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PROBLEMS AND DIRECTIONS FOR IMPROVING THE METHODOLOGY FOR ASSESSING THE IMPACT OF CLIMATE RISKS ON THE SUSTAINABILITY OF MELIORATIVE AGRICULTURE

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Abstract. *Global climate change drives aridization and instability of soil-moisture conditions, which threatens sustainable development in agriculture and creates preconditions for accounting for these changes in the design of irrigation and drainage (land reclamation) systems and their operating regimes. Existing methods for designing irrigation and drainage often do not account for current climate trends (seasonal shifts, increased duration of rainless periods, changes in temperature regime), which creates a need for their systematic improvement. The article presents an approach to assessing the impact of climate risks on irrigated agriculture that integrates up-to-date indicators (moisture-supply deficit, reference evapotranspiration, crop coefficients, soil water-holding capacity and field capacity, the frequency and intensity of droughts, heat waves and precipitation intensity) with scenario analysis to forecast different moisture regimes under expected climate conditions. The concept of a methodology adapted to the regional diversity of Ukraine is outlined. For testing, pilot regions with contrasting climate-soil characteristics are proposed: the arid South, the moderately arid Center (periodic temperature stress, high inter-annual variability of precipitation), and the West, which is excessively humid in spring and slightly arid in summer (risks of waterlogging, the need for effective drainage at the beginning of the growing season and additional moisture supply during the rest of the period). A monitoring and validation program is proposed, including regular collection of meteorological data (daily temperatures, precipitation, radiation, wind, humidity), biometric indicators of plant growth and development (development stages, leaf-area indices, actual yield), soil characteristics (moisture, structure, nutrient content), as well as performance indicators of irrigation and drainage networks. Based on these data, crop coefficients and modelling parameters are refined, which makes it possible to perform hourly–daily calculations of water deficit, to develop adaptive irrigation and moisture-supply schedules, and to test SSP-based climate scenarios. The use of modern digital and automated tools (local weather stations, soil-moisture sensors, etc.) forms the basis for the digitalization of irrigation and water-regulation management in line with impact indicators. The improved methodology will make it possible to increase water-use efficiency in existing reclamation systems, incorporate updated climate parameters into new designs, reduce the vulnerability of agro-systems to droughts and other extreme weather events, minimize yield losses, and ensure production stability under climate change. An additional advantage is the possibility of ranking investment options according to economic efficiency indicators.*

Keywords: *climate risks, irrigation, meliorative agriculture, water deficit, scenario analysis, sustainable development*

Relevance of the research and problem statement. Global climate change is causing aridization of territories and instability of moisture regimes, which threatens the sustainable development of agriculture and creates an additional need for irrigation [1–8]. In particular, according to the Fifth National Climate Assessment [9], rising temperatures and changes in rainfall patterns lead to more frequent droughts and generally lower soil moisture, increase evapotranspiration and the need for irrigation, which raises the risks of reduced yields and agricultural productivity. For example, according to projections of current warming trends, by the end of the 21st century in California and Nevada an increase of reference evapotranspiration by

13–18 % is expected, which will accelerate soil drying and increase the risks of droughts and wildfires. This, in turn, will significantly increase the need for irrigation water [10]. Already now, in traditionally arid regions of the world, there are simultaneous decreases in precipitation and increases in temperature, which is reflected in the growth of the water stress index (the ratio of water use to available water resources) [11, 12].

Similar trends are recorded in Ukraine. In the period 2010–2020 the climate was characterised by increasing aridity (especially in the South and Centre) and moisture deficit during the growing season [13–17]. The current climate of most of Ukraine is classified as semi-arid, except for the western regions with sufficient moisture [13, 14]. Estimates show that about 46 % of the country's agricultural land cannot provide adequate yields without irrigation, about 43 % requires irrigation for high water-consuming crops, and only about 11 % has sufficient natural moisture [18–20]. Since the existing systems were not adapted to current conditions at the design stage [21, 22], and taking into account the current state and the continuous trend towards worsening climate conditions, the question arises of the need to revise water requirements and irrigation regimes, with consideration of methodological approaches to assessing climate risks and the vulnerability of the agricultural sector [23]. According to research estimates, ignoring the new climate conditions will lead to yield reductions of up to 69 % in the most arid regions (under a pessimistic scenario) [9, 13, 14]. In some dry years, the volumes of irrigation water use in the South of Ukraine exceed the average indicators of wet years by 50 % [18, 20], whereas in wet periods the need for irrigation significantly decreases. Such variability of climate conditions requires the use of more flexible approaches to maintain sustainable agricultural production.

