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Long-term forecast of changes in soil erosion losses during spring snowmelt caused by climate within the plain part of Ukraine

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Abstract. The paper deals with the forecast of changes in erosion soil losses during the spring snowmelt due to climate change in the regions of Ukraine in the middle of the 21st century (during 2031–2050) and at its end (during 2081–2100) compared with the values of the baseline period (1961–1990). The forecast is based on the use of the so-called

“hydrometeorological factor of spring soil loss”. This factor is a part of the physical-statistical mathematical model of soil erosion loss during spring snowmelt, developed at the Department of Physical Geography of Odesa I. I. Mechnikov State (since 2000 — National) University during the 1980s – 1990s. The long-term average value of the hydrometeorological factor is linearly related to the long-term average value of spring erosion soil loss. Therefore, the relative change in the hydrometeorological factor corresponds to the relative change in soil erosion losses. The developed methodology for assessing climate-induced changes in soil erosion losses in five regions of Ukraine (North, West, Center, East and South) takes into account the change in water equivalent of snow cover at the beginning of snow melting, the change in surface runoff and its turbidity, and changes in soil erodibility. The forecast of changes in erosion soil loss was carried out using projections of annual and monthly average air temperatures and precipitation for 2031–2050 and 2081–2100 in accordance with scenario A1B from AR4 of the IPCC. As a result of the research, it was found that both in the middle and at the end of the 21st century a decrease in the rate of soil erosion during the period of spring snowmelt is expected. During 2031–2050, the expected soil losses will be less than corresponding baseline period values within the West region by 79%, within the North and East regions by 81%, and within the Center region by 85%. In the South region, the spring soil losses will be zero due to the lack of snow cover. During 2081–2100 snow cover will be absent not only in the South region, but also in the Center and East regions. In the regions North and West snow cover will remain, but the spring soil erosion losses will decrease by dozens of times and will be so small that they can also be ignored.

Keywords: climate change, period of spring snowmelt, erosion soil losses, forecast until 2100, plains part of Ukraine

Довгостроковий прогноз обумовлених кліматом змін ерозійних втрат ґрунту в період весняного сніготанення в рівнинній частині України

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Анотація. Стаття присвячена прогнозу ерозійних втрат ґрунту в період весняного сніготанення під впливом зміни клімату в регіонах України в середині ХХІ століття (протягом 2031-2050 рр.) і в його кінці (протягом 2081-2100 рр.) в порівнянні з базовим періодом (1961-1990 рр.). Прогноз ґрунтується на використанні так званого «гідрометеорологічного фактору весняних втрат ґрунту, який є складовою частиною фізико-статистичної математичної моделі ерозійних втрат ґрунту в період весняного сніготанення, розробленої на кафедрі фізичної географії Одеського державного (з 2000 р. – національного) університету імені І. І. Мечникова в 1980-х – 1990-х роках. Багаторічне середнє значення гідрометеорологічного фактору лінійно пов'язано з багаторічним середнім значенням весняних ерозійних втрат ґрунту, тому відносна зміна гідрометеорологічного фактору відповідає відносній зміні ерозійних втрат ґрунту. Розроблена методика оцінки обумовлених кліматом змін ерозійних втрат ґрунту по п'яти регіонах України (Північ, Захід, Центр, Схід і Південь) враховує зміни запасів води в сніговому покриві на початок сніготанення, поверхневого весняного стоку, його каламутності, а також піддатливості ґрунту ерозії. Довгостроковий прогноз змін ерозійних втрат ґрунту виконаний з використанням проєкцій середніх річних і місячних температур повітря і атмосферних опадів для 2031-2050 рр. і 2081-2100 рр., розроблених відповідно до сценарію А1В з АР4 ІРСС. В результаті виконаних досліджень встановлено, що як в середині ХХІ сторіччя, так і в його кінці очікується зниження ерозійних втрат ґрунту в період весняного сніготанення. Протягом 2031-2050 років очікувані втрати ґрунту в період весняного сніготанення будуть менше відповідних значень базового періоду в межах Західного регіону на 79%, в межах Північного і Східного регіонів

– на 81%, в межах Центрального регіону – на 85%. В регіоні Південь змив ґрунту в період весіннього сніготанення буде дорівнювати нулю в зв'язку з відсутністю снігового покриву. Протягом 2081-2100 рр. сніговий покрив буде відсутній не тільки в регіоні Південь, але також в регіонах Центр і Схід. У регіонах Північ і Захід сніговий покрив збережеться, але весняні ерозійні втрати ґрунту зменшаться в десятки разів і будуть настільки малі, що їх також можна буде не враховувати.

Ключові слова: зміна клімату, період весняного сніготанення, ерозійні втрати ґрунту, прогноз до 2100 р., рівнинна частина України

Introduction. Water erosion of soils is the most widespread soil degradation process in Ukraine (Fig. 1a), the negative consequences of which affect almost all components of landscape systems, but primarily the soil cover. According to the National Report on Soil Fertility State in Ukraine (Balyuk et al., 2010) the country's area of eroded agricultural land is equal to 15.953 million hectares or 38.4% of their area or 26.4% of the country's total area. The most eroded lands are situated in the south of the Forest–Steppe zone and in the north of the Steppe zone (Fig. 1b). Here within some administrative regions in varying degrees eroded soils occupy more than 80% of agricultural land (Balyuk et al., 2010; Kozyra et al., 2017). At the same time, the area of eroded lands in the country is constantly increasing. During the first decade of the 21st century, for example, this area increased by an average of 200 thousand hectares per year or by 1.5% annually.

Rainstorm erosion is predominant in the south of Ukraine, accounting for about 90% of the total soil losses. In the central part, the share of the rainstorm erosion is on average 60-70%. However, in the west and northwest of the country the contribution of erosion by rainstorms and snow melting to the erosion losses of soil is quite comparable. Thus, despite the predominant role of rainstorm soil erosion in the country, the forecast of changes of soil erosion by snowmelt waters in Ukraine, as in several other countries of the temperate climatic zone, has important theoretical and practical significance.

In recent decades to the problem of changing soil erosion under influence of the climate change is given a lot of attention in connection with the ongoing global warming and available climate change projections (Climate Change, 2007; Climate Change 2013, etc.). However, only rainstorm erosion is the subject of study in most researches devoted to the long-term

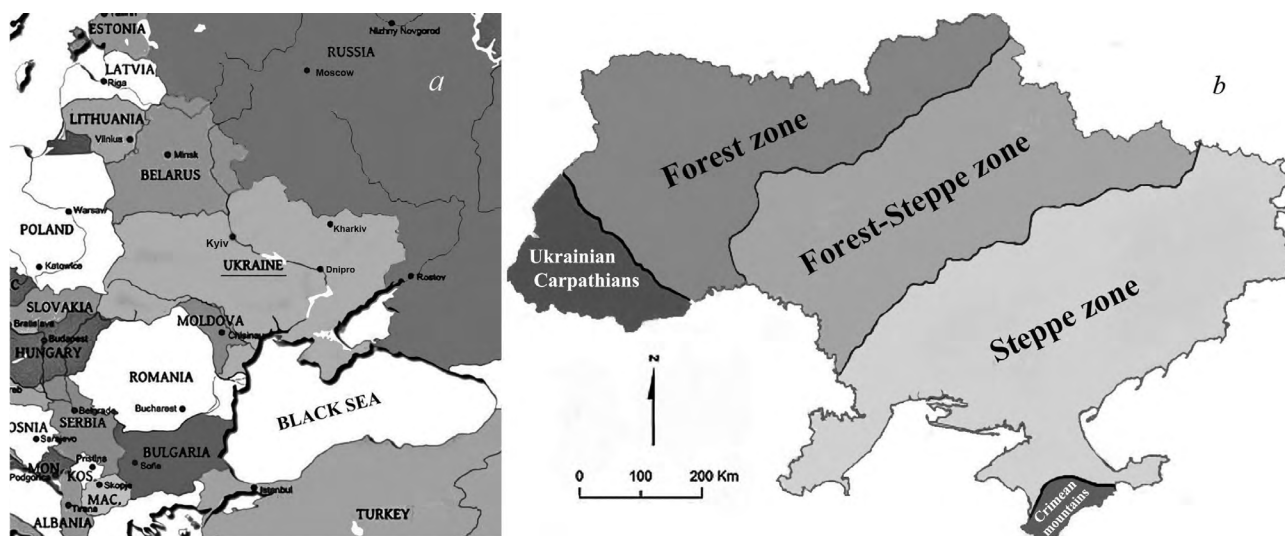


Fig. 1. Position of Ukraine on the map (a) and physical-geographical zoning of Ukraine (b)

Within the flat part of Ukraine, which occupies about 95% of the country's territory, rainstorm erosion during the warm season of the year (May–October) is a leading kind of soil erosion. However, taking into account the large size of the territory of the country (603.6 thousand square kilometers) and the large distance from north to south (about 900 km), the relationship between rainstorm erosion and erosion by snowmelt water significantly varies by area.

forecasting of changes in soil erosion (Ciscar et al., 2009; Routschek et al., 2014; Paroissien et al., 2015; Li et al., 2016; Eekhout and DeVente, 2019; Perović et al., 2019 and others). The number of publications dedicated to the long-term forecast of changes in soil erosion by melt waters is relatively small. In this regard, the results of many years monitoring of soil erosion by melt water and its factors (such as accumulation and melting of snow, soil freezing, and runoff of

melt waters) conducted in different countries are very important. They allow identification of trends in modern temporal dynamics of spring soil erosion.

Long-term monitoring conducted within the within the East European Plain revealed a strong tendency to reduction of spring surface runoff and soil erosion in the recent decades (Barabanov et al., 2016; Golosov et al., 2011; Gusarov et al., 2018; Medvedev et al., 2016; Petelko and Panov, 2014; Petelko and Barabanov, 2016; Sobol et al., 2015). Medvedev et al. (2016) and Gusarov et al. (2018) believe that the main reasons for reduction of the spring surface runoff and soil erosion are decrease of water equivalent of snow by the beginning of snow melting and decrease of soil freezing depth. It has been revealed (Barabanov and Panov, 2012; Komissarov and Gabbasov, 2014) that spring surface runoff wasn't observed regardless of water equivalent of snow cover, soil moisture and type of vegetation in the years when the freezing depth of soils was less than a certain critical value.

The earlier spring snow melting is another consequence of the current climate warming. According to the research of Stone et al. (2002) in northern Alaska since the mid 1960s to 2000, the melting date has advanced on average by 8 days. On the rivers of plain part of Ukraine, the beginning of the snowmelt-induced flood during 1989–2008 was observed on average two weeks earlier than in the previous period (Grebin, 2008). With further warming, this trend will undoubtedly continue. In particular, based on the long-term forecasting of snowmelt and runoff for two mountain watersheds in South Korea, it was established that at the end of the 21st century their beginning will shift to earlier dates by approximately a month (Shin et al., 2008).

As for studies directly devoted to the long-term forecast of climate-induced changes in erosion soil losses during spring snowmelt, their results are contradictory.

The IPCC Technical Paper (Bates et al., 2008), in particular, notes that “the shift of winter precipitation from less erosive snow to more erosive rainfall due to increasing winter temperatures enhances erosion”. Only the results of mathematical modeling of soil loss using the WEPP erosion model in the Palouse region (northwest United States) received by Farrell and others (2015) are consistent with the trend stated by Bates et al. (2008). In this research, it was obtained that the predicted warming by 4 °F (2.2 °C) in the middle of the 21st century compared with 1979–2009 and a significant increase in winter precipitation will lead to increasing of soil loss on agricultural land under conventional tillage from 0.17 to 0.5 t a⁻¹yr⁻¹, that

is, by 192%. At the same time, at the end of autumn soil loss will increase by 30% and in winter—by several times. It should be noted that historically the main part of precipitation in this region falls during the cold season and the most intensive soil erosion is observed in October–January. Erosion losses in spring here are insignificant.

In study by Trotouchaud (2015) based on simulations using RCP scenarios (Climate Change, 2013) it was found that in the 21st century in Tufion, Georgia (USA) the average monthly soil loss will vary differently in different months of the year. Projected soil losses in January–March and November will decrease by 20–40%, while in December they will significantly increase (by 40–60%) in accordance with increasing of precipitation. The study (Wang et al., 2018) found that within the southern part of the Great Lakes region (USA) occupied by crops and grasses, soil losses are expected to decrease in spring, mainly due to increasing of air temperature.

In Ukraine, studies about long-term forecasting of changes in the soil erosion by thawed waters due to climate change have not been conducted. Unfortunately, the lack of an appropriate information base makes it impossible to use here dynamic physically based models of soil erosion such as WEPP for solving the reviewed problem. Under such conditions, regional forecast of changes of spring soil erosion can be carried out based on reliable regional empirical mathematical models of soil erosion. In the 1970s–1990s, several such models were developed in Ukraine (Shvebs, 1974, 1981; Sribnyi and Vergunov, 1993; Svetlitchnyi, 1999). Availability of such models, projections of main climate characteristics for the regions of Ukraine for 2031–2050 and 2081–2100 (Krakovska et al., 2013; Shestoe..., 2013) and results of studies of modern features of spring runoff within the plain part of Ukraine (Gopchenko et al., 2012; Loboda and Bozhok, 2016; Ovcharuk, 2018; Shakirzanova, 2015) created preconditions for a quantitative assessment of expected changes of spring erosion within the investigated territory.

Accordingly, the aim of this study is a spatially distributed long-term (until 2100) forecast of changes in spring erosion soil losses on agricultural lands within the plain part of Ukraine under the influence of climate change using the considered prerequisites. At the same time, the impact on soil erosion of changes in such its factors as the structure of sown areas, a set of crops, and their cultivation technologies is not considered in this paper.

Material and Methods. General approach to assessment of climate-induced changes in soil erosion

during spring snowmelt. As a basis for assessment of climate-induced changes of the characteristics of soil erosion during spring snowmelt the so-called “hydrometeorological factor of spring soil erosion” (or spring soil loss) K_{HMS} was used. The K_{HMS} is a part of physical-statistical mathematical model of erosion-sedimentation developed in Odesa I. I. Mechnikov State (since 2000 National) University (Shvebs, 1974, 1981; Prokopenko, 1986; Svetlitchnyi, 1999; Svetlitchnyi et al., 2004). The model is designed to calculate the average annual soil losses at a given point of a slope or agricultural field ($t\ ha^{-1}\ yr^{-1}$) and is the product of the average annual value of the hydrometeorological factor and factors of relief, soil, vegetation (crop rotation) and soil protection measures, i.e., has a structure similar to USLE/RUSLE. It is important that in accordance with this model the value of soil erosion loss is linearly related to the value of the hydrometeorological factor. Therefore, the relative change of the hydrometeorological factor corresponds to the relative change in the erosion soil losses.

The average annual value of the hydrometeorological factor K_{HMS} ($g\cdot m^{-2}$) is described by the equation

$$K_{HMS} = 10^{-5} h \cdot \rho, \quad (1)$$

where h is the average annual depth of spring surface runoff (mm); ρ is the average annual concentration of sediments in the surface runoff (water turbidity) during the melting of snow in spring ($g\cdot dm^{-3}$).

Changes in the hydrometeorological conditions of spring soil erosion due to climate change are primarily associated with changes in surface runoff (h). A change in the spring runoff inevitably affects the sediment concentration in the surface runoff during the period of spring snowmelt (ρ). Based on (1), the dimensionless coefficient k_{HMS} , which characterizes the change in the hydrometeorological factor of the spring erosion due to climate change, has the form:

$$k_{HMS} = \frac{K_{HMS_proj}}{K_{HMS_base}} = \frac{h_{proj} \rho_{proj}}{h_{base} \rho_{base}} = k_h k_\rho, \quad (2)$$

where K_{HMS_proj} , h_{proj} , ρ_{proj} are the average projected values of the hydrometeorological factor, depth of the spring runoff and sediment concentration in it, respectively; K_{HMS_base} , h_{base} , ρ_{base} are the annual average values of the hydrometeorological factor, depth of the spring runoff and its turbidity, respectively, for a period that is considered as the baseline one; k_h and k_ρ are the dimensionless coefficients characterizing

the changes under the influence of the climate of the spring runoff depth and the sediment concentration in the surface runoff, respectively.

Taking into account (2) the long-term average annual value of the hydrometeorological factor for the forecast period will be:

$$K_{HMS_proj} = k_h k_\rho K_{HMS_base}. \quad (3)$$

However, climate warming affects not only the factors of spring soil erosion, which are taken into account by the hydrometeorological factor. Climate warming also affects the properties of soils, which determine the erodibility of soil cover. Possible changes in soil erodibility can be divided into related to a) changes in temperature regime in the cold season and b) changes in agricultural activities aimed at adaptation to climate change (changes in the structure of sown areas, in a set of crops, in soil cultivation system, in amount of fertilizers, etc.). Changes in soil erodibility due to the changes in agricultural practices are a separate research topic and in this paper were not considered.

In this case

$$k_j = \frac{j_{proj}}{j_{base}}, \quad (4)$$

where k_j is the dimensionless coefficient that takes into account the climate-induced change of soil erodibility; j_{proj} is the predicted soil erodibility taking into account influence the temperature regime of cold season; j_{base} is the soil erodibility for the baseline period.

The product of coefficients taking into account the climate-induced change in the hydrometeorological factor (k_{HMS}) and in soil erodibility (k_j) will characterize the relative change in spring erosion (k_w):

$$k_w = k_{HMS} k_j, \quad (5)$$

As the baseline period the standard climatic period 1961–1990 is used in the paper. The maps of the average annual air temperatures, spring surface runoff and the hydrometeorological factor, which are used in the study as the baseline maps, were constructed using the data of observations and field studies during this period. Climatic norms for weather stations presented in the Climate Cadastre of Ukraine (Klimaty`chny`j ..., 2006) correspond to this period as well.

Periods 2031–2050 and 2081–2100 are considered as the forecast periods. The first period allows us to estimate the change in the hydrometeorological conditions of spring erosion compared to the baseline

period in the middle of the current century, the second – at the end of the century.

Method of assessment of changes in spring surface runoff depth. It is known that the spring surface runoff depth (h , mm) is equal to the sum of water equivalent of snow cover at the beginning of snow melting (S_m , mm) and precipitation amount during snow melting (ΔP , mm) multiplied by the surface runoff coefficient (η , dimensionless), that is

$$h = (S_m + \Delta P) \cdot \eta. \quad (6)$$

To estimate the predicted values of the surface runoff depth, the regression models developed for the plain territory of Ukraine (Gopchenko et al., 2012; Ovcharuk, 2018) were used. The models were developed using data from 103 meteorological stations about water equivalent of snow cover, from 315 stations about precipitation, and from 340 hydrological stations about spring runoff. The models have the form:

$$\bar{S}_m = 147.8 - 12.906 \bar{T}, \quad (7)$$

$$\bar{\eta} = 1 - 0.102 (\bar{T} - 4), \quad (8)$$

where \bar{S}_m , \bar{T} and $\bar{\eta}$ are the average annual amounts of water equivalent of the snow at the beginning of snow melting (mm), air temperature (°C), and spring surface runoff coefficient, respectively. The coefficient of determination (R^2) for both models is equal to 0.81; the correlation coefficient (r) is equal to 0.90.

Method of assessment of changes in sediment concentration in spring surface runoff. The expected changes in sediment concentration in the spring surface runoff were determined using the power dependence of the sediment concentration in the spring runoff of the runoff depth, according to which

$$k_\rho = \left(\frac{h_{proj}}{h_{base}} \right)^m, \quad (9)$$

where m is an exponent.

In accordance with the model of spring soil losses (Instrukcija..., 1979) developed using data of runoff plots located throughout the territory of the former USSR, the exponent m in (9) varying for agricultural land depending on their use (ploughed land, winter crops, stubble, perennial grass) from 0.3 to 0.6 with a modal value of 0.4. This value corresponds well with the exponent in empirical formulae of transport capacity of streams, close to 0.5 (Karaushev, 1977).

In the formula by Govers (1990), the volumetric transport capacity of overland flow is proportional to its depth with an exponent, which is approximately equal to 0.35. This formula has been used successfully, in particular, in soil erosion models LISEM (De Roo et al., 1996) and EUROSEM (Morgan et al., 1998).

Method of assessment of changes in soil erodibility. The quantitative assessment of changes in erodibility of the soils of plain part of Ukraine is based on the correlation dependence of the soil erodibility index of the aggregation factor of topsoil according to Baver and Rhoades (1932) established by Bulygin and Lisetskiy (1992):

$$k_j = \left(\frac{K_{a\,proj}}{K_{a\,base}} \right)^{-0.25}, \quad (10)$$

where $K_{a\,proj}$ and $K_{a\,base}$ are the Baver-Rhoades aggregation factors for the forecast and baseline periods, respectively. The Baver-Rhoades aggregation factors are determined for the sizes of soil aggregates and soil particles (mm) satisfying the condition $0.25 > d > 0.05$.

The main reason for the change in soil aggregation during the cold season is the periodic freezing and thawing of the topsoil at transition of the air temperature through 0 °C (Chornyy et al., 2015).

Information database. To estimate h_{proj} based on (6)–(8) the projections of average annual and monthly values of air temperature and precipitation for 2031–2050 and 2081–2100 developed at the Ukrainian Hydrometeorological Institute (UkrHMI) (Krakovska et al., 2013; Shestoe..., 2013) are used. The projections were carried out for five regions of Ukraine (Fig. 2) using ten regional climate models for air temperature and four models – for precipitation for the most likely scenario of greenhouse gas dynamics A1B from the AR4 of IPCC (Climate Change, 2007).

The forecast values of the average annual air temperatures and average February precipitation for the regions of Ukraine given in Tables 1 and 2.

Considering the large size of the territory of Ukraine, its location within three physical-geographical zones (Fig. 1b) and distinct spatial variability of hydrometeorological conditions of spring soil erosion within Ukraine, solution of the problem was carried out using geoinformation (GIS) technologies. The digital spatial database includes raster maps of the average for the baseline period annual values of air temperature (T_{base}) (Fig. 3a), spring surface runoff depth (h_{base}) (Fig. 3b) and the hydrometeorological factor (K_{HMS_base}) (Fig. 3c).

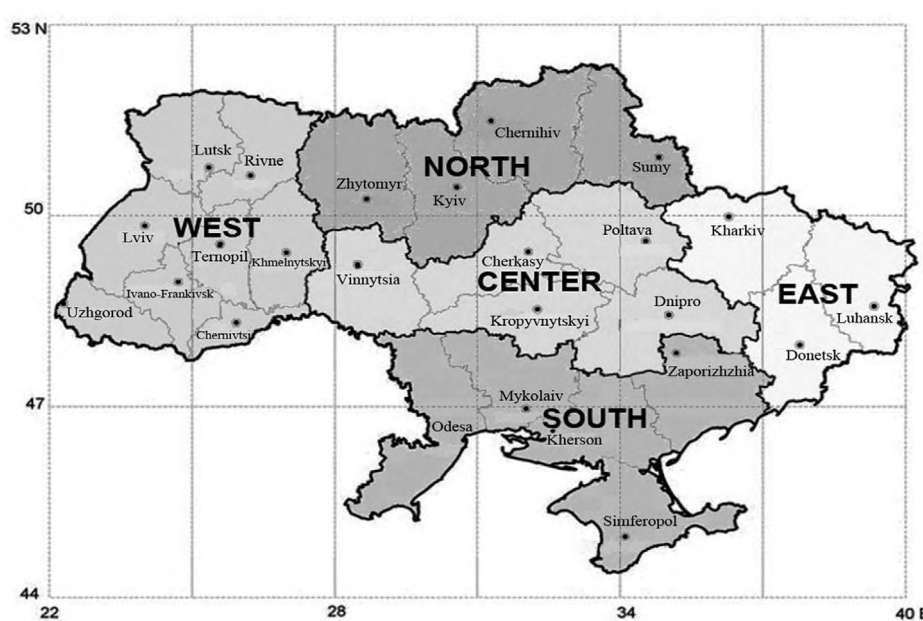


Fig. 2. Division of the territory of Ukraine into regions (Krakovska et al., 2013; Shestoe..., 2013)

As a basis for creating a digital raster map of the average annual air temperature, the corresponding map from the monograph *Climate of Ukraine* (Lipinsky et al., 2003) was used to create a map of the average annual spring runoff depth – the corresponding map from the electronic *Atlas of Ukraine* (Atlas..., 2000). Both base maps were constructed using observational data prior to 1990. The digital raster map of the hydrometeorological factor of spring soil loss was built based on the corresponding paper map (Prokopenko, 1986), which was supplemented with information concerning the southern part of the region South.

digital maps were performed using the capabilities of the PCRaster package (PCRaster..., 2018).

Results.

Validation of the model (6)–(8). Evaluation of the model (6)–(8) adequacies was performed using averages for the baseline period of input and output data averaged over five regions of Ukraine (Fig. 2).

During the baseline period, in the south of Ukraine spring flood began on average February 20–25, in the center and in the east—March 1–5, in the west and in the north—March 5–10. Duration of the influx of melt water into the network of canals varied from 100 to 200 hours (4–8 days) in the south to

Table 1. Projections of the average annual air temperature [°C] for the regions of Ukraine (Krakovska et al., 2013; Shestoe..., 2013)

Periods, years	Regions of Ukraine				
	North	West	Center	East	South
2031–2050	9.5	9.3	10.2	10.2	11.8
2081–2100	11.2	11.1	12.0	12.0	13.7

To create digital maps, the WGS84 UTM coordinate system was used. All the maps have the same raster size of 934 x 1315 and cell size of 1000 m. The subsequent analytical transformations of the

250–450 hours (10–19 days) in other regions (Shakirzanova, 2015). Thus, in the spring the surface runoff in the south of the country was observed on an average in the last decade of February, its average dura-

Table 2. Projections of the average monthly February precipitation [mm] for the regions of Ukraine (Krakovska et al., 2013; Shestoe..., 2013)

Periods, years	Regions of Ukraine				
	North	West	Center	East	South
2031–2050	38	39	31	43	28
2081–2100	42	42	33	42	30

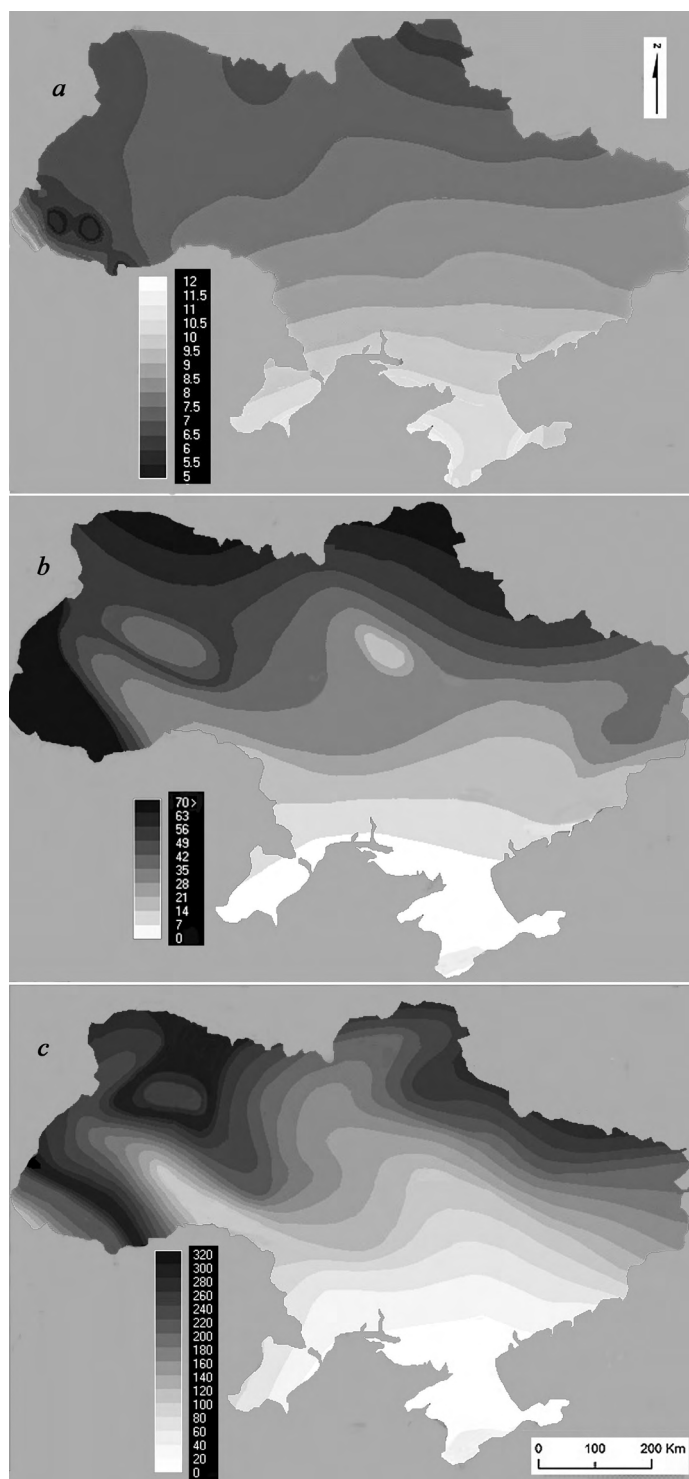


Fig. 3. Maps of average annual for the baseline period air temperature [°C] (a), spring surface runoff depth [mm] (b) and the hydrometeorological factor [$\text{g}\cdot\text{m}^{-2}$]

tion was equal to six days or one fifth of the month. In other regions of Ukraine the runoff of thawed water occurred in March, its duration on average was equal to 14.5 days, that is, almost half a month. Based on the assumption that precipitation is evenly distributed throughout the month, it can be assumed that in the formation of spring surface runoff in the South region 20% of the February precipitation participated, in other regions—50% of March precipitation.

The results of testing the possibility of using the model (6)–(8) for the average annual spring surface runoff depth (h_{calc}) assessment for the regions of Ukraine are shown in Table 3 and Fig. 4. The actual average values of air temperature (T_{act}) and spring runoff depth (h_{act}) for regions were obtained by averaging the corresponding digital raster maps (Fig. 3a and 3b) within the regions (or their plain parts, as for the regions West and South) in the PCRaster

Table 3. Calculation of the average depth of spring surface runoff for the regions of Ukraine for the base period (1961–1990) (see details in the text)

Regions	T_{act} [°C]	P [mm]	\bar{S}_m^c [mm]	$\bar{\eta}^d$	h_{calc} [mm]	h_{act} [mm]
North	7.0	37 ^a	57.5	0.69	52.7	51.3
West	7.0	34 ^a	57.5	0.69	51.7	51.6
Center	7.9	32 ^a	45.8	0.60	37.2	34.0
East	8.0	33 ^a	44.6	0.59	36.1	34.9
South	9.5	32 ^b	25.2	0.44	13.9	12.2

^a March precipitation, ^b February precipitation, ^c annual average water equivalent of snow cover at the beginning of snow melting, ^d annual average spring surface runoff coefficient.

package environment. The average monthly precipitation amounts of February for the South region and of March for other regions were determined by averaging the corresponding data for individual meteorological stations from the Climate Cadastre of Ukraine (Klimatychnyj ..., 2006).

Comparison of the actual (h_{act}) and calculated (h_{calc}) regional average runoff depth (Fig. 4) showed linear relationship between them with an angular coefficient close to 1.0 (0.97) and high coefficient of determination R^2 (0.99). Thus, the validation of the model (6)–(8) confirmed that it could be used to solve the problem under consideration.

Forecast of the spring surface runoff depth. Taking into account the expected significantly higher average annual air temperature in 2031–2050 (11.8 °C) compared to the baseline period (9.5 °C) (Table 1), in the mid-21st century in the south of Ukraine in accordance with (7) water equivalent of snow cover will be zero ($S_m = 0$). In the rest of the country, spring snowmelt will shift to mid-February and take place over a shorter time, taking into account the predicted

dynamics of air temperature and the tendency that has already formed (Grebin, 2010; Ovcharuk, 2018).

At the end of the century (2081–2100) in accordance with (7) the water equivalent of snow cover will be zero not only in the south, but also in the center and in the east of Ukraine. In the north and in the west of the country, where the snow cover will remain ($S_m > 0$), one can expect a shift of spring snowmelt to the beginning of February and a further decrease in its duration.

The results of forecast of average depth of the spring runoff for the 2031–2050 and 2081–2100 using the model (6)–(8) are presented in Tables 4 and 5. Herewith, the projections of average February and annual values of air temperature and precipitation of the corresponding periods for the regions (Tables 1 and 2) were used.

Comparison of the predicted values of the spring surface runoff depth for 2031–2050 with the baseline values shows that in the middle of the century the surface runoff will decrease in all regions of Ukraine (Table 4). In the West region the spring runoff will

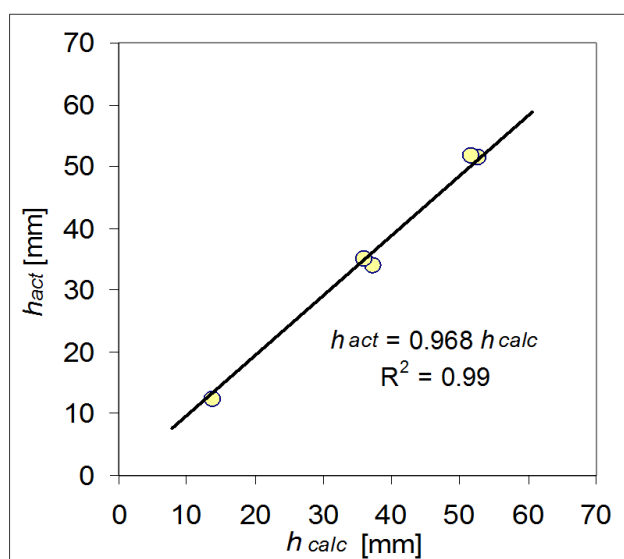
**Fig. 4.** Ratio between average regional values of h_{act} and h_{calc} for the baseline period

Table 4. Forecast of the annual average spring surface runoff depth for the regions of Ukraine for 2031–2050 (see text for more detail)

Regions	T [°C]	P_{Feb} [mm]	\bar{S}_m [mm]	$\bar{\eta}$	h_{proj} [mm]	h_{proj}/h_{act}
North	9.5	38	25.2	0.44	18.3	0.36
West	9.4	39	26.5	0.45	21.3	0.41
Center	10.2	31	16.2	0.37	10.5	0.31
East	10.2	43	16.2	0.37	12.5	0.36
South	11.8	28	— ^a	— ^a	— ^a	— ^a

^aNo snow cover.

decrease by 59%, in the North and East regions—by 64%, in the Center region—by 69%. In the South region, meltwater runoff in spring will be absent due to the lack of snow cover.

At the end of the 21st century (2081–2100) within the territory of Ukraine in accordance with performed forecast, snow cover and runoff of melt waters will retained only in the North and West regions. The forecast values of spring runoff depth for these regions are 4.3 and 4.5 mm, respectively (Table 5), which is more than 10 times less than the corresponding values for the baseline period.

temperature regime of the cold season the results of laboratory studies of changes in the state of aggregation of soils of the Steppe Zone of Ukraine (Chornyy et al., 2015) were used. In these studies it was established that after thirty freezing-thawing cycles of the soil sample (60 transitions through 0 °C), the content of aggregates with a diameter of more than 0.25 mm decreased from 88.7 to 82.3%.

Analysis of the data from meteorological station Askania Nova, located approximately in the center of the South region, showed that during October–March 1961–2010 the number of air temperature transitions

Table 5. Forecast of the average spring surface runoff depth for the regions of Ukraine for 2081–2100

Regions	T [°C]	P_{Feb} [mm]	\bar{S}_m [mm]	$\bar{\eta}$	h_{proj} [mm]	h_{proj}/h_{act}
North	11.2	42	3.6	0.27	4.3	0.08
West	11.2	42	4.2	0.27	4.5	0.09
Center	12.0	33	— ^a	— ^a	— ^a	— ^a
East	12.0	42	— ^a	— ^a	— ^a	— ^a
South	12.0	30	— ^a	— ^a	— ^a	— ^a

^a No snow cover.

Forecast of changes of sediment concentration in surface runoff. The forecast of climate-related changes of sediment concentration in the spring surface runoff (k_p) is carried out using the equation (9) and predicted values of the spring surface runoff depth (Tables 3, 4 and 5). The obtained values of the coefficient k_p for the middle and end of the 21st century are presented in Table 6.

Table 6 shows that for those regions of Ukraine where the snow cover will remain the decrease of sediment concentration in the surface runoff in the middle of the century will be 30–38%, at the end of the century—62–63%.

Forecast of changes in soil erodibility. To assess the change of soil erodibility related to changes in the

through 0 °C varied within 72–170 with an average value equal to 116. At the same time, there was a clear tendency to decrease in the number of temperature transitions through 0 °C with increasing air temperature. For the Askania-Nova weather station the dependence of the number of air temperature transitions through 0 °C (n) of the average annual air temperature (T , 0 °C) is approximated by a linear function $n = 340 - 22.147 \cdot T$ with a correlation coefficient (r) equal to 0.67. In accordance with this dependence at an air temperature of 11.8 and 13.7 °C, which correspond to the projections of the air temperature for the South region for 2031–2050 and 2081–2100 (Table 1), the average number of transitions of air temperature through 0 °C will be 79 and 37, respectively.

Table 6. Values of the coefficient k_p [dimensionless] for the middle and end of the 21st century

Regions	h_{base} [mm]	2031–2050		2081–2100	
		h_{proj} [mm]	k_p	h_{proj} [mm]	k_p
North	51.3	18.3	0.66	4.3	0.37
West	51.6	21.3	0.70	4.5	0.38
Center	34.0	10.5	0.62	— ^a	— ^a
East	34.9	12.5	0.66	— ^a	— ^a
South	12.2	— ^a	— ^a	— ^a	— ^a

^a No snow cover.

For other regions of Ukraine located to the north of the South region with a more stable winter the number of air temperature transitions through 0 °C is less and the impact of climate warming is not so significant. In particular, for weather station Lubny located in the Center region the average number of air temperature transitions through 0 °C for October–March 1961–1970 will equal 110, and for the period 2001–2010 equal 106, that is, only 4 units less. For weather station Askania-Nova, these figures are 127 and 106, respectively.

Thus, the warming of the climate will inevitably lead to a decrease in the number of air temperature transitions through 0 °C during the cold season, accompanied by periodic freezing-thawing of the soil and the destruction of soil aggregates. Consequently, with the climate warming the ability of soils to resist destruction by thawed waters will increase.

However, analysis shows that the expected change in the number of transitions of air temperature through 0 °C will not lead to a significant change in the erodibility of soils of the territory under consideration. In accordance with (10), even in 2081–2100 a decrease in soil erodibility due to a decrease in the number of soil freezing-thawing cycles will not exceed 20% of the baseline period values. Almost the same change (up to 15%) in the K-factor of the USLE can be obtained using the Soil Erodibility Nomograph

(Renard et al., 1997) when the soil structure changes by one class. A larger change in soil structure during the cold season because of climate warming is hardly possible even by the end of the century. On this basis, for the middle of the century (2031–2050) the coefficient of soil erodibility change (k_j) for the South and West regions was taken equal to 0.85, for other regions of Ukraine—0.90.

Forecast of changes of the hydrometeorological factor and spring soil loss. The forecast of the hydrometeorological factor for 2031–2050 and 2081–2100 for the regions of Ukraine is presented in Table 7. The product of the correction factors k_h and k_p gives a relative change in the hydrometeorological factor in relation to the baseline period (k_{HMS}). Multiplication of this product by the K_{HMS} value for the baseline period in accordance with (3) gives the forecast value of the hydrometeorological factor.

As follows from Table 7, in accordance with the climate projection under scenario A1B from AR4 IPCC (2007), in the middle of the 21st century and at its end the decrease of the hydrometeorological factor of spring erosion throughout Ukraine is expected.

In the middle of the 21st century, the hydrometeorological factor will decrease relative to the baseline period values in the West region by 75%, in the North and East regions by 79%, in the Center region by 83%. In the South region, the spring erosion

Table 7. Forecast of the hydrometeorological factor of spring soil loss ($K_{HMS_proj} \cdot 10^5$) for the regions of Ukraine for 2031–2050 and 2081–2100

Regions	$K_{HMS_base} \cdot 10^5$ [g·m ⁻²]	k_h		k_p		$k_h \cdot k_p$		$K_{HMS_proj} \cdot 10^5$ [g·m ⁻²]	
		2031–2050	2081–2100	2031–2050	2081–2100	2031–2050	2081–2100	2031–2050	2081–2100
North	209	0.36	0.08	0.66	0.37	0.21	0.02	44	4
West	227	0.41	0.09	0.70	0.38	0.25	0.03	57	7
Center	127	0.31	— ^a	0.62	— ^a	0.17	— ^a	26	— ^a
East	170	0.36	— ^a	0.66	— ^a	0.21	— ^a	41	— ^a
South	36	— ^a	— ^a	— ^a	— ^a	— ^a	— ^a	— ^a	— ^a

^a No snow cover.

by meltwaters will be completely absent due to lack of snow cover. The expected changes in soil losses due to climate, taking into account changes both the hydrometeorological factor and soil erodibility, will be less than the baseline period values for the West region by 79%, for the North and East regions by 81%, for the Center region by 85% (Table 8).

liquid precipitation (rain) in cold season is unlikely to lead to a significant increase in the erosion hazard of the territory. Due to the relatively high water permeability of soils of the plain part of Ukraine, the soil erosion process can be formed only because of rains of high intensity. However, such rains (showers) are formed at substantially higher air temperatures than in the cold

Table 8. Forecast of changes in soil losses during spring snowmelt for 2031–2050 and 2081–2100 compared with the baseline period

Regions	$k_h \cdot k_p \cdot k_j$		Changes of soil loss [%]	
	2031–2050	2081–2100	2031–2050	2081–2100
North	0.19	0.02	–81	–98
West	0.21	0.02	–79	–98
Center	0.15	— ^a	–85	— ^a
East	0.19	— ^a	–81	— ^a
South	— ^a	— ^a	— ^a	— ^a

^a No snow cover.

At the end of the 21st century due to the expected further warming of the climate and the absence of snow cover, the soil erosion by melt water will be absent not only in the South region, but also in the Center and East regions. In the North and West regions decreasing of the hydrometeorological factor as well as of the soil losses relative to 1961–1990 are projected by dozens times (Table 8). Due to this, the soil losses by melt waters in these regions can be ignored because of their small values. Thus, at the end of the 21st century erosion hazard within the whole territory of Ukraine will be determined only by liquid precipitation.

Discussion. The fulfilled forecast confirms the tendency of decreasing spring erosion losses of soil by melt waters outlined in recent years (Barabanov et al., 2016; Golosov et al., 2011; Gusarov et al., 2018; Komissarov and Gabbasov, 2014; Medvedev et al., 2016; Petelko and Panov, 2014; Petelko and Barabanov, 2016; Sobol et al., 2015). In Ukraine, it is a decrease of the surface runoff of melt waters that will play the main role in the predicted very significant decrease in the magnitude of erosion soil loss. Changes in soil erodibility because of increase in the temperature of the cold season will be insignificant (–10 ... –20% of the baseline values).

It should be noted that for the territory of Ukraine the replacement of solid precipitation (snow) with

season in Ukraine. During the baseline period in all regions of Ukraine except the South region erosion-hazardous rains are observed only in May–October. In the South region, such rains observed from the end of April to the beginning of November, but the contribution of April and November to the annual soil loss was not more than 2% (Chornyy, 1996; Svetlitchnyi et al., 2004).

Proceeding from this, the predicted increase in air temperature will only slightly widen the erosion-hazardous period by adding parts of April and November. In the remaining months of the cold period (December–March), due to the relatively low predicted air temperatures (Tables 9 and 10) and the absence of soil freezing, the erosion soil loss will be not significant.

The expected contribution to the annual soil loss of November and April is different. The forecasted air temperature of November will not higher than the average October temperature of the baseline period, and the predicted change in monthly precipitation is insignificant (–3 ... +11%). Based on this, it can be assumed that November's contribution to annual soil losses in the middle and in the end of 21st century will analogous to the October's contribution of the baseline period. That is, it will be equal to 1–2%. The expected contribution of October will be more significant than

Table 9. Average monthly and annual air temperatures [°C] for the Center region of Ukraine for different periods (Krakovska et al., 2013; Shestoe..., 2013)

Periods, years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1961–1990	–6.4	–5.2	–0.1	8.6	15.5	18.6	19.8	18.9	13.9	7.5	1.4	–3.1	7.5
2031–2050	–1.7	–1.8	3.1	10.5	16.4	20.4	23.1	22.3	16.3	10.2	4.0	–0.3	10.2
2081–2100	–0.3	0.0	4.7	11.9	17.9	22.2	25.5	24.7	18.4	11.4	5.8	1.4	12.0

Table 10. Average monthly and annual air temperatures [°C] for the South region of Ukraine for different periods (Krakovska et al., 2013; Shestoe..., 2013)

Periods, years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1961–1990	–3.1	–2.0	2.2	9.6	15.6	20	22.4	21.6	16.4	9.6	4.4	0.3	9.8
2031–2050	0.1	0.1	4.6	10.8	17.0	21.7	24.7	24.2	18.3	12.3	6.2	2.0	11.8
2081–2100	1.5	1.8	6.2	12.4	18.6	23.9	27.4	26.6	20.6	13.6	8.0	3.5	13.7

before, both because of higher air temperatures and an increase in monthly precipitation by 19–27%. Most likely, this increase will be a few percent. Similarly, April's contribution will increase slightly. However, quantification of this increase requires separate consideration and is beyond the scope of this paper.

Conclusions. 1. In accordance with the climate change scenario A1B from AR4 IPCC, in the middle and at the end of the 21st century, a decrease of erosion soil loss during spring snow melting compared to the base period 1961–1990 is predicted throughout the whole territory of Ukraine.

2. The expected changes in soil period values for the West region of Ukraine are by 79%, for the North and East regions by 81%, for the Center region by 85%. In the South region, permanent snow cover and, accordingly, spring snowmelt and soil erosion by melt water will be absent.

3. At the end of the 21st century (2081–2100), due to predicted further warming of the climate in Ukraine, the soil erosion by melt water will be absent not only in the South region, but also in the Center and East regions. In the North and West regions decrease is projected of the hydrometeorological factor and spring erosion relative to the baseline period by dozens of times. In this regard, at the end of the century erosion hazard within the whole territory of Ukraine will be determined only by liquid precipitation.

4. In accordance with preliminary assessment, some expansion of the warm season and the replacement of solid precipitation (snow) by liquid precipitation (rain) in the cold season will not lead to a practically significant increase in the soil erosion danger within the plain territory of Ukraine. However, this question requires further study.

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