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Agricultural Dependence of the Formation of Water Balance Stability of the Sluch River Basin under Conditions of Climate Change

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ABSTRACT

The purpose of the research was to calculate water footprint in growing the basic field crops and establish the volumes of additional water accumulation to provide the hydro-functioning of the Sluch river basin in the territory of Ukraine under conditions of climate change. The research was based on the data of climate change analysis in 1901–2022, decoding of the actual satellite imagery of the spacecraft Sentinel 2 and statistical data on crop rotation structure in the agro-landscapes of the water catchment area in the research region. The volumes of water footprint were calculated for the vegetation periods of the basic field winter and spring crops in 2018–2021: 2018–2019 – a semi-wet year grows into a dry year; 2019–2020 – a dry year grows into a semi-wet year; 2020–2021 – a semi-wet year grows into a wet year. Spatio-temporal regularities of the formation of water footprint and the ratio of green and blue water use in growing different agricultural crops were determined. The total volume of water footprint in growing the field crops of a certain crop rotation equaled: in 2018–2019 – 1991 mln m^3, 2019–2020 – 2440 mln m^3, 2020–2021 – 2363 mln m^3. The total volume of precipitation in the vegetation period within the river water catchment area was: in 2018–2019 – 3760 mln мм^3, 2019–2020 – 4423 mln m^3, 2020–2021– 4839 mln m^3. The total volume of additional accumulation of green (rain) water in the vegetation period in the agro-landscapes of the river basin equaled: in 2018–2019 – 1769 mln m^3, or 47.0% of precipitation in the vegetation period (Pv); 2019–2020 – 1983 mln m^3, or 44.8% of Pv; 2020–2021 – 2476 mln m^3, or 51.2% of Pv. The proposed research scheme and the obtained results are important for adjusting and substantiating water- and resource-saving agro-technologies and crop rotations depending on climate change, for determining water balance stability of the river basin in accordance with the indicators of additional accumulation of green water.

Keywords: climate, water footprint, agriculture, field crops, water consumption, river basin, modelling, Sluch river.

INTRODUCTION

Climate change is an important global challenge for humanity, which requires an interdisciplinary approach to overcome it. Climate change manifests itself in intensity and frequency of climate anomalies, extreme weather phenomena at different hierarchy levels in space and time. Over the past 30 years there has been a considerable increase in the frequency and intensity of dangerous weather phenomena (Lisetskii et al, 2016; Pichura et al, 2022; Asgarizadeh et al, 2023) causing substantial economic losses (Mei et al, 2020; Koasidis et al, 2023), threatening the existence of basin landscape (Lisetskii et al, 2017; Zhang et al, 2022; Prajapati et al, 2023) and aquatic ecosystems (Pichura et al, 2020a; Lyu et al, 2023), human health and life (Chowdhury et al, 2020; Paquin, 2022; Ma et al, 2022). Therefore, the issue of balanced management of natural resources in developing climate-oriented farming (Coleman et al, 2021; Yin et al, 2023), which requires selection of a special spatial unit of the biosphere, is becoming significant. In this context, the river basin was selected to establish spatio-temporal regularities of organization and correlations of stabilizing (the natural environment) and destabilizing (the anthropogenic environment) components of ecosystems (Pichura et al, 2017; Han et al, 2023; Liu et al, 2023). In particular, the terrain and climatic characteristics of a territory is a determining factor of the formation and functioning of river basins (Zhang et al, 2023; Pei et al, 2023). An excess of the amount of precipitation in comparison with the amount of evaporation and water filtration in soil determines balance of surface runoff from the water catchment area and its accumulation in channel systems (Pichura et al, 2018; Rivaes et al, 2022; Tobias et al, 2023). A river basin is a spatio-temporal water balance stable system, in which precipitation evolves into other elements of water balance that maintains internal, functionally cohesive closed migration currents of surface and internal soil water runoff (Pichura, 2020b; Xie et al, 2023).

The most important function of interrelations of ecosystem components (biotic and abiotic) having genetic, historical and functional relationships, manifesting themselves in continuous exchange of substances, energy and information, is performed at a basin level (Bai et al, 2023; Montes et al, 2023). A river basin acts as an integral system with established ecological, social and economic relationships (Li et al, 2022; Jiang et al, 2023). Moreover, a river basin is a naturally organized territorial unit which allows establishing real spatio-temporal regularities of the consequences and the degree of the impact of human activity on degradation of natural ecosystems (Qu et al, 2020; Lavet et al, 2021; Liu et al, 2023).

Regularities of physical organization of a basin functioning are determined by surface water runoff and discharge of solid substances depending on climatic characteristics and anthropogenic loads on water catchment (Pichura et al, 2020c; Kim et al, 2022). The main anthropogenic factors determining the level of hydro-functioning of a river basin include an industrial complex (Xiong et al, 2021), agriculture and household systems (Prasood et al, 2021; Madeira et al, 2023). Agriculture is a leading large-scale sector in terms of exploitation of natural resources. It causes enormous agrogenic transformation of basin landscape structures (Breus et al, 2021, 2022) and a considerable increase in migration of highly toxic and biogenic substances related to soil erosion, worsening ecological state of water catchment beyond the boundaries of the initial pollution sources (Dudiak et al, 2019a; Santos et al, 2023).

The current problems caused by fresh water scarcity can be exacerbated in the future because of an increasing demand for water resources, their limited availability and lower quality. Scientists predict that the problems of availability of water resources will be deeper that will threaten food security in the world and ecological sustainability of the environment. Agriculture is water-consuming, its share in water footprint reaching 86% (Hoekstra et al, 2008). Agricultural producers worry because of climate changes which worsen due to their activity (Dudiak et al, 2019b). In particular, long-term precipitation deficit in water catchment areas causes meteorological aridity (Wu et al, 2023) which later manifests itself in lower soil moisture content (Breus et al, 2023; Furtak et al, 2023) that is intensified by evaporation (Chen et al, 2019), that disrupts the state of ecological system of a river basin. Therefore, under conditions of climate change and unstable water supply, it is important to maintain balanced functioning of water management and agriculture that will manifest itself in improvement of the system of evaluation and efficient use of available water resources in farming as a component of an integral system in the structure of basin exploitation of natural resources, environmental protection and life maintenance quality on the basis of advanced methods.

Maintenance of balanced water use in the agro-landscapes of the river water catchment area must be based on the ratio of precipitation and the volume of water resources necessary for growing agricultural crops (Pichura et al 2023a, 2023b), with selection of an optimal structure of crop rotation (Domaratskiy et al, 2018a; Tsai et al, 2023; Benini et al, 2023), substantiation of climate-oriented and resource-saving agro-technological practices (Domaratskiy et al, 2018b, 2019; Korkhova et al, 2023; Skok et al, 2023). Calculation of water footprint (WF) in growing the basic field crops of crop rotation is an efficient instrument for objective evaluation of the volumes of water use and determination of the level of rainwater accumulation in the agro-landscapes of the river water catchment area (Gao et al, 2023; Wen et al, 2023). Water footprint is an instrument which allows for thorough evaluation of a consumer's or a producer's attitude toward using fresh water systems (Wu et al, 2022). Calculation of water footprint provides objective information about the use of water volumes for different farming purposes, is a basis for drawing conclusions about sustainability of water resources, their distribution, and also evaluation of ecological, social and economic consequences at a basin level (Pellicer-Martínez et al, 2016; Muratoglu, 2019).

Application of the instrument of water footprint allows: establishing distribution of water resources in space and time for industrial, agricultural and household needs; evaluating sustainability and efficiency of using water resources within the water catchment area; substantiating strategic directions in the development of water sector and agriculture at different levels of basin management (Novoa et al, 2019; D'Ambrosio et al, 2020; Sauvé et al, 2021; Song et al, 2023).

The purpose of the research is to calculate water footprint in growing the basic field crops and determine additional water accumulation for maintaining the hydro-functioning of the Sluch river basin under conditions of climate change.

MATERIAL AND METHODS

Research scheme and materials

The scheme of the research of the water catchment area of the Sluch river and calculation of water footprint in growing agricultural crops involves six logically successive blocks of research organization (Fig. 1). In order to identify watercourses, establish their orders and determine the boundaries of the water catchment area of the Sluch river basin, we used a digital model of the terrain (DMT) on the basis of the data of *SRTM*-90 with spatial resolution of 90×60 m/pixel, which was displayed on the official website of the USA Geological Survey (https://earthexplorer.usgs.gov/). The research was carried out by means of the program *ArcGIS* on the basis of the DMT using an improved algorithm (Pichura et al, 2017, 2020b) of the hydrological geomodeling of the module Hydrologytools of Spatial Analyst Tools. In order to divide the river basin into groups depending on the order of the main stream, we applied the approach of Strahler-Filosofov (Strahler, 1952).

The land structure of the Sluch basin was calculated on the basis of the data of the satellite imagery of the spacecraft Sentinel 2 (with spatial resolution of 10 m/pixel) created on October 15–16, 2022 using the method «land use land cover (LULC)» of *ArcGIS*. Spatio-temporal regularities of changes in climatic conditions in the water catchment area of the river basin between 1901 and 2022 were established on the basis of the data of Climatic Research Unit of the University of East Anglia (https://crudata.uea.ac.uk/cru/data/hrg/) and the data of NASA POWER (https://power.larc.nasa.gov/data-access-viewer/). To calculate evapotranspiration processes, we used the reference data of FAO (https://www.fao.org/3/X0490E/x0490e00.htm#Contents). The coefficients of water use by the basic field crops under different

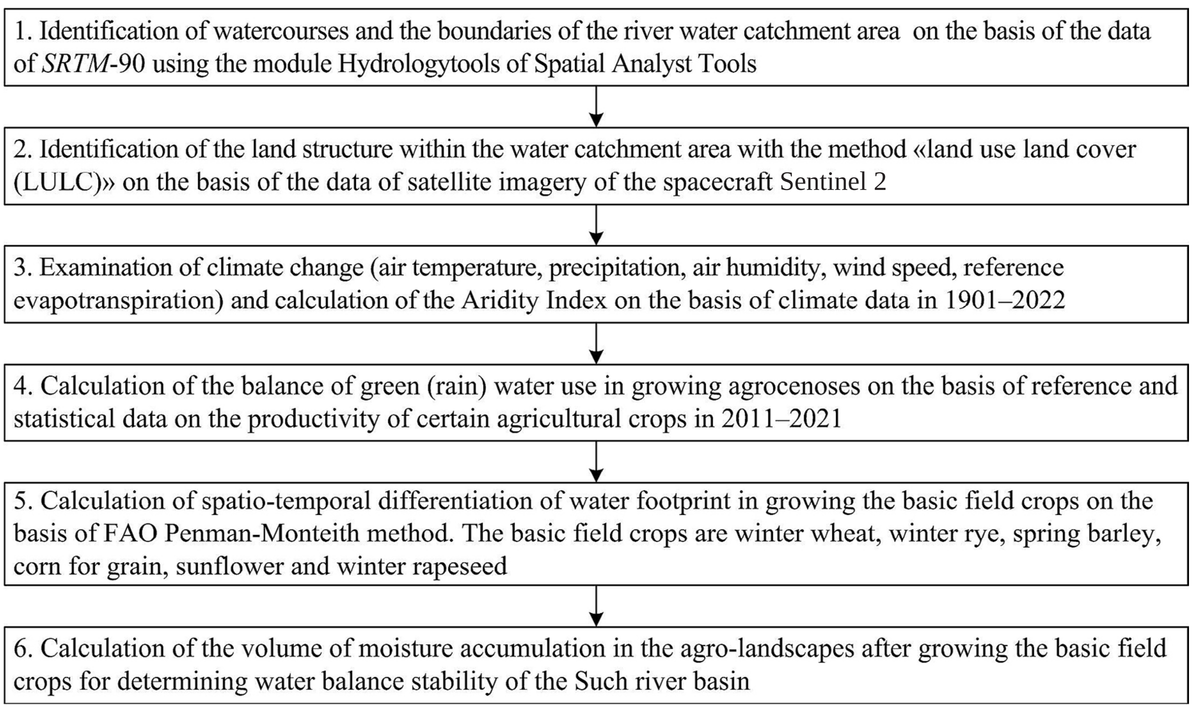

Figure 1. Structural-logical methodological scheme of the research of the water catchment area of the Sluch river and calculation of water footprint in growing agricultural crops

conditions of natural moisture were taken from the reference books for typical physical-geographical conditions of Polissia in Ukraine (http://agro-business.com.ua/ahrarni-kultury/item/16506-systema-povnoho-zabezpechennia-posiviv-volohoiu-za-umov-zroshennia.html), which correspond to the conditions of growing agrocenoses within the Sluch river basin.

