НАЦІОНАЛЬНА АКАДЕМІЯ АГРАРНИХ НАУК УКРАЇНИ

ІНСТИТУТ ВОДНИХ ПРОБЛЕМ І МЕЛІОРАЦІЇ

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# МЕЛІОРАЦІЯ
# І ВОДНЕ ГОСПОДАРСТВО

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**Засновник** – Інститут водних проблем і меліорації Національної академії аграрних наук України. Свідоцтво про державну реєстрацію – серія КВ № 24001-13841Р. Ідентифікатор медіа R30-05221.

Журнал включено до «Переліку наукових фахових видань України» (категорія «Б») за спеціальностями: 201 – Агрономія, 208 – Агроінженерія, 202 – Захист і карантин рослин, 101 – Екологія, 192 – Будівництво та цивільна інженерія, 194 – Гідротехнічне будівництво, водна інженерія та водні технології на підставі наказів Міністерства освіти і науки України № 409 від 17.03.2020 р.; № 320 від 07.04.2022 р. та № 582 від 24.04.2024 р.

У журналі відображено результати теоретичних та експериментальних досліджень із пріоритетних напрямів: агроресурси, водні ресурси, зрошення, осушення, гідрологія, екологія, гідротехніка, агроінженерія тощо. Журнал буде корисним для науковців, фахівців водного та сільського господарства. Два видання журналу за рік публікують оригінальні наукові статті, а також огляди, пов'язані з профілем журналу.

Журнал включено до міжнародних та національних інформаційних і наукометричних баз, репозитаріїв і пошукових систем:

*The International System for Agricultural Science and Technology (FAO)*

*Research Bib Journal Database (Японія)*

*CrossRef (США)*

*BASE – Bielefeld Academic Search Engine (Німеччина)*

*DOAJ (Directory of Open Access Journals)*

*Національна бібліотека України ім. В.І. Вернадського*

*Open Ukrainian Citation Index (OUCI) (Ukraine)*

*Scientific Indexing Services (США)*

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*Google Scholar (США)*

*The German Union Catalogue of Serials (ZDB), (Німеччина)*

*Internet Archive (Fatcat) (США)*

Пристатейний список літератури продубльовано відповідно до вимог міжнародних систем транслітерації (зокрема наукометричної бази SCOPUS)

**Рекомендовано до друку вченою радою Інституту водних проблем і меліорації НААН 19 грудня 2024 року (протокол № 18).**

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"LAND RECLAMATION AND WATER MANAGEMENT"

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«МЕЛІОРАЦІЯ І ВОДНЕ ГОСПОДАРСТВО»





**KYIV • 2024**

МІЖНАРОДНИЙ ЖУРНАЛ

«МЕЛІОРАЦІЯ І ВОДНЕ ГОСПОДАРСТВО»

№ 1 • 2024

"LAND RECLAMATION AND WATER MANAGEMENT"



**КИЇВ • 2024**

## Шановні автори та читачі журналу!

Маємо велику приємність і честь повідомити Вас, що засновник та видавець нашого журналу Інститут водних проблем і меліорації Національної академії аграрних наук України 23 грудня 2024 року святкує своє 95-річчя. Точніше розпочинає своє святкування зважаючи на те, що саме 23 грудня 1929 року на засіданні Ради народних комісарів УРСР було прийнято рішення про заснування при Наркомземсправ УРСР на базі крайових меліоративних організацій та дослідних станцій Науково-дослідного Інституту сільськогосподарських меліорацій, а роботу новостворений Інститут розпочав у травні 1930 року у м. Харкові. У листопаді-грудні цього ж року Інститут було переведено до Одеси, де він працював до 1941 року. Свою роботу після перерви, спричиненої війною, Інститут відновив у травні 1944 року у Києві, де продовжує свою діяльність і сьогодні. Впродовж періоду з 1935 р. по 1992 р. Інститут носив назву Український науково-дослідний Інститут гідротехніки і меліорації, з 1992 р. до 2011 р. – Інститут гідротехніки і меліорації Української академії аграрних наук, а з 2011 р. і до нині – Інститут водних проблем і меліорації Національної академії аграрних наук України.

Інститут є провідною державною науковою установою України з питань наукового забезпечення розвитку водного господарства та меліорації земель. Станом на 01.12.2024 року науковий кадровий потенціал Інституту складає 104 наукових працівники, з них 12 докторів наук, у т.ч. – 3 академіки НААН і 1 член-кореспондент НААН, 41 кандидат наук. До структури Інституту входять 8 наукових відділів, Сарненська науково-дослідна станція та 2 дослідних господарства.

Інститутом ведеться потужна науково-дослідна робота за напрямами «Водні ресурси» та «Меліорація земель». Ці дослідження виконувались і виконуються разом із співвиконавцями у складі Державних програм наукових досліджень, що формуються на п’ятирічний період.

Сьогодні Інститут, як головна наукова установа, проводить та координує дослідження співвиконавців у складі ПНД НААН 4 «Стале водокористування, формування водної безпеки, розвиток меліорації земель в умовах змін клімату» шляхом виконання фундаментальних та прикладних завдань (проектів) за трьома підпрограмами:

– Формування водної безпеки та відтворення водних ресурсів в умовах змін клімату;

– Відновлення та розвиток зрошення і дренажу в Україні в умовах змін клімату;

– Використання меліорованих земель в умовах змін клімату.

Дослідження Інституту характеризуються комплексністю, гармонійним поєднанням фундаментальних та прикладних досліджень, мають новаторський інноваційний характер, відомі не тільки в Україні, а й за її межами.

Найважливішими з них, що виконані в останні 15-20 років, є наукові засади Стратегії зрошення та дренажу в Україні, Водної стратегії України, наукове обґрунтування Загальнодержавної цільової програми розвитку водного господарства та екологічного оздоровлення басейну річки Дніпро, наукові засади протипаводкового захисту в басейнах гірських річок Карпат, наукові засади захисту територій та сільських населених пунктів від підтоплення ґрунтовими та затоплення поверхневими водами, концепції сільськогосподарського водопостачання, відновлення та розвитку зрошення в південному регіоні України, ефективного використання осушуваних земель гумідної зони України, відновлення виробництва сучасної дощувальної техніки в Україні, велика кількість технологій та технічних засобів для реалізації процесів зрошення та осушення земель, підготовки води в системах сільгоспводопостачання та водовідведення, технології вирощування сільськогосподарських культур за краплинного зрошення, комп’ютерні інформаційно-аналітичні та інформаційно-дорадчі системи управління технологічними процесами на зрошуваних і осушуваних землях, оцінка впливу зміни клімату на стан водної безпеки, водність річок та екологічний стан водних об’єктів України та умови вологозабезпечення її території на основі сучасних моделей кліматичних змін.

Розробки Інституту, як правило, доводяться до рівня, що забезпечує можливість їх практичного використання. Дослідження та розробки Інституту за період його існування, були вагомим внеском, а часто слугували основою створення та функціонування потужного водогосподарсько-меліоративного комплексу України, який включає зрошувальні та осушувально-зволожувальні системи на загальній площі понад 5 млн. га, гідровузли та канали, що за своїми технічними характеристиками відповідають кращим світовим аналогам.

За успіхи у розвитку меліоративної науки і підготовці наукових кадрів 27 грудня 1979 р.

Інститут нагороджено орденом Трудового Червоного Прапора. Високий науковий рівень та практична значимість розробок Інституту підтверджується чисельними нагородами та преміями, що отримані співробітниками установи, у тому числі премія Ради Міністрів СРСР (1984 р.), Державна премія України у галузі науки і техніки (1997 р.), премії НААН «За видатні досягнення в аграрній науці» (2008, 2014 рр.), премія Кабінету Міністрів України за розроблення і впровадження інноваційних технологій (2020 р.) та Національна премія імені Бориса Патона (2024 р.). За вагомий внесок у забезпечення розвитку аграрної науки та високий професіоналізм 22 співробітники Інституту були відзначені державними нагородами, 9 одержали звання «Заслужений працівник». За видатні наукові здобутки Інститут було відзначено Почесною грамотою Кабінету Міністрів України (2005, 2019 рр.). У 2019 р. трудовий колектив ІВПіМ НААН було нагороджено Грамотою Верховної Ради України за заслуги перед Українським народом.

Свідченням вагомості наукових результатів Інституту є його визнання за межами України: Інститут як базова наукова установа представляє Україну в Міжнародній комісії з іригації і дренажу (МКіД), Глобальному водному партнерстві, виконує делеговані йому Європейським центром з відновлення річок (ЄЦВР) функції Національного центру з відновлення річок.

Інститут підтримує зв'язки з відомими зарубіжними науковими центрами та фірмами США, Німеччини, Франції, Японії, Нідерландів, Ізраїлю, Польщі, Угорщини та інших країн.

Співробітники Інституту постійно беруть участь та виступають з науковими доповідями на Всесвітніх водних форумах, конгресах МКіД з питань раціонального використання і охорони водних ресурсів та меліорації земель.

Наукові працівники Інституту за результатами конкурсів постійно проходять стажування у провідних наукових центрах зарубіжних країн – Університет прикладних наук (Нідерланди), Університети штатів Колорадо, Техас, Огайо та Каліфорнія (США) та за міжнародними програмами: "Cochran" (США), Міністерство сільського господарства (США), Японська агенція з міжнародної співпраці (Японія), "Mashav" (Ізраїль), Асоціація голландських компаній "PLUS" (Нідерланди), імені Лейна Кіркланда (Польща).

Науковий авторитет Інституту на міжнародній арені підтверджується його участю у виконанні міжнародних проектів із Фондом цивільних досліджень і розвитку (CRDFGlobal), FAO та EBRD.

В Інституті створені та функціонують наукові школи з питань енергоефективного, екологобезпечного водокористування на зрошувальних системах (академік НААН та Італійської академії с.-г. наук, професор Коваленко П. І.), краплинного зрошення, екологобезпечних режимів зрошення та моніторингу меліорованих земель (академік НААН, професор Ромащенко М. І.; член-кореспондент НААН, професор Шатковський А. П.), біоенергетичних екологозбалансованих систем землеробства на меліорованих землях (академік НААН, професор Таракіо Ю. О.), системного математичного моделювання та управління водо- і землекористуванням (доктор технічних наук, професор Ковальчук П. І.) та інші.

При Інституті функціонують аспірантура, докторантура та спеціалізована вчена рада із захисту докторських і кандидатських дисертацій. За приблизними підрахунками, починаючи з 30-х років минулого століття в ІВПіМ НААН захищено 35 докторських і 443 кандидатських дисертацій. Упродовж 2020–2024 рр. співробітники Інституту захистили 11 дисертації з отримання ступеня доктора філософії.

При Інституті з 2002 р. діє Технічний комітет стандартизації «Меліорація і водне господарство» (ТК 145). За цей період розроблено понад 200 Національних стандартів України з питань якості води, іригаційного устаткування та технологій зрошення, більшість з яких – гармонізовані з міжнародними та європейськими.

Інститут веде активну видавничу діяльність. З 1967 р. по 2018 р. в Інституті видавався міжвідомчий тематичний науковий збірник «Меліорація і водне господарство». Всього видано 108 випусків збірника. З 2019 р. саме на його базі видається науковий журнал «Меліорація і водне господарство». Загалом щороку співробітниками Інституту друкується більше 200 статей у вітчизняних та зарубіжних виданнях, біля 10 монографій, подається до 10 заявок на винаходи та патенти.

Науковці Інституту є членами редакційних колегій та рецензентами в наукових журналах, які індексуються SCOPUS ("Journal of Water and Land Development") та Web of Science ("Agriculture Science and Practice").

Інститут щорічно проводить наукові конференції з питань водних ресурсів до Дня води (березень) та з питань меліорації земель (грудень). Свої наукові розробки Інститут постійно демонструє на різних міжнародних та всеукраїнських виставках, форумах та нарадах.

Нові розробки та концептуальні підходи, напрацьовані Інститутом, знайшли відображення у Водному Кодексі України, Законах України «Про меліорацію земель», «Про організації водокористувачів та стимулювання гідротехнічної меліорації земель», «Стратегії зрошення та дренажу в Україні на період до 2030 року», «Водній стратегії України на період до 2050 року», «Загальнодержавній цільовій програмі розвитку водного господарства та екологічного оздоровлення басейну річки Дніпро на період до 2021 року», «Загальнодержавній програмі «Питна вода України» на 2011–2021 роки», Схемах та Програмах протипаводкового захисту в басейнах річок Тиса, Прут, Дністер, Стрий, Схемі захисту сільськогосподарських угідь та населених пунктів Херсонської області від затоплення поверхневими та підтоплення ґрунтовими водами.

Широко впроваджена в системі Держводагентства України також «Методика формування ціни на подачу води на зрошення, промислові та комунальні потреби», яка стала оновою запровадження механізму платного водокористування в галузі водного господарства та меліорації земель.

Загалом отримані результати та розробки з питань раціонального використання та охорони меліорованих земель стали в довоєнний період організаційно-правовою, науково-методичною та техніко-технологічною основою забезпечення експлуатації зрошувальних систем та проведення поливів на площі близько 500 тис га та водорегулювання на площі близько 300 тис га щорічно. На вказаних землях щорічно, незалежно від погодних умов, вирощували продукції рослинництва на загальну суму близько 20 млрд грн.

Після 24 лютого 2024 року Інститут активно долучився до вирішення проблем, спричинених військовою агресією рф.

Всі працівники Інституту активно допомагають воїнам Збройних Сил України, вірять у перемогу України і якнайшвидший мир, з настанням якого обов’язково з’являться додаткові потреба і можливості плідно працювати задля відновлення водогосподарсько-меліоративного комплексу України.

Вітаємо всіх співробітників Інституту з 95-річчям із дня заснування установи, дякуємо за плідну та надзвичайно потрібну державі та українському народу роботу, бажаємо подальших наукових успіхів і відкриттів, цікавих ідей та інноваційних проектів, зичимо міцного здоров’я та нових здобутків на благо України! Слава Україні! Наближаємо перемогу разом!

З повагою,
директор ІВПіМ НААН — Михайло ЯЦЮК

Головний редактор журналу
«Меліорація і водне господарство» — Михайло РОМАЩЕНКО

**Dear authors and readers of the Journal!**

We have great pleasure and honor to inform you that the founder and publisher of our journal, the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine, celebrates its 95th anniversary on December 23, 2024. To be more precise, it begins its celebration in view of the fact that it was on December 23, 1929, at a meeting of the Council of People's Commissars of the Ukrainian SSR that a decision was made to establish the Research Institute of Agricultural Reclamation under the People's Commissariat of Land Resources of the Ukrainian SSR on the basis of regional reclamation organizations and research stations, and the newly created Institute began its work in May 1930 in Kharkiv. From November to December of the same year, the Institute was transferred to Odesa, where it operated until 1941. After a break caused by the war, the Institute resumed its work in May 1944 in Kyiv, where it continues to operate today. During the period from 1935 to 1992, the Institute was called the Ukrainian Research Institute of Hydraulic Engineering and Land Reclamation, from 1992 to 2011 – the Institute of Hydraulic Engineering and Land Reclamation of the Ukrainian Academy of Agrarian Sciences, and from 2011 to the present – the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine.

The Institute is the leading state scientific institution of Ukraine in the field of scientific support for the development of water management and land reclamation. As of 01.12.2024, the scientific staff of the Institute consists of 104 researchers, including 12 Doctors of Sciences, including 3 Academicians of the National Academy of Sciences of Ukraine and 1 Corresponding Member of the National Academy of Sciences of Ukraine, 41 Candidates of Sciences. The structure of the Institute includes 8 scientific departments, Sarny Research Station and 2 experimental farms.

The Institute conducts extensive research in the areas of Water Resources and Land Reclamation. These studies have been and are being carried out together with co-executors as part of the State Research Programs formed for a five-year period.

Today, the Institute, as the lead research institution, conducts and coordinates the research of co-executors within the framework of the NAAS IPA 4 "Sustainable water use, formation of water security, development of land reclamation in the context of climate change" by performing fundamental and applied tasks (projects) under three subprograms:

– Formation of water security and reproduction of water resources in the context of climate change;

– Restoration and development of irrigation and drainage in Ukraine in the context of climate change;

– Use of reclaimed land in the context of climate change.

The Institute's research is characterized by complexity, a harmonious combination of fundamental and applied research, and is innovative and pioneering, known not only in Ukraine but also abroad.

The most important of these, completed in the last 15-20 years, are the scientific foundations of the Irrigation and Drainage Strategy in Ukraine, the Water Strategy of Ukraine, the scientific substantiation of the National Target Program for the Development of Water Management and Environmental Rehabilitation of the Dnipro River Basin, the scientific foundations of flood protection in the basins of mountain rivers of the Carpathians, the scientific foundations of protection of territories and rural settlements from groundwater and surface water flooding, the concepts of agricultural water supply, restoration and of

As a rule, the Institute's developments are brought to a level that ensures the possibility of their practical use. Over the period of its existence, the Institute's research and development has made a significant contribution and often served as the basis for the creation and functioning of a powerful water management and reclamation complex of Ukraine, which includes irrigation and drainage systems on a total area of more than 5 million hectares, hydroelectric power stations and canals that meet the best world analogs in terms of their technical characteristics.

On December 27, 1979, the Institute was awarded the Order of the Red Banner of Labor for success in the development of land reclamation science and training of scientific personnel. The high scientific level and practical significance of the Institute's developments are confirmed by numerous awards and prizes received by the staff of the institution, including the USSR Council of Ministers Award (1984), the State Prize of Ukraine in Science and Technology (1997), NAAS Awards for Outstanding Achievements in Agricultural Science (2008, 2014), the Cabinet of Ministers of Ukraine Award the Development and Implementation of Innovative Technologies

(2020), and the Borys Paton National Prize (2024). For their significant contribution to the development of agrarian science and high professionalism, 22 employees of the Institute were awarded state awards, 9 received the title of "Associate of Honour". For outstanding scientific achievements, the Institute was awarded the Diploma of the Cabinet of Ministers of Ukraine (2005, 2019). In 2019, the staff of the Institute of Plant Industry and Mechanics of NAAS was awarded the Diploma of the Verkhovna Rada of Ukraine for services to the Ukrainian people.

The Institute's scientific results are recognized outside of Ukraine: As a basic research institution, the Institute represents Ukraine in the International Commission on Irrigation and Drainage (ICID), the Global Water Partnership, and performs the functions of the National Center for River Restoration delegated to it by the European Center for River Restoration (ECRR).

The Institute maintains ties with well-known foreign research centers and companies from the United States, Germany, France, Japan, the Netherlands, Israel, Poland, Hungary, and other countries.

Employees of the Institute regularly participate and make scientific presentations at the World Water Forums, ICID congresses on the rational use and protection of water resources and land reclamation.

Based on the results of competitions, the Institute's researchers are constantly undergoing internships at leading research centers in foreign countries – the University of Applied Sciences (Netherlands), the Universities of Colorado, Texas, Ohio and California (USA) and under international programs: "Cochran (USA), the Department of Agriculture (USA), the Japan International Cooperation Agency (Japan), Mashav (Israel), the Association of Dutch Companies PLUS (Netherlands), and the Lane Kirkland Foundation (Poland).

The scientific authority of the Institute in the international arena is confirmed by its participation in international projects with the Civilian Research and Development Foundation (CRDFGlobal), FAO and EBRD.

The Institute has created and operates scientific schools on energy efficient, environmentally friendly water use in irrigation systems (Academician of the NAAS and the Italian Academy of Agricultural Sciences, Professor Kovalenko P. I.), drip irrigation Professor P. I. Kovalenko), drip irrigation, environmentally friendly irrigation regimes and monitoring of reclaimed lands (Academician of NAAS, Professor M. I. Romashchenko; Corresponding Member of NAAS, Professor A. P. Shatkovsky).), bioenergy ecologically balanced farming systems on reclaimed lands (Academician of NAAS, Professor Tarariko Y. O.), system mathematical modeling and management of water and land use (Doctor of Technical Sciences, Professor Kovalchuk P. I.) and others.

The Institute has a postgraduate program, a doctoral program, and a specialized academic council for the defense of doctoral and candidate dissertations. According to approximate estimates, since the 1930s, 35 doctoral and 443 PhD theses have been defended at the Institute of Food Science and Technology of the National Academy of Agrarian Sciences of Ukraine. During 2020-2024 , the Institute's staff defended 11 dissertations for the degree of Doctor of Philosophy.

