) *p*-value of the EWTL trend. C) Var of EWTL. D) K_{RS} trend for the period from 2003 to 2022. E) p-value of trend of the K_{RS}. F) Var of trend for K_{RS}. Legend: Locations of graphs in fig. 4: 1. The Komi Republic (Fig. 4 A); 2. The Novgorod Oblast (Fig. 4 B); 3. The Voronezh Oblast (Fig. 4C)

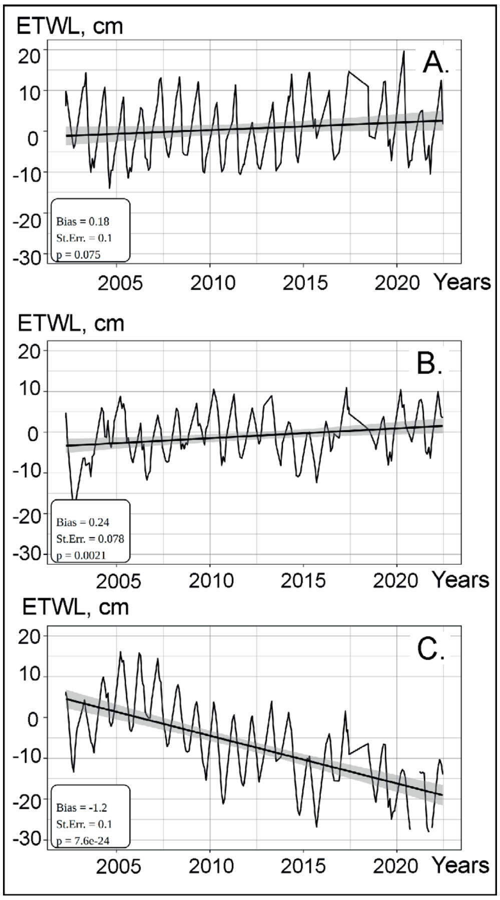

Fig. 4. EWTL changes for the period from 2002 to 2022 in points (see Fig. 3). A) The Komi Republic B) The Novgorod Oblast. C) The Voronezh Oblast

4C) demonstrates a distinct trend of decreasing multiyear moisture regime in Voronezh Oblast. It should be noted that there has been no decrease observed in the reduction rate of the EWTL in recent years (Fig. 4 C). The data, combined with the highly dependable trends observed in this area and the persistent natural driving force that diminishes water storage, suggest a forthcoming worsening of moisture availability in the southern regions and a greater role of the non-chernozem zone in agriculture of the East European Plain within the next decades.

The joint analysis of the Selyaninov remote sensing coefficient and EWTL reveals a consistently decreasing trend in moisture availability for both indicators across the southern regions of the East European Plain (Fig. 3 A, D, and Fig. 4 C). However, a slight increase in moisture content is observed in Novgorod Oblast (Fig. 3 A, D; Fig. 4 A, B and Table).

Based on the analysis of trends in the Selyaninov remote sensing coefficient and EWTL, it is hypothesized that there will be no significant changes in moisture availability in the non-chernozem zone of the East European Plain during the next decade. However, it is anticipated that water storage in the southern regions of the East European Plain will further decrease. Since moisture availability significantly affects the productivity of agricultural land (Gulyanov 2022, Javadinejad et al. 2021), the forthcoming trends may decrease agricultural productivity in the south while increasing the non-chernozem zone's importance in providing agricultural products.

CONCLUSION

1. The observed trend of the arid zone shifting northwest emphasizes the pressing need for implementing sustainable land-use management practices in affected regions. This is crucial to mitigate the impact of drought on agricultural productivity and prevent land degradation effectively.

2. The sustained moisture availability in the non-chernozem zone signals the potential for enhancing agricultural production in this region. It is advisable to formulate development policies and target investments strategically to maximize sustainable agricultural growth.

3. The results of this study provide valuable, objective insights for decision-makers involved in land use management, agricultural development, and the formulation of climate change adaptation strategies relevant for the Eastern European Plain and other regions facing similar challenges.

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