In addition, a practical problem is that the design of land-reclamation systems was carried out according to historical climate norms, equipment energy-efficiency norms and typical operating conditions, while current temperature regimes and shifts in the seasonality of precipitation affect both crop water requirements and peak loads on water supply and drainage. Accordingly, without taking into account these changes and the methods of climate-risk assessment when defining design parameters, the modernization of even individual technical elements of irrigation systems may not ensure their proper adaptation to new climate conditions [13, 18, 19].

Thus, climate change has created an urgent need to adapt land-reclamation systems to new climate realities and to develop and implement scientifically based approaches that take climate risks into account in the practice of designing modernization projects for existing systems and constructing new land-reclamation systems. This will make it possible to increase the efficiency of water use, minimise yield losses and ensure food security [21, 22]. Improving the methodology for assessing the impact of climate change on irrigated agriculture is an important component of developing an adaptation strategy for agricultural production to new climate realities.

Analysis of recent studies and publications. The issue of assessing and mitigating the negative impact of climate risks by improving and expanding the use of land reclamation (melioration) attracts considerable attention from researchers worldwide. In particular, a climate risk management system for irrigation systems in arid regions was introduced in 2023 [8], and in 2021 researchers implemented concepts of "climate-smart" agriculture and intelligent irrigation systems based on digital solutions [25]. In the U.S. National Climate Assessment, the consequences of global warming for the agricultural sector are especially emphasised and described in detail [9]. Studies carried out in Ukraine, including with the participation of the authors of this article [26], have shown that there is a "hot phase" of climate change in Ukraine, which started in the late 1980s – early 1990s and continues today. It is characterised by the highest rate of increase of the mean annual air temperature in Europe (more than 0,45 °C per 10 years), with almost unchanged, and in the last decade slightly lower, mean annual precipitation. This has caused a significant increase in total evaporation and in the deficit, both annual and monthly, of the climatic water balance and, as a result, a progressive development of the process of drying of the territory of Ukraine, which has led to a significant deterioration of natural soil moisture conditions and a reduction in the volume of water resources available for use. The same studies, using climate change projections for 2050 and 2100 developed at the Ukrainian Hydrometeorological Research Institute under different scenarios, carried out a zoning of the territory of Ukraine by the value of the annual climatic water balance. The results made it possible to justify the need to use irrigation and water regulation by drainage systems as one of the most effective tools for adapting agriculture to climate change, and to determine the demand and main directions for improving the design of reclamation systems and technologies of irrigation and water regulation. The studies showed a significant mismatch between existing volumes of irrigation and water regulation and the current level of aridity [20] and became the basis for the "Strategy for Irrigation and Drainage in Ukraine for the Period until 2030" approved by the Cabinet of Ministers of Ukraine [21] and its Action Plan [22]. The above results were later confirmed by the conclusions of the World Bank Analytical Report (2024) taking into account climate trends [18].

Modern studies also emphasise the change in the conditions of use and parameters of irrigation systems under the influence of climate change: a 2024 study [27] notes a shift in phenological phases of vegetable crops and corresponding changes in crop coefficients (Kc) under different warming scenarios. Therefore, the issue of revising the basic conditions and guidelines for calculating water demand is important, where the FAO-56 Penman–Monteith method can be applied [28]. In the field of adaptation to droughts, a number of strategies have been developed, including for the conditions of Ukraine [29], to mitigate their impact on agricultural production, including for farms. To take into account the uncertainty of the climate future, a scenario approach is widely used: in particular, a set of global development scenarios, the so-called Shared Socioeconomic Pathways (SSP), has been formed to model trends in climate and related indicators [30]. The effectiveness of scenario analysis in irrigation planning has been confirmed in studies on optimisation of system management strategies, where multi-criteria optimisation of irrigation regimes for winter wheat was performed based on the combination of the AquaCrop-OSP model with the NSGA-III evolutionary algorithm. The obtained results showed that the scenario approach makes it possible to increase water productivity and yield stability at the same time under different projected water-resource constraints due to the advance optimisation of the system for forecast scenarios [31].