Since 2002, the Technical Committee for Standardization "Land Reclamation and Water Management" (TC 145) has been operating at the Institute. Over this period, more than 200 National Standards of Ukraine on water quality, irrigation equipment and irrigation technologies have been developed, most of which are harmonized with international and European standards.

The Institute conducts active publishing activities. From 1967 to 2018, the Institute published an interdepartmental thematic scientific collection "Land Reclamation and Water Management". A total of 108 issues of the collection were published. Since 2019, the scientific journal "Land Reclamation and Water Management" has been published on its basis. In general, every year, the Institute's staff publishes more than 200 articles in domestic and foreign publications, about 10 monographs, and files up to 10 applications for inventions and patents.

Institute scientists are members of editorial boards and reviewers in scientific journals indexed by SCOPUS (Journal of Water and Land Development) and Web of Science (Agriculture Science and Practice).

The Institute annually organizes scientific conferences on water resources on Water Day (March) and on land reclamation (December). The Institute constantly demonstrates its scientific developments at various international and national exhibitions, forums and meetings.

The new developments and conceptual approaches developed by the Institute are reflected in the Water Code of Ukraine, the Laws of Ukraine "On Land Reclamation", "On Organizations of Water Users and Stimulation of Hydraulic Land Reclamation", "Irrigation and Drainage Strategy in Ukraine for the Period up to 2030", "Water Strategy of Ukraine for the Period up to 2050", "The National Target Program for the Development of Water and Environmental Rehabilitation of the Dnipro River Basin for the Period up to 2021, The National Program "Drinking Water of Ukraine" for 2011-2021, Flood Protection Schemes and Programs in the basins of the Tisza, Prut, Dniester, and Stryi Rivers, and the Scheme for the Protection of Agricultural Land and Settlements in Kherson Region from Surface Water Flooding and Groundwater Flooding.

The Methodology for Pricing Water Supply for Irrigation, Industrial and Municipal Needs has also been widely implemented in the State Agency of Ukraine for Water Resources, which has become an update to the mechanism of paid water use in the water management and land reclamation sector

In general, the results and developments on the rational use and protection of reclaimed land in the pre-war period became the organizational, legal, scientific, methodological, technical and technological basis for ensuring the operation of irrigation systems and irrigation on an area of about 500 thousand hectares and water regulation on an area of about 300 thousand hectares annually. On these lands, regardless of weather conditions, crops were grown annually for a total of about UAH 20 billion.

After February 24, 2024, the Institute was actively involved in solving the problems caused by the military aggression of the Russian Federation.

All the employees of the Institute actively help the soldiers of the Armed Forces of Ukraine, believe in the victory of Ukraine and the soonest peace, which will certainly create additional needs and opportunities to work fruitfully to restore the water management and reclamation complex of Ukraine.

We congratulate all the staff of the Institute on the 95th anniversary of the institution's foundation, thank them for their fruitful work, which is extremely necessary for the state and the Ukrainian people, wish them further scientific success and discoveries, interesting ideas and innovative projects, and wish them good health and new achievements for the benefit of Ukraine! Glory to Ukraine! Let's bring victory closer together!

Sincerely yours,
Director of the IWPaLR of the NAAS — Mykhailo Yatsiuk

Editor-in-Chief of the journal
"Land Reclamation and Water Management" — Mykhailo Romashchenko

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# ASSESSMENT OF THE CURRENT ECOLOGICAL STATE OF THE FASTIV RESERVOIR USING GROUND AND SATELLITE DATA

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***Abstract.*** *The article presents the results of researches on assessing the ecological state of the Fastiv Reservoir using ground and satellite data according to the developed scientific approach, which provides for the following sequence for a water body with a large area: conducting field observations, involving satellite information, and creating a resulting map of the current ecological state based on a certain set of indicators, which is the goal of the research. The relevance of the research is defined by the significant deterioration of the water condition in the reservoir, which was caused by an increase in air temperature, uneven distribution of precipitation throughout the year, a decrease in the reservoir filling to 92.7 % of the design level, intensive increase in water use and discharge of domestic wastewater. In the conducted studies, it was advisable to compensate the lack of spatially concentrated information (from points of field measurements) with spatially distributed information. During field surveys, hydrobiological and physicochemical indicators were determined in 3 sections of the reservoir – points observations, and maps of water depth, temperature, and transparency were created based on the results. Such results of field observations as an increased turbidity and low transparency made it necessary to use satellite data, especially those containing red and infrared ranges, when calculating spectral indices. From the perspective of remote sensing, water bodies have their own spectral characteristics, which depend on the concentration of various substances dissolved and suspended in water – diffuse reflectance. To compensate the lack of information, the Sentinel-2 L2A image was used, which is the closest with no cloud cover to the date of field observations, and spectral indices were calculated in the open software product Land Viewer: NDVI, GCI, NDWI. Only the NDWI map was useful, providing an insight about the transparency within the entire reservoir. The obtained comprehensive information made it possible to create a resulting map of the current ecological state of the Fastiv Reservoir based on the ground and satellite data.*

***Keywords:*** *reservoir, ecological state, ground surveys, satellite data, spectral indices, resulting map*

**Relevance of the research.** Increasing greenhouse gas concentrations lead to climate changes, air temperature increasing, changes in the annual distribution of precipitation throughout the year, biomass increasing, and intensification of biochemical processes in surface waters, which has significantly worsened their ecological state. To these negative factors an increase in man-made load on water bodies due to unauthorized sources of pollution and discharges of domestic wastewaters should be added. Another problem that needs to be addressed is the pollution of water bodies with untreated and insufficiently treated return waters due to the unsatisfactory technical condition of treatment facilities, which leads to the entry of insufficiently treated wastewaters into natural waters. Therefore, timely assessment of the ecological state of surface waters is an urgent task. An example of an unsatisfactory ecological state of waters is the Fastiv Reservoir, which is a vital reservoir for the city of Fastiv, as the water level in it affects the water debit in wells and provides a stable water supply to over 45 thousand residents. Due to the unsatisfactory technical condition of the gates of the hydraulic structure and the lack of flushing in the reservoir, its basin silted up, and the influx of insufficiently treated wastewaters from the city's industrial enterprises has caused a significant deterioration in the ecological condition of the reservoir today. For a comprehensive assessment of the large reservoir state, field surveys of the reservoir's hydromorphological state and the physicochemical characteristics of the water are not enough, as those results represent point-based data that correspond to the locations of direct water sampling. For a more in-depth analysis of the water bodies' eutrophication processes, there is a need for spatially distributed data, which is provided to specialists by satellite images. In the case of the Fastiv Reservoir, when assessing the current ecological state, it was advisable to complete the point-based data with spatially distributed information [1]. The issue of completing the indicators during the environmental assessment using ground data by aerospace data is also addressed in the work of H. Godı´nez-Alvarez, J.E. Herrick, M. Mattocks, et al. [2].

**Analysis of recent research and publications.** The issues of assessing the transparency and turbidity of waters is covered in the works [3, 4]. The thesis of Pichura V.I. describes the identification of water transparency in individual Dnipro reservoirs using remote sensing (RS) data. Also, one of the important issues of the water bodies ecological state, which has been addressed by a large number of researchers, is the spread of blue-green algae, which is known as water "bloom". It is necessary to highlight the work of Adam Trescott [5], who in his papers obtained empirical models based on remote sensing data for the estimation of chlorophyll concentration in open water bodies. Scientists have found that the best results for assessing algae development are obtained from the relationships that use the values of B1, B2, and B3 bands of the Landsat 7 satellite mission. The work of the American researcher Mohammad Haji Gholizadeh stands out for its thoroughness [6]. The author analyzed numerous research results, which dedicated to study the application of remote sensing in the water bodies ecological assessment. The Chinese scientist Shengkun Zhang devoted his research to the assessment of the chlorophyll concentration in Laizhou Bay (China) [7]. The paper describes how, based on data from the Landsat 8 OLI and the results of field surveys, a regression model was obtained and, based on it, the spatial distribution of chlorophyll concentration was estimated and the water quality in the coastal waters of the studied bay was assessed. Analysis of research and publications shows that the main attention while assessing surface waters using satellite data is devoted to determining transparency and turbidity, as well as the possibility of compensating for the lack of ground-based information with satellite data.

**The aim of the research** is to assess the ecological state of the Fastiv Reservoir using ground and satellite data.

**Research methods and materials.** The work presents an analytical analysis of scientific works on the ecological survey of surface waters using ground and satellite data, ground surveys and experimental studies of the Fastiv Reservoir using generally accepted and certified methods, and a geospatial and system analysis of the obtained results.

The research methodology included the following components:

– analytical analysis of scientific works on the identified problem;

– conducting field surveys, which included measuring the depth of the reservoir, water sampling, measuring transparency, turbidity (content of suspended solids), color, and water temperature;

– search for publicly available satellite information and analysis of the possibility of its application to the research problem;

– calculations of spectral indices for vegetation, green chlorophyll, and water;

– analysis of the obtained results.

During field surveys, hydrobiological and physicochemical indicators were determined in 3 sections of the reservoir – point observations and, additionally, spatially distributed satellite data on the ecological state of the reservoir were obtained.

**Research results and their discussion**. The Fastiv Reservoir is located on the Unava River, which is a right tributary of the Irpin River. The reservoir is located on the southwestern edge of the Fastiv city, partially wedged into the city limits. The reservoir has existed since 1907, but acquired its modern appearance after the commissioning of hydraulic structures on the Unava River in 1935. The length of the reservoir is 6.20 km, the average width is 390 m, the widest section is 700 m, the average depth is 3.77 m. The normal supporting water level (NSWL) is set at 158.00 m (Baltic height system). The area of the water mirror at NSWL is 2.41 km$^2$, and the volume of the reservoir is 5.06 million m$^3$. The usable volume is 4.87 million m$^3$.

The area of the Unava River catchment to the hydroelectric power station is 462 km$^2$. The river is fed by snow and rain, the flow volume at 50 % of availability is 26.65 million m$^3$. The reservoir is the main water supply source for the railway junction and some industrial enterprises in Fastiv city. During the operation time of the reservoir, the hydraulic facilities were reconstructed in 1929, 1932, 1961, and 1998. Over the past 15-25 years, flow regulation by gates has been practically not carried out, which has led to significant silting of the reservoir. According to the results of the survey of the reservoir by the specialists from the Institute of Water Problems and Reclamation of the National Academy of Agrarian Sciences (IWPiM of NAAS) in August 2022, it was noted that the water level in the reservoir was below the NSWL and the regulated volume of water in the reservoir was 4.69 million $m^3$, which is 92.7 % of the reservoir's design capacity. The main reason for the decrease in the reservoir filling was low water conditions of the current year on the background of significant filtration losses through the hydraulic facility, which is due to the unreliable operation of the gate valves (Fig. 1).

Figure 1. Hydraulic facility of the Fastiv Reservoir

However, not only hydrotechnical and climatic (air temperature increase, uneven distribution of precipitation throughout the year) conditions have caused the deterioration of the ecological state of water in the reservoir. In recent decades, there has been an intensive increase in water use, which has also led to a deterioration in water quality. Surface runoff from agricultural fields, which contains mineral fertilizers, pesticides, and biogenic substances, also causes harm. A significant negative environmental impact on the water body is caused by LLC "Eko-Vtor", which is engaged in the extraction of polyester fibers from PET bottles and incineration of polymer waste, resulting in the formation of various toxic substances – acetaldehyde, terephthalic and other organic acids. Also, the State Environmental Inspection and the Fastiv Prosecutor's Office discovered violations of water legislation in the work of the communal enterprise "Fastivvodokanal". Such violations contributed to the increase in water "bloom" (Fig. 2) from year to year.

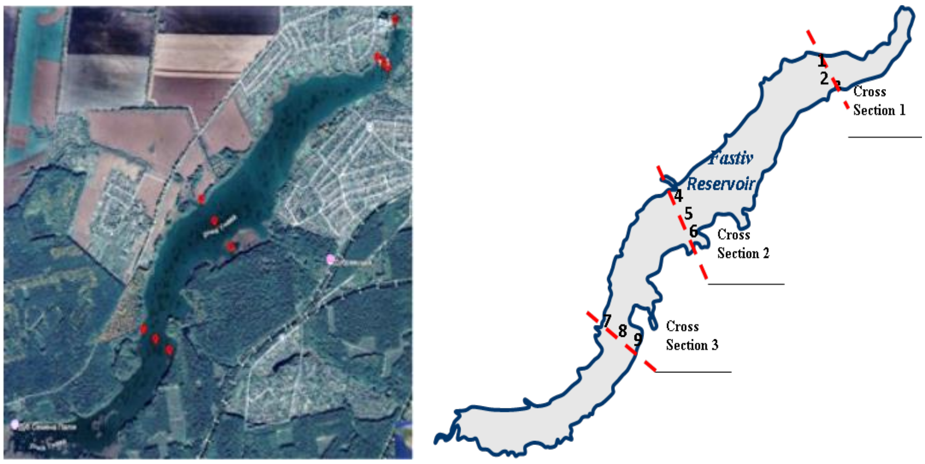
a

b

Figure 2. Water pollution in the Fastiv Reservoir: a – upstream, b – downstream.

Therefore, in August 2024, specialists from the IWP&LR of NAAS conducted a survey of the Fastiv Reservoir regarding the ecological state of the waters – hydrobiological (turbidity, transparency) and physicochemical (soluble iron content in the water). Three lines were selected: line 1 with observation points 1–2–3 closer to the dam; line 2 with points 4–5–6 in the middle of the reservoir; line 3 with points 7–8–9 in the ending part. The schemes of the research are shown in Fig. 3.

During the survey (Fig. 4), depth measurements, water sampling, and measurements of transparency, turbidity (content of suspended solids), color, and water temperature were performed.




a b

Figure 3. Schemes of research: a – the coordinates of observation points on a satellite image, b – layout of observation lines

a b

Figure 4. Survey conducting: a – the upperstream; b – using a boat to measure the depth of water and take water samples

The results of field surveys and laboratory analyzes of water samples from the Fastiv Reservoir are given in Tables 1, 2.

1. The results of field survey of the Fastiv Reservoir

| Coordinates of observation points | Water sampling point number | Water temperature, °C | Transparency, m | Depth, m |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| 50°4’27,00" 29°53’42,00" | 1 | 23,8 | 0,32 | 2,2 |
| 50°4’25,44" 29°53’44,82" | 2 | 23,8 | 0,35 | 4,6 |
| 50°4’23,6" 29°53’47,17" | 3 | 23,8 | 0,32 | 2,6 |
| 50°3’49,44" 29°52’1,15" | 4 | 24,0 | 0,30 | 1,9 |
| 50°3’42,58" 29°52’7,46" | 5 | 22,3 | 0,31 | 6,9 |
| 50°3’34,18" 29°52’15,56" | 6 | 23,0 | 0,30 | 1,2 |

Table 1 (ending)

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| 50º3’12,17"<br>29º51’25,24" | 7 | 24,0 | 0,33 | 2,0 |
| 50º3’8,82"<br>29º51’31,35" | 8 | 23,8 | 0,33 | 2,8 |
| 50º3’5,11"<br>29º51’38,28" | 9 | 22,8 | 0,31 | 1,4 |

2. Results of laboratory analyzes of water from the Fastiv Reservoir

| Water sampling point number | Turbidity, mg/dm³ | Fe, mg/dm³ | Transparency, cm |
|---|---|---|---|
| 1 | 30,16 | 0,70 | 19 |
| 2 | 31,90 | 0,74 | 11 |
| 3 | 33,06 | 0,62 | 5,8 |
| 4 | 34,80 | 0,74 | 4,5 |
| 5 | 40,80 | 0,68 | 6,2 |
| 6 | 33,64 | 0,74 | 5,5 |
| 7 | 40,60 | 0,54 | 5 |
| 8 | 38,28 | 0,79 | 5,3 |
| 9 | 31,90 | 0,70 | 16,5 |

Since the dispersion of observation points is significant, instead of creating the dependence graphs, we created schematic maps based on field and laboratory observations using the method of approximation between the points (Fig. 5).

From the maps it is clear that the water temperature decreases with the increase of depth, and the water transparency changes in a small range, which is explained by the total spread of blue-green algae during the active development phase in the summer time. Data from field surveys and laboratory analyzes differ. Transparency is usually determined by two methods – using a Secchi disk in the field conditions and using a Snellen device in the laboratory. In this case, the results of the certified Snellen device method were used.

The concentration of iron oxide was determined as a physicochemical characteristic of water. Normally, it should decrease with the increase of water body volume, which is a natural phenomenon. However, the reservoir filling was equal to 92 % and the concentration of soluble iron in average was 0.7 mg/dm³ throughout the water area and is not significant as a characteristic.

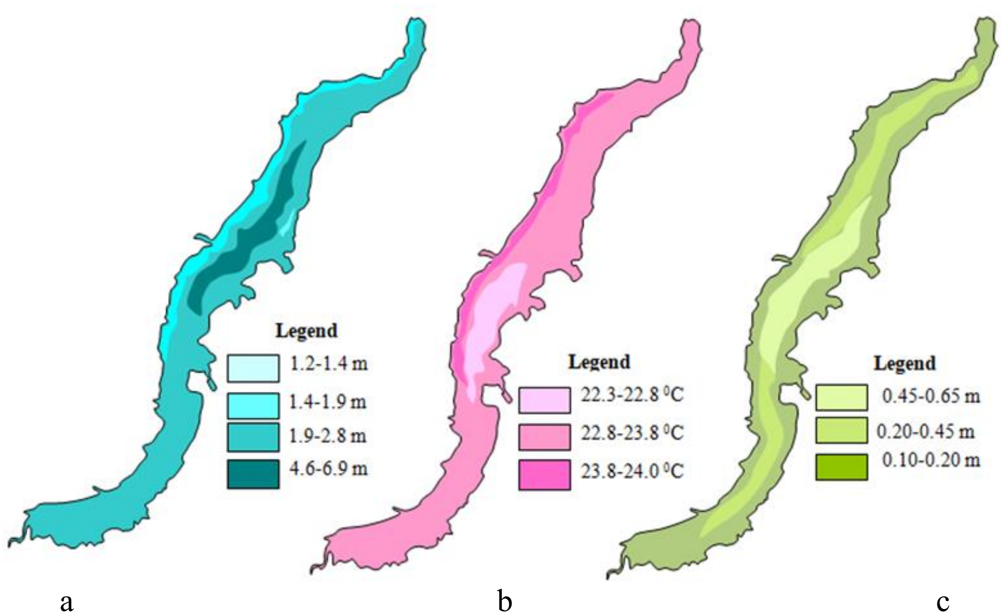



Figure 5. Schematic maps of the field survey results: a – depths; b – temperatures; c – transparency

Water turbidity is determined by the content of finely dispersed impurities suspended in water – insoluble or colloidal particles of various origins. Turbidity of water also determines some other characteristics of water, in particular, the presence of sediment, suspended solids, coarse impurities. Water turbidity is one of the important indicators of its quality. This indicator reflects the presence of inorganic and organic undissolved particles in water and was equal to 30–40 mg/dm$^3$ during the observation period.

Such results of field surveys as increased turbidity and low transparency have made it necessary to use satellite data, especially those contain red and infrared bands, in calculating spectral indices. From the point of view of remote sensing, water bodies have their own spectral characteristics, which depend on the concentration of various dissolved and suspended substances in water – diffuse reflectance.