Characteristic of the research territory

The Sluch river begins its flow in a small lake feeding on groundwater, located in a gulch and 1 km eastward from the village Chervona Sluch in Khmelnytskyi region in Ukraine, at elevation of 320 m (Fig. 2). The Sluch river empties from the right tributary to the river Horyn within the village Liutynsk in Rivne region. The total length of the river equals 451 m, the water catchment area is 13.83 thous. km^2, the fall of the stream is 183 m (Fig. 2b). The terrain height within the river basin from its source to the estuary ranges from 376 m to 137 m (Fig. 2c), the average slope of the water surface is smooth, being 0.4%. The upper part of the basin is an elevated plain, split by incised river valleys 50–100 m long and a dense gulch network. The average density of the river network is 0.39 km/km^2, the density of the river network reaches 0.7 km/km^2 in the upper part of the Sluch basin. The basin morphometry has a form elongated northward, 300 km long, with the medium and maximum width – 46 km and 110 km, respectively. The river catchment area is located in two geomorphological zones, namely: the upper and the middle parts of the basin are in Volyn-Podillia Upland and

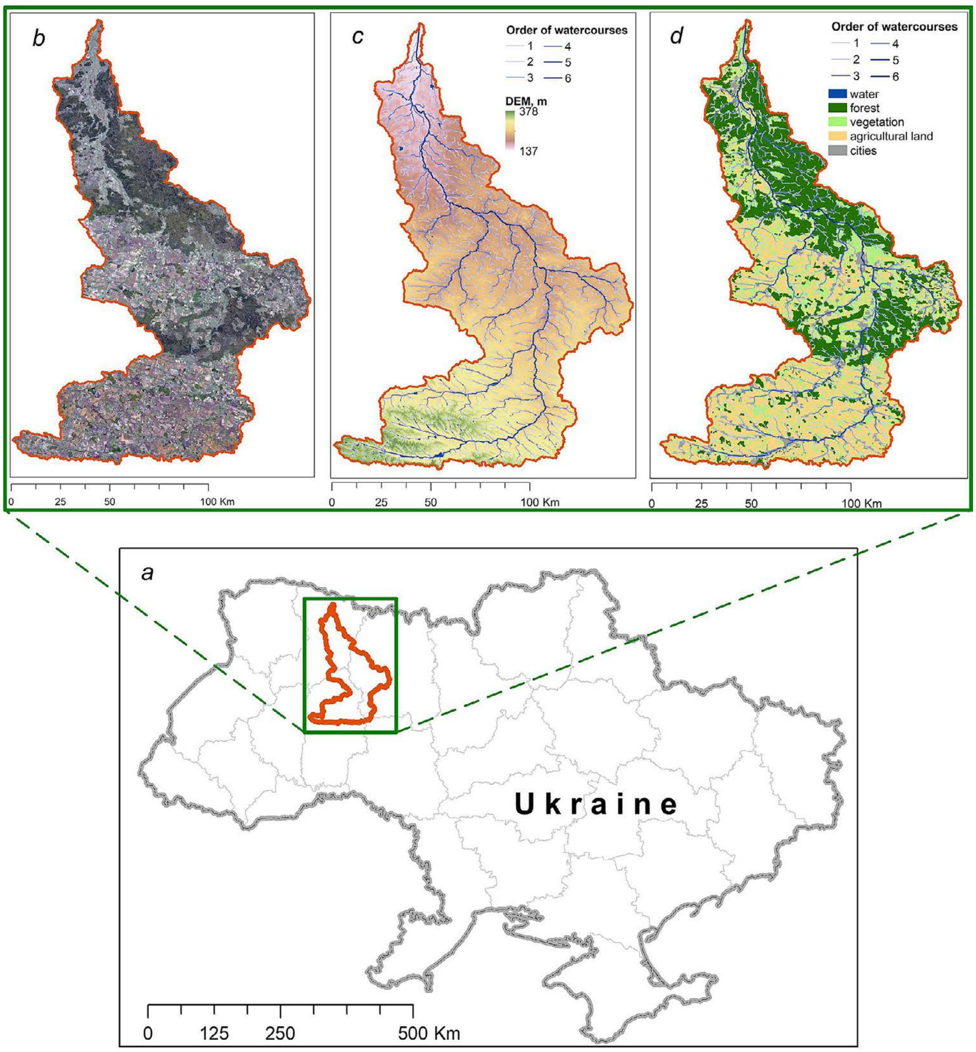

Figure 2. Spatial location and characteristic of the Sluch river basin: (a) location in the territory of Ukraine; (b) satellite imagery of the spacecraft Landsat 2 created on October 15–16, 2022; (c) a digital model of the terrain and distribution of the hydrological network within the basin; (d) the structure of farmlands

its branches, called Volyn Polissia; the lower part of the water catchment area is within the great plain Polissia (Pripyat Polissia). The river stream is meandering, it has steep banks from 20–40 m to 50 m high in some places, the banks are moderately steep, rarely – sloping 5–15 m high in other places. The plain is 1.5–5.0 km wide in the lower course. The floodplain is double sided, overgrown with grassland vegetation, waterlogged in some places. The woodiness of the basin is 30.8%, other vegetation (meadows, windbreaks, vegetation on gulch lands) – 10.7%, waterlogging – 13.0%, water bodies – 0.3%, farmlands – 39.7%, settlements – 5.4% (Fig. 2*d*). On the Sluch river, in the city Novohrad-Volynskyi, there is a water storage reservoir with the water volume of 1.8 mln m^3 (the area is 95.5 ha), which is used for farming and households. Water consumption is 1.96 mln m^3 per year (Priymachenko, 2013). The Sluch river is used as a source of hydro-energy (Myropilksa HES, Liubarska HES, Pedynkivska HES). The ponds within the Sluch basin are designed for fisheries. Flow distribution throughout the year is not even. It depends on the amount of precipitation and the air temperature regime. Most of the flow is observed over the period of spring flooding, within 40–80% of the river runoff. In a summer low-water period the river mainly feeds on groundwater (Biedunkova, 2013). Floods occur in a summer-autumn period. The largest water storage in snow equals 102 mm, the medium – 47 mm, supplied by 10% – 86 mm, by 25% – 65 mm. The amount of annual precipitation for 50% of the years of the research is 562 mm, for 75% – 481 mm, for 95% – 401 mm. The river velocity under maximum water losses reaches 1.0–1.4 m/c, the average velocity is 0.3–0.5 m/s in a low-water period. On average, mineralization of surface water is: in spring floods – 313 mg/dm^3; a spring-summer low-water period – 321 mg/dm^3; a winter low-water period – 349 mg/dm^3. According to the complex ecological evaluation in the period of 2005–2021, the quality of surface water in the Sluch river in most cases of sample collection was considered to be of Class II – 'good' condition, with excessive content of nitrite nitrogen, the index of BOD_5 (biochemical oxygen demand over five days) and phosphate phosphorus (Biedunkova et al, 2023), that is an evidence of the presence of biogenic elements of anthropogenic origin in the water composition of the investigated river.

The method for calculating Aridity Index (AI)

The AI is an aridity index which is determined on the basis of the ratio of annual precipitation (P) to annual values of reference evapotranspiration (ET_o) by the formula (Stadler, 2005; Colantoni et al, 2015):

$$AI = P/ET_o \tag{1}$$

The aridity index (AI) can be defined as a bioclimatic index, since it involves physical phenomena (precipitation and evaporation), and biological processes (plant transpiration). In addition, this index is one of the most important indexes for investigating processes of desertification (Sgroi et al 2014). As a rule, the value of the AI lower than 0.5 indicates arid or semi-arid territories, whereas the value over 0.65 indicates humid or hyper-humid zones as given in Table 1. The Aridity Index is used in the United Nations Environment Programme (http://www.unep.org/), Food and Agriculture Organization (http://www.fao.org/) and United Nations Convention to Combat Desertification (http://www.unccd.int/main.php) for classifying climates, evaluating the supply of precipitation and irrigation management in a certain research territory.

Method for calculating crop evapotranspiration (ET_c)

Spatio-temporal differentiation of evapotranspiration of green and blue water in the period of growing the basic field agricultural crops was calculated on the basis of FAO Penman-Monteith method, which is based on calculation of reference evapotranspiration (ET_o) and further computation of crop evapotranspiration (ET_c) involving the crop coefficient (K_c). The FAO Penman-Monteith method is maintained as the sole standard method for the computation of ET_o from meteorological data:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where: ET_o – reference evapotranspiration, mm/day; R_n – net radiation at the crop surface, MJ/m^2 day^1; G – soil heat flux density, MJ/m^2 day^1; T – air temperature at 2 m height, °C; u_2 – wind speed at 2 m height, m/s; e_s – saturation vapour pressure, kPa; e_a – actual vapour pressure, kPa; e_s - e_a – saturation vapour pressure deficit, kPa; Δ – slope vapour pressure curve, kPa/°C; γ – psychrometric constant, kPa/°C.

Table 1. Aridity index values

Climate classification	Aridity index (AI) values
Hyper-arid	≤0.05
Arid	0.05-0.20
Semi-arid	0.20-0.50
Dry sub-humid	0.50-0.65
Humid	0.65-0.75
Hyper-humid	>0.75

The index ET_o is calculated on the basis of climatic parameters. It reflects evaporation in a certain region in a particular period of the year, but it does not cover yield specificity and soil characteristics. Crop evapotranspiration (ET_c) differs from reference evapotranspiration (ET_o), since it involves aerodynamic features of yield stability of agricultural crops (K_c). The K_c value changes depending on certain crop characteristics and only partially depends on climate.

The index of crop evapotranspiration (ET_c) is calculated by the formula:

$$ET_c = ET_0 \cdot K_c \tag{3}$$

The value of crop evapotranspiration ET_c is calculated on the condition that the following factors are excluded: crop growth rate, groundwater and salinity, sowing density, presence of pests and diseases, weediness and soil fertility. The K_c coefficient involves the values of transpiration characteristics of a certain crop and average effects of evaporation from soil. Calculation of ET_c includes four stages, namely:

1. Identifying growth stages of certain crops. Soil cover, plant height and leaf area change over the course of plant growth. Due to the differences in evaporation at different growth stages, the K_c values for a certain crop change over the entire vegetation period, which, according to the method of FAO Penman-Monteith, is divided into four phenological growth stages (Fig. 3*a*): L_{ini} – initial, L_{dev} – crop development, L_{mid} – mid-season, L_{late} – late season. Each crop has its own duration of a certain vegetation stage in accordance with sowing dates and the region of cultivation. Typical dates of individual phenological stages of plant growth are given in the sources of FAO (https://www.fao.org/3/X0490E/x0490e0b.htm#TopOfPage). In particular, three values are necessary for describing and creating a curve of yield coefficients (Fig. 3b, K_c): at the initial stage (K_{c_ini}), in the mid-season (K_{c_mid}), and in the late season (K_{c_and}). Table 2, according to FAO grading, presents typical values of yield coefficients for different agricultural crops, which have the largest portion in crop rotation in the research region. The coefficients belonging to one group of crops are usually similar, since plant height, leaf area, soil cover and management of water resources are almost identical.
2. Adjusting the selected K_c coefficients for frequency of wetting or climatic conditions throughout the vegetation period. The K_c values at the initial stage and the stage of crop development depend on the impact of a fluctuation-induced force of the frequency of wetting the crop area, therefore the values of the K_{c_ini} coefficient should be specified. The K_{c_mid} and K_{c_and} values are adjusted according to weather conditions of the research territory using the actual data of the average value of wind speed (u_2, m/s) and relative

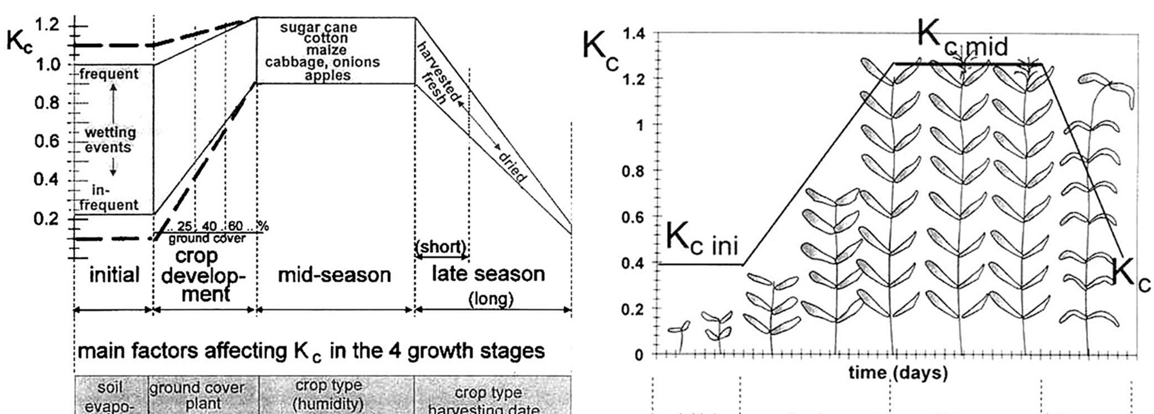

Figure 3. Major phenological stages of plant growth for calculating K_c: (a) typical ranges expected in K_c for the four growth stages; (b) generalized crop coefficient curve for the single crop coefficient approach

Table 2. Single (time-averaged) crop coefficients, K_c, and mean maximum plant heights for non-stressed, well-managed crops in subhumid climates ($RH_{min} \approx 45\%$, $u_2 \approx 2$ m/s) for use with the FAO Penman-Monteith ET_o

Crop	Maximum crop height (h), m	K_{c_ini}	K_{c_mid}	K_{c_and}
Winter wheat	1.0	0.40	1.15	0.25
Winter rye	1.0	0.40	1.15	0.25
Spring wheat	1.0	0.30	1.15	0.25
Spring barley	1.0	0.30	1.15	0.25
Corn for grain	2.0	0.30	1.20	0.35
Sunflower	2.0	0.35	1.00	0.35
Winter rapeseed	0.6	0.35	1.00	0.35

air humidity (RH_{min}, %) in the territory of growing certain agricultural crops. Adjustment of coefficients is made by the formula:

$$K_{c_{mid\ or\ end}} = K_{c_{(mid\ or\ end)(Tab)}} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad (4)$$

where: $K_{c\_(mid\ or\ end)\ (Tab)}$ – value for K_{c_mid} and K_{c_end} taken from Table 1; u_2 – mean value for daily wind speed at 2 m height over grass during the mid and late seasons growth stage (m/s), for 1 m/s ≤ u_2 ≤ 6 m/s; RH_{min} – mean value for daily minimum relative humidity during the mid and late seasons growth stage (%), for 20% ≤ RH_{min} ≤ 80%; h – mean plant height during the mid and late seasons stage (m) for 0.1 m < h < 10 m. For late seasons stage no adjustment is made when $K_{c\_end\ (Tab)}$ < 0.45 (i.e., $K_{c\_end} = K_{c\_end\ (Tab)}$). Where no data on u_2 or RH_{min} are available, the general classification for wind speed and humidity data given in Table 3 can be used.

3. Creation of the curve of yield coefficients allows determining the K_c value for any vegetation period. Only three point values for K_c are required to describe and to construct the K_c curve. Divide the growing period into four general growth stages that describe crop phenology or development (initial, crop development, mid-season, and late season stage), determine the lengths of the growth stages, and identify the three K_c values that correspond to K_{c_ini}, K_{c_mid} and K_{c_end}.

4. Calculation of ET_c by formula 3. After finding the K_c values, crop evapotranspiration (ET_c) is calculated, through multiplying the K_c value by the corresponding ET_o values. The K_c coefficient for any period of the growing season can be derived by considering that during the initial and mid-season stages K_c is constant and equal to the K_c value of the growth stage under consideration. During the crop development and late season stage, K_c varies linearly between the K_c at the end of the previous stage (K_{c_prev}) and the K_c at the beginning of the next stage (K_{c_next}), which is K_{c_end} in the case of the late season stage:

$$K_{ci} = K_{cprev} + \left[\frac{i - \sum(L_{prev})}{L_{stage}}\right](K_{cnext} - K_{cprev}) \quad (5)$$

where: i – day number within the growing season (1... length of the growing season); K_{ci} – crop coefficient on day i; L_{stage} – length of the stage under consideration, days; $\sum(L_{prev})$ – sum of the lengths of all previous stages, days.

Space imagery processing, cartogram creation, spatio-temporal, correlation and regression analyses were performed using the licensed program product ArcGis 10.6 and Microsoft Excel 2010.

Table 3. Empirical estimates of monthly wind speed data (u_2) and typical values for RH_{min} compared with RH_{mean} for general climatic classifications

Description	u_2, m/s	Climatic classification	RH_{min}, %	RH_{mean}, %
Light wind	≤ 1.0	Arid	20	45
Light to moderate wind	2.0	Semi-arid	30	55
Moderate to strong wind	4.0	Sub-humid	45	70
Strong wind	≥ 5.0	Humid	70	85
General global conditions	2.0	Very humid	80	90

RESULTS AND DISCUSSION

Research of climate change

The speed of the development of plant cover and the time of reaching effective entire cover depend on weather conditions on the whole, and precipitation and the air temperature in particular. Therefore, the period between sowing and effective entire cover of agrocenoses, the level of water use, the duration of certain phenological stages and productivity, change depending on climate, physical-geographical conditions of the area (latitude, longitude), sowing dates, varietal characteristics and the level of agro-technological practices. After reaching effective entire plant cover, the speed of phenological development (flowering, seed or grain development, maturation and dieback) depends on a plant genotype and agrocenosis plasticity with regard to climatic conditions. A lack of precipitation and high temperatures reduce the duration of phenological stages, accelerate plant maturation and dieback. In particular, long-term air temperature (> 35°C) and moisture deficit accelerate the rate of maturation, reduce the duration of mid- and late-season stages of plant vegetation that causes an increase in the level of the values of evapotranspiration processes, a fall in agrocenosis productivity and soil moisture deficit. Therefore, complex evaluation of moisture conditions of any territory, forecasting productivity, calculation of water use and moisture supply for agricultural crops are performed taking into consideration agro-meteorological indexes, in particular: precipitation, air temperature, wind speed, and also derivative indicators (climate energy, air humidity, evapotranspiration, climate coefficients and idexes etc.).

The water catchment area of the Sluch river basin belongs to the zone of an optimal level of moisture supply and good conditions for obtaining high yields of agricultural crops. Over the past 120 years (Fig. 4) the annual amount of precipitation within the water catchment area ranged from 487 mm to 716 mm. A relatively low value of precipitation is registered in the river source area (487–586 mm), in the middle part of the main course the value ranges from 580 mm to 716 mm, in the river mouth it is between 590 mm and 630 mm. Over the observation period, there were four ten-year periods with the maximum value of precipitation and three periods with the minimum value of atmospheric moisture supply (Fig. 7a).

Air temperature is a factor of the formation of water content of hydrological network, soil moisture reserves, water footprint in growing agricultural crops, the duration of phenological stages of plants and activeness of evapotranspiration process. Since the 80s of the 20th century (Fig. 7b), there has been a gradual increase in the air temperature regime in the territory of the Such river basin. Over the past 40 years the average annual temperature in the water catchment area has risen by 1.9°C on average, that caused a considerable increase in evapotranspiration processes, a fall in moisture supply in the basin landscape and aquatic territorial structures. It also determined a rise in the agrocenosis water use for the formation of a unit of production (t/ha).

Over the past 120 years the value of reference evapotranspiration (ET_o) in the water catchment area of the Sluch river has ranged between 1.72 and 2.25 mm/day (Fig. 5). Its minimal value was registered in the period of wet years: in 1921–1930 – 1.79–1.94 mm/day and in 1971–1980 – 1.72–1.88 mm/day (Fig. 7c). The maximum ET_o value has been registered over the past 30 years, ranging between 1.86 and 2.25 mm/day, that is determined by an increase in the air temperature and asynchronous precipitation. High values of reference evapotranspiration were observed within the basin landscape and aquatic territorial structures of the upper course of the Sluch river – from 1.87 mm/day (the wet year) to 2.25 mm/day (the dry year). Within the basin of the river middle course, the ET_o value ranged from 1.80 to 2.15 mm/day, from 1.72 mm/day to 2.00 mm/day in the river mouth.

Spatio-temporal variation of ET_o is an important indicator of aridity, changes in the formation of water regime, moisture supply in basin landscape structures, the level of plant water use, the volume of water footprint in growing agrocenosis, etc. In particular, aridity is a stochastic climatic phenomenon that occurs as a consequence of substantial deficit of precipitation and an extreme increase in the air temperature, which have a negative impact on the functioning of basin landscape and aquatic territorial structures, and a reduction in agrocenosis productivity. Aridity is a part of a natural climatic cycle that can last several months or years. It is a complex phenomenon, the frequency of its manifestations has increased considerably over the past years causing negative ecological and socio-economic consequences for regions with its manifestations. Aridity is a result

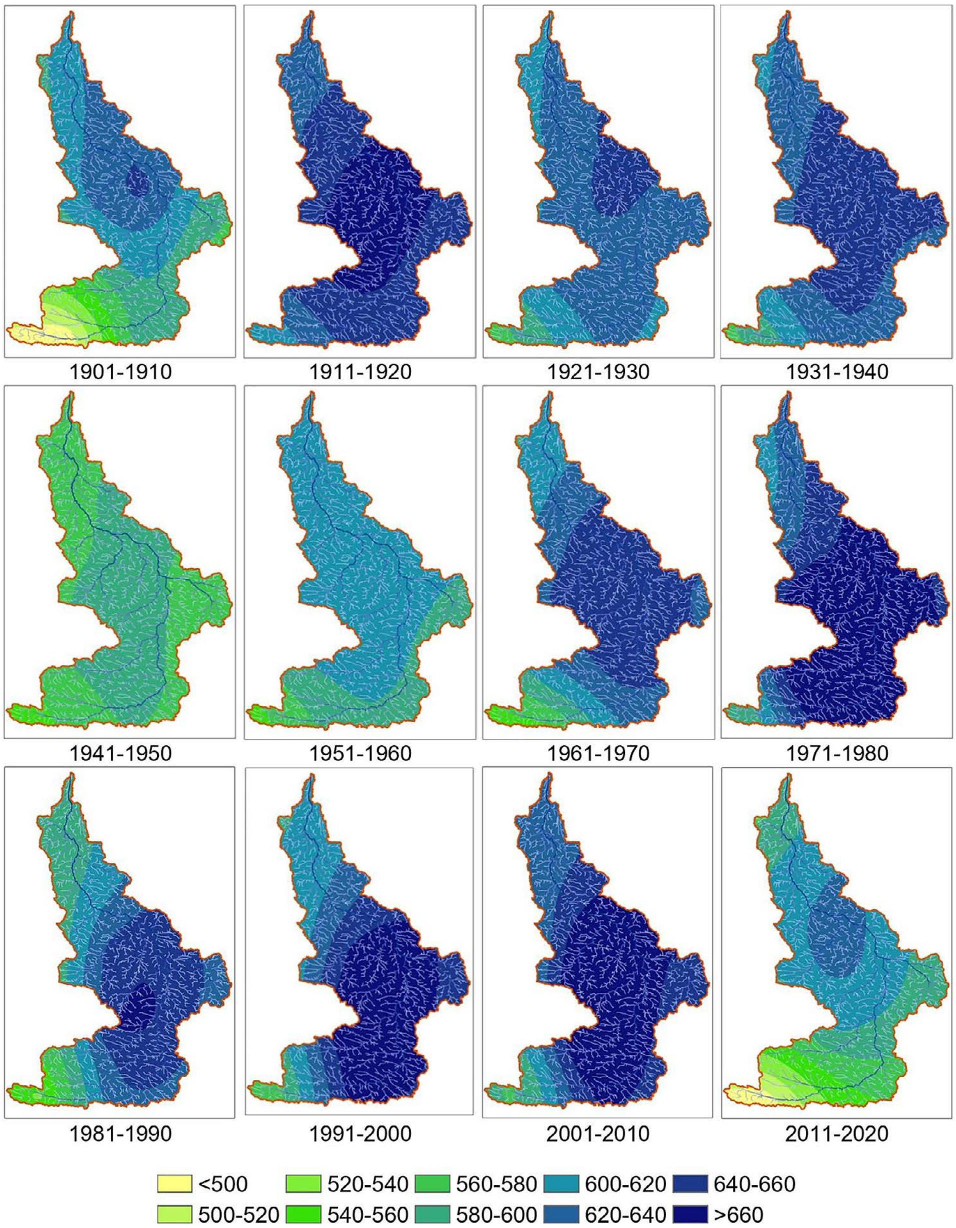

Figure 4. Spatio-temporal differentiation of the amount of atmospheric precipitation within the Sluch river basin in 1901–2020

of a combination of natural and anthropogenic factors that causes water deficit, deterioration of the circulation of substances in natural ecosystems and functioning of the socio-economic sector. Therefore, determination of the periods and characteristics of aridity allows establishing its degree, cyclicity and tendencies, identifying risks of its manifestations, that makes it possible to outline a number of measures aimed at preventing climate changes, that will be realized through implementation of climate-adaptive technologies in different areas of economy. In climatology, different types of aridity are identified by means of the Aridity Index which characterizes the degree of aridity on the basis of one or several climate indicators. The ratio of the amount of precipitation and reference evapotranspiration is used for it. Aridity Indexes reflect spatio-temporal regularities and conditions of climate change, manifestations of dry climate anomalies, delays of hydrological impacts (moisture losses from soil and water from aquatic areas). The degree of aridity affects agrocenosis productivity (t/ha) and an increase in the coefficient of water use (m^3/t), that characterize spatio-temporal changes in water footprint in growing agricultural crops.

Calculation of the Aridity Index allows establishing spatio-temporal regularities of climate

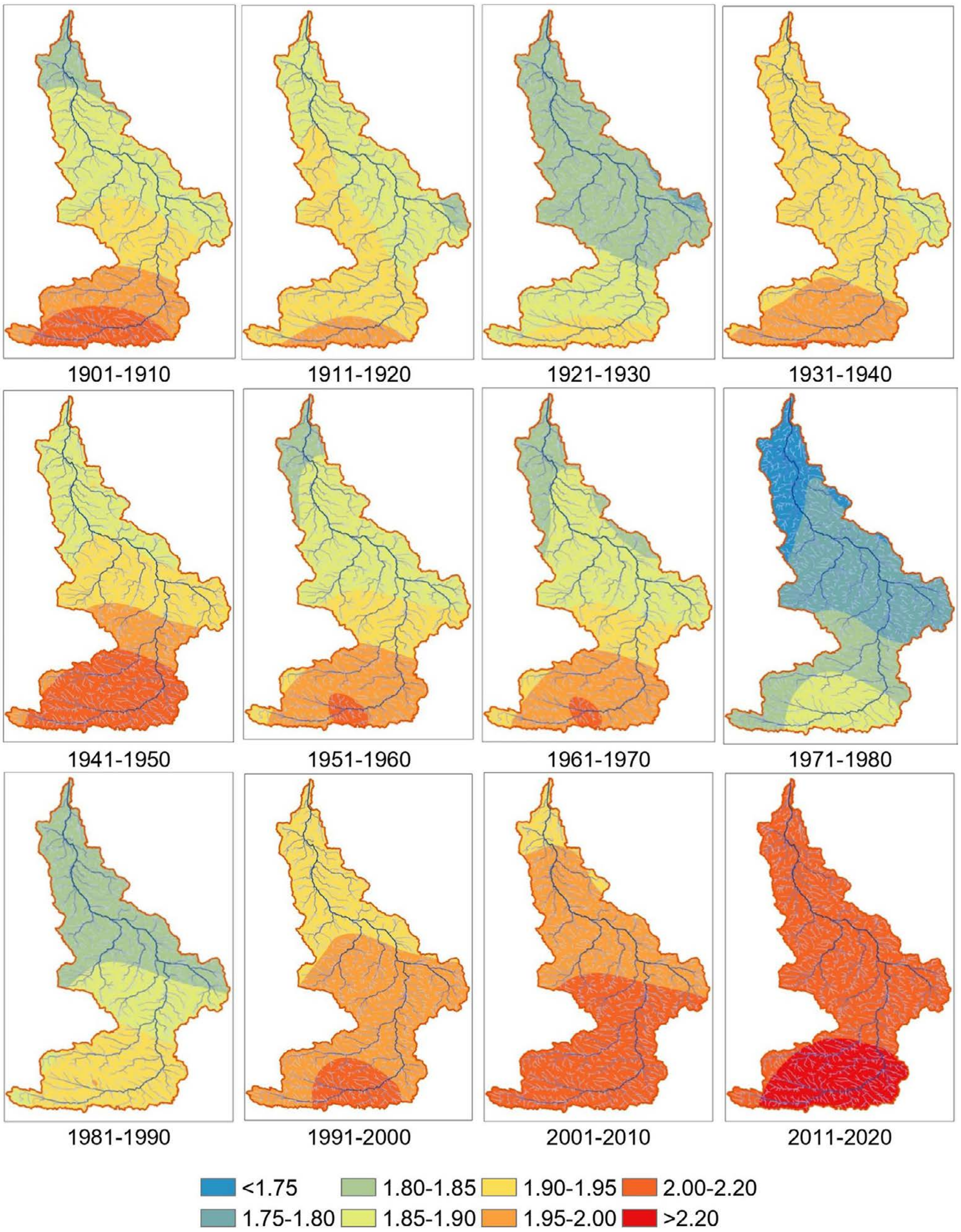

Figure 5. Spatio-temporal differentiation of the reference evapotranspiration value (ET_o, mm/day) within the Sluch river basin in 1901–2020

change, classifying them, determining the periods or years with probable manifestations of aridity, identifying the trend of complex evaluation of the changes in moisture supply of the river water catchment area and agro-meteorological characteristics of agricultural crop yields. According to the results of spatio-temporal calculation of the *AI* over the past 40 years in the water catchment area of the Sluch river basin, there has been considerable warming and a reduction in moisture supply (Fig. 6, Fig. 7d).

Over 120 years of observations the *AI* value has ranged from 0.61 to 1.08. The climate within the river basin was considered to be «hyper-humid» in most of the years. However, climate changes over the past 10–15 years have caused considerable spatial differentiation of moisture supply in the water catchment area of the Sluch river, in particular: 33.5% of the water catchment area which is located within the upper river course is characterized by dry sub-humid (6.5%) and humid climate (27.0%). Though currently the Sluch river basin is still a natural region with good moisture supply, but the tendencies of global warming show inevitability of an increase in the water catchment area with a dry sub-humid

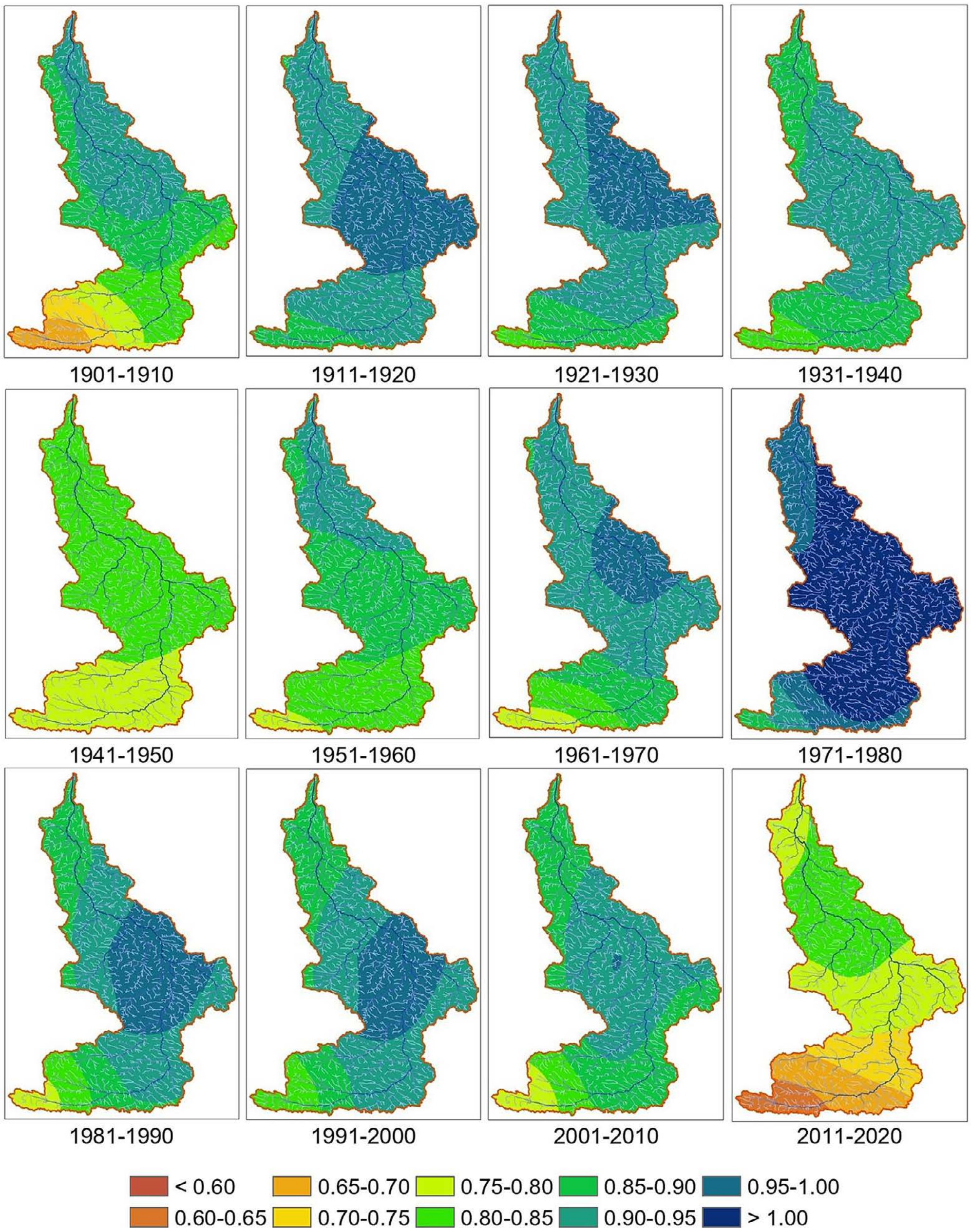

Figure 6. Spatio-temporal differentiation of the Aridity Index (*AT*) value within the Sluch river basin in 1901–2020

climate in the upper part of the river basin that will result in a reduction in water content and may cause small streams' drying up in the upper course of the Sluch river. In particular, climate-related problems of the upper part of the water catchment area are being exacerbated by a high level of anthropogenically damaged lands (farmlands and populated areas) at the level of 68.9% and limited natural landscapes (lands covered by forests and other natural vegetation, wetlands) – 31.1%. It is worth noting that natural vegetation performs stabilizing and climate-regulating function for the environment, contributes to a reduction in evapotranspiration processes and aridity manifestations. According to the ratio «anthropogenically damaged lands and natural lands», the upper part of the water catchment area is characterized by a «destructive» type of the state of the basin landscape structures.

The past 40 years are characterized by the formation of new climatic conditions with a distinctive increase in the temperature regime and asynchronous changes in precipitation, which cause moisture deficit, a fall in the level of circulation of substances in the ecosystem of the Sluch river basin, application of climate-resilient

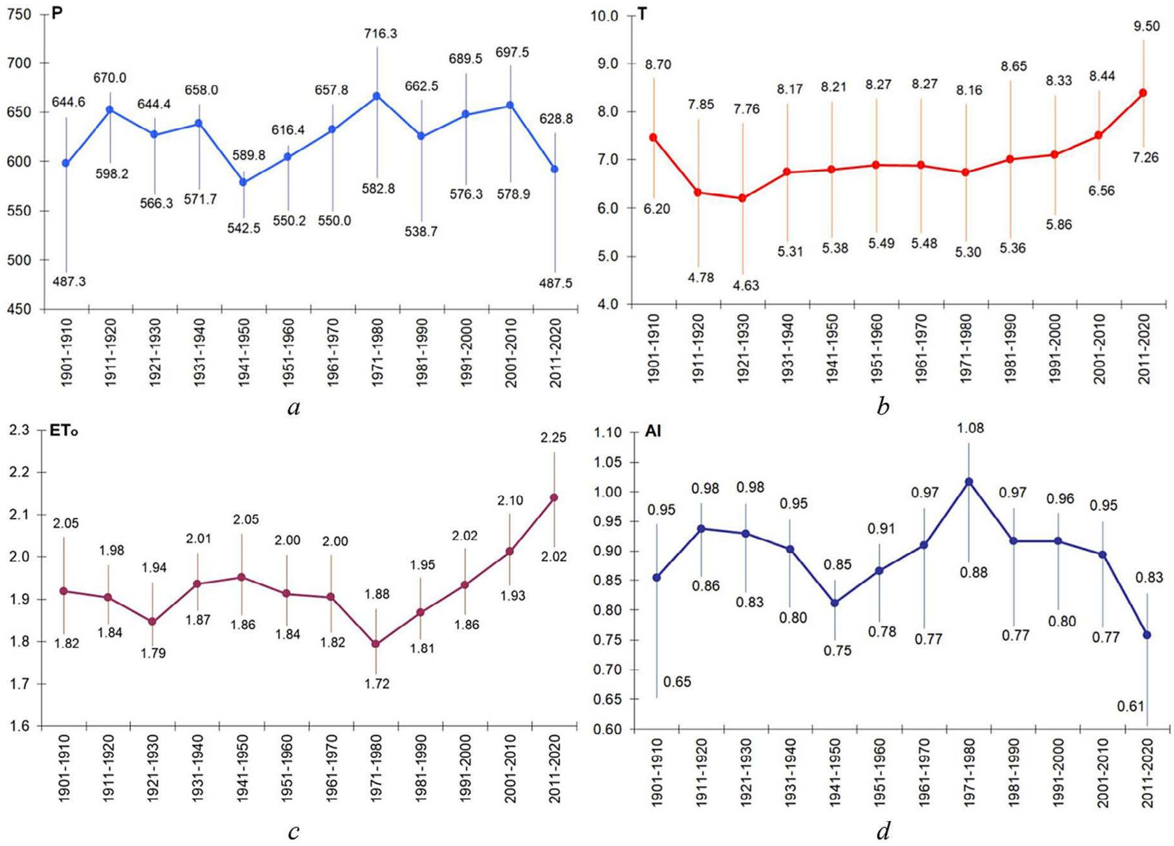

Figure 7. Climatic characteristics of the water catchment area of the Sluch river in 1901–2020: a – amount of precipitation per year (*P*), mm; b – average annual air temperature (*T*), °C; c – reference evapotranspiration (ET_o, mm/day); d – aridity index (*AI*) value

plant breeding and use of water-saving agricultural technologies in order to obtain stable yields and retain soil moisture. Climatic conditions of a certain year form the volume of water footprint that is defined as the amount of green water which evaporates and green water which is used by plants throughout their life cycle. The level of plant use and evaporation of green water depends on the amount of precipitation, a change in the air temperature and wind speed throughout the vegetation period of agrocenosis. Therefore, the research on the dynamics of green water use on non-irrigated lands under the basic field crops was conducted for the years with different levels of moisture supply within the Sluch river basin in 1981–2022. This period of observations is characterized by an increase of the average annual air temperature from 6.6°C to 8.5°C (Fig. 8a) and unstable precipitation with a rise in the variance from 11% to 16% (Fig. 8c), that led to a reduction in the average annual value of air humidity from 86% to 79% (Fig. 8b) and an increase in reference evapotranspiration by 0.3 mm/day (Fig. 8d). The results of correlation analysis of the impact of the basic climate indexes on the change in the value of reference evapotranspiration (ET_o) allowed establishing that the main climatic component of differentiation of ET_o is air temperature. The level of correlation between the average annual values of T and ET_o equals 0.79, that of the annual monthly values being 0.95. The regularity of a change in RH and ET_o was also found, the correlation being 0.35 for the average annual values and 0.91 for the average monthly values.

Calculation of the average annual ET_o value on the basis of meteorological data:

$$ET_o = \begin{cases} 0.0993T + 1.1725;\ r = 0.79, r^2 = 0.62 \\ -0.0275RH + 4.1333;\ r = 0.35, r^2 = 0.59 \\ -0.13 \cdot 10^{-3}P + 0.096T + 1.2721;\ r = 0.79, r^2 = 0.63 \\ -0.02972RH - 0.19826WS + 5.1863;\ r = 0.66, r^2 = 0.44 \end{cases} \quad (6)$$

Calculation of the average monthly ET_o value on the basis of meteorological dataz

$$ET_o = \begin{cases} 0.1462T + 0.8324;\ r = 0.95, r^2 = 0.90 \\ -0.1289RH + 12.318;\ r = 0.91, r^2 = 0.83 \\ 0.02306P + 0.10557T + 0.03783;\ r = 0.96, r^2 = 0.92 \\ -0.00774RH - 2.27485WS + 12.5608;\ r = 0.95, r^2 = 0.90 \end{cases} \quad (7)$$

According to the method FAO, crop evapotranspiration (ET_c) was specified in calculation of the values of reference evapotranspiration

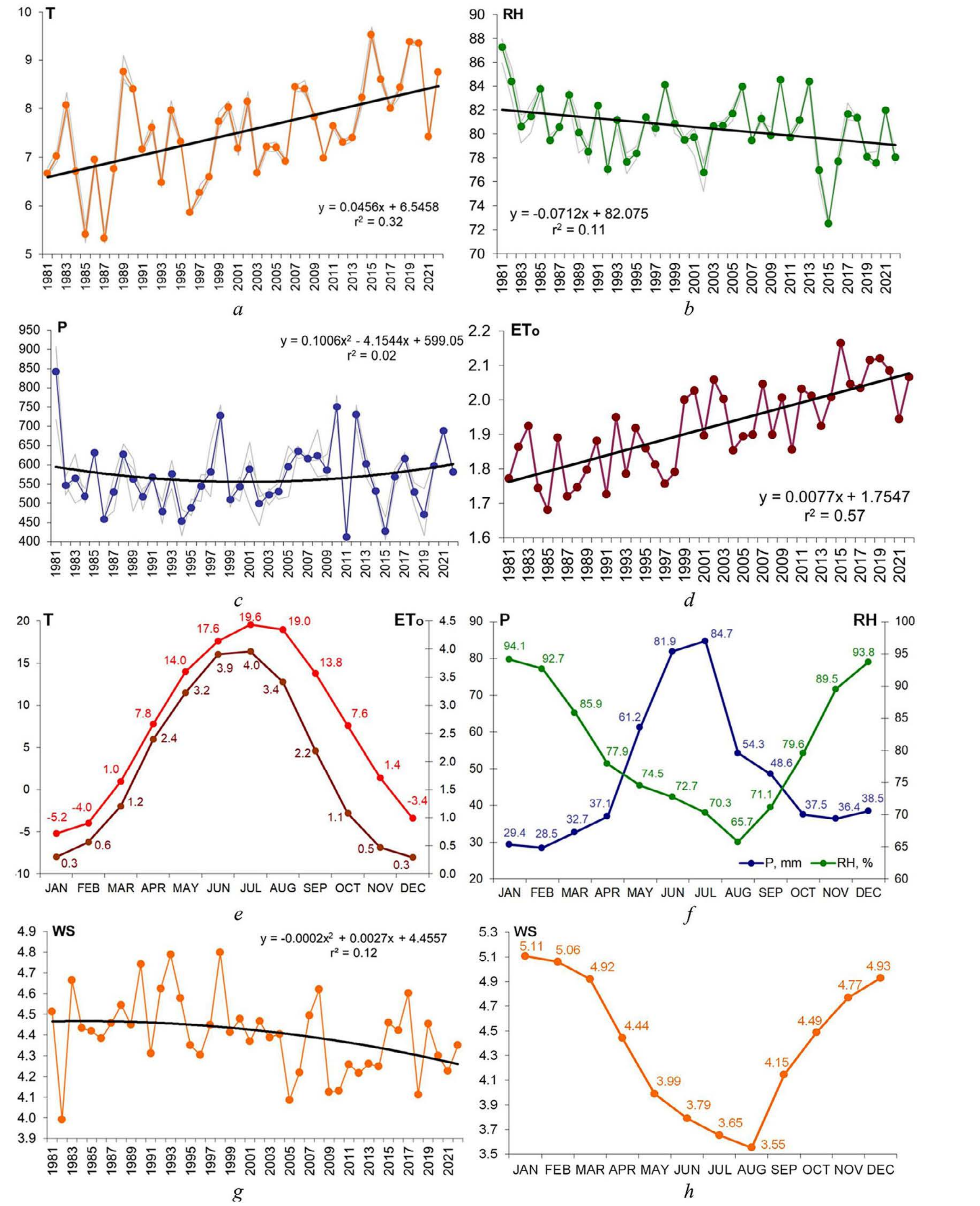

Figure 8. Climatic characteristics of the water catchment area of the Sluch river in 1981–2022: (a) average annual air temperature (*T*), °C; (b) average annual air humidity (*RH*), %; (c) amount of precipitation per year (*P*), mm; (d) reference evapotranspiration (ET_o), mm/day; (e) average monthly *T* and ET_o values; (f) average monthly *P* and *RH* values; (g) average annual wind speed (*WS*), m/s; (h) average monthly *WS* value

(ET_o), further calculation of green water use by certain crop species throughout the life cycle was performed and the importance of the indicator of wind speed (*WS;* u_2) and relative air humidity (*RH*) was established. A high level of correlation of the two-factor model of calculation of ET_o depending on *RH* and *WS*, aimed at calculating the average annual ET_o values was established for the water catchment area of the Sluch river. The level of the model approximation is 0.44, the average monthly value *(ETo)* being 0.90. The proposed models are optimal for calculation of spatio-temporal differentiation of ET_o within the water catchment area of the Sluch river on the basis of different climate data.

Seasonal characteristics of climate changes (Fig. 8e, f, h) are necessary for determining the coefficient of productivity (K_c), calculating crop evapotranspiration (ET_c) and water footprint (WF, m^3/year) in growing the basic agricultural crops within the Sluch river basin.

The balance of green (rain) water use in growing agrocenosis on the basis of reference and statistical data on productivity of certain agricultural crops

In 2020 the portion of farmlands in the land structure of Ukraine was 68.7% (41.4 mln ha), including: arable lands – 79.0% (32.7 mln ha), pastures – 12.8% (5.3 mln ha), hayfields – 5.56 % (2.3 mln ha), perennial plantations – 2.17% (0.9 mln ha), fallow lands – 0.47% (0.2 mln ha). In the structure of farmlands 53.4% of crop areas are under grain and leguminous crops, including: wheat – 23.8%, barley – 9.0%, corn for grain – 16.6%. 33.5% of crop areas are under industrial crops: sunflower – 22.4% and rapeseed – 3.6%. 13.1% of crop areas are under other crops. Water use by agricultural crops depends on plant biological characteristics, productivity, soil-climate and organizational-technological conditions. The coefficient of water use mainly depends on soil-climate conditions of the zone of growing agrocenosis and the level of natural moisture supply in the vegetation period.

In particular, depending on the level of moisture supply in the year, plant water use for the formation of a ton of commodity products in the Polissia zone is as follows: for winter grain crops – from 350–450 m^3/t in wet years to 500–550 m^3/t in dry years, spring grain crops – from 375-435 m^3/t to 500–530 m^3/t, industrial crops – from 480–615 m^3/t to 685–720 m^3/t (Tabl. 4). Thus, the level of plant water use increases 1.2–1.3 times in dry years, that is determined by more intensive evapotranspiration processes. Such conditions are characteristic of growing the basic field crops in the water catchment area of the Sluch river.

In the Forest Steppe zone, crop water use per unit of product increases 1.30–1.45 times, in particular: winter grain crops –1.30–1.40 times, spring grain crops – 1.40–1.45 times, corn for grain – 1.38–1.40 times, industrial crops – 1.30–1.40 times. In turn, agrocenosis water use rises 2 times in the Steppe zone.

Reference coefficients of plant water use (m^3/t), established according to moisture conditions of the year (m^3/ha) and statistical data on productivity (t/ha), allow calculating the volumes of green water use for growing agricultural crops in the region's crop rotations. Calculation of green water use in growing basic the field crops within the Sluch river basin was performed using the data of the State Statistics Service of Ukraine (https://www.ukrstat.gov.ua/). The values of crop productivity in Khmelnytskyi and Zhytomyr regions, whose agro-landscapes comprise the water catchment area of the Sluch river, were averaged. Statistical data on productivity and green water use of the basic field crops depending on climatic characteristics of the year are given in Table 5.

The obtained results allow outlining the level of fluctuations of changes in green water use for the formation of productivity of certain agricultural crops, determining green water use (m^3/ha) for other agricultural needs and hydro-functioning of the water catchment area. Cyclicity of an increase in crop water use (Fig. 9a) depending on climatic conditions of a certain year was established (Fig. 8). The value of water use was calculated according to the ratio of saturation of crop rotation with grain and industrial crops in the research region (65:35%). Under conditions

Table 4. Coefficients of crop water use in the Polissia zone of Ukraine depending on moisture supply in the year, m^3/t

Crop	Wet year	Medium year	Dry year
Winter wheat	350–450	450–500	500–525
Winter rye	400–425	425–450	450–550
Spring wheat	400–435	435–465	465–500
Spring barley	375–425	425–500	500–530
Corn for grain	265–335	335–375	375–395
Sunflower Winter rapeseed	480–615	615–685	685–720

Table 5. Productivity (t/ha) and green water use (m³/ha) of the basic field crops within the Sluch river basin in 2011–2021

Year		Crops					
		Wheat	Spring barley	Winter rye	Corn for grain	Sunflower	Winter rapeseed
2011	t/ha	3.2–4.5	2.5–3.3	1.9–2.9	6.6–7.8	1.8–2.0	1.5–2.2
	m³/ha	1636–2288	1303–1700	955–1445	2541–3007	1230–1413	1040–1554
2012	t/ha	3.5–4,3	3.0–3.7	2.2–2.7	7.3–7.4	1.9–2.0	2.3–2.4
	m³/ha	1380–1720	1196–1464	890–1121	2187–2229	1047–1091	1282–1293
2013	t/ha	3.2–4.2	2.7–3.3	2.0–2.7	7.9–8.9	2.2–2.3	2.5–2.8
	m³/ha	1292–1672	1080–1304	832–1108	2376–2664	1206–1255	1343–1551
2014	t/ha	4.1–5.5	3.8–4.7	2.5–3.6	7.8–8.3	2.2–2.7	2.7–3.4
	m³/ha	1933–2627	1750–2181	1082–1586	2780–2939	1456–1775	1781–2217
2015	t/ha	4.5–5.8	4.0–4.7	2.8–3.9	5.3–6.0	2.6–2.9	2.6–3.3
	m³/ha	2309–2996	2060–2431	1420–1935	2056–2325	1793–2004	1800–2348
2016	t/ha	4.7–5.8	3.9–4.9	2.8–4.8	7.3–7.8	2.6–3.2	1.9–2.9
	m³/ha	2214–2736	1810–2273	1240–2094	2584–2780	1716–2087	1261–1853
2017	t/ha	4.3–6.2	3.5–5.3	2.8–5.7	6.6–7.8	2.4–3.1	3.0–3.2
	m³/ha	2052–2945	1625–2454	1235–2501	2343–2773	1554–2015	1944–2093
2018	t/ha	4.3–5.7	3.3–4.5	2.5–4.4	9.2–9.9	2.5–3.2	2.7–3.3
	m³/ha	2043–2684	1537–2093	1113–1945	3270–3511	1638–2054	1749–2171
2019	t/ha	4.3–4.7	3.5–4.3	3.2–4.0	6.5–7.9	2.4–3.2	2.2–2.8
	m³/ha	2215–2420	1680–2065	1600–2000	2505–3045	1690–2250	1550–1970
2020	t/ha	4.9–5.9	3.7–4.5	3.4–4.4	8.4–9.8	2.5–3.3	2.8–3.2
	m³/ha	2330–2805	1670–2030	1480–1920	2940–3430	1625–2145	1820–2080
2021	t/ha	5.0–6.4	4.1–4.7	3.6–5.2	8.2–11.2	2.8–3.8	3.0–3.6
	m³/ha	2000–2560	1720–1975	1490–2160	2450–3360	1540–2100	1650–1980

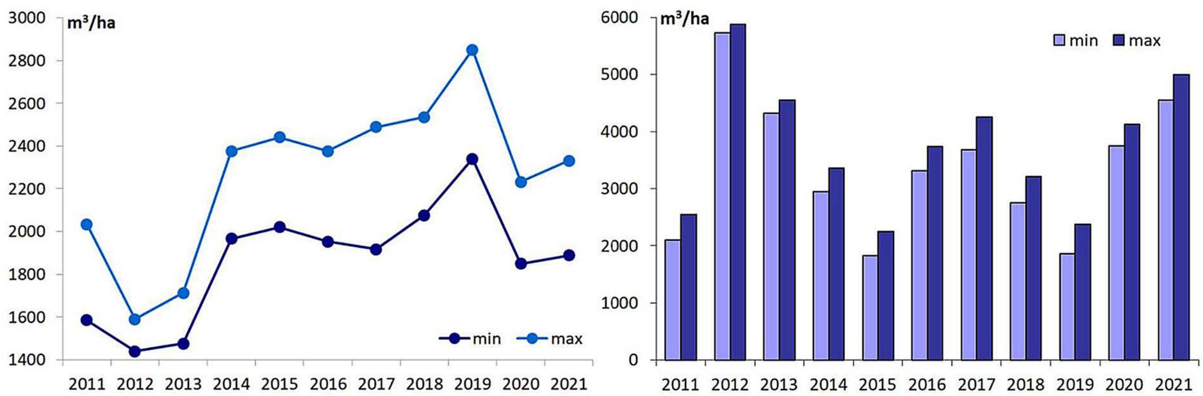

Figure 9. Balance of green water use by agricultural crops within the Sluch river basin: (a) the average of water use coefficient per hectare (m³/ha); (b) accumulation of green water (m³/ha) for maintaining water-balance stability of the river basin

of dynamic changes in precipitation and a continual increase in the air temperature over the past 11 years, the largest volume of green water use for growing the basic field crops within the water catchment area of the Sluch rivers was registered in 2019: from 2340 m³/ha to 2850 m³/ha, and the minimum value was registered in 2012, 2013 and 2021 – 1440–1590 m³/ha, 1475–1715 m³/ha and 1890–2330 m³/ha, respectively. In the dry years of 2011, 2015 and 2019 characterized by precipitation deficit, accumulation of green water (m³/ha) in the water catchment area ranged from 1830

m^3/ha to 2545 m^3/ha (Fig. 9b). In the wet years of 2012, 2013 and 2021, this index equaled 4315–5875 m^3/ha. It was established that the share of using rainwater by agrocenoses in the dry years was 38.4–60.5%, in the semi-dry years – 31.0–48.0%, in the wet years – 19.7–34.0%. The total volume of green water use in the river basin landscapes in the calculation of the farmland share (39.7% (549.05 thous. ha)) was 1005–1565 mln m^3 in 2011–2021, in the dry years – 1110–1565 mln m^3, in the semi-wet years – 1015–1390 mln m^3, in the wet years – 790–1280 mln m^3. The proposed approach and the results of the calculation should be used for identifying the tendencies in green water use in growing the basic field crops of a certain region. The proposed approach does not consider the course of plant vegetation development and spatio-temporal changes in evapotranspiration processes in crop cultivation within the water catchment area. Therefore, thorough calculation of water footprint should be performed on the basis of the data on natural moisture supply and water use in the plant vegetation period taking into consideration evapotranspiration processes.

Differentiation of water footprint in growing the basic field crops and calculation of the volume of moisture accumulation within the Sluch river basin

Winter crops have 2 periods of active vegetation: autumn (45–50 days: the end of September – the end of November) and spring-summer (75–100 days: the end of March – the beginning of July). Between these periods, plants are in the state of dormancy. The entire vegetation period of winter wheat lasts from 180 to 215 days. The vegetation period of spring grain crops is shorter than that of winter crops: spring barley – 80–105 days (the beginning of March – the end of June), spring wheat – 85–105 days (the beginning of March – the beginning of July), the amount of nutrition elements used for yield formation in both of them is nearly identical. The root system of spring grain crops is weaker, and the process of tillering is worse. These peculiarities should be taken into consideration in order to maintain full-blown plant nutrition throughout the vegetation period. The vegetation period of sunflower lasts 100–120 days on average (the end of April, the beginning of May – the end of August, the beginning of September). The vegetation period of winter rapeseed (autumn and spring-summer) lasts 180–225 days (the end of August – the beginning of July). The duration of the vegetation period of corn for grain in the Polissia zone ranges from 150 to 170 days (the end of April and the beginning of May – the end of August and the beginning of September). These periods should be taken into account to specify the crop coefficient (K_c) and adjust calculation of crop evapotranspiration (ET_c) and water footprint (*WF*). High temperatures accelerate crop maturation and reduce the duration of the vegetation period by 8.0–24.0%, increase evapotranspiration processes and decrease the level of soil moisture. In the vegetation period, agricultural crops are supplied with moisture to 60–70% by precipitation, to 30–40% – by soil moisture reserves. This regularity should be taken into consideration when calculating water footprint which consists of «green» and «blue» water resources, i.e. «rain» and «soil or surface» water that evaporates in growing agricultural crops.

According to the generalized FAO data, the duration of the main phenological stages of plants belonging to the basic field crops and similar growing conditions within the Sluch water catchment area are as follows: for winter wheat with the vegetation period of 180 days, including L_{ini} – 20 days, L_{dev} – 60 days, L_{mid} – 70 days, L_{late} – 30 days; winter rye – no available data; spring wheat and barley with the vegetation period of 120 days, including L_{ini} – 15 days, L_{dev} – 25 days, L_{mid} – 50 days, L_{late} – 30 days; grain for corn with the vegetation period of 125 days, including L_{ini} – 20 days, L_{dev} – 35 days, L_{mid} – 40 days, L_{late} – 30 days; sunflower with the vegetation period of 130 days, including L_{ini} – 25 days, L_{dev} – 35 days, L_{mid} – 45 days, L_{late} – 25 days; winter rapeseed – no available data. The given data do not correspond to the exact characteristics of the vegetation period and phenological stages of the development of the basic field crops for the research territory. Therefore, Table 5 gives the duration of phenological development stages of agricultural crops and sowing dates in accordance with climatic conditions of the water catchment area of the Sluch river.

Due to an increase in the air temperature and erratic precipitation over the past years, new climatic conditions for growing agricultural crops and volumes of water use are forming. Therefore, research and calculation of the volumes of green and blue water use were performed using the example of new conditions for climate formation with different levels of moisture supply and evapotranspiration processes, in particular: 2019

– a dry year with a high level of evapotranspiration (P = 741 mm, T = 9.4°C, ET_o = 2m12 mm/day); 2020 – a semi-wet year (P = 595 mm, T = 9.3°C, ET_o = 2.09 mm/day); 2021 – a wet year with a low level of evapotranspiration (P = 690 mm, T = 7.4°C, ET_o = 1.95 mm/day).

For calculating the volumes of water footprint, the vegetation periods of the basic field crops in 2018–2021 (Table 6) were selected. Winter crops: 2018–2019 – a semi-wet year grows into a dry year; 2019–2020 – a dry year grows into a semi-wet year; 2020–2021 – a semi-wet year grows into a wet year. Figure 10 presents distribution of the values of climate characteristics in the vegetation periods of 2018–2021 for establishing and adjusting the crop coefficient value (*Kc*) using the method FAO Penman-Monteith ET_o (https://www.fao.org/3/X0490E/x0490e0b.htm#TopOfPage). The research period involves the vegetation periods of the basic field crops within the Sluch river basin.

Given the climate characteristics of the region and conditions of a certain year of crop cultivation, the crop coefficients (*Kc*) were determined according to plant water use at certain phenological stages (Table 7). The proposed coefficients were used for calculating the values of crop evapotranspiration (ET_c) and spatio-temporal modelling of water footprint volumes,

Table 6. Characteristics of the vegetation dates of the basic field crops under climatic conditions of the Sluch river basin

Crop		Vegetation dates			Duration of the main phenological stages of plant development, days				
		Wet year	Semi-wet year	Dry year	Year characteristics	L_{ini}	L_{dev}	L_{mid}	L_{late}
Winter wheat	Sowing dates (day, month)	15-20.09	15-20.09	20-25.09	Wet	95	80	20	20
	Harvesting dates (day, month)	20-25.07	15-20.07	10-15.07	Semi-wet	90	75	18	15
	Vegetation period (days)	215	198	180	Dry	85	70	10	15
Winter rye	Sowing dates (day, month)	25.08-01.09	20.08-05.09	01-10.09	Wet	110	80	15	20
	Harvesting dates (day, month)	20-25.07	20-25.07	10-20.07	Semi-wet	100	75	15	15
	Vegetation period (days)	225	205	185	Dry	90	70	10	15
Spring wheat	Sowing dates (day, month)	01-05.04	25.03-01.04	20-25.03	Wet	35	30	25	15
	Harvesting dates (day, month)	25-28.07	25-30.07	15-25.07	Semi-wet	30	30	20	15
	Vegetation period (days)	105	95	85	Dry	30	25	20	10
Spring barley	Sowing dates (day, month)	01-05.04	25.03-01.04	20-25.03	Wet	35	30	25	15
	Harvesting dates (day, month)	25-28.07	25-30.07	15-25.07	Semi-wet	30	30	20	15
	Vegetation period (days)	105	95	80	Dry	30	20	20	10
Corn for grain	Sowing dates (day, month)	10-15.05	05-10.05	25.04-02.05	Wet	45	45	50	30
	Harvesting dates (day, month)	15-20.10	10-15.10	01-10.10	Semi-wet	50	45	45	25
	Vegetation period (days)	170	165	155	Dry	50	45	40	20
Sunflower	Sowing dates (day, month)	10-15.05	05-10.05	25.04-2.05	Wet	50	35	15	20
	Harvesting dates (day, month)	20-25.09	15-20.09	05-15.09	Semi-wet	45	30	15	18
	Vegetation period (days)	120	108	105	Dry	45	30	15	15
Winter rapeseed	Sowing date s (day, month)	10-15.08	15-20.08	25.08-01.09	Wet	125	50	30	20
	Harvesting dates (day, month)	15-20.07	05-10.07	01-05.07	Semi-wet	120	40	25	15
	Vegetation period (days)	225	200	185	Dry	115	35	20	15

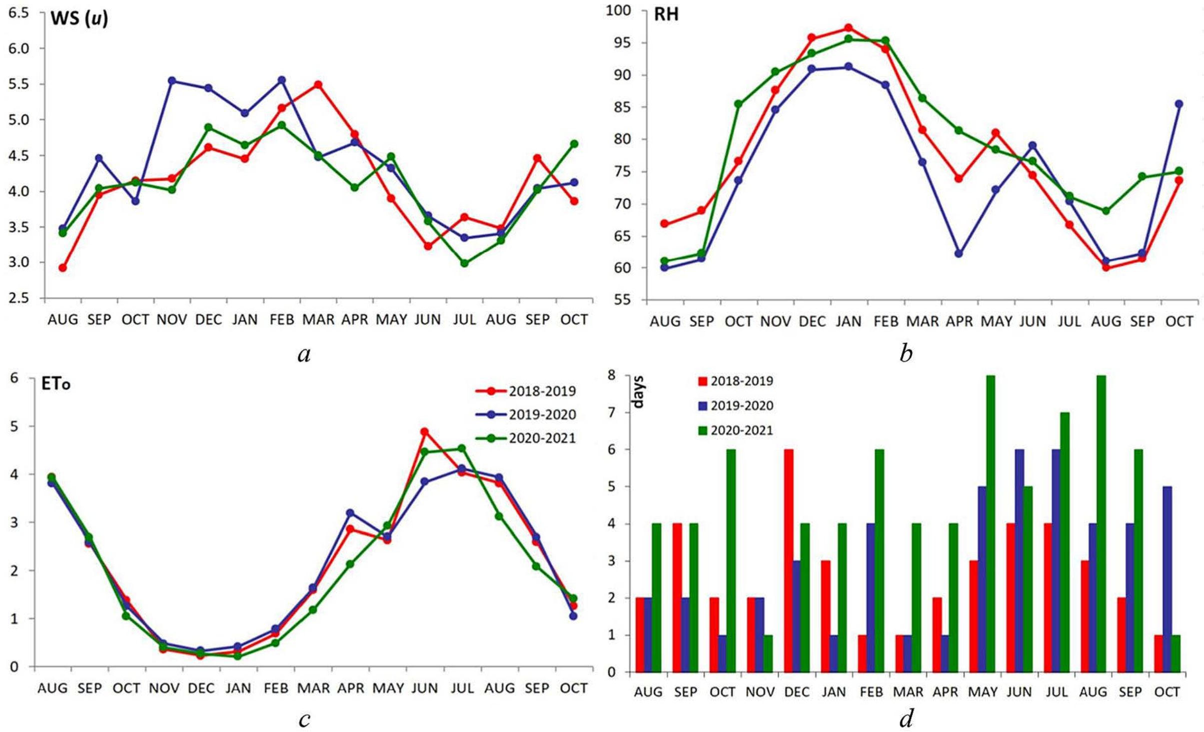

Figure 10. Distribution of the values of climate characteristics in the vegetation periods of 2018–2021 for establishing and adjusting the crop coefficient value (*Kc*) in accordance with the method FAO Penman-Monteith ET_o: (a) wind speed, m/c; (b) air humidity, %; (c) the value of reference evapotranspiration, mm/day; (d) precipitation in the form of rain and snow, days

determining the portion of green water use according to climate characteristics of a certain year and a typical structure of crop rotation within the agrolandscapes of the Sluch river basin.

It was found that the average volume of water footprint in the vegetation period of 2018–2021 in the agro-landscapes of the water catchment area (Fig. 11) for winter wheat was 3336–3525 m^3/ha, winter rye – 3322–3528 m^3/ha, spring barley and wheat – 2360–2475 m^3/ha, corn for grain – 3968–4634 m^3/ha, sunflower – 2496–2787 m^3/ha, winter rapeseed – 3435–3650 m^3/ha. The registered zonal peculiarities of spatial distribution of the volume of water use are characterized by its rise in the upper part of the river basin due to an increase in evapotranspiration processes by 5.0–17.0%. Such processes result in a reduction in the volume of green water accumulation for maintaining the hydro-functioning of the upper courses of the Sluch river.

Table 8 presents calculations of water footprint dynamics in growing the basic field crops in the vegetation periods of 2018–2021. The ratio of green water use for transpiration and growing the basic field crops (*WUha*, m^3/ha; *WUt*, m^3/t) and evaporation of soil (blue) moisture (*Eha*, m^3/ha; *Et*, m^3/t) were established. The portion of green water distribution varies depending on climatic conditions, crop rotation, vegetation periods and crop productivity. The value of water use per 1 ha (*WUha*, m^3/ha) involves water use for plant development and transpiration from the plant surface. In particular, the *WUha* value depends on climatic condition of the year, crop yields (*AY*, t/ha) and water use per 1 ton of products (*WUt*, m^3/t).

Relatively high values of water footprint (*WFha*) per 1 ha were registered in growing corn for grain – from 4159 m^3/ha to 4203 m^3/ha and winter crops, including: winter wheat – 3294–3628 m^3/ha, winter rye – 3335–3594 m^3/ha and winter rapeseed – 3325–3770 m^3/ha. In particular, relatively low values of *WFha* are characteristic of crops with a short vegetation period, including: spring barley – 2230–2530 m^3/ha and sunflower – 2500–2850 m^3/ha. Yields (*AY*, t/ha) and water footprint (*WUt*) depending on climate characteristics of the year of agrocenosis vegetation are an important feature of the total volume of green water use and calculation of the volume of evaporated soil moisture. High values of *WFt* are registered in industrial crops – 864–1330 m^3/t, low values of *WFt* are characteristic of corn for

Table 7. Distribution of the *Kc* values in the vegetation period of the basic field crops under climatic conditions of the Sluch river basin

Tears	Crops	Months														
		AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT
The value of the crop coefficient (*Kc*)																
2018–2019	Winter wheat		0.45	0.50	0.50	0.50	0.50	0.50	0.63	0.84	1.06	1.17	0.25			
	Winter rye	0.20	0.45	0.50	0.50	0.50	0.50	0.50	0.63	0.84	1.06	1.17	0.25			
	Spring wheat								0.35	0.67	0.71	1.17	0.25			
	Spring barley								0.35	0.67	0.71	1.17	0.25			
	Corn for grain										0.38	0.53	0.80	1.12	1.35	0.35
	Sunflower										0.38	0.53	0.80	1.11	0.35	
	Winter rapeseed	0.20	0.45	0.50	0.50	0.50	0.50	0.50	0.64	0.85	0.97	1.02	0.35			
2019–2020	Winter wheat		0.30	0.50	0.50	0.50	0.50	0.50	0.63	0.93	1.10	1.21	0.25			
	Winter rye		0.30	0.50	0.50	0.50	0.50	0.50	0.63	0.93	1.10	1.21	0.25			
	Spring wheat								0.35	0.78	0.84	1.21	0.25			
	Spring barley								0.35	0.78	0.84	1.21	0.25			
	Corn for grain										0.50	0.51	0.76	1.11	1.33	0.35
	Sunflower										0.50	0.51	0.76	1.10	0.35	
	Winter rapeseed	0.20	0.30	0.50	0.50	0.50	0.50	0.50	0.71	0.95	1.00	1.01	0.35			
2020–2021	Winter wheat		0.40	0.50	0.50	0.50	0.50	0.50	0.50	0.71	1.06	1.21	0.25			
	Winter rye	0.20	0.40	0.50	0.50	0.50	0.50	0.50	0.50	0.71	1.06	1.21	0.25			
	Spring wheat									0.30	0.82	1.21	0.25			
	Spring barley									0.30	0.82	1.21	0.25			
	Corn for grain										0.50	0.53	0.73	1.06	1.25	0.35
	Sunflower										0.50	0.53	0.73	1.06	0.35	
	Winter rapeseed	0.20	0.40	0.50	0.50	0.50	0.50	0.50	0.50	0.71	0.97	1.03	0.35			
The value of the crop evapotranspiration (ET_c), mm/day																
2018–2019	Winter wheat		1.15	0.69	0.18	0.12	0.16	0.35	1.00	2.39	2.79	5.70	1.01			
	Winter rye	0.79	1.15	0.69	0.18	0.12	0.16	0.35	1.00	2.39	2.79	5.70	1.01			
	Spring wheat								0.56	1.91	1.87	5.70	1.01			
	Spring barley								0.56	1.91	1.87	5.70	1.01			
	Corn for grain										1.00	2.58	3.22	4.27	3.50	0.44
	Sunflower										1.00	2.58	3.22	4.23	0.91	
	Winter rapeseed	0.79	1.15	0.69	0.18	0.12	0.16	0.35	1.02	2.42	2.55	4.97	1.41			
2019–2020	Winter wheat		0.78	0.63	0.24	0.17	0.21	0.39	1.03	2.97	2.97	4.65	1.03			
	Winter rye		0.78	0.63	0.24	0.17	0.21	0.39	1.03	2.97	2.97	4.65	1.03			
	Spring wheat								0.57	2.49	2.27	4.65	1.03			
	Spring barley								0.57	2.49	2.27	4.65	1.03			
	Corn for grain										1.35	1.96	3.12	4.36	3.58	0.37
	Sunflower										1.35	1.96	3.12	4.32	0.94	
	Winter rapeseed	0.76	0.78	0.63	0.24	0.17	0.21	0.39	1.16	3.03	2.70	3.88	1.44			
2020–2021	Winter wheat		1.08	0.53	0.20	0.14	0.11	0.25	0.59	1.51	3.11	5.40	1.13			
	Winter rye	0.79	1.08	0.53	0.20	0.14	0.11	0.25	0.59	1.51	3.11	5.40	1.13			
	Spring wheat									0.64	2.40	5.40	1.13			
	Spring barley									0.64	2.40	5.40	1.13			
	Corn for grain										1.47	2.36	3.31	3.31	2.60	0.49
	Sunflower										1.47	2.36	3.31	3.31	0.73	
	Winter rapeseed	0.79	1.08	0.53	0.20	0.14	0.11	0.25	0.59	1.51	2.84	4.59	1.59			

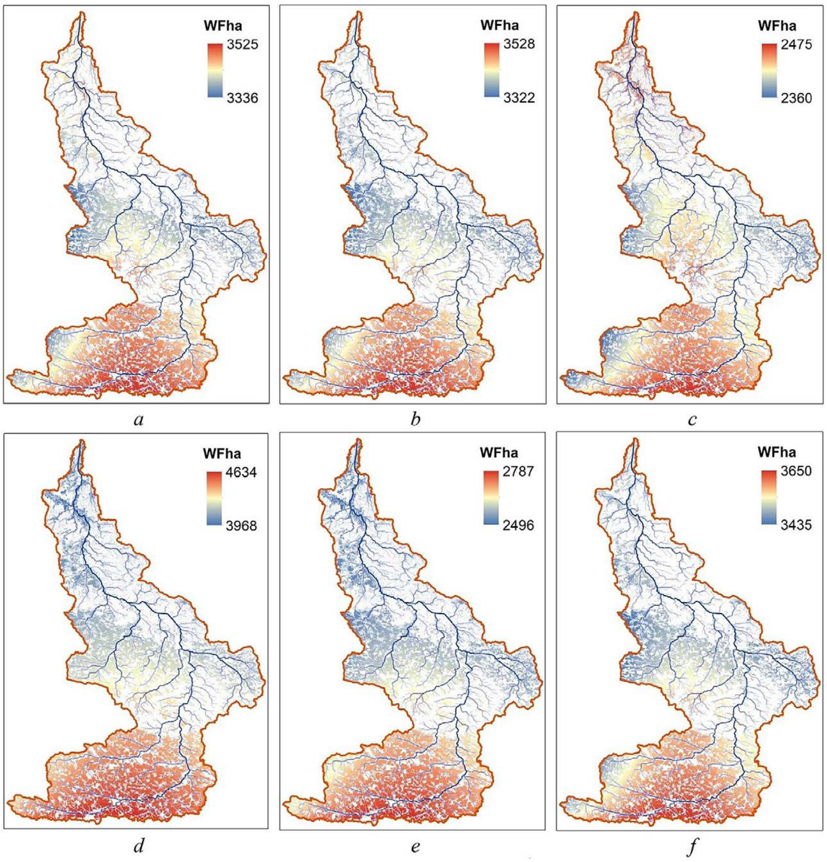

Figure 11. Spatial differentiation of water footprint (*WFha*, m^3/ha) in growing the basic field crops in the vegetation periods of 2018–2021: (a) winter wheat, (b) winter rye; (c) spring barley and wheat; (d) corn for grain; (e) sunflower; (f) winter rapeseed

Table 8. The average of water footprint dynamics in growing the basic field crops in the vegetation periods of 2018–2021

Crop		Vegetation period								
		AY, t/ha	WFha, m^3/ha	WUha, m^3/ha	Eha, m^3/ha	WFt, m^3/t	WUt, m^3/t	Et, m^3/t	WUt/WFt	Et/WFt
Winter wheat	2018–2019	4.5	3294	2318	976	732	515	217	0.70	0.30
	2019–2020	5.4	3628	2568	1060	672	476	196	0.71	0.29
	2020–2021	5.7	3354	2280	1074	588	400	188	0.68	0.32
Winter rye	2018–2019	3.6	3335	1800	1535	926	500	426	0.54	0.46
	2019–2020	3.9	3594	1700	1894	922	436	486	0.47	0.53
	2020–2021	4.4	3347	1825	1522	761	415	346	0.55	0.45
Spring barley	2019	3.9	2230	1873	357	572	480	92	0.84	0.16
	2020	4.1	2495	1850	645	609	451	157	0.74	0.26
	2021	4.4	2530	1848	682	575	420	155	0.73	0.27
Corn for grain	2019	7.2	4203	2775	1428	584	385	198	0.66	0.34
	2020	9.1	4526	3185	1341	497	350	147	0.70	0.30
	2021	9.7	4159	2905	1254	429	299	129	0.70	0.30
Sunflower	2019	2.8	2500	1970	530	893	704	189	0.79	0.21
	2020	2.9	2570	1885	685	886	650	236	0.73	0.27
	2021	3.3	2850	1820	1030	864	552	312	0.64	0.36
Winter rapeseed	2018–2019	2.5	3325	1760	1565	1330	704	626	0.53	0.47
	2019–2020	3.0	3534	1950	1584	1178	650	528	0.55	0.45
	2020–2021	3.3	3770	1815	1955	1142	550	592	0.48	0.52

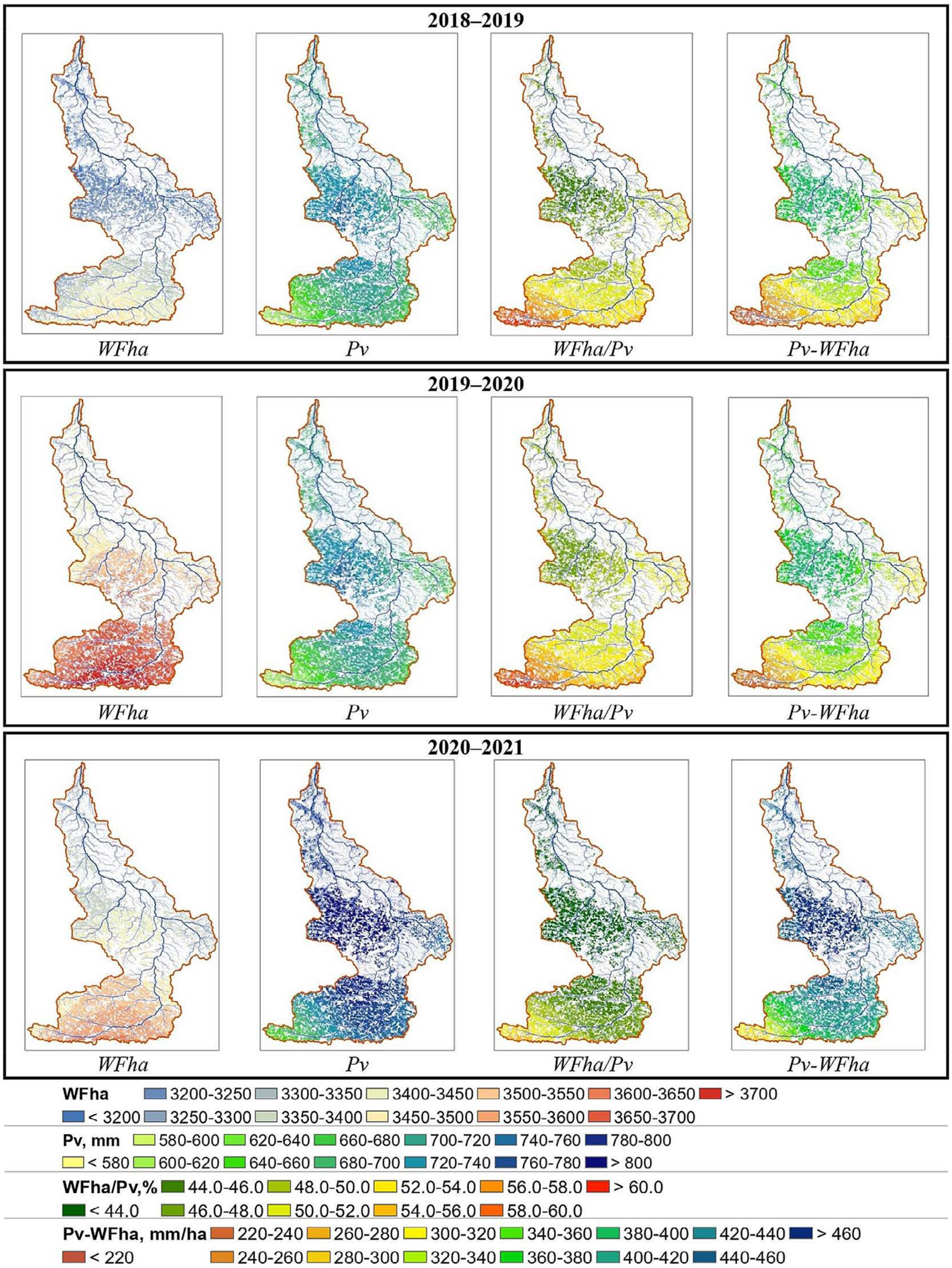

Figure 12. Balance of green water use by the basic field crops in the vegetation periods of 2018–2021: *WFha* – water footprint in growing the field crops, m^3/ha, *Pv* – the total amount of precipitation in the vegetation period, mm; *WFha/Pv* – the ratio of rain (green) water use in the vegetation period, %; *Pv-WFha* – accumulation of green water in the agro-landscapes of the water catchment area, mm/ha

grain – from 429 m^3/t to 584 m^3/t and spring barley – 572–609 m^3/t. Therefore, saturation of crop rotation with industrial crops causes an increase in the volumes of water footprint 1.5–2.3 times and evaporation of soil (blue) moisture – 1.3–4.0 times. A considerable portion of the volume of evaporated soil (blue) moisture (*Et/WFt*) is registered under winter rye and winter rapeseed – from 0.45 to 0.53. It characterizes a high level of green water use, low productivity of crop cultivation and a lack of their agro-ecological efficiency in creating optimal models of using soil (blue) moisture for the research region. The given calculations show the ratio of green (*WUt/WFt*) and blue (*Et/WFt*) water use in growing certain field crops within the Sluch river basin.

Spatial differentiation of water footprint (*WFha*, m^3/ha, *WF*, m^3/vegetation) in growing agrocenoses in the vegetation periods of 2018–2021 and the volume of green water accumulation in the agro-landscapes are calculated in accordance with the ratio of saturation of crop rotations with the basic field crops within the Sluch river basin, in particular: winter wheat – 24.3%, winter rye – 1.9%, spring barley – 7.5%, corn for grain – 31.3%, sunflower – 24.8%, winter rapeseed – 10.2%. The highest *WFha* values (Fig. 12) were registered in the vegetation period from August, 2019 (a dry year) to October, 2020 (a semi-wet year) – from 3385 m^3/ha to 3739 m^3/ha. In the vegetation period from August, 2018 (a semi-wet year) to October, 2019 (a dry year), the *WFha* value equaled 3157–3508 m^3/ha; from August, 2020 (a semi-wet year) to October, 2021 (a wet year), the *WFha* value ranged from 3329 m^3/ha to 3621 m^3/ha. The total volume of water footprint (*WF*, m^3/vegetation) in growing a crop rotation of the field crops was: in 2018–2019 – 1991 mln m^3, 2019–2020 – 2440 mln m^3, 2020–2021 – 2363 mln m^3. Precipitation (*Pv*, mm) in the vegetation period of 2018–2019 within the agro-landscapes of the river water catchment area equaled 556–716 mm; in 2019–2020 – from 595 mm to 744 mm; in 2020–2021 – from 646–817 mm. The total volume of precipitation in the vegetation period within the agro-landscapes of the river water catchment area equaled: in 2018–2019 – 3760 mln m^3, 2019–2020 – 4423 mln m^3, 2020–2021 – 4839 mln m^3.

Spatio-temporal regularities of a change in the portion of using precipitation by a crop rotation of the field crops in the vegetation years with different climate conditions were established on the basis of the ratio of the *WFha* and *Pv* data. In particular, in the vegetation period of 2018–2019 (semi-wet → dry) the portion of using precipitation (*WFha/Pv*, %) was 45.2–61.5%; in 2019–2020 (dry → semi-wet) – from 47.4% to 61.6%; in 2020–2021 (semi-wet → wet) – from 41.4% to 55.2%. The obtained results allow calculating the volume of accumulation of rain (green) water (*Pv-WFha*, mm) in the agro-landscapes for maintaining the hydro-functioning of the water catchment area of the Sluch river. It was found that in the vegetation period of 2018–2019, green water accumulation after growing the basic field crops was 215–392 mm/ha; in 2019–2020 – 229–389 mm/ha; in 2020–2021 – 289–477 mm/ha. The total volume of green water accumulation in the vegetation period from the agro-landscapes for maintaining water-balance stability of the river basin was: in 2018–2019 – 1769 mln m^3, or 47.0% from precipitation *Pv;* 2019–2020 – 1983 mln m^3, or 44.8% from *Pv*; 2020–2021 – 2476 mln m^3, or 51.2% from *Pv*. The research results are of high agricultural and ecological value, since they allow adjusting and substantiating resource-saving agro-technologies and crop rotations depending on climate changes and moisture deficit, the volumes of efficient water use by an individual crop, the options of rain (green) water accumulation and retention of soil (blue) moisture for creating further favorable conditions for the vegetation of a field crop rotation. In terms of ecology, the results are important for calculating the volumes of retention and additional accumulation of moisture and establishing water balance stability of the river basin.

CONCLUSIONS

Spatio-temporal regularities of the differentiation of water footprint in growing agricultural crops and the formation of water balance stability of the Sluch river basin in the Polissia zone of Ukraine under climate change were established on the basis of the analysis of the data of Climatic Research Unit of the University of East Anglia, NASA POWER, FAO and decoding of the satellite imagery of the spacecraft Sentinel 2. A series of climate maps and maps of the balance of green water use by the basic field crops in the vegetation periods were created, that allowed conducting research on climate change, the formation of water footprint volumes depending on crop rotations and climatic conditions of the vegetation period, finding the ratio of using rain (green) water and soil (blue) moisture in the vegetation period, calculating the volumes of green water accumulation in the agro-landscapes of the water catchment area for establishing water balance stability of the Sluch river basin. It was found that over the past 120 years the amount of precipitation per year within the water catchment area of the Sluch river basin has ranged from 487 mm to 716 mm. Over the past 40 years the average annual temperature in the water catchment area has risen by 1.9°C on average, that led to a considerable increase in evapotranspiration processes from 1.79 mm/day to 2.25 mm/day, a reduction in moisture supply in the basin landscape and aquatic territorial structures by 20–25%. The results of correlation analysis allowed establishing that the main climate component of the differentiation of reference evapotranspiration (ET_o) is air temperature (T). The level of correlation of the average annual T and ET_o values is 0.79, that of the average monthly values equals 0.95. The volumes of water footprint were calculated for the vegetation period of a crop rotation of the basic field winter and spring crops in 2018–2021, in particular: 2018–2019 – a semi-wet year grows into a dry year; 2019–2020 – a dry year grows into a semi-wet year; 2020–2021 – a semi-wet year grows into a wet year. The ratio of saturation of crop rotations in the years of the research was as follows: winter wheat – 24.3%, winter rye – 1.9%, spring barley – 7.5%, corn for grain – 31.3%, sunflower – 24.8%, winter rapeseed – 10.2%. The volumes of virtual water use and the ratio of rain (green) and soil (blue) water use were calculated for the crops of crop rotations. High saturation of crop rotations with industrial crops results in an increase in the volumes of water footprint for growing 1 ton of products – 1.5–2.3 times and evaporation of soil (blue) moisture – 1.3–4.0 times. Therefore, high saturation of crop rotations with these crops causes a low level of their agro-ecological efficiency in terms of green water accumulation and optimization of soil (blue) moisture use aimed at creating favorable conditions for water balance stability of the river basin. The ratio of «green:blue» water use for the basic field crops in the agro-landscapes of the water catchment area is as follows: winter wheat – 0.7:0.3; winter rye – 0.52:0.48; winter rapeseed – 0.52:0.48; spring barley – 0.77:0.23; corn for grain – 0.69:0.31; sunflower – 0.72:0.28. It was established that the portion of using precipitation by a crop rotation of the field crops in the vegetation years with different climate conditions ranged from 45.2% to 61.5% in 2018–2019 (semi-wet → dry); in 2019–2020 (dry → semi-wet) – from 47.4% to 61.6%; in 2020–2021 (semi-wet → wet) – from 41.4% to 55.2%. It caused heterogeneity of additional accumulation of green water in the agro-landscapes for maintaining water balance stability of the river basin at the following level: in 2018–2019 – 1769 mln m^3, or 47.0% from precipitation (Pv); 2019–2020 – 1983 mln m^3, or 44,8% from Pv; 2020–2021 – 2476 mln m^3, or 51.2% from Pv. The proposed research scheme and the obtained results are important for adjusting and substantiating resource-saving agro-technologies and crop rotations in accordance to climate changes, establishing water balance stability of the river basin through the index of additional accumulation of green water.

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