The basic approaches to planning and operation of irrigation traditionally rely on:

(1) calculation of reference evapotranspiration and transfer to crop water demand through crop coefficients (Kc) (as in FAO approaches) [28, 32];

(2) planning of irrigation schedules and regimes according to irrigation management methods [33];

(3) design based on historical climate norms or a limited set of "typical" years. These elements are necessary, but they are not sufficient to assess climate risks for the stability of irrigated agriculture under climate change.

The problem is that current methods do not ensure the integration of key indicators for the full chain "climate–water–soil–engineering infrastructure–yield", namely:

– the deficit of water supply is not considered as a risk metric (no transition from calculating water demand to assessing the risk of water under-supply);

– the frequency and intensity of droughts, the duration of rainless periods, and the combination of droughts with heatwaves are not included in the analysis (temperature stresses) [9, 10];

– the intensity of precipitation and the risks of extreme wetting are not included in the analysis (which is also important for drainage systems in overly wet zones) [2, 17];

– indicators of soil water-holding capacity and field capacity are not included as a "buffer" against drought, although they define the resilience of the system and the feasibility of irrigation under different conditions [35];

– the dynamics of Kc and phenological shifts of crops under warming, which change the seasonal profile of water consumption, are not taken into account [27];

– there is no scenario analysis of future conditions as a basis for stress-testing water infrastructure and agricultural production [30, 31].

Thus, the improvement of the methodology should consist in moving from a normative, calculation-based approach under average conditions to a risk-oriented approach with stress-testing and the inclusion of melioration-specific indicators that reflect both climate impacts and the limitations of infrastructure and the soil component of the water balance [38–40].

Goal of the research. The goal of this research is to improve the methodology for assessing the impact of climate risks on the sustainability of meliorative (irrigated) agriculture. To achieve this goal, the methodology proposes integrating updated climate indicators, applying scenario analysis of years with different rainfall availability, and using modern monitoring tools. The updated methodology should ensure the adaptive capacity of irrigation to changing climate conditions, increase the efficiency of energy and water use in agro-systems, and ensure the sustainable development of meliorative agriculture.

Materials and methods of the research. For a comprehensive assessment of the influence of climate factors on agro-systems, a list of indicators has been defined that should be included in the risk-assessment methodology:

– Water-supply deficit – an integral indicator of the water balance that reflects the lack of available water for plants over a certain period.

It is calculated as the difference between the crop's water requirement (reference evapotranspiration adjusted by the crop coefficient, ETc) and the incoming moisture (effective precipitation, soil moisture) [33]. The value of the deficit characterises the level of aridity: a higher deficit corresponds to a higher risk of drought and, accordingly, to an increased need for irrigation. This indicator is a basic one for calculating the level of climate risk for agriculture.

– Crop coefficients (Kc) – indicators representing the ratio of the actual evapotranspiration of a crop to the reference evapotranspiration (ET_0). They take into account the biological characteristics of plants (for example, growth stages) and are used for calculating water consumption. This indicator depends on the type of crop and reflects the dependence of yield on the level of water availability. Among crops vulnerable to water deficit are rice and alfalfa, compared with, for example, chickpea [28]. Climate change affects the development of crops during the season through changes in evaporative demand, because with increasing air temperature the growing period may become shorter, and total water consumption may increase due to higher daily water requirements [10][9]. Accordingly, the methodology should take into account updated crop coefficients for major crops and projected changes of these indicators under different climate scenarios, in order to assess risks in a differentiated way [27].

– Soil water-holding capacity – an indicator that characterises the ability of the soil to retain a certain amount of water available for plants between rainfall or irrigation events. It depends on soil texture and organic-matter content and serves as a buffer during drought, from which the crop satisfies its water needs [35]. Soils with higher water-holding capacity (clayey soils, soils rich in humus) can support plants longer without rainfall, whereas light sandy soils lose moisture more quickly. Including this indicator allows assessing the regional specificity of soil conditions and the feasibility of agricultural production under certain conditions (in some regions, adaptation measures may be economically impractical due to low water-holding capacity and high operational irrigation costs).

– Frequency of dry years – a statistical indicator that reflects the probability of extreme precipitation deficit in a region. The indicator characterises the probability of acute (that is, intensive) climate risks [41–44].

– Temperature regime (during the growing season) – mean and extreme air temperatures during the crop's growing season. Temperature affects evapotranspiration and plant development. High temperatures increase water demand and may suppress photosynthesis, raising the risk of yield loss during drought [9, 10]. Accordingly, the methodology should consider the temperature background: mean monthly temperatures, the number of extremely hot days, the sum of effective temperatures, and other parameters. This will help adjust the assessment of water requirements and determine periods when the combination of heat and drought is especially dangerous for crop cultivation.

– Monthly ET_0 values – the reference evapotranspiration indicator for each month of the growing season, which reflects the seasonal dynamics of water demand. Maximum ET_0 values usually occur in summer, and minimum values occur in spring and autumn. Including monthly ET_0 values in the methodology is important for identifying critical periods with the highest likelihood of water deficit. For example, if in peak summer months ET_0 reaches 200 mm and rainfall during this period is only 50 mm, water deficit will inevitably arise without additional irrigation. Climate change affects not only the annual total but also the monthly distribution of ET_0: with rising temperatures, reference ET_0 is expected to increase, with peak values in summer [10, 33]. Accordingly, the methodology should analyse the monthly water balance and compare ET_0 with monthly rainfall norms. This will make it possible to determine the volume of irrigation required for each month and to predict the technical capacity of the system to provide peak water supply [28, 36, 37].

The indicators listed above are interconnected and together make it possible to comprehensively assess potential climate risks for irrigated agriculture [21]. Their inclusion in the methodology increases its accuracy and allows compiling integrated risk ratings for different regions or agro-systems, where climate, soil conditions and crop characteristics are taken into account. This creates a scientific basis for defining the priority of implementing adaptation measures and refining design decisions in meliorative practice.

Scenario analysis of climatic conditions. The improved methodology proposes including the application of a scenario approach. Such an approach makes it possible to consider the realisation of potential risks under different projected conditions. In particular, for the purposes of improving the methodology, it is advisable to implement this approach through projected conditions of agro-system functioning in years with different levels of rainfall availability (from a conditionally worst – dry year, to a conditionally best – wet year) [30, 31]. This approach makes it possible to test the resilience of land-reclamation systems across the full range of climate changes. In particular, it is proposed to include two basic scenarios consistent with modern projections developed by the Intergovernmental Panel on Climate Change (IPCC):

– an extremely dry scenario (analogous to scenario SSP5 – economic development based on fossil fuels with minimal actions to counter climate change), which serves as a stress test for the irrigation system under minimal precipitation, and

– an excessively wet scenario (analogous to scenario SSP2 – a moderate pathway to achieving climate neutrality, in which significant resources are allocated for mitigation and adaptation), when precipitation exceeds the norm [45–48].

In the first case, the analysis makes it possible to assess the maximum water deficit and the ability of the system to meet the needs of the agricultural sector under extreme drought; in the second case – to check whether the system can cope with excess water drainage and use favorable conditions (accumulating soil moisture for future periods, etc.) [18, 45]. Designing only for an average year does not take into account peak extremes and relies solely on historical trends, while designing for the worst year for all crops may be economically impractical due to high capital and operational costs of maintaining such systems [21]. Scenario analysis in stress-testing and risk-management practices is widely applied and helps find a balance between the level of resource availability and an acceptable level of risk by quantitatively assessing yield losses or water deficit for each option [31]. This approach is an international practice for planning reliable strategies not only in business operations but also in the functioning of irrigation systems [49][50]. Including two polar scenarios in the methodology makes it possible to conduct a full assessment of the resilience of land-reclamation systems, justify design parameters under different conditions consistent with reality, and plan mitigation measures for negative consequences [21], minimising the impact of climate variability on yields.

Selection of pilot regions. Practical testing and improvement of the methodology is proposed in several pilot regions of Ukraine with different climatic conditions. In particular, three contrasting regions in terms of water-resource availability may be covered:

(1) a dry southern region (semi-arid climate, chestnut and southern chernozem soils with moderate water-holding capacity, a developed network of main irrigation canals). This is a zone of risky agriculture where most crops depend on irrigation (up to 60 % of all irrigated lands of Ukraine are concentrated here) [18, 24];

(2) a central forest-steppe region (close to a dry subhumid climate, heavy chernozem soils with high water capacity, mainly local sprinkler and drip irrigation systems). Traditionally, this is a rainfed zone, but recent aridization trends increase the relevance of irrigation for this region as well [18, 21];

(3) a western Polissya/foothill region (humid subhumid climate, in some areas heavy gley soils, high groundwater levels in drained zones, land reclamation functions mainly as drainage). In this region droughts are rare, but there are risks of both over-wetting and over-drying of the soil [13, 51].

The selected regions cover a range of conditions from extreme water deficit to excess moisture, which makes it possible to test the applicability of the methodology under different moisture conditions. Pilot testing in real farms with long-term data will make it possible to identify which climate-risk indicators are the most critical for each zone and ensure that the methodology adequately accounts for both drought risk and excessive moisture risk. It is advisable to involve existing land-reclamation systems in the research, where long-term observations are available and there is technical capability to implement the recommendations [21].

Programme for methodology validation. The improved methodology will require testing under real conditions. Trials are planned to be conducted at selected pilot sites over several years in order to cover weather variability. During each growing season, regular monitoring of the following indicators will be carried out on the experimental plots:

– meteorological data (amount of precipitation for the period, average daily and extreme temperatures, humidity, wind speed, etc.) [52–56];

– soil conditions (soil texture, hydro-physical characteristics, moisture in the root zone, depth of wetting after rainfall/irrigation, groundwater level in drainage zones);

– irrigation and moisture regimes (dates and rates of irrigation/moisture application);

– plant development (dates of growth-stage onset);

– yield and product quality.

Collecting these data will make it possible to compare the indicators predicted by the methodology with actual ones and quantitatively assess the accuracy of forecasts. If systematic discrepancies are identified, model calibration will be carried out – adjustment of the methodology parameters to real conditions [27, 21]. After that, validation will continue using independent data from subsequent years or regions. Field validation followed by adjustment is a widely accepted practice in the implementation of agro-ecosystem models [21] and will ensure reliability and credibility of the improved methodology before its large-scale application.

Material and technical support. For the practical implementation of the proposed methodology, modern instrumental and software support is required. It is envisaged to use the following tools (if available):

– data from the national network of meteorological observations as a basic source of information on temperature, precipitation, humidity, wind and other parameters (with unified data series and quality-control procedures), as well as, if available, local sensors/devices installed in farms [35];

– software tools for calculating ET_0 using the Penman–Monteith formula (the official FAO ETo calculator) for the purpose of automating computations [28];

– computer models and algorithms for forecasting the water balance, which, with the involvement of artificial intelligence methods, will predict moisture deficit and irrigation needs in advance [31, 66,67];

– geographic information systems and remote-sensing data (satellite images of NDVI, EVI indices, thermal field scanning) for spatial analysis of risks and crop conditions [57–65].

The integration of these components into a single decision-support system corresponds to the concept of so-called "smart agriculture" and will allow automation and increased accuracy of irrigation management [25]. Adherence to standard methods will ensure unification and the possibility of comparing risk-assessment results in different regions [28].

Conclusions. Existing methods for planning irrigation systems, their operation and design have faced challenges under climate change and require updating. International studies confirm that rising temperatures and changes in precipitation regimes lead to increased water deficit and drought risk; therefore, the integration of climate indicators is a necessary condition for assessing melioration needs under current conditions and for the effective operation of land-reclamation systems [28, 10, 68]. At the same time, to bring the methodology in line with the content of the task of assessing climate risks in irrigated agriculture, it is necessary to take into account not only basic calculations of water requirements and irrigation planning, but also specific risk-oriented indicators and scenario uncertainty, which determine system resilience under extremes and seasonal shifts [69, 70, 71]. It is proposed to include widely accepted approaches of scenario analysis of extremely dry and wet conditions, which cover a wide range of possible impacts on systems and increase the reliability of management decisions in accordance with modern principles of risk management [40, 79]. The developed methodology will be tested in different climatic zones of Ukraine – from the arid steppe to the humid Polissia. The use of modern software will simplify the process of assessing and modelling climate risks and will allow effective management of them. The implementation of the improved methodology will contribute to increased efficiency of water-resource use, reduced vulnerability of the agricultural sector to droughts and extreme weather events, and the sustainable development of irrigated agriculture under global climate change. This is consistent with the goals of national food security and the recommendations of leading international organisations regarding adaptation of agricultural production to climate change [1, 2, 6, 7]. A scientifically grounded methodology for assessing climate risks will become the foundation for making effective management decisions and for investing in land-reclamation infrastructure [72–78].

Prospects for further research. Further research should be aimed at adapting the methodology to different types of land-reclamation systems, taking into account practical aspects and operating conditions, improving the module for forecasting climate indicators, developing digital platforms for real-time risk assessment, and integrating economic indicators into the analysis. In addition, the methodology may become a scientifically grounded basis for implementing support policies in agriculture aimed at introducing resource- and energy-saving technologies and ensuring financial mechanisms for infrastructure modernization [80].

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Use of artificial intelligence: the authors confirm that they did not use artificial intelligence technologies during the creation of this work.

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ПРОБЛЕМИ ТА НАПРЯМИ УДОСКОНАЛЕННЯ МЕТОДИКИ ОЦІНКИ ВПЛИВУ КЛІМАТИЧНИХ РИЗИКІВ НА СТАЛІСТЬ ВЕДЕННЯ МЕЛІОРАТИВНОГО ЗЕМЛЕРОБСТВА

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Анотація. *Глобальна зміна клімату зумовлює аридизацію та нестабільність умов зволоження ґрунтів, що ставить під загрозу сталий розвиток у сільському господарстві, а також формує передумови щодо її врахування при проектуванні меліоративних систем та режимів. Існуючі методики проектування зрошення та дренажу часто не враховують поточні кліматичні тренди (зміщення сезонів, збільшення тривалості бездощових періодів, зміна температурного режиму), тому виникає потреба в їх системному удосконаленні. У статті представлено підхід до оцінки впливу кліматичних ризиків на зрошуване землеробство, який передбачає інтеграцію актуальних показників (дефіциту вологозабезпечення, еталонної евапотранспірації, коефіцієнтів культур, водоутримувальної здатності та вологоємності ґрунтів, частоти та інтенсивності посух, теплових хвиль і інтенсивності опадів) зі сценарним аналізом для прогнозування різних режимів зволоження відповідно до очікуваних кліматичних умов. Розкрито концепцію методики, адаптованої до регіонального різноманіття України. Для апробації запропоновано пілотні регіони з контрастними кліматично-ґрунтовими характеристиками: посушливий Південь, помірно посушливий Центр (періодичні температурні стреси, висока міжрічна мінливість опадів) та надмірно зволожений весною і легко посушливий влітку Захід (ризики перезволоження, потреба в ефективному дренажі на початку вегетації і додатковому зволоженні в решту часу). Запропоновано програму моніторингу й валідації: регулярний збір метеоданих (добові температури, опади, радіація, вітер, вологість), біометричних показників росту та розвитку рослин (фази розвитку, показники листкової поверхні, фактична врожайність), характеристик ґрунтів (вологість, структура, вміст поживних речовин) а також показників роботи зрошувальних і дренажних мереж. На базі цих даних уточнюються коефіцієнти культур і параметри моделювання, що дає змогу здійснювати погодинно-добові розрахунки водного дефіциту, формувати адаптивні графіки поливів та зволоження і тестувати сценарії (SSP-сценарії). Використання сучасних цифрових та автоматизованих інструментів (локальні метеостанції та датчики ґрунтової вологи та ін.) закладає основу для цифровізації управління зрошенням та водорегулюванням залежно від індикаторів впливу. Удосконалена методика дозволить підвищити ефективність водокористування на існуючих меліоративних системах, врахувати оновлені кліматичні параметри при проектуванні, зменшити вразливість агросистем до посух та інших екстремальних погодних явищ, мінімізувати втрати врожайності та забезпечити стабільність виробництва в умовах зміни клімату. Окремою перевагою є можливість ранжування інвестицій за показниками економічної ефективності.*

Ключові слова: *кліматичні ризики, зрошення, меліоративне землеробство, водний дефіцит, сценарний аналіз, сталий розвиток*