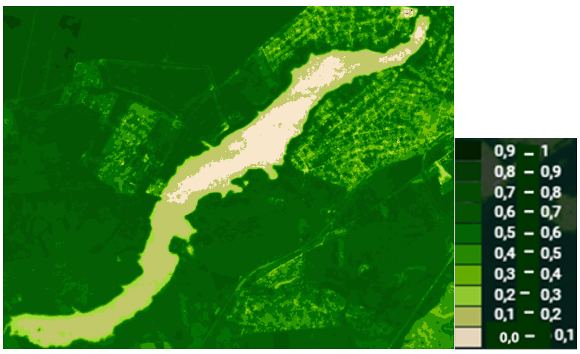



Figure 6. Map of NDVI distribution within the Fastiv Reservoir

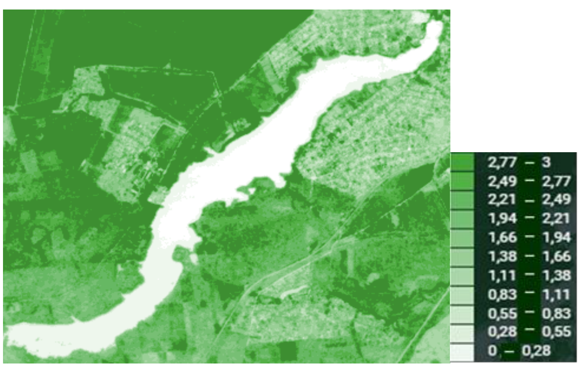



Figure 7. Map of GCI distribution within the Fastiv Reservoir

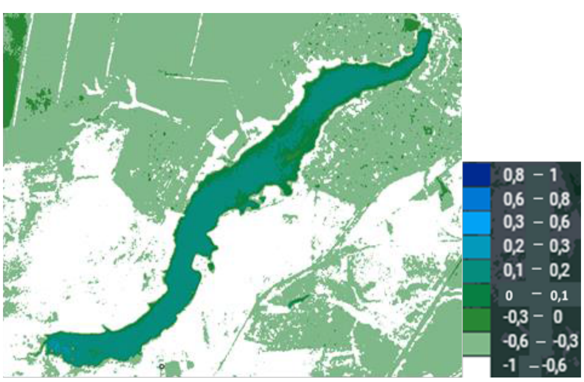



Figure 8. Map of NDWI distribution within the Fastiv Reservoir

For the study we used the Sentinel-2 L2A image dated 25.07.2024, the closest date with no cloud cover to the date of field surveys, and calculated the following spectral indices in the open software product LandViewer: Green Chlorophyll Index (GCI), Normalized Difference Water Index (NDWI) [8, 9, 10], Normalized Difference Vegetation Index (NDVI) [11]. Based on the results of the calculations, maps of these indices were obtained (Fig. 6–8).

The classical NDVI map distinguishes coastal vegetation – reeds in the range of 0,30–0,40 microns and finely dispersed impurities in the water in the range of 0–0,10 microns. The GCI map is not informative, since it only concerns vegetation, and on the surface of the reservoir it is absent, and gives only clear contours of the reservoir itself. However, the NDWI map is obtained by the calculation that uses the near-infrared (NIR) band with a wavelength range of 0,78–0,90 microns and the mid-infrared (SWIR) band with a wavelength range of 1,56–1,66 microns, provides the most information about the trophic state of the reservoir. With an NDWI value above 0,3, an open body of water is distinguished; the values from 0 to 0,3 shows the presence of vegetation with a high water content or partially submerged areas of vegetation; a value of 0 usually indicates dry soil or vegetation with a low water content. It is important to note that these threshold values can vary depending on the specific environment and should be calibrated according to local conditions. Thus, during the research, more information about transparency was obtained, which made it possible to produce a resulting map of the current ecological state of the Fastiv Reservoir (Fig. 9) based on ground and satellite data.

On the resulting map produced according to the existing methodology [12], yellow color corresponds to "satisfactory" water condition at NDWI values of 0,3–0,6 and transparency of 0,45–0,65 m, brown color corresponds to "bad" condition at NDWI values of 0,2–0,3 and transparency of 0,20–0,45 m, red color corresponds to "very bad" condition at NDWI values of 0,0–0,2 and transparency of 0,10–0,20 m.

**Conclusions.** The use of the Normalized Difference Water Index in combination with ground measurements and laboratory studies made

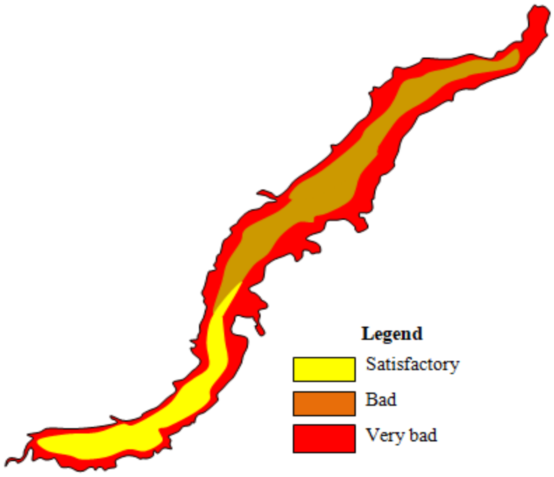



Figure 9. Resulting map of the current ecological state of the Fastiv Reservoir based on ground and satellite data

it possible for the first time to assess the current trophic state of the Fastiv Reservoir as a whole during the period of active water "blooming".

During the conducted research, it was found that based on the results of ground surveys of a large water body, it is advisable to create schematic maps, rather than graphs, due to the large dispersion (scatter) of observation points.

It has been established that increased turbidity and poor water transparency necessitate the use of satellite data, especially those containing red and infrared ranges of the electromagnetic radiation spectrum, when calculating spectral indices.

It is proven that it is possible to produce the resulting map of the current ecological state of a water body, which may contain individual water areas of different ecological states, based on certain indicators obtained in the complex. The allocation of categories of the ecological state of different areas in the corresponding color (yellow – satisfactory, brown – bad, red – very bad) is carried out in accordance with the existing methodology for assigning a surface water body, as well as a significantly modified surface water body, to one of the classes of ecological potential of an artificially or significantly modified surface water body.

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## ОЦІНКА СУЧАСНОГО ЕКОЛОГІЧНОГО СТАНУ ФАСТІВСЬКОГО ВОДОСХОВИЩА ЗА НАЗЕМНИМИ ТА СУПУТНИКОВИМИ ДАНИМИ

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***Анотація.*** *У статті викладено результати досліджень з оцінки екологічного стану Фастівського водосховища за наземними та супутниковими даними за розробленим науковим підходом, який передбачає наступну послідовність для водного об'єкта з великою площею: проведення натурних спостережень, залучення супутникової інформації та побудови за певним комплексом показників результуючої карти сучасного екологічного стану, що є метою досліджень. Актуальність проведення досліджень випливає з значного погіршення стану води у водосховищі, яке спричинили підвищення температури повітря, нерівномірний розподіл опадів впродовж року (зменшення наповнення 92,7 %), інтенсивний ріст водокористування та скидання господарсько-побутових стічних вод. У проведених дослідженнях доцільним було компенсувати нестачу просторово зосередженої інформації просторово розподіленою. При натурних обстеженнях визначали гідробіологічні і фізико-хімічні показники у 3-х створах водосховища – точкові спостереження, а за результатами було побудовано карти глибин, температури та прозорості води. Такі результати натурних спостережень, як збільшена каламутність та слабка прозорість, а також неможливість обстеження з технічних причин третьої частини водосховища (акваторія у хвості), викликали необхідність застосувати супутникові дані, особливо ті, що містять червоні та інфрачервоні канали при розрахунках спектральних показників. З точки зору дистанційного зондування, водні об'єкти мають свої спектральні характеристики, які залежать від концентрації різних розчинених і завислих у воді речовин – дифузного відбиття. Щоб компенсувати нестачу інформації, було задіяне знімок Sentinel-2 L2A, який є найближчим з відсутньою хмарністю до дати проведення натурних спостережень і розраховано спектральні індекси у відкритому програмному продукті LandViewer:NDVI,GCI, NDWI. Корисною виявилася лише карта NDWI, яка давала уявлення про прозорість у межах всього водосховища. Отримана комплексна інформація дала можливість побудувати результуючу карту сучасного екологічного стану Фастівського водосховища за наземними та супутниковими даними.*

***Ключові слова:*** *водосховище, екологічний стан, наземні обстеження, супутникові дані, спектральні індекси, результуюча карта*

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# CONVERSION OF AQUEOUS AMMONIA SOLUTIONS USING AN ADAPTIVE WATER PURIFICATION SYSTEM

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***Abstract.*** *Water purification from ammonium nitrogen is currently an urgent task for protecting drinking water sources and ensuring the required water quality for consumers in various sectors of the Ukrainian economy. The technological approaches covered in this article can be used to remove other ammonium-based compounds from water. The obtained results of the adaptive water purification system (AWPS) with a simulated highly concentrated aqueous ammonium solution (1,16 g/dm$^3$) suggest their use in water purification technologies from hydrobionts and side-products of biogas systems (digestat purification). Pulsed electrochemical methods were used in the operation of the AWPS in combination with ultrasonic exposure on oxidation-reduction processes with controlled injection of gas mixtures. A high correlation between all the variables studied was established. The same was confirmed by the regression analysis made in the process of empirical modeling of the relationship between the treatment time and the change in pH and in the concentrations of ammonium nitrogen, nitrates and nitrites. That is, all the indicators of multiple correlation and determination in the constructed significant models indicate a very high correlation with the treatment time. The decrease in pH from 11 to 9.6 can be explained by the fact that acids were formed during the treatment of the model solution, which caused the decrease.*

*The energy efficiency of the AWPS operation was assessed by analyzing changes in the concentrations of the main component of the simulated solution (ammonium) and its derivatives using the example of nitrites and nitrates and a fixed operating time of 60 min. The use of electrolysis methods allowed the conversion of ammonium in an aqueous solution into derivatives – an aqueous solution of nitrites and nitrates, to record changes in their concentrations, and when using membrane electrolysis to obtain them in an ionic form, which is optimally suitable for plant nutrition and direct synthesis of nitrogen-containing fertilizers with simultaneous application by irrigation or spraying.*

***Keywords:*** *water purification, ammonium, nitrites, nitrates, pulsed electrolysis, adaptive power source, current form, adaptation*

**Relevance of the research**. The entry of ammonium nitrogen and its derivatives into aqueous solutions is a common phenomenon. The traditional ways of entry of these substances (natural ones with organic compounds and manmade ones with industrial effluents) are supplemented now by technogenic ones, including the results of military hostilities in the territory of Ukraine.

The development of modern or improving existing technological approaches to the purification or conversion of nitrogen-containing compounds into useful forms will be constantly relevant. At present, the development of new technological solutions for hydrobiont cultivation systems is promising, and the existing approaches to closed water supply systems (RAS) require improvement, especially from the perspective of the development of hydroponics and aquaponics. Moreover, the issue of purification of biogas system discharges, the so-called digestate, has not been resolved globally. Phosphorus and other substances are also present in the digestate, and we expect that electrochemical methods will also affect them, converting them into less toxic or useful derivatives in a regulated technological mode. The filtrate of water effluents from solid waste landfills also has excess concentrations of nitrogen forms and its purification is an important task.

**Analysis of recent research and publications.** Modern technological solutions for the purification of aqueous solutions from ammonia and ammonium use a diverse range of approaches, depending on the historical factors of their formation. The most common methods include biological (most often used in RAS), reagent, ion exchange, electrochemical, and sorption [2–5]. All of them have their strengths and weaknesses. In the recent publication on electrochemical purification of aqueous solutions from ammonium, there is a grounded approach [4, 5] but its key disadvantages are the non-recirculation of the technological cycle, the absence of pulsed current loading of the electrolyzer electrodes and the absence of ultrasound, which reduces the efficiency of conversions.

Given the importance of the development of renewable energy sources (biogas systems), industrial hydrobiont cultivation systems (RAS), and combined hydroponics and aquaponics systems, the development of technologies on ammonium purification and conversion into other forms from aqueous solutions [8–9] is the subject of research and development by many scientists.

**Research objective.**

Known progressive solutions [4, 5] use the correct basis, but the most promising are electrochemical methods that use electrolysis methods as controlled ones with high development potential. In our solutions described in previous publications [10–13], we have foreseen the advantages of electrochemical combined methods and considered their various technological variations, which were implemented when creating the AWPS. The difference between these solutions is that we additionally use pulsed electrolysis with an adaptive power source, additional regulated oxidation or reduction, and a more complex recirculation hydraulic scheme, which expands the possibilities of settings and the effect of electrolysis methods in combination with ultrasound. The task was to investigate the operation and energy efficiency of the developed ASOV under its action on a concentrated aqueous solution of ammonium.

**The purpose of the research** is to research the processes of ammonium conversion into nitrates and nitrites when using the AWPS and, based on the results obtained, to determine the efficiency of water purification and energy efficiency of individual units and the AWPS as a whole.

**Materials and research methods**. An artificially simulated aqueous solution was prepared from water from a well in a 200 l container with the addition of 0,5 l of a 25 % aqueous ammonium solution. 30 l of the model solution was fed into the AWPS per 1 experiment. The operating temperature at the beginning of the experiments was 19 °C.

The ammonium conversion process was going in recirculation mode through an electrolyzer with insoluble anodes (ORTA) on a titanium base, which contains 4 electrodes of 0,1 m × 0,2 m. The current partially passes through a group (3 pcs.) of electrolysis two-sided turbo hydrocyclones with an insoluble graphite anode with a diameter of 20 mm and a height of 20 cm. pH control was made using a pH-150 MI pH meter. To control the parameters of pulse electrolysis, a FNIRSI DSO-138 mini-oscilloscope was used, built into an adaptive power supply unit, and connected to the load voltage output terminals of the electrolyzer electrodes. The power source provided a current of ~ 45 V electrodes with a pulse electrolysis frequency of 3 Hz to the electrolyzer, and the pulse shape front increase mode was set. To record and control energy consumption for technological processes of AWPS, a PEACEFAIR wattmeter of PZEM-008 model with a maximum permissible current of 100 A, and an accuracy of ± 1 % was used. The total area of the system electrodes involved was 0,24 $m^2$.

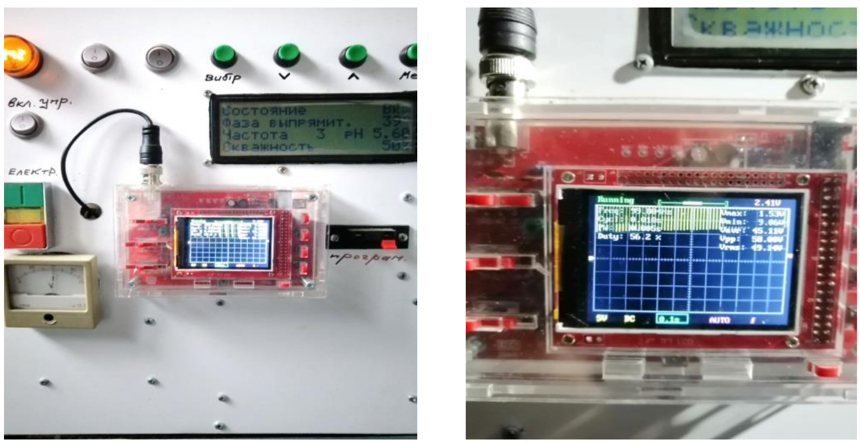
Chemical changes of the model solution during the operation of the AWPS were studied using three samples in the Laboratory of Hygiene of Natural Drinking Water of the State Institute named after O.M. Marzeev of the National Academy of Medical Sciences of Ukraine. The PI7.2/13 method was used for determining ammonium, the PI7.2/12 method – for nitrites, and the method according to DSTU 4078-2001 – for nitrates.

**Research results and their discussion**. AWPS when using an adaptive power supply unit with a pulsed supply mode to the electrolyzer electrodes is shown in Fig. 1. The basic functional and technological as well as general hydraulic diagram was given in [13].

The adaptive power supply of AWPS under operation is presented in Fig. 2.

The wattmeter for monitoring of the total energy consumption of AWSP is presented in Fig. 3.

Fig. 1. General view of AWPS



a b

Fig. 2. Overview of the adaptive power supply of electrolysis units

a – control and parameter monitoring panel, including an integrated portable oscilloscope;
b – oscilloscope in operating mode

a) b) c) d) e) f)

Fig. 3. Data of the wattmeter on the general control of energy consumption during operation and conducting experiments:

a – energy consumption for ultrasound; b – energy consumption for electrolysis (dynamic); c – energy consumption per a pump (variable, there are two of them in the system); d – total energy consumption for the entire operation of AWPS along with the pumps (2 pcs.), electrolysis, ultrasound and control systems at the beginning of the experiment; e – after 20 min.; f – after 60 min

The actual electrode load current ranged from 1,84 to 3A depending on changes in the electrical conductivity of the model solution. It increases when ammonium is converted to nitrites and nitrates, as stronger electrolytes than ammonium are synthesized.

The current density is calculated by the largest current parameter 3 A/0,24 m$^2$=12,5 A/m$^2$.

The changes in the energy consumption of AWPS during the experiment are presented in Fig. 4.

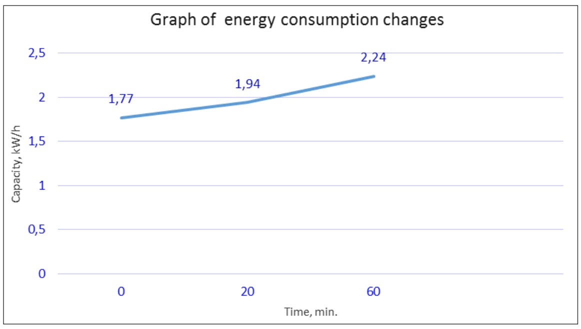



Fig. 4. Graph of changes in the energy consumption of AWPS

From the graph in Fig. 4 it is clear that during the experiment a change in the energy consumption of the unit was observed in the range from 1,77 to 2,24 kW·h, which indicates a change in the electrical conductivity of the model solution. Taking into account the volume of the latter in AWPS, the specific energy consumption for a change in the ammonium concentration from 1,16 g/dm$^3$ to 0.48 g/dm$^3$ is 66,8 W/l.

The results of the experiments are presented in the form of graphs (Fig. 5). As we can see from the presented dependences, a 2,5-fold decrease in the ammonium concentration is clearly observed during one-hour treatment of the solution. The concentration of nitrites and nitrates increases similarly.

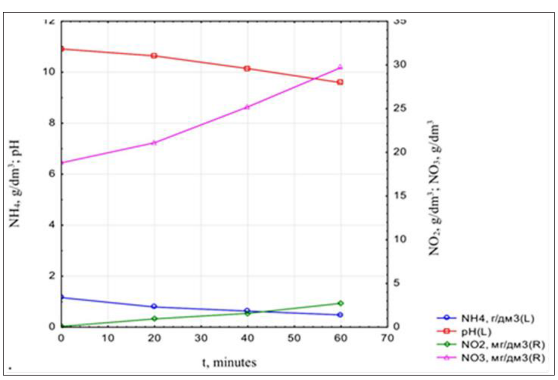



Fig. 5. Graphs of the changes in the studied indicators that occurred during the treatment of the model solution

During the operation of the unit, electrochemical processes occur, which are determined both by the composition of the source water and the specifics of the electrolyzers. For example, the synthesis of the coagulant is determined, among other things, by the Cl- content and the electrode material:

$$Fe + 3Cl^- + 3e = FeCl_3,$$
$$FeCl_3 + 3H_2O = Fe(OH)_3\downarrow + 3HCl.$$

The synthesis of the antiseptic – oxidant goes in a similar way due to the presence of a membrane – a ceramic semi-permeable membrane of 2 mm thick with an area equal to the area of the electrodes:

$$2NaCl + 2H_2O = 2NaOH + H_2\uparrow_{(cathode)} + Cl_2\uparrow_{(anode)}.$$

In the anode space, partial hydrolysis occurs with the formation of chloride and hypochloride acids:

$$Cl_2 + H_2O = HCl + HClO.$$

Synthesized in the cathode space NaOH is used to neutralize acids formed as a result of hydrolysis:

$$HCl + NaOH = NaCl + H_2O.$$

The study of correlations between the studied indicators was made using Pearson's parametric correlation and is presented as a Table 1.

1. Establishing mutual correlations

| | **t** | **$NH_4$** | **$NO_2$** | **$NO_3$** | **pH** |
|---|---|---|---|---|---|
| **t** | 1,000 | –0,972 | 0,993 | 0,990 | –0,989 |
| **$NH_4$** | –0,972 | 1,000 | –0,957 | –0,931 | 0,928 |
| **$NO_2$** | 0,993 | –0,957 | 1,000 | 0,991 | –0,990 |
| **$NO_3$** | 0,990 | –0,931 | 0,991 | 1,000 | –1,000 |
| **pH** | –0,989 | 0,928 | –0,990 | –1,000 | 1,000 |

Correlations marked in red are significant when p <0,05000

The empirical model of the change in $NH_4$ concentration during the treatment of the model solution depending on the treatment time is given as equation (1).

$$NH_4\_M=1,095-0,011t, \qquad (1)$$

where $NH_4\_M$ – model of change in $NH_4$ concentration, g/dm$^3$; t – treatment time, min.

Model characteristics are: multiple correlation – R = 0,972; determination – $R^2$ = 0,945; adjusted determination – $R^2$ = 0,917; Fisher F parameter (1,2) = 34,326; p < 0,02792; standard error of estimate is 0,084.

A comparison of the $NH_4\_M$ model and the results of the observations of changes in $NH_4$ concentration is shown in Fig. 6.

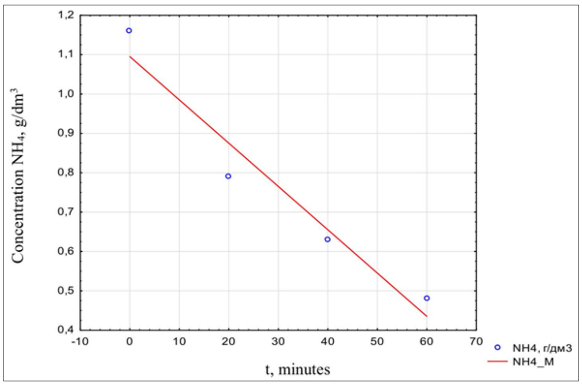



Fig. 6. Comparison of the $NH_4$_M model
and field results during the treatment process

The empirical model of the change in $NO_2$ concentration during the treatment of the model solution depending on the treatment time is given as equation (2).

$$NO_2\_M=0,055+0,043t, \quad (2)$$

where $NO_2$_M – model of the change in $NO_2$ concentration, mg/dm³; t – treatment time, min.

Model characteristics are: multiple correlation – R = 0.993; determination – $R^2$ = 0.987; adjusted determination – $R^2$ = 0,98; Fisher F parameter (1,2) = 148,73; p < 0.0067; standard error of estimate is 0,157.

Comparison of the $NO_2$_M model and the results of the observations of the change in $NO_2$ concentration are shown in Fig. 7.

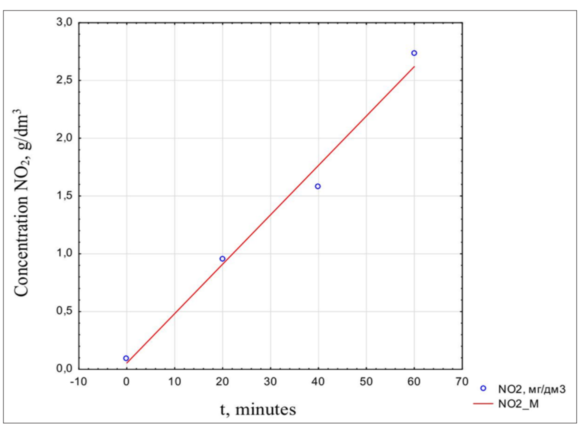



Fig. 7. Comparison of the $NO_2$_M model
and field results during the treatment process

The empirical model of the change in $NO_3$ concentration during the treatment process depending on the treatment time is given as equation (3).

$$NO_3\_M= 18,18 + 0,184t, \quad (3)$$

where $NO_3$_M – model of the change in $NO_3$ concentration, mg/dm³;

t – treatment time, min.

Model characteristics are: multiple correlation – R = 0,99; determination – $R^2$ = 0,981; adjusted determination – $R^2$ = 0,97; Fisher F parameter (1,2) = 103,54; p < 0,00952; standard error of estimate is 0,8087.

Comparison of the $NO_3$_M model and the results of the observations of the change in $NO_3$ concentration are shown in Fig. 8.

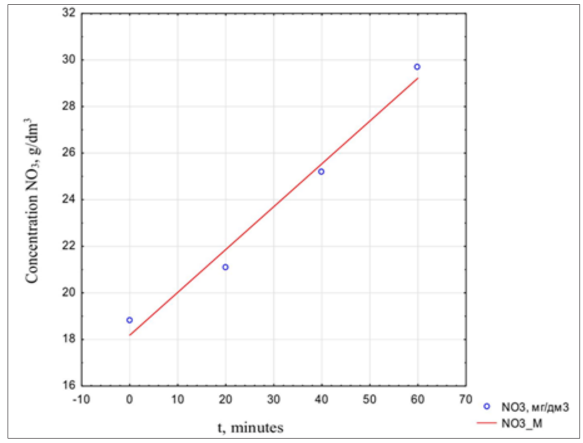



Fig. 8. Comparison of the $NO_3$_M model
and field results

The empirical model of pH change during the treatment of the model solution depending on the treatment time is given as equation (4).

$$pH\_M= 10,989-0,0223t, \quad (4)$$

where pH_M is a model of pH change; t – treatment time, min.

Model characteristics are: multiple correlation – R = 0,989; determination – $R^2$ = 0,979; adjusted determination – $R^2$ = 0,969; Fisher F parameter (1,2) = 93,74; p < 0.001050; standard error of estimate is 0,103.

Comparison of the pH_M model and the results of the observations on pH change are shown in Fig. 9.

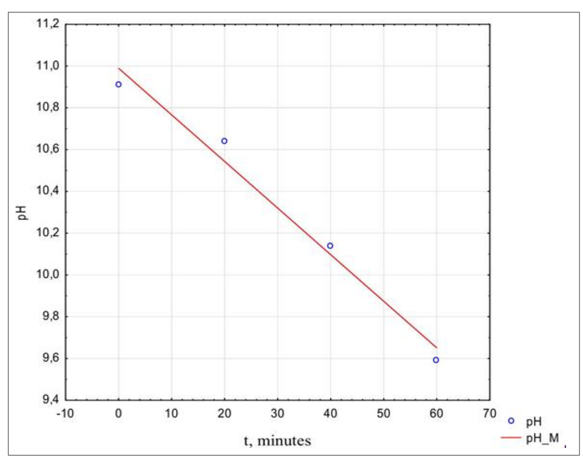



Fig. 9. Comparison of the pH_M model
and field results

## Conclusions

1. A high correlation was established between all the studied variables. This statistically confirms the influence of the treatment period on changes in the studied pH indicators and changes in the concentrations of nitrogen compounds.

It was confirmed by the regression analysis made in the process of empirical modeling of the relationship between treatment time and changes in pH indicators and in the concentrations of ammonium nitrogen, nitrates and nitrites. That is, all indicators of multiple correlation and determination in the developed significant models indicate a very high correlation with treatment time.

2. The decrease in pH from almost 11 to 9,6 can be explained by the fact that acids were formed during the treatment of the model solution, which caused the decrease.

3. The decrease in $NH_4$ concentration can be explained by the partial transition of nitrogen to compounds in the form of nitrates and nitrites and the possible formation of atomic nitrogen from ammonia nitrogen during the electrolysis process with its release into the atmosphere.

4. Probable chemical processes that occurred during the treatment of the model solution are:

– nitrites formed during the electrochemical oxidation of ammonium can be additionally converted into nitrates as a result of the reaction:

$$NO_2^- + O = NO_3^-, \quad (5)$$

when using oxygen from the decomposition products of water.

When an electric current passes through the treated water, atomic oxygen, hydrogen peroxide, and free radicals, which are strong oxidants, can be obtained as a result of electrochemical reactions. And if the treated water contains more than 20 mg/dm$^3$ of chlorides, there are simultaneous reactions to form chlorine, chlorine dioxide, and hypochlorous acid, which are capable of disinfecting water containing residual chlorine.

The main reactions occurring at the electrodes are:

at the anode:

$$2H_2O \rightarrow O_2\uparrow + 4H^+ + 4e; \quad (6)$$

at the cathode:

$$2H_2O + 2e \rightarrow H_2 + 2OH^-, \quad (7)$$

at the anode:

$$3H_2O \rightarrow O_3\uparrow + 6e + 6H^+; \quad (8)$$

at the cathode $2H_2O + O_2 + 2e \rightarrow H_2O_2 + 2OH^-$, (9)

at the anode: $2Cl^- \rightarrow Cl_2 + 2e;$ 10)

$$Cl_2 + H_2O \rightarrow HClO + H^+ + Cl^-; \quad (11)$$

$$Cl_2 + OH^- \rightarrow HClO + Cl^-. \quad (12)$$

The direct electrolysis method in various versions enables us to purify water from iron, hydrogen sulfide, ammonium, manganese, reduce water hardness, remove taste, color, turbidity, and disinfect from bacteria and viruses.

Below are the main reactions occuring during the removal of ammonium.

$$2NH_3 + 3O_2 \rightarrow 2HNO_2 + 2H_2O, \quad (13)$$

$$NH_3 + 2O_2 \rightarrow HNO_3 + H_2O, \quad (14)$$

$$NH_3 + 4H_2O_2 \rightarrow HNO_3 + 5H_2O, \quad (15)$$

$$NH_3^- + 4HClO \rightarrow HNO_3 + 4HCl + H_2O. \quad (16)$$

5. The energy consumption for the AWSP operation is insignificant. When all the system blocks are under operation, the total energy consumption was from 1,77 kW to 2,24 kW, and the specific energy consumption was 66,8 W/dm$^3$.

6. The parameters of the electrolyzer with insoluble electrodes were previously determined. In our opinion, it is advisable to maximize the time of remaining the working solution in the interelectrode space. The feasibility of using the recirculating structure of the hydraulic circuit combined with the use of an adaptive power source for electrolyzers with a changing shape of the pulse current and the use of an electrolyzer of an original design with built-in ultrasonic emitters has been proven.

7. The proposed AWSP system is promising for constructing on its basis more complex systems for purification and disinfection of aqueous solutions containing complex combined pollutants of high concentration, for systems of aqueous solutions regeneration, purification of leachate effluents from solid waste landfills, effluents from biogas systems (digestate), mine waters and other multi-element and highly concentrated aqueous solutions.

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УДК 628.1

# ПЕРЕТВОРЕННЯ ВОДНИХ РОЗЧИНІВ АМОНІЮ ПРИ ЗАСТОСУВАННІ АДАПТИВНОЇ СИСТЕМИ ОЧИЩЕННЯ ВОДИ

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***Анотація.*** *Очищення води від амонійного азоту нині є актуальним завданням для захисту джерел питного водопостачання та забезпечення необхідної якості води для споживачів різних галузей економіки України. Технологічні підходи, висвітлені в цій статті, можуть бути використані для видалення із води інших сполук на основі амонію. Отримані результати роботи адаптивної системи очищення води (АСОВ) із змодельованим висококонцентрованим водним розчином амонію (1,16 г/дм$^3$) передбачають їх використання в технологіях для очищення води після гідробіонтів та біогазових систем (очищення дигестату). У роботі АСОВ застосовували імпульсні електрохімічні методи у поєднанні з ультразвуковим впливом, окисненням і частковим відновленням з контрольованим інжектуванням газових сумішей. Встановлено високу кореляцію між усіма досліджуваними змінними величинами. Те ж підтвердили і регресійний аналіз, виявлений у процесі емпіричного моделювання зв'язків часу обробки зі зміною показників pH, та зміни концентрацій амонійного азоту, нітратів і нітритів. Тобто всі показники множинної кореляції і детермінації в побудованих значимих моделях свідчать про дуже високий кореляційний зв'язок з часом обробки. Зниження pH від майже 11 до 9,6 можливо пояснити тим, що в процесі обробки модельного розчину утворювались кислоти, які і стали причиною цього зниження. Проведено оцінювання енергоефективності роботи АСОВ та ефективності системи через аналізування змін концентрацій головного компонента змодельованого розчину (амонію) та похідних речовин від нього на прикладі нітритів і нітратів та фіксованим часом роботи 60 хв. Використання електролізних методів дало змогу провести перетворення амонію у водному розчині на похідні – водний розчин нітритів та нітратів, зафіксувати зміну їх концентрацій, при використанні мембранного електролізу отримати їх в іонній формі, яка оптимально підходить для живлення рослин та прямого синтезу азотовмісних добрив з одночасним внесенням методом поливу чи розпилення.*

***Ключові слова:*** *очищення води, амоній, нітрити, нітрати, імпульсний електроліз, адаптивне джерело живлення, форма струму, адаптація*

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# ANALYSIS OF THE IMPACT OF GLOBAL CLIMATE CHANGE TRENDS ON THE BLOOMING OF THE DNIPRO RIVER IN THE DNIPRO-DONBAS CANAL AREA

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***Abstract.*** *The hydrodynamic properties of a reservoir can affect the potential for cyanobacterial blooming. Slow-flowing or stagnant waters are more conducive to blooming stability. Therefore, water with a faster flow, more intensive mixing, or higher rotation speed is less likely to develop cyanobacterial blooming. The Kremenchutske and Kamianske reservoirs have an essential impact on the blooming of the Dnieper River in the Dnieper-Donbas Canal area. Their temperature regime in the warm season favors the development of zooplankton and phytoplankton. Aquatic vegetation is most common in shallow water. Water blooming is observed in summer, and this process covers up to 70 % of the area of reservoirs, especially in the southern part and bays, deteriorating water quality. Higher frequency and intensity of precipitation, accompanied by longer periods of drought, can create contribute greater nutrient mobility. Longer periods of high temperatures also contribute to this process, at that there is no mixing of water layers. Cyanobacteria can quickly utilize nutrients that enter water bodies due to rainfall. Strong winds can also affect the cyanobacteria population, pushing cyanobacterial cells and colonies towards the banks, where they accumulate.These reservoirs are located in the temperate continental climate zone and belong to water bodies that warm up well. That is due to their width, which makes wind mixing possible in the middle and lower parts of the reservoirs, as a result of which the temperature is distributed evenly and horizontally. To confirm and supplement the results of field studies, statistical processing of water quality indicators of the Dnipro River in the area of the Dnipro-Donbas Canal was carried out. Trends were determined by regression analysis of time series of water quality indicators. The distribution was checked for normality using the Kolmogorov-Smirnov and Shapiro-Wilk tests. Correlation analysis was performed using the Pearson parametric method and the Spearman nonparametric method. The fluctation period was determined using the spectral Fourier transform method. The comprehensive analysis made it possible to establish the factors that are the main cause of water blooming in the studied area, which makes it possible to control the necessary water treatment processes.*

***Keywords****: water resources, climate change, cyanobacteria, water blooming, water quality*

**Relevance of the research.** Rising temperatures and climate change, which affect the intensity and duration of droughts, can strongly influence cyanobacterial growth rates and algae blooming. Rising air temperatures can lead to higher water temperatures, longer ice-free seasons, and increased thermal stratification. Conversely, low winter temperatures combined with cold springs can lead to more intensive mixing of water in a reservoir and the resuspension of sediment nutrients [1]. Climatic factors can also counteract the development of cyanobacterial populations, for example, through winds and precipitation, which promote water mixing, washout, destabilization, and blooming propagation. The timing and duration of cyanobacterial blooming are also influenced by climatic conditions and other factors such as the size and location of the inoculum.

A general concern is that rising global temperatures caused by climate change could further expand the geographic distribution of toxin-producing cyanobacterial blooming in temperate regions, as well as an overall global increase in the frequency and intensity of blooming. It is supposed that rising global temperatures is at least partly responsible for the spread of certain cyanobacterial species outside of tropical and subtropical climates. The adaptation of cyanobacteria to cold has been proven by researchers as they were detected at temperatures below 20 °C. There are conflicting opinions among researchers about the effects of higher temperatures on cyanobacteria compared to other phytoplankton, so further research is needed on this issue [2].

**Analysis of recent studies and publications**. Some cyanobacteria grow at optimal temperatures above 25 °C, which are higher than other phytoplankton species. *Cylindrospermopsis* can thrive at temperatures from 20° to 35 °C, with maximum growth at 30 °C [3]. It has been suggested that tolerance to this temperature range helps to explain the occurrence of *C. raciborskii* in temperate regions during the summer months and the year-round blooming in some tropical and subtropical regions [4–6]. On the other hand, *Microcystis* and many other taxons are also able to survive in sediments and can survive more than a single overwintering period. This has important implications, as overwintering populations of toxin-producing cells can then re-inoculate the reservoir during the spring thaw or during the growing season during resuspension [7–9].

There is little information on the relative survival of toxic strains versus non-toxic strains under these conditions. The toxic potential of *Microcystis* cells was well preserved during overwintering, but it is unlikely that these toxic cells had a competitive advantage. *Cylindrospermopsis raciborskii* can form resting stages called akinetes that may protect the organism at adverse temperatures. Some authors state that increasing temperatures confer a direct advantage on cyanobacteria because they prefer higher growth temperatures [10–13]. Others suggest that cyanobacteria benefit indirectly from the rise of temperatures by increasing stratification, water column stability, and lengthening the growing season [14; 15]. In many cases, all of these factors may likely contribute to cyanobacterial blooming.

Many cyanobacteria have photoadaptive characteristics that allow them to lead other phytoplankton in the competition for light sources. They have numerous photosynthetic pigments that allow utilizing wavelengths of light that are not favorable to many competing phototrophic species [16]. They also function at extreme light levels and thus can outcompete other phytoplankton found in high-light conditions (e.g., at the surface), in deeper or turbid waters, or bottom sediments. Some cyanobacteria regulate their buoyancy and can optimize their position in the water column according to the amount of available light or move (slide) to more illuminated areas of the bottom substrate [17].

Light requirements vary among cyanobacterial species. For example, *Microcystis* species prefer environments with higher light levels, while others, such as *Planktothrix agardhii* and *Cylindrospermopsis raciborskii*, prefer low light levels [18]. *Cylindrospermopsis* is known to be less buoyant than other cyanobacteria, and deeply mixed water bodies may favor its dominance [19]. This and other cyanobacteria, such as *Gloeotrichia*, can acclimatize and utilize nutrient-rich deeper layers or low-light bottom areas [20]. Then as a result of water layers mixing, these taxons can increase their primary production when they move to the upper, more light-rich layers. For benthic populations, sufficient light capable of penetrating to the bottom of the water layer is an important criterion for determining the depth of cyanobacterial growth occurring [21].

**Purpose of the study** is to make a comprehensive analysis of the impact of global climate change on local trends of the Dnieper River blooming in the Dnieper-Donbas Canal area. That will allow us to determine the need for changes in operating the necessary water treatment processes in the study area.

**Materials and methods of the study**. During the study, the following water quality indicators at the observation post of the Dnipro-Donbas Canal (0,5 km, Shulhivka village, after the main catchwater canal of the Dnipro-Donbas Canal) of the Dnipro River were analyzed for the period from 2016 to 2018: biomass, mg/dm$^3$; biochemical oxygen consumption for 5 days, $mgO_2/dm^3$; odor, points; dissolved oxygen, $mgO_2/dm^3$; transparency, cm; temperature, degrees C; phytoplankton, thousand cells/dm$^3$. For statistical processing of experimental data, the STATISTICA 10 comprehensive statistical analysis package, developed by StatSoft, was used. The STATISTICA 10 package implements procedures for data analysis, data management, data extraction, and data visualization. Trends were determined by the regression analysis method of time series of water quality indicators. The distribution was checked for normality using the Kolmogorov-Smirnov and Shapiro-Wilk tests.

Correlation analysis was made using the parametric Pearson method and the nonparametric Spearman method. The fluctation period was determined using the spectral Fourier transformation method.

**Results of the study and their discussion**. The thermal regime of the Kremenchuk and Kamianskereservoirs, which have the biggest impact on the blooming of the Dnieper River in the area of the Dnieper-Donbas Canal, is characterized by uneven distribution of water temperature along the length, width, and depth, and has an unstable nature. Intensive warming of the reservoirs occurs first near the tributaries' mouths. The temperature in spring rises much faster than it decreases in autumn. The maximum heat is observed in the July – August period and the least – in the December – March period.

The catchment area belongs to typical humus-rich black and gray forest soils. Suspended matter in these reservoirs is formed under a sharp decrease in flow transportation capacity, which leads to a noticeable water clearing compared to river conditions. One of the reasons of the turbidity of reservoir water is the impact of wind waves on the bank zone. In addition, when waves approach the banks obliquely, along-bank sediment flows are formed. Silt enters the reservoirs from the outside, and it is also formed in the reservoirs, as a result of bank and bottom abrasion influenced by wind waves and the development and death of phytoplankton. The hydrochemical regime of these reservoirs is formed under the influence of external and internal factors.

External factors include river runoff, soil, and vegetation type in the river catchment, precipitation, and the ingress of various pollutants into the water in the process of human activity. Internal factors include decreasing flow velocity, increasing productivity and hyperproduction of some types of algae, changes in the quantitative and qualitative composition of organic matter, etc.

To confirm and supplement the results of field studies, water quality indicators were statistically processed in the studied area of the Dnipro River. Trends were determined by a regression analysis method of time series of water quality indicators.

The obtained model equations and their characteristics are shown on the graphs of qualitative indicators observations (Fig. 1). The applied regression analysis method of time series made it possible to determine that the trends of such qualitative indicators as biomass, phytoplankton, odor, and temperature are directed towards increasing concentrations.

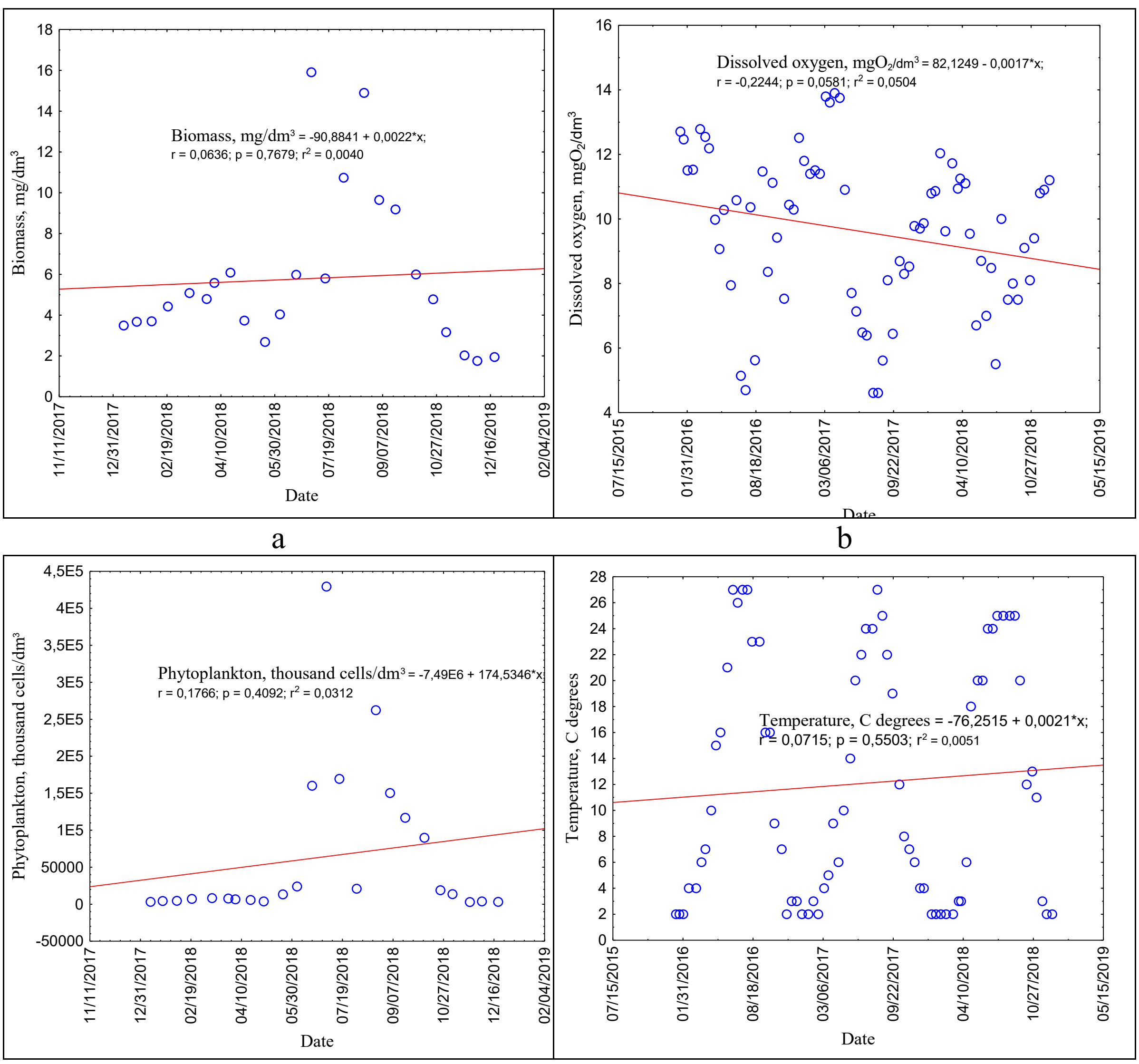


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Fig. 1 Graphs of water quality indicators observations during 2016–2018

Verifying the distribution compliance with the normal was performed using the Kolmogorov-Smirnov and Shapiro-Wilk tests. The built graphs and histograms of the studied indicators enabled us to specify that no indicator corresponds to the common distribution law. Therefore, the values of most indicators related to the organic component are determined mainly by the temperature cycle.

Given that most of the data do not follow a normal distribution, both the parametric Pearson method (Table 1) and the nonparametric Spearman method (Table 2) were used to determine correlations. The correlation results are presented in the form of correlation tables.

The fluctation period was determined using the spectral method of Fourier transforms (Fig. 2). One mark on the Period axis corresponds to half a month, i.e. the scale corresponds to a semi-monthly discreteness.

Correlation analysis, which used parametric and nonparametric methods, revealed a significant relationship between biochemical oxygen consumption for 5 days, odor, phytoplankton, water clarity, and biomass with temperature and dissolved oxygen. Determining the fluctuation period, performed using the spectral transformation method of Fourier, enabled us to establish that such indicators as biochemical oxygen consumption for 5 days, odor, dissolved oxygen, water clarity, and temperature have a seasonal nature of fluctuation due to the temperature cycle. The periodicity of the key fluctuations peak is in the range of 11,1–11,5 months.

1. Indicators correlation by the Pearson method to normal correlation

| | **Biomass, mg/dm$^3$** | **Biochemical oxygen consumption for 5 days, mg$O_2$/dm$^3$** | **Odor, points** | **Dissolved oxygen, mg$O_2$/dm$^3$** | **Water clarity, cm** | **Temperature, C degrees** | **Phyto-plankton, thousand cells/dm$^3$** |
|---|---|---|---|---|---|---|---|
| Biomass, mg/dm$^3$ | 1,000 | 0,396 | 0,667 | –0,524 | –0,617 | 0,631 | 0,833 |
| Biochemical oxygen consumption for 5 days, mg$O_2$/dm$^3$ | 0,396 | 1,000 | 0,037 | –0,128 | –0,497 | 0,186 | 0,264 |
| Odor, points | 0,667 | 0,037 | 1,000 | –0,836 | –0,604 | 0,782 | 0,809 |
| Dissolved oxygen, mg$O_2$/dm$^3$ | –0,524 | –0,128 | –0,836 | 1,000 | 0,444 | –0,903 | –0,786 |
| Water clarity, cm | –0,617 | –0,497 | –0,604 | 0,444 | 1,000 | –0,472 | –0,520 |
| Temperature, C degrees | 0,631 | 0,186 | 0,782 | –0,903 | –0,472 | 1,000 | 0,812 |
| Phytoplankton, thousand cells/dm$^3$ | 0,833 | 0,264 | 0,809 | –0,786 | –0,520 | 0,812 | 1,000 |

Note: The red values in the table correspond to normal correlation.

2. Indicators correlation by the Spearman method

| | **Biomass, mg/dm$^3$** | **Biochemical oxygen consumption for 5 days, mg$O_2$/dm$^3$** | **Odor, points** | **Dissolved oxygen, mg$O_2$/dm$^3$** | **Water clarity, cm** | **Temperature, C degrees** | **Phyto-plankton, thousand cells/dm$^3$** |
|---|---|---|---|---|---|---|---|
| Biomass, mg/dm$^3$ | 1,000 | 0,755 | 0,721 | –0,354 | –0,368 | 0,666 | 0,772 |
| Biochemical oxygen consumption for 5 days, mg$O_2$/dm$^3$ | 0,755 | 1,000 | 0,194 | 0,045 | –0,299 | 0,306 | 0,578 |
| Odor, points | 0,721 | 0,194 | 1,000 | –0,526 | –0,485 | 0,609 | 0,750 |
| Dissolved oxygen, mg$O_2$/dm$^3$ | –0,354 | 0,045 | –0,526 | 1,000 | 0,513 | –0,713 | –0,729 |
| Water clarity, cm | –0,368 | –0,299 | –0,485 | 0,513 | 1,000 | –0,613 | –0,380 |
| Temperature, C degrees | 0,666 | 0,306 | 0,609 | –0,713 | –0,613 | 1,000 | 0,816 |
| Phytoplankton, thousand cells/dm$^3$ | 0,772 | 0,578 | 0,750 | –0,729 | –0,380 | 0,816 | 1,000 |

Note: The red values in the table correspond

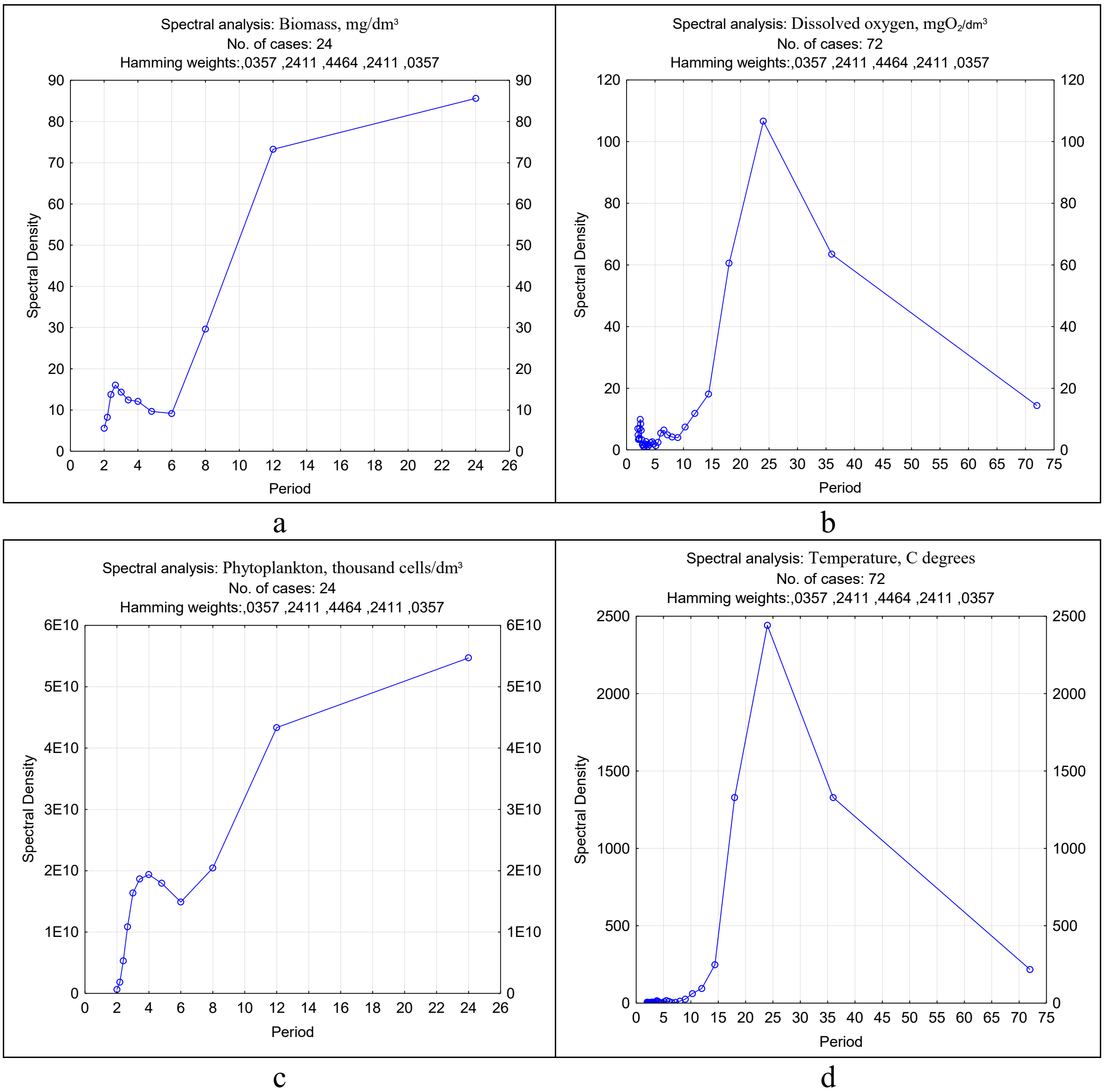


Fig. 2 Determining the fluctation period using the spectral transformation method of Fourier

**Conclusions.** A comprehensive analysis of the impact of global climate change on local trends in the Dnipro River blooming in the Dnipro-Donbas Canal area revealed the presence of a corresponding correlation. The features of the life cycle of cyanobacteria, which are the main cause of water blooming, are influenced by such factors as: temperature regime, climatic zone, catchment area, conditions of suspended matter formation, hydrochemical regime of the reservoir, etc. Statistical processing of water quality indicators in the studied area showed that most indicators related to the organic component have a trend toward increasing concentrations.

Correlation regression analysis revealed a significant relationship between biomass, phytoplankton, water clarity, odor, biochemical oxygen consumption for 5 days, and temperature and dissolved oxygen, which correlates with global trends in climate change. Most of the studied indicators are of a seasonal nature of fluctuations due to the temperature cycle. These dependencies, combined with the impact of global climate change on local trends in the Dnipro River blooming in the area of the Dnipro-Donbas Canal make it possible to predict changes in the specified indicators during the calendar year to manage the necessary water treatment processes in the studied area.

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УДК 556;581.526.325

## АНАЛІЗ ВПЛИВУ ГЛОБАЛЬНИХ ТРЕНДІВ ЗМІН КЛІМАТУ НА ЦВІТІННЯ РІЧКИ ДНІПРО В РАЙОНІ КАНАЛУ ДНІПРО–ДОНБАС

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***Анотація.*** *Гідродинамічні властивості водойми можуть впливати на потенціал розвитку цвітіння ціанобактерій. Повільно текучі або стоячі води більше сприяють стабільності цвітіння. Тому вода зі швидшим потоком, сильнішим змішуванням або вищою швидкістю обертання має меншу ймовірність розвитку цвітіння в ній ціанобактерій. Найбільший вплив на цвітіння р. Дніпро в районі каналу Дніпро–Донбас мають Кременчуцьке та Кам'янське водосховища. Їх температурний режим у теплий період року сприяє розвитку зоо- та фітопланктону. Водяна рослинність найпоширеніша на мілководді. Влітку спостерігається цвітіння води. Цей процес охоплює до 70 % площі водосховищ, особливо у південній частині та затоках, погіршуючи якість води. Вища частота та інтенсивність опадів, що супроводжуються більш тривалими періодами посухи, можуть створити більшу рухливість поживних речовин і триваліші періоди високих температур без змішування. Ціанобактерії здатні швидко використовувати поживні речовини, що надходять до водойм внаслідок дощів. Сильні вітри також можуть впливати на популяцію, приштовхуючи клітини та колонії ціанобактерій до берегів, де вони накопичуються. Ці водосховища розташовані у помірно континентальній кліматичній зоні й належать до водойм, які добре прогріваються. Цьому сприяє їх ширина, завдяки якій спостерігається інтенсивне вітрове перемішування в середній і нижній частинах водосховищ, унаслідок чого температура розподіляється рівномірно і горизонтально. З метою підтвердження та доповнення результатів натурних досліджень було проведено статистичну обробку якісних показників води р. Дніпро в районі каналу Дніпро–Донбас. Визначення трендів проведені методом регресійного аналізу часових рядів якісних показників води. Перевірку відповідності розподілу до нормального виконували за тестами Колмогорова–Смірнова та Шапіро–Уілка. Кореляційний аналіз було проведено за допомогою параметричного методу Пірсона та непараметричного методу Спірмана. Визначення періоду коливань виконано за допомогою спектрального методу перетворень Фур'є. Проведений комплексний аналіз дав можливість встановити чинники, що є головною причиною цвітіння води в досліджуваному районі, що дає змогу керувати необхідними процесами водопідготовки.*

***Ключові слова:*** *водні ресурси, зміни клімату, ціанобактерії, цвітіння води, якість води*

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# ASSESSMENT OF THE EVAPOTRANSPIRATION COMPONENTS DYNAMICS IN DIFFERENT AGRO-CLIMATIC ZONES OF UKRAINE USING THE PENMAN – MONTEITH – LEUNING MODEL

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***Abstract.*** *The results of the assessment of evapotranspiration (ET) and its components based on remote sensing data are presented in the paper. To obtain this assessment, a special software was developed, namely the scripts using the JavaScript programming language for remote data processing in the Google Earth Engine (GEE) cloud software environment. This software allows to adjust the Penman – Monteith – Leuning (PML) model for the conditions of Ukraine and visualize the spatial distribution of ET. The usage of the cloud capabilities of the service made it possible to access the collection of images and carry out their remote processing using the Penman – Monteith – Leuning algorithm calibrated according to the data of the global network of eddy covariance monitoring stations. The result of such an assessment was a composite mosaic – a spatially distributed generalized image of evapotranspiration and its three main components: transpiration from vegetation (Ec), evaporation from the soil (Es) and evaporation of precipitation intercepted by vegetation cover (Ei) on the territory of Ukraine for the 2020 growing season. Understanding the dynamics of these components helps to optimize the water resources use and develop effective irrigation schemes, especially in the climate change conditions. As a result of the analysis of the evapotranspiration components' dynamics during the growing season, the most important component of evapotranspiration for different agro-climatic zones was determined.*

*However, the models, which are using remote data to estimate evapotranspiration dynamics, require additional validation and comparison with field measurements to improve their accuracy. Quantitative indicators obtained through modeling should be consistent with the data from ground-based greenhouse gas flows monitoring stations, which will contribute to the improvement of the methodology and its adaptation to the conditions of different agricultural regions. In addition, the use of the maps of geospatial distributed evapotranspiration allows to identify regions with increased transpiration and potential shortage of water resources. Such maps become a valuable tool for planning and forecasting water resources, which is critically important for the agricultural sector.*

***Key words:*** *evapotranspiration, components of evapotranspiration, agro-climatic zones, remote sensing, soil-plant-atmosphere, information system, Penman – Monteith – Leuning model, PML-V2, GEE programming*

**Relevance of the research.** Actual evapotranspiration (ET) measured using remote sensing data, which includes transpiration from vegetation (Ec), evaporation from soil (Es), and evaporation of intercepted precipitation by vegetation cover (Ei), is the most important component of the energy balance in the "soil–plant–atmosphere" system [1]. ET and its components play a key role in linking ecosystem functioning, climate feedback, and water resources [2]. Water consumption by agricultural crops is a critical parameter for water and energy exchange in agricultural production [3]. Understanding the dynamics and characteristics of crops' ET components has a great importance for the estimation of irrigation water needs [4], the evaluation of water use efficiency [5], and the design of optimal irrigation or drainage schemes [6].

Ground-based methods for the determination of components have not been widely applied in scientific research mainly due to limitations related to time consumption, expensive equipment, and susceptibility to measurement manipulations and significant assumptions in calculations [7]. Therefore, great efforts have been made to disentangle ET and its components using independent approaches, namely the acquisition of datasets using satellite measurements and simulations with a major focus on improving the surface conductivity model based on the Penman – Monteith (PM) model. The improvement of this model included taking into account the stomatal conductivity of the reflected surface, that is the Penman – Monteith model as a result of Leuning's improvement (PML) [2, 8, 9] received a connection with the vegetation located on the scanned surface and its productivity. The combination of the obtained results with the measurements of flows performed by the eddy covariance towers made it possible to obtain a relatively accurate set of global data.

Due to differences in climate, geomorphology, soil, hydrological regimes, and agricultural practices, ET components and the share of components for agricultural crops differ significantly depending on agro-climatic zones [2]. Evapotranspiration is a critical process and the most important component of the so-called "green" water cycle [10, 11]; and, therefore, the quantification of ET components and understanding of their dynamics can help in better and more efficient management of limited natural water resources, in spatial assessment and dissemination of local results, as well as in determining optimal zones for the use of natural water resources, determining optimal irrigation and drainage schemes. However, the changes and characteristics of ET components are still not fully understood and require further research. Therefore, this study was conducted to obtain information in the form of maps on the spatial distribution of evapotranspiration and its components depending on different agro-climatic zones. The total evapotranspiration according to the Penman – Monteith – Leuning model, and its components – heat energy flows measured by remote sensing data – was actually investigated.

**Analysis of recent research and publications.** Evapotranspiration indicators are defined at the global level for the Earth's surface areas based on the Penman – Monteith – Leuning (PML) dataset of the second version (V2) according to Zhang [1]. Evapotranspiration (ET) in the "soil-plant-atmosphere" system includes direct evaporation from the soil (Es), transpiration from vegetation (Ec), and evaporation of intercepted precipitation from vegetation (Ei), i.e. the moisture that has evaporated from the moistened plant surface (leaves). ET is the main pathway for returning water to the atmosphere and plays a key role in the water-energy-carbon cycle [12]. ET is an important component in water resources management, drought monitoring, water accounting, the assessment of water productivity and global climate change. Separating ET components into Es, Ec, and Ei can improve understanding of the global interaction between terrestrial ecosystems and the atmosphere [13].

The assessment of the accuracy of evapotranspiration (ET) measurement methods using remote sensing data, in particular the Penman – Monteith method in irrigated areas, was carried out using the RS-PML (Remote Sensing Penman – Monteith – Leuning) model. This study included irrigated vineyards, which are difficult to analyze due to the impact on microclimate and water resource requirements [8]. RS-PM models were found to show higher accuracy compared to other models, such as METRIC and TSEB-PT (Sebal), at different time scales, including instantaneous, daily, weekly, and seasonal ones. The root mean square error (RMSE) for RS-PM models was the lowest and amounted up to 23 % [8]. This highlights the significant advantages of RS-PM models on irrigated areas.

The RS-PMS algorithm, which is based on the combination of RS-PM with the Stewart stomatal conduction model, deserves special attention when assessing accuracy. This algorithm provided the highest accuracy among all the models analyzed achieving an RMSE of 19 %. However, spatial extension of this model requires adaptation to individual conditions, including crop and regional peculiarities, as well as an increase in the number of input parameters, such as local climate data, soil type, and irrigation practices [8]. This demonstrates the potential of RS-PMS for more accurate evapotranspiration forecasting, but also indicates the difficulty of its implementation at the global scale.

Analysis of seasonal variations of evapotranspiration (ET) components showed that they are significantly correlated with major meteorological variables such as air temperature, relative humidity, and precipitation. However, the ratio of ET components has been shown to be more dependent on irrigation practices, water management methods, and other local conditions than on general meteorological variables [14]. This means that successful application of ET measurement models requires a comprehensive approach that takes into account both climatic factors and agronomic practices.

To test the accuracy of global evapotranspiration models, the researchers used the global PML-V2 product, which was calibrated based on observations from eddy covariance stations located in China covering nine functionally different vegetation types. The results showed that the global model performs well in cross-validation mode, confirming its high accuracy. In addition, more accurate evapotranspiration models were developed for the territory of China using PML-V2 compared to previous versions [15–16], which was made possible by increasing the frequency of receiving input parameters, such as daily (instead of 8-day) satellite data of better detailing for determining evapotranspiration. This allowed, in addition to calculating the dynamics of evapotranspiration, to determine arable fields with a double crop system, which contributes to more accurate measurement of ET in agricultural areas [12]. Verification of the proposed model in Ukrainian conditions has not yet been carried out.

Publications indicate active development of research in the field of using new high-resolution data on evapotranspiration and vegetation productivity (GPP models). Also, extensive cloud environments with a large number of satellite images are becoming the basis for real-time monitoring of water resources. These technologies are actively used by researchers in collaboration with water and environmental departments in various countries around the world to manage water resources, assess climate change, and the impact of agronomic practices on ecosystems.

**The aim of the research.** Determination of the evapotranspiration components' spatial distribution, analysis of its dynamics in different agro-climatic zones based on remote sensing data with the use of PML-V2 model algorithms, cloud servers, and the developed software.

**Materials and research methods.** Obtaining accurate knowledge of actual evapotranspiration (ET) and its components with high resolution is critically important for understanding the dynamics of processes in the "soil-plant-atmosphere" system. To carry out this study, a method of evapotranspiration calculation based on the analysis of a series of satellite images and digital data sets was chosen. In particular, the Penman – Monteith – Leuning model (abbreviated as PML-V1 and PML-V2) was used. This model was proposed by Leuning in 2008 [9], and also improved by Zhang in 2010, 2016, and 2019 [17–18]. Based on the set of initial data, using the algorithms of the PML model [19], evaporation and its components were determined, namely transpiration from vegetation (Ec), direct evaporation from soil (Es), evaporation of intercepted precipitation from vegetation (Ei), and its spatial distribution over the territory of Ukraine.

The PML-V2 model uses total primary productivity and atmospheric $CO_2$ concentration to estimate the conductivity of the study surface, thus establishing a relationship and jointly estimating ET and total primary productivity. ET in this study is obtained separating it into three main components: vegetation transpiration (Ec), soil evaporation (Es), and precipitation evaporation intercepted by plants (Ei), which are calculated as follows [1, 14].

$$ET = E_c + E_s + E_i , \qquad (1)$$

$$E_c = \frac{\varepsilon A_c + \left(\frac{\rho C_p}{\gamma}\right) D_a G_a}{\varepsilon + 1 + \frac{G_a}{G_c}} , \qquad (2)$$

$$E_s = \frac{f \varepsilon A_s}{\varepsilon + 1} , \qquad (3)$$

$$E_i = \begin{cases} f_v P P < P_{wet} \\ f_v P_{wet} + f_v \left(P - P_{wet}\right) P \gg P_{wet} \end{cases} , \qquad (4),$$

where ε = s/γ, γ is the psychrometric constant (kPa/°C), s is the the slope of the curve, which is the ratio of water vapor pressure at saturation point to the temperature (kPa/°C); A is the available energy absorbed by the surface (MJ/($m^2$ per day)), i.e. net absorbed radiation minus soil heat flux; $A_s$ and $A_c$ are the available energy of soil and vegetation cover respectively; ρ is the air density (g/$m^3$); $C_p$ is the specific heat capacity of air at constant pressure (MJ/(g°C)); $D_a$ is the air water vapor pressure deficit (kPa); $C_a$ is the aerodynamic conductivity (m/s); $G_c$ (m/s) is the plant surface conductivity, which is a function of atmospheric carbon dioxide ($CO_2$) concentration, pressure, and water vapor pressure deficit; $f$ is the dimensionless variable that determines the availability of water for evaporation from the soil; $f_v$ is the leaf area of the studied surface; $P$ is the daily precipitation (mm/day); $P_{wet}$ is the precipitation threshold when the studied surface is sufficiently wet.

To obtain spatial assessment and analysis of distribution results, special software was developed, namely scripts using the JavaScript programming language for remote data processing using the cloud software environment in the Google Earth Engine (GEE) [20]. This software allows to customize the PML model for Ukrainian conditions and visualize the spatial distribution of ET.

The calculation of evapotranspiration and its components is carried out using the formulas (1–4) on GEE servers for the entire Earth's surface. The input data for further processing is available through the developed user interface and is an ImageCollection object. The model code is publicly available and is distributed under the GPLv2 license [21]. The model is accessed by executing user requests on the GEE server. The result of the analysis of the territory in our study according to the Penman – Monteith – Leuning model is a composite mosaic, that is a generalized image of the territory with detailing at the selected points [22]. The flowchart of the implementation of the Penman–Monteith–Leuning model in GEE is shown in Figure 1 [21].

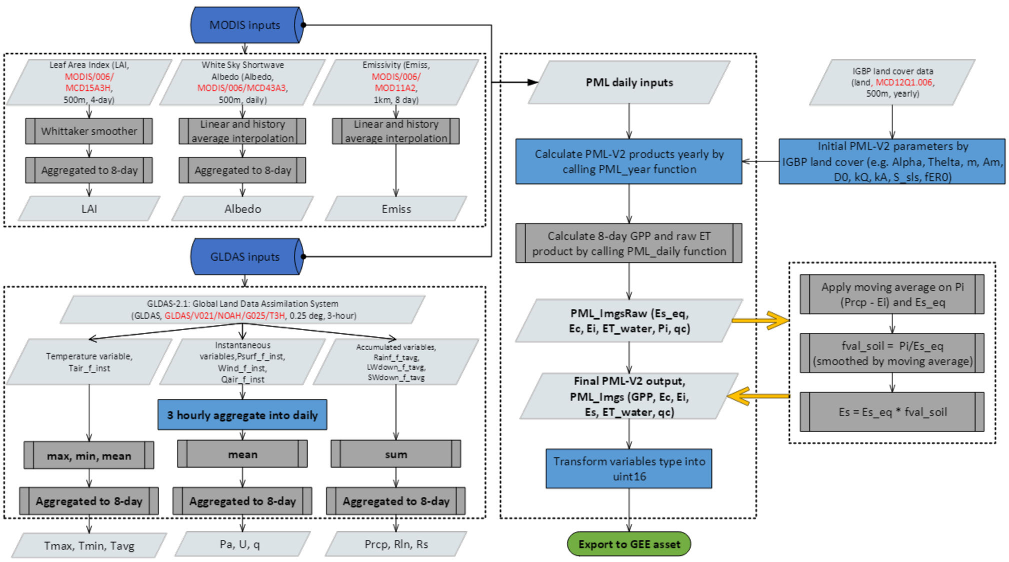



Fig. 1. Flowchart of the implementation of the Penman–Monteith–Leuning model in the Google Earth Engine

The usage of the service's cloud capabilities allowed to access the collection of images and perform their remote processing using the Penman – Monteith – Leuning algorithm, which is calibrated using the towers of the global network of eddy covariance observation stations on the base of a territory mask. The result of the assessment is a spatially distributed generalized image of evapotranspiration and its components over the territory of Ukraine.

The PML model uses 500 m resolution of MODIS for data regarding leaves, albedo, and surface emissivity, as well as meteorological data coming from the Global Land Data Assimilation System (GLDAS) version 2. GLDAS receives observational data from both satellites and ground-based sources on temperature variability, instantaneous pressure, wind speed, and relative humidity, as well as total daily precipitation, long- and short-wave solar radiation. Using modern methods of Earth surface modeling and data assimilation, the GLDAS system generates optimal fields of Earth surface states and flows. The GLDAS 2 input data has a spatial resolution of 0.25° (~25 km), which is interpolated to the 500-meter grid of the PML dataset [21]. Evapotranspiration is calculated once per every 8 days, the calculation components are measured at 3-hour intervals and aggregated into 1-day and 8-day values (Fig. 1).

To analyze the distribution of evapotranspiration components, territories, on which the intensity of evapotranspiration was the same, were initially identified based on remote sensing data. For agro-climatic zones on the maps, these territories were identified in an independent manner. In different zones (Fig. 2) reference points were selected in the form of three plots of 0.25 km$^2$ each, namely the territory in the Steppe zone under irrigation (Kherson region), in the Forest-Steppe – agricultural fields (Cherkasy region), and Polissya – reclaimed forests (Volyn region) for the growing season of 2020, when the irrigation systems of southern Ukraine worked intensively.

The distribution of evapotranspiration components, which depends on applied agricultural practices, was clarified on the plots. That is, an analysis on the amount of moisture evaporating from the open soil surface, transpiration of moisture by plants, and evaporation directly from the leaf surface was conducted. Thus, on each of the plots of preliminary studies, we tested the hypothesis regarding the dynamics of the ET components distribution.

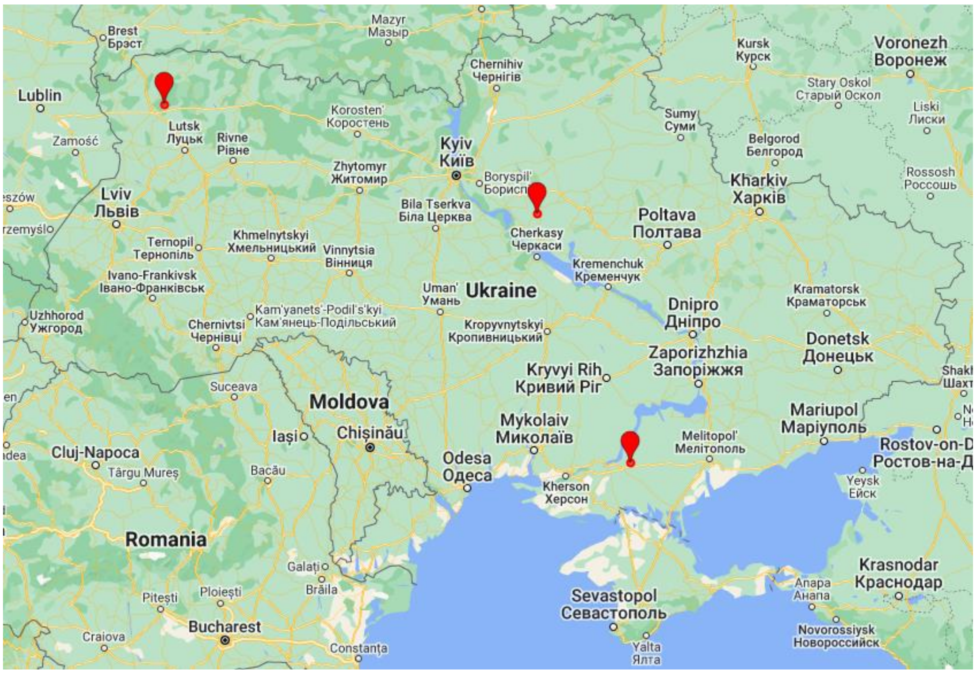


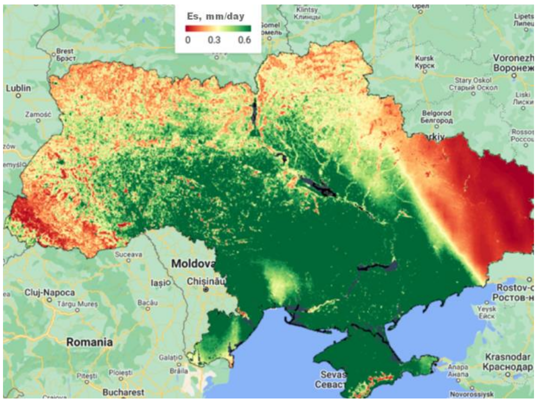

Fig. 2. Locations of the studied plots for different agro-climatic zones of Ukraine (Steppe, Forest-Steppe, Polissya)

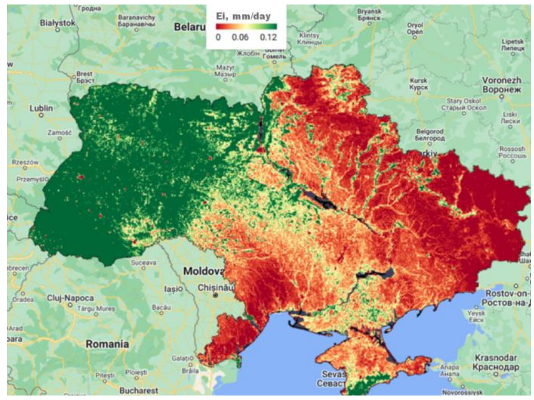
**Research results and their discussion**. To determine and assess the state of available water resources, effectively implement climate change adaptation strategies, the determination of the components of the water balance is a key element of effective water resources management. Evapotranspiration is the main and the most important component in the water cycle. In the study, the $E_c$ component of the split evapotranspiration flux is estimated to assess the actual water consumption by plants at the country level. The $E_i$ component is used to assess the effectiveness of precipitation, and the $E_s$ component is used to assess soil moisture and the shading degree. Generalized images – the maps of the spatial distribution of evapotranspiration components – were obtained (Fig. 3). The scale was chosen to visualize the differentiation of evapotranspiration components. Within the territory of Ukraine, some of the maximum values are deliberately excluded and are not represented on the palette to increase the contrast of the average seasonal values visualization. That is, the maximum values in the case of visual assessment, e.g. of $E_s$, are 0.6 mm/day and above.

The soil evaporation distribution map ($E_s$) represents the moisture evaporation from the open soil surface and depends on the availability of soil moisture, the degree of surface shading by vegetation, and the deficit of atmospheric moisture. The spatial distribution of $E_s$ reflects the regions of the country, in which the soil loses moisture most intensively through evaporation from the open soil surface (Fig. 3a). The Steppe and Forest-Steppe regions have the highest evaporation intensity values.

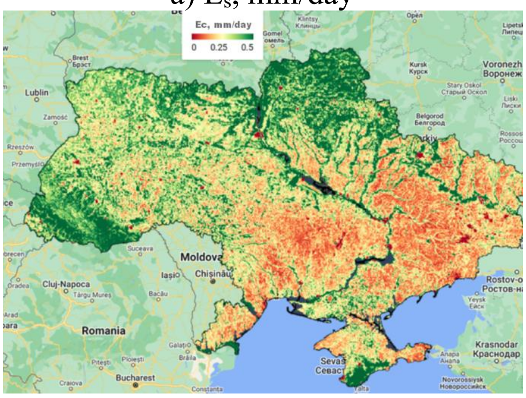
The map of distribution of the evaporation of precipitation retained by vegetation is used to estimate the fraction of precipitation that goes to evapotranspiration. This component depends on the amount of precipitation and the vegetation cover particularities. The spatial distribution of $E_i$ shows how efficiently precipitation is used by plants in different zones (Fig. 3b). This indicator reaches its highest value in the regions densely covered with vegetation.

The vegetation transpiration distribution map ($E_c$) determines the dynamic flow of $E_c$. The map represents the agro-climatic zones that have the highest or the lowest rates of plants' water use, which is critical for water management in agriculture.




a) $E_s$, mm/day b) $E_i$, mm/day



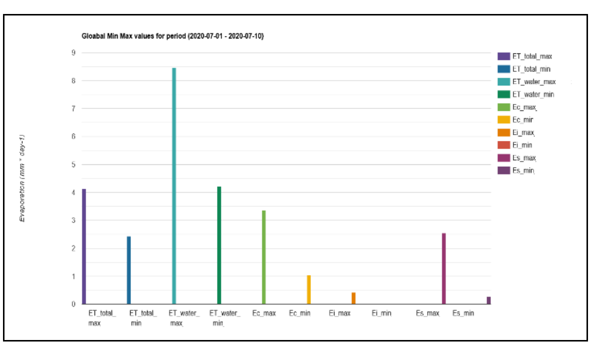


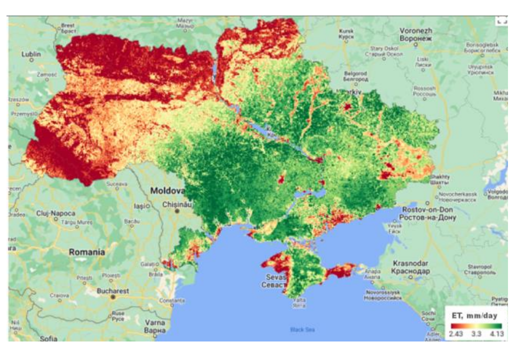
c) $E_c$, mm/day d) ET, mm/day

Fig. 3. Maps of the distribution of the evapotranspiration components intensity for the growing season of 2020 (01.04.20–30.09.20)

Thus, the distribution map of the total average intensity of evapotranspiration identifies agro-climatic zones with increased evapotranspiration, which in the obtained results coincide with the regions where negative trends in the availability of water resources for plants are observed (Fig. 3d).

Daily evapotranspiration values were studied on individual images and presented as a series of observations visualized in the form of histograms and maps of evapotranspiration spatial distribution and stored in database tables. Figure 4a shows the distribution of global maximum and minimum values based on minimax analysis across the country in the form of histograms, which corresponds to daily ET estimated using the PML model. For example, as of July 3, 2020, the maximum recorded ET value from the water surface is 8.5 mm, the maximum evapotranspiration from the land surface is 4.13 mm, while the minimum value is 2.43 mm.




a b

Fig. 4. Spatial distribution of absolute values of evapotranspiration in the form of a histogram and a map for 03.07.2024

It is important to mention that the studied plot of 0.25 km$^2$ includes various topographic elements, for example, the Steppe zone area may include both irrigated and non-irrigated areas (field roads, roadsides, etc.), since the pixel of the satellite image does not always fall completely within the boundaries of the field. The actual flow from this plot reflects both the evapotranspiration data of an individual monoculture and all adjacent areas included in the observation zone.

By analyzing the distribution of components in different agro-climatic zones, it was determined that in each zone the percentage of the contribution from each component to the total evapotranspiration is different. The absolute value of total transpiration during the season also differs. So, in the Steppe 60 % of ET is the transpiration from plants, in the Forest-Steppe this component amounts to 66 %, and in the Polissya zone – to 65 %. However, the largest difference in percentage between zones has the evaporation of precipitation retained by vegetation. In the Steppe zone it only amounts to 2 %, while in the Polissya its share is 24 % (Fig. 5).

The dynamic values of $E_s$, $E_c$, $E_i$ from remote sensing maps are accumulated in the form of daily data tables and form a static value of the number of mm evaporated from the studied pixel of 0.25 km$^2$ plot during the season. Data on absolute and percentage distribution are given in Table 1.

1. Total ET values for the season and its components distribution in absolute and percentage forms during the growing season.

| Component | Steppe | | Polissia | | Forest-Steppe | |
|---|---|---|---|---|---|---|
| | mm | % | mm | % | mm | % |
| $E_c$ | 269,68 | 60 | 216,96 | 65 | 302,24 | 66 |
| $E_i$ | 10,80 | 2 | 78,00 | 23 | 18,00 | 4 |
| $E_s$ | 170,24 | 38 | 36,96 | 11 | 136,96 | 30 |
| ET | 450,72 | 100 | 331,92 | 100 | 457,20 | 100 |

The dynamics of evapotranspiration components during the growing season also varies depending on the selected agro-climatic zone (Figure 6).

A feature of the distribution dynamics for reclaimed areas of the Steppe with early vegetation restoration is a representative reduction of the evaporation from the open soil surface at the beginning of the season and its increase in the middle, after the end of the active agricultural crops' vegetation and early harvest of

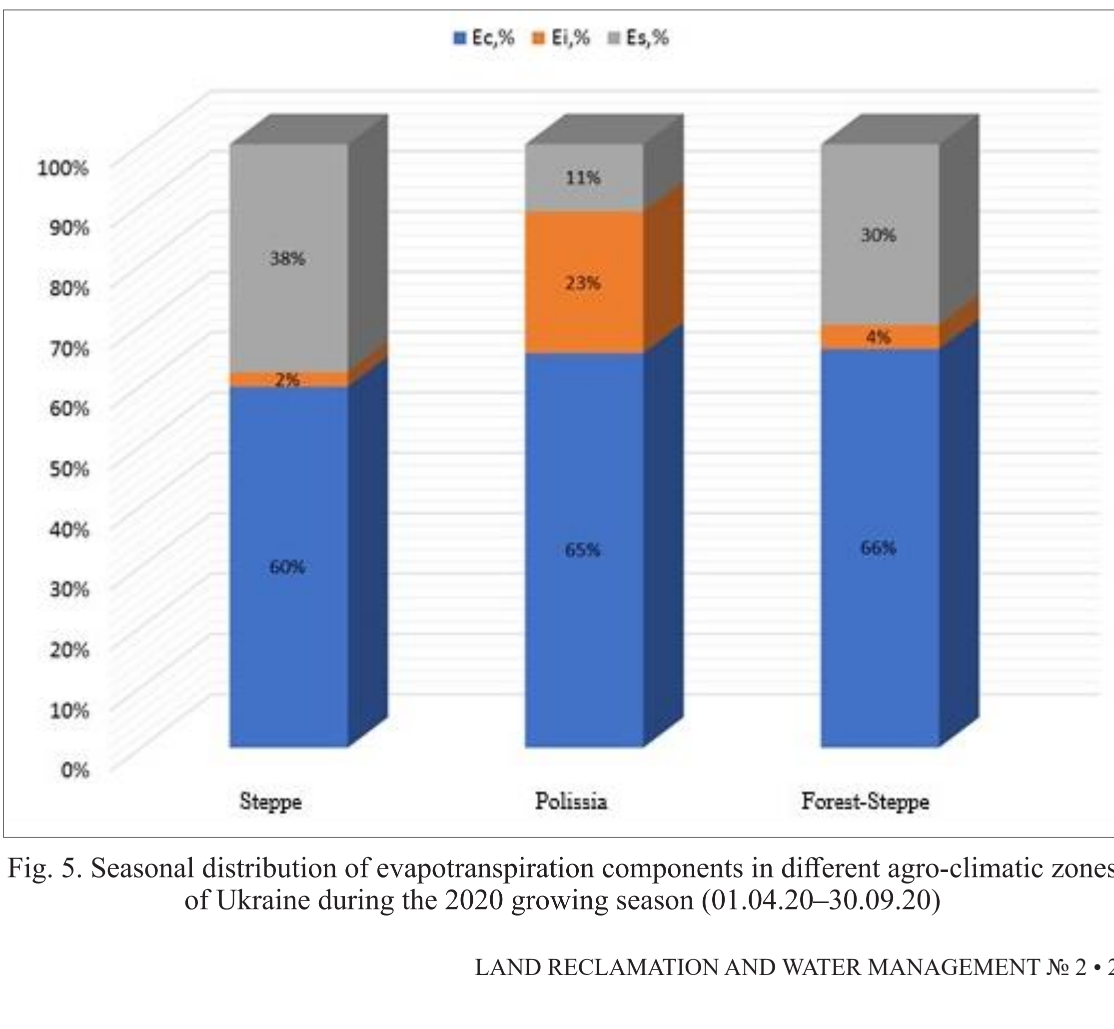
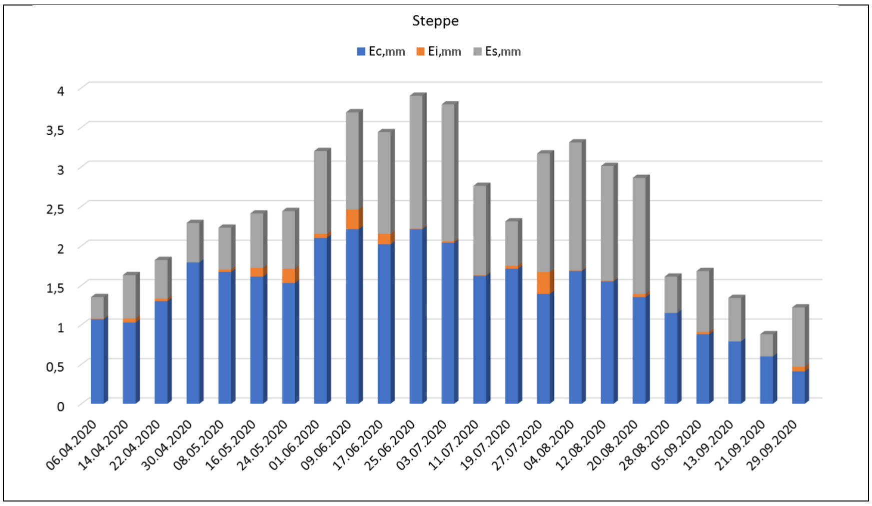
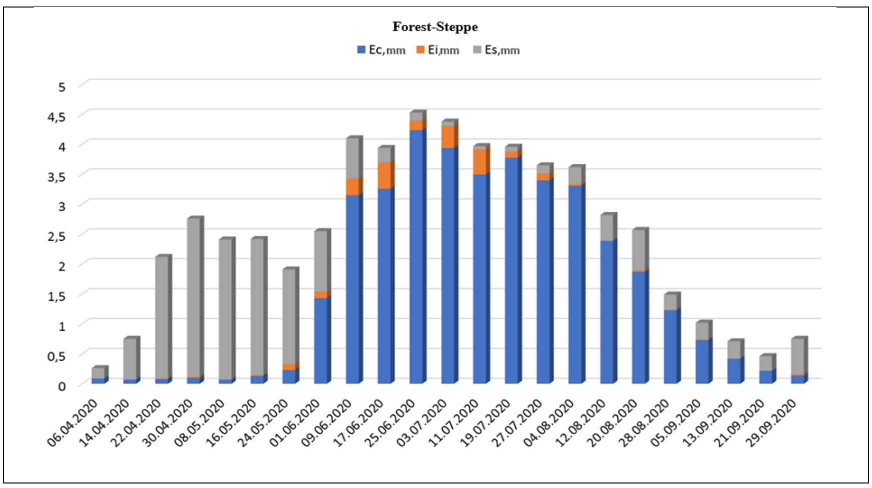


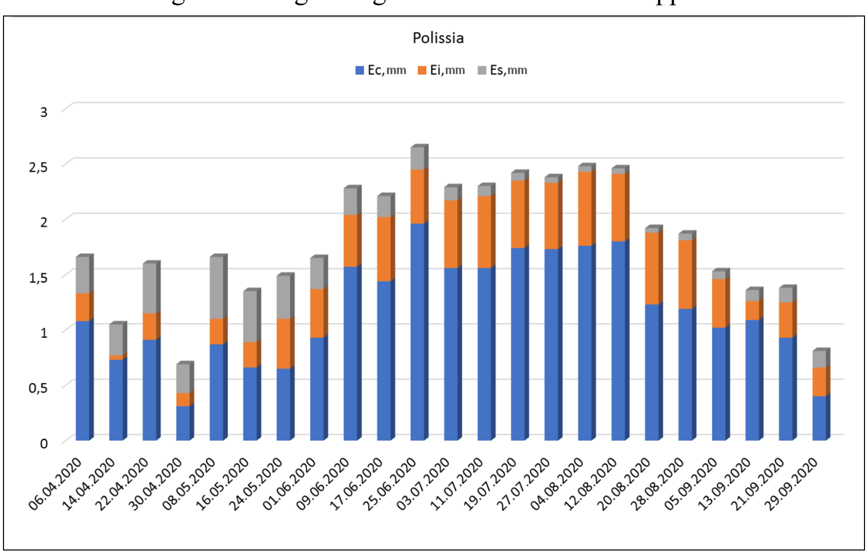

Fig. 5. Seasonal distribution of evapotranspiration components in different agro-climatic zones of Ukraine during the 2020 growing season (01.04.20–30.09.20)




a) Dynamics of the distribution of evapotranspiration and its components during the 2020 growing season in the Steppe zone




b) Dynamics of the distribution of evapotranspiration and its components during the 2020 growing season in the Forest-Steppe zone




c) Dynamics of the distribution of evapotranspiration and its components during the 2020 growing season in the Polissya zone

Fig. 6. Dynamics of the distribution of evapotranspiration and its components during the 2020 growing season in different agro-climatic zones of Ukraine

cereals (Fig. 6a). The value of evapotranspiration of a selected plot will depend significantly on the irrigation technologies used by the farm. In the 2020 growing season, evapotranspiration in the Steppe zone according to the remote sensing data (daily values were observed within the range of 3,83–5,12 mm) indicates insufficient water in the soil to fully cover the moisture deficit.

Figure 6b characterizes the areas with complete turning over of the arable soil layer, therefore, in the dynamics at the beginning of the growing season, evaporation from the open soil prevails, but after that it decreases with the development of vegetation cover. Figure 6c characterizes the territories of the Polissya with reclaimed forests. In the dynamics of the distribution of total evapotranspiration, compared to the other regions, evaporation from the surface of plants prevails and the evaporation of precipitation intercepted by vegetation is also noticeably present. Since the soil is covered with a layer of plant residues, evaporation from the open surface is smaller.

The algorithm and the applied model for obtaining estimates of ET and its components showed the distribution of evapotranspiration and its components in different agro-climatic zones on a regional scale. To obtain more detailed maps of the distribution, more detailed remote sensing data is needed and further cross-validation of the model using eddy covariance towers is possible. Further research will focus on determining the relationship between evapotranspiration and its components with gross primary production and on verifying the model in Ukrainian conditions.

**Conclusions.**

1. The implemented algorithm based on the use of remote sensing data effectively performs spatial estimation of evapotranspiration (ET) and its components based on the improved Penman – Monteith – Leuning method. The use of remote sensing data provides an opportunity to perform detailed ET modeling over large areas with high resolution, which contributes to the optimization of water use processes.

2. The possibility of using geospatial datasets from remote servers for spatial assessment of evapotranspiration and its components using software developed by the authors has been proven. A software product has been developed to analyze the spatial distribution of evapotranspiration components in different agro-climatic zones. The program code is located in the Google Earth Engine repository and is constantly being improved both by the team of authors of the article, who develop applied technologies for using remote sensing data for assessment, and by the providers of the datasets.

3. The resulting generalized images and geospatial maps of evapotranspiration components based on remote sensing data are an important tool for water resources management. Visualization of the dynamics of evapotranspiration processes allows making justified decisions regarding water supply management in different agro-climatic zones taking into account local natural conditions. This is especially important for the water-scarce zones, where evapotranspiration control can ensure efficient water use and prevent losses due to inefficient irrigation and tillage technologies.

4. Models, which are using remote sensing data for estimating evapotranspiration dynamics, require additional validation and comparison with actual field measurements. Quantitative indicators obtained through the modeling should be coordinated with the data from ground-based stations of the greenhouse gas fluxes monitoring to improve the forecasts accuracy and to identify possible deviations. This will ensure further improvement of the methodology and facilitate its adaptation to the conditions of different agricultural regions.

5. The use of maps of geospatial distribution of evapotranspiration over Ukraine based on global data allows identifying regions with higher transpiration and a potential shortage of available water resources. These maps are a valuable tool for forecasting the availability and for planning of the usage of water resources, which is critically important for the agricultural sector. Identification of the such zones will help introduce the preventive measures to improve water availability, implement effective irrigation methods, and preserve agricultural crops in arid conditions.

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УДК 631.67:004

# ОЦІНКА ДИНАМІКИ КОМПОНЕНТІВ ЕВАПОТРАНСПІРАЦІЇ В РІЗНИХ АГРОКЛІМАТИЧНИХ ЗОНАХ УКРАЇНИ З ВИКОРИСТАННЯМ МОДЕЛІ ПЕНМАНА – МОНТЕЙТА – ЛЕУНІНГА

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***Анотація.*** *У статті проаналізовано результати оцінки евапотранспірації (ET) та її компонентів за даними дистанційного зондування Землі. Для отримання цієї оцінки було розроблено спеціальне програмне забезпечення, а саме скрипти з використанням мови програмування JavaScript для віддаленої обробки даних у хмарному програмному середовищі Google Earth Engine (GEE). Це програмне забезпечення дозволяє налаштувати для умов України модель Пенмана – Монтейта – Леунінга (PML) та візуалізувати просторовий розподіл ET. Використання хмарних можливостей сервісу дозволило отримати доступ до колекції знімків та проводити віддалену їх обробку за алгоритмом Пенмана – Монтейта – Леунінга, що відкалібрований за даними світової мережі станцій спостереження вихрової коваріації. Результатом такої оцінки стала композитна мозаїка – просторово розподілене узагальнене зображення евапотранспірації та її трьох основних компонентів: транспірацію з рослинності (Ec), випаровування з ґрунту (Es) і випаровування перехоплених опадів рослинним покривом (Ei) на території України за вегетаційний сезон 2020 року. Розуміння динаміки цих компонентів сприяє оптимізації використання водних ресурсів та розробці ефективних схем зрошення, особливо в умовах змін клімату. В результаті аналізу динаміки складових евапотранспірації протягом вегетаційного сезону здійснене визначення найбільш вагомого компоненту евапотранспірації у різних агрокліматичних зонах.*

*Проте моделі, що використовують дистанційні дані для оцінки динаміки евапотранспірації, вимагають додаткової валідації та порівняння з польовими вимірюваннями для підвищення їхньої точності. Кількісні показники, отримані через моделювання, повинні узгоджуватися з даними наземних станцій моніторингу потоків парникових газів, що сприятиме вдосконаленню методології та адаптації її до умов різних аграрних регіонів. Окрім того, використання карт геопросторового розподілу евапотранспірації дозволяє ідентифікувати регіони з підвищеною транспірацією та потенційним дефіцитом водних ресурсів. Такі карти стають цінним інструментом для планування і прогнозування водних ресурсів, що є критично важливим для аграрного сектору.*

***Ключові слова:*** *евапотранспірація, компоненти евапотранспірації, агрокліматичні зони, дистанційне зондування Землі, ґрунт-рослина-атмосфера, інформаційна система, модель Пенмана – Монтейта – Леунінга, PML-V2, GEE програмування*

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# EVALUATION OF THE POSSIBILITY OF FLUSHING OF DRIP IRRIGATION SYSTEMS WITH ELECTROCHEMICALLY ACTIVATED LOW-CONCENTRATION SALT SOLUTIONS

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***Abstract.*** *The practice of using drip irrigation systems shows that contamination of drip outlets, including products of organic origin, is a serious threat to their reliable operation. In Ukraine, to combat such contamination, drip irrigation pipelines are flushed with environmentally hazardous 15 % sodium hypochlorite AquaDoctor made in China. At the same time, there is evidence in the world practice of the possibility of effective use of environmentally friendly electrochemically activated low-concentrated saline solutions, in particular, anolyte, for such purposes. The analysis of the domestic market of disinfectants, bactericidal agents and antiseptics suggested that the anolyte "Crystal" produced by PE "Personnel Lux" (Kharkiv), which has a high biocidal effect. Kharkiv), which has a high biocidal activity at a mass total concentration of 0.1 % of ADR, and electrochemically activated low-concentrated sodium hypochlorite "Secobren" with a hypochlorite content of up to 0.06 % produced by "UKRTEK PRODUCT" LLC (Kyiv), which may have similar properties, can be used for flushing drip outlets.*

*Laboratory and field studies have been conducted to determine the possibility of flushing drip irrigation pipelines with electrochemically activated low-concentrated saline solutions to remove contamination of drip irrigation outlets with products of organic origin. The study was conducted during the flushing of drip irrigation pipelines with integrated drippers from ASSIF (METZER, Israel) with AquaDoctor, Crystal and Secobren disinfectants. Laboratory studies were conducted in the laboratory of the Institute of Plant Industry and Mechanics of the National Academy of Agrarian Sciences of Ukraine, accredited in the UkrSEPRO system, and field studies were conducted on subsurface drip irrigation systems in Cherkasy and Kyiv regions. For flushing in the field, the "Forced installation of supply and mixing of PUPS" developed by IRRIGATOR UKRAINE LLC was used.*

*The results of laboratory and field studies have shown that the washing capabilities of environmentally safe products "Kristal" and "Secobren" are comparable to those of environmentally hazardous hypochlorite "AquaDoctor". This makes it expedient to conduct further research to develop the technology of washing drip outlets depending on the nature and intensity of their pollution.*

***Keywords****: irrigated agriculture, drip irrigation systems, drip outlets, biological pollution, flushing, electrochemically activated low-concentration salt solutions, anolyte, sodium hypochlorite*

**Relevance of the study.** Information sources and the practice of using drip irrigation systems indicate that the development and use of advanced water treatment systems and filters, as well as the use of labyrinthine drip outlets with self-cleaning functions and anti-siphon systems, have largely eliminated the issue of drip irrigation contamination with inorganic particles. At the same time, there is a growing problem in the world of contamination of drip irrigation systems with various kinds of pollutants of organic origin, primarily the remains of microbial waste products in the form of biofilm in the labyrinths of drip outlets. As a rule, chlorine-containing substances are used to combat such pollution. In Ukraine, foreign-made sodium hypochlorite with 15 % chlorine content is used, which, when dissolved in water, forms by-products that are very dangerous for humans, animals and plants, such as trihalomethanes and halogenated acetic acids. This creates significant environmental risks for the soil and products grown on irrigated land.

At the same time, there are environmentally safe, electrically activated low-concentration substances with a low chlorine content that have powerful bactericidal properties and can be used to clean pipelines and drip outlets from biological contaminants. Identifying and testing the possibility of using such domestically produced substances that can effectively clean drip irrigation pipelines and drip outlets is an important practical task, the solution of which will improve the reliability of drip irrigation systems, ensure the preservation of soil fertility and reduce the environmental risks of negative environmental impact.

**Analysis of recent research and publications**. The main limiting factor that determines the efficiency, reliability and durability of drip irrigation systems is the issue of the reliability of drip outlets, which was noted by researchers in the late 70s of the last century [1] . It was also determined that the reliability of drip irrigation outlets is primarily related to the state of their clogging and the main types of pollution were identified – physical, salt and biological [1–4]. Clogging of drip irrigation outlets significantly reduces the uniformity of water distribution over irrigated areas, can lead to both excessive and insufficient moisture of plants, and negatively affects crop growth and yield [4–6]. The ever-increasing shortage of fresh water in the world and the aggravation of environmental problems associated with the need to dispose of wastewater have led to the widespread use of such water in drip irrigation systems over the past two decades [5, 7, 8] and have further exacerbated the need to clean drip irrigation pipelines and drip outlets from biological contamination. Until recently, the main method of combating biological pollution of water was its chlorination [9]. When chlorine comes into contact with water, it forms a mixture of hypochlorous (HClO) and hypochlorous (HCl) acids:

$$Cl_2 + H_2 O \rightarrow HClO + HCl \ (1).$$

Hypochlorous acid is the main active ingredient formed when chlorine dissolves in water. It is a weak, environmentally safe acid and dissociates in water to form hypochlorous ion (ClO-) and hydrogen ion ($H^+$):

$$HClO \leftrightarrow H^+ + ClO^- \ (2).$$

HClO is a much more effective disinfectant than ClO because of its ability to penetrate the cell walls of microorganisms. It acts on microorganisms without damaging animal and plant cells [10]. But, in addition to it, chloramines, trihalomethanes, and halogenated acetic acids are also formed when chlorine dissolves in water [9]. These by-products of water chlorination are harmful to both humans and plants. In connection with these possible negative consequences of using chlorinated water for cleaning drip irrigation pipelines and drip outlets, in recent years, sodium hypochlorite (NaClO), which is also an effective disinfectant, has been used to flush drip irrigation pipelines [11]. When dissolved in water, hypochlorite forms hypochlorous acid (HClO), which, as in the case of chlorination, is the main bactericidal agent:

$$NaClO + H_2 O \leftrightarrow HClO + Na^+ + OH^- \ (3),$$

According to the practice of using sodium hypochlorite in Ukraine, it can effectively neutralize organic formations in drip irrigation pipelines and drip outlets [11], but at high concentrations of active chlorine, its use has the same disadvantages as chlorination.

An alternative to chlorine and sodium hypochlorite is chlorine dioxide ($ClO_2$), which is used as a disinfectant in various industries, including water treatment, food processing, healthcare, and catering [12–14]. There is also experience in its use for cleaning drip irrigation systems [15]. Chlorine dioxide dissolves in water to form various products, including chloric ($HClO_2$) and hypochlorous ($HClO_3$) acids. During the dissolution of chlorine dioxide, hypochlorous acid is not formed, and chlorite ($ClO_2^-$) and chlorate ($ClO_3^-$) ions are the active disinfectants. However, according to some recent studies [14, 16], **the disinfectant effect of hypochlorous acid HClO exceeds the similar properties of** chlorate and chlorite ions. In this regard, for example, to ensure effective drinking water treatment, it is envisaged, in some cases, that it should be treated with sodium hypochlorite after chlorine dioxide treatment [14]. In general, hypochlorous acid [10] is one of the most interesting, effective, and environmentally friendly substances. It is naturally formed in the human body – produced by our white blood cells to fight pathogens. Hypochlorous acid has been investigated as a possible wound care product, and in 2016, the FDA approved it as a primary active ingredient in the treatment of wounds and various infections in humans and animals [10]. In 2020, disinfectants based on an electrochemically activated solution of hypochlorous acid HClO as an active ingredient also appeared on the Ukrainian market. Such products have a wide range of effects and are used in various applications. The safety of these products has been proven by research by Ukrainian and international specialized institutions [10]. In 2021, hypochlorous acid in a concentration of up to 200 PPM was included in the Order of the Ministry of Health of Ukraine dated 28.03.2020 No. 722 "Organization of Medical Care for Patients with Coronavirus Disease (COVID-19)».

Some authors, noting the extreme importance of biofilm control as one of the most dangerous types of biological contamination of pipelines and drip water outlets [17], emphasize that **an** effective substance for biofilm control can be **anolyte**, one of the environmentally safe components of electrochemically activated water, which also contains hypochlorous acid [18].

The use of anolyte is considered as an alternative to chlorine for disinfection of decentralized water supply systems and prevention of biofilms. There are significant advantages of such disinfection compared to chlorination: anolyte effectively reduces the formation of biofilms (the biomass of fixed biofilms is reduced by 37.5–79.9 %) [19]. Studies of the process of biofilm formation. call the reason for this – the vital activity of bacteria. **Anolyte** prevents the formation of biofilms better than other disinfectants by counteracting the attachment of inactivated microorganisms to the walls of pipes and emitters and removes existing microorganisms from surfaces [20]. Today, within the framework of the European Union's Horizon 2020 research and innovation program, in accordance with grant agreement No. 6, research is being conducted abroad on the use of anolyte for water disinfection in horticulture [21]. It is noted that heaters and UV installations do not affect the formation of biofilm, but anolyte effectively copes with this task. It can be used to destroy microorganisms in irrigation pipelines during the growing season, taking into account its environmental safety [22].

**The aim of the** study is to investigate the possibility and feasibility of flushing drip irrigation systems with electrochemically activated low-concentration saline solutions.

**Research methods and materials.** Theoretical and empirical methods of scientific research are used: analysis and synthesis, deduction and induction, comparison, as well as laboratory and field methods.

**Research results and discussion.** To achieve this goal, we analyzed the availability of anolites on the Ukrainian market, which are produced in industrial volumes and have high bactericidal properties. Literature sources state that all anolites demonstrate high antiseptic properties and environmental safety at low concentrations of their components, and some differences in the ratio of their components make it almost impossible for the vast majority of pathogens to develop resistance to them [22]. According to their characteristics, anolites are divided into acidic (pH 1 to 5,2), neutral (pH + 7,0 ± 1,5) and alkaline (pH = 9 or more). Neutral anolyte (NA), which is produced using catholyte, is the main type of anolyte widely used as a disinfectant today. There are anolyte production plants of various designs around the world with capacities ranging from 5 to 500 liters per hour. Before the war with Russia, the Ukrainian market offered a variety of anolites from foreign and domestic producers, which were used as disinfectants and decontaminants. Since the beginning of the war, this market has shrunk significantly. The main reason for this is the absence of domestic industrial facilities for the production of anolites in Ukraine. At the same time, anolites are present on the Ukrainian market and are produced at foreign facilities according to technical documentation approved in Ukraine. One of the largest producers of neutral anolyte in Ukraine is Personnel Lux PE (Kharkiv). The anolyte "Crystal" (Fig. 1, a) it produces has high biocidal properties and contains hypochlorous acid and highly active oxygenated chlorine compounds, chlorine free radicals, and oxygen: HClO; $ClO_2$; $ClO^-$; $O_3$; H $O_3{}^+{}_2$; H $O_3{}^+$; $O_2$ ; $Cl^0$. At the same time, their mass concentration in terms of active chlorine is only 0.1 %, which makes this reagent safe for humans, plants and animals. Most of the anolyte components relax into ordinary weakly mineralized water after some time (maximum several days) and do not accumulate in plants and soil. According to TU U24.2-3736315-001:2011, which is used to produce this anolyte, its alkalinity can range from 6 to 8. Studies of the Ukrainian market of disinfectants also revealed the presence of electrochemically activated, environmentally safe hypochlorite Secobren manufactured by UKRTEK PRODUCT LLC (Kyiv). In accordance with TU U 20.2-43534135-001:2020, chlorine-containing compounds in it are no more than 0.6 % (sodium hypochlorite – up to 0.06 %, sodium chloride – up to 0.5 %) (Fig. 1, b).

The analysis of the characteristics of the anolyte "Crystal" according to the indicators standardized by DSTU 7591:2014 "Water quality for drip irrigation systems. Agronomic, environmental and technical criteria" [23], shows that its use (even without dilution) does not pose environmental risks.


a) b)

Fig. 1. Domestic environmentally safe, electrochemically activated low-concentration substances in commercial containers and permits for their production:
a – Crystal anolyte; b – Secobren hypochlorite

Thus, the increase in the permissible values of toxic ion concentrations by soil groups given in Table 1 of DSTU 7591 "Assessment of irrigation water quality for the risk of secondary soil salinization (according to DSTU 2730)» when applying the anolyte "Crystal" even without dilution with water can be from 0.6 to 4 %. When diluted with water for washing in a ratio of 1:100, the increase in indicators can be only 0,006…0,04 %, i.e., there will be no practical impact.

Table 2 of DSTU 7591 "Assessment of irrigation water quality for the risk of soil alkalization (according to DSTU 2730)» shows that the introduction of the anolyte "Crystal", whose pH is 7.2, will not change the water quality class. The same applies to the impact on the risk of soil salinization (Table 3 of DSTU 7591 "Assessment of irrigation water quality for the risk of soil salinization (according to DSTU 2730)»).

The analysis of the environmental safety of anolyte (Tables 5, 6 and 7 of DSTU 7591) shows that it cannot pose a threat according to the indicators given in these tables, as it does not contain trace elements and heavy metals, pesticides, phenols, cyanides, oil products, etc. Due to its extremely low degree of mineralization, it will not affect the suitability of irrigation water in terms of the degree of impact on the elements of drip irrigation systems (Table 8 of DSTU 7591).

The same conclusions can be drawn from the analysis of the characteristics of electrochemically activated low-concentration sodium hypochlorite "Secobren"

The effectiveness of the use of Crystal and Secobren for cleaning drip irrigation pipelines and drip outlets in comparison with AquaDoctor anolyte (China) with 15 % active chlorine content, which is currently used for these purposes, was tested in the laboratory and in the field. Laboratory studies were carried out on three samples of pipelines (METZER Israel) 1,5, 2,3 and 2,4 m long with compensated drippers with a nominal flow rate of 0,85 l/h (≈ 14 ml/min) with a distance between drip outlets of 0,5 m. The samples were taken from the underground irrigation system installed by Irrigator Ukraine LLC in the POA "UKRAINE" of Boryspil district, Kyiv region, near Velyka Karatul village. Water is supplied to the system from the Dnipro River, which is why there was little sand and silt in the water during the irrigation period, but a significant amount of algae. To preserve the vital activity of the pathogenic biota, the samples were delivered to the laboratory filled with water. The research was carried out at the stand for testing drip irrigation pipelines at the Laboratory for Testing Irrigation and Drainage Facilities of the Institute of Water Resources and Management of NAAS (Certificate of Measurement Capabilities No. PT-8/24 of 11.01.2024). The research was carried out according to the test methodology for microirrigation technical means developed at IWPIM NAAS [24].

During the tests, the flushing capacity and efficiency of cleaning drip outlets from contaminants were determined by the following agents: AquaDoctor sodium hypochlorite (China) with an active chlorine content of 15 %, Crystal anolyte and Secobren hypochlorite.

**Results of laboratory tests.** Flushing of drip outlets was carried out in two stages. At the first stage, the concentration of the solutions was 1‰, measurements of the change in the capacity of the drip outlets were carried out at operating pressures from 0,025 to 0.1 MPa with a step of 0,025 MPa *(nominal operating flow rate of the drip outlet is 0,85 l/h ( 14 ml/min)* (Table 1):

1. Evaluation of changes in the flow characteristics of drip outlets depending on the impact of different types of detergents

| Active ingredient | %, drip water outlets | Pressure, MPa | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0,15 | | | 0,2 | | | 0,25 | | | 0,3 | | |
| | | Flow rate depending on pressure, ml/60s | | | | | | | | | | | |
| | | to | after | %, changes from nominal | to | after | %, changes from nominal | to | after | %, changes from nominal | to | after | %, changes from nominal |
| Aqua Doctor | 33 | 0 | 7 | 50 | 0 | 11 | 79 | 0 | 14 | 100 | 12 | 14 | 100 |
| | 33 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 34 | 1 | 0 | 0 | 2 | 0 | 0 | 4 | 0 | 0 | 3 | 0 | 0 |
| Secobren | 25 | 8 | 10 | 71 | 13 | 13 | 93 | 12 | 13 | 93 | 12 | 13 | 93 |
| | 25 | 7 | 8 | 57 | 10 | 10 | 71 | 10 | 11 | 79 | 10 | 12 | 86 |
| | 25 | 6 | 8 | 57 | 9 | 9 | 64 | 10 | 10 | 71 | 11 | 10 | 71 |
| | 25 | 5 | 1 | 7 | 4 | 4 | 29 | 12 | 12 | 86 | 13 | 13 | 93 |
| Crystal | 20 | 7 | 7 | 50 | 9 | 10 | 71 | 11 | 11 | 79 | 12 | 12 | 86 |
| | 20 | 7 | 8 | 57 | 6 | 10 | 71 | 9 | 10 | 71 | 7 | 8 | 57 |
| | 20 | 6 | 7 | 50 | 8 | 10 | 71 | 11 | 11 | 79 | 11 | 12 | 86 |
| | 20 | 7 | 7 | 50 | 8 | 10 | 71 | 11 | 12 | 86 | 12 | 13 | 93 |
| | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

At both stages, after draining the water that filled the samples during transportation to the laboratory, one of the samples was filled with AquaDoctor, the second with Crystal, and the third with Secobren.

The samples filled with reagents were kept for 48 h, after which the washing agents were drained and the flow rates of the drip outlets were determined. Drip flow rates were measured after pressure stabilization for 10 min at a given gradation: at the first stage – 0,025, 0,05, 0,075, 0.1 MPa, at the second stage – 0,15, 0,2, 0,25, 0,3 MPa. The flow rates of the droppers were determined by the volumetric method using 25 ml measuring cups and a stopwatch. The determination time at each pressure was 60 seconds. The pressure was created by the test bench pump, controlled by a manometer, and regulated by a valve.

Sampling of underground drip irrigation pipelines for research was associated with the difficulty of digging them out and transporting them with water to the laboratory. This made it impossible to select long sections of pipelines with a number of drip outlets that could provide statistical processing of the results in accordance with the methodology [24]. Therefore, it can be assumed that the results obtained give a general idea and trends about the phenomena under study, in our case, the possibility of flushing drip irrigation systems with electrochemically activated low-concentrated saline solutions without quantifying them using mathematical statistics. Next year, the study is planned to continue to obtain statistically reliable results of flushing efficiency and to develop elements of the technology for flushing drip irrigation systems with environmentally friendly electrochemically activated saline solutions.

As can be seen from Table 1, 30 % of the drip outlets were flushed with AquaDoctor hypochlorite with a flushing solution concentration of 1 ppm and pressures of 0,025, 0,05, 0,075, 0,1 MPa, and the flow rate of only 33 % of the flushed drippers was restored to the nominal value. 67 % were not flushed. All 100 % of the drips washed with Secobren hypochlorite restored their throughput to values close to the nominal value. 60 % of the drips washed with Kristall anolyte restored their capacity almost completely, 20 % restored partially, and 20 % were not washed.

At the second stage, the concentration of solutions was 5‰, and measurements of changes in the throughput of drip water outlets were carried out at the following operating pressures from 0,15 to 0,3 MPa with a step of 0,025 MPa (Table 2).

2. Evaluation of changes in the flow characteristics of drip outlets depending on the impact of different types of detergents

| Active ingredient | %, drip water outlets | Pressure, MPa | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0,15 | | | 0,2 | | | 0,25 | | | 0,3 | | |
| | | Flow rate depending on pressure, ml/60s | | | | | | | | | | | |
| | | to | after | %, changes from nominal | to | after | %, changes from nominal | to | after | %, changes from nominal | to | after | %, changes from nominal |
| Aqua Doctor | 33 | 14 | 13 | 93 | 14 | 14 | 100 | 14 | 14 | 100 | 14 | 14 | 100 |
| | 33 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 34 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 36 |
| Secobren | 25 | 13 | 14 | 100 | 13 | 14 | 100 | 13 | 14 | 100 | 13 | 14 | 100 |
| | 25 | 12 | 10 | 71 | 12 | 12 | 86 | 12 | 12 | 86 | 12 | 12 | 86 |
| | 25 | 10 | 13 | 93 | 10 | 11 | 79 | 10 | 11 | 79 | 10 | 11 | 79 |
| | 25 | 13 | 10 | 71 | 13 | 14 | 100 | 13 | 13 | 93 | 13 | 14 | 100 |
| Crystal | 20 | 12 | 12 | 86 | 12 | 13 | 93 | 12 | 13 | 93 | 12 | 13 | 93 |
| | 20 | 8 | 9 | 64 | 8 | 9 | 64 | 8 | 7 | 50 | 8 | 11 | 79 |
| | 20 | 12 | 13 | 93 | 12 | 12 | 86 | 12 | 14 | 100 | 12 | 14 | 100 |
| | 20 | 13 | 13 | 93 | 13 | 13 | 93 | 13 | 14 | 100 | 13 | 14 | 100 |
| | 20 | 0 | 13 | 93 | 0 | 13 | 93 | 0 | 14 | 100 | 0 | 14 | 100 |

The results of laboratory tests show that of all the droppers that were washed with AquaDoctor hypochlorite solution, 33 % of the droppers recovered completely, 33 % partially, and 34 % did not recover at all. 50 % of the drips washed with Secobren recovered 100 %, 25–90 %, and 25–80 %. Of those washed with Kristall, 60 % restored their capacity by 100 %, 20 % by 93 %, and 20 % by 79 %.

The data obtained indicate that domestic environmentally safe electrochemically activated low-salt solutions of anolyte "Crystal" and sodium hypochlorite "Secobren" exceed the environmentally hazardous 15 % sodium hypochlorite "AquaDoctor" produced in China in terms of their washing capacity to clean drip outlets from contaminants of biological origin.

**Results of field research**.

Field studies were conducted jointly with IRRIGATOR UKRAINE LLC on two subsurface drip irrigation systems: in the fields of the PAO "UKRAINE" in Boryspil district of Kyiv region and LLC SPF "Urozhay" in Cherkasy region (near the village of Liplyave). The pumping stations of both systems take water from the Dnipro River.

The areas irrigated by drip irrigation systems created by Irrigator Ukraine LLC are divided into irrigation blocks. The systems of POA UKRAINE and Urozhay LLC have 10 of them (1–1 to 1–10). During the irrigation cycle, the irrigation blocks work in pairs, creating an irrigation shift. Bermad Turbo IR M water meters are used to record the flow rate in each pair of simultaneously operating units (Fig. 2).

a b c

Fig. 2. Fittings and equipment for flushing subsurface drip irrigation pipelines in the field:
a – Bermad Turbo IR M water meter; b – installation for flushing subsoil drip irrigation pipelines designed by IRRIGATOR UKRAINE LLC; c – end cranes of two adjacent pipelines

During the irrigation season, data on consumption is recorded in the irrigation log. When operating subsurface irrigation systems, they are flushed from mechanical contamination on a monthly basis, and flushed with chemicals during algae blooms and at the end of the season. An indicator for flushing the system is a reduction in the consumption of irrigation modules by more than 5 %. The quality of flushing is assessed by the following factors: a – the renewal of module consumption; b – the degree of transparency of drain water after preliminary flushing and keeping water with a chemical in the pipeline for 24 hours (the darker the color, the higher the quality of flushing); c – inspection of the condition of the components of the drippers.

Comparison of the flushing effect on the cleaning of drip irrigation pipelines and drip outlets from contaminants of biological origin with AquaDoctor, Crystal and Secobren substances was carried out using the flushing unit of the PUPZ LLC “IRRIGATOR UKRAINE” [25] (Fig. 2, b) . Three irrigation blocks of these subsurface irrigation systems with a length of irrigation pipelines of 300 m with compensated drippers ASSIF (METZER Israel) with a nominal flow rate of 0,85 l/h in each of the farms were first emptied through the end taps (Fig. 2, c), and then filled separately with solutions of “AquaDoctor”, “Crystal” and “Secobren” and left for 24 hours. After that, the solutions were drained, and the pipelines and drip outlets were flushed with irrigation water under a pressure of up to 0,3 MPa. The concentration of solutions during flushing was: in SPF “Urozhay” – 1,5 liters of “AquaDoctor”, “Crystal” and “Secobren” were dissolved in 3,1 m of$^3$ water (the concentration of solutions was equal to (about 0,5‰); in PJSC “UKRAINE” – 3 liters of “Crystal” and “Secobren” and 1 liter of “AquaDoctor” were dissolved in 2,6 m of$^3$ water (the concentration of solutions was equal to 1,15 and 0.38‰). Due to the fact that the flushing was carried out after the end of the irrigation season, water was delivered by tankers and the use of Bermad Turbo IR M water meters, which are equipped with the systems, was impossible. During the research, the transparency of the drain water after preliminary flushing and aging with water and chemicals in the pipeline for 24 hours was visually analyzed (Fig. 3).

This assessment showed comparable results of the quality of flushing with all three tested substances – hypochlorites “AquaDoctor” and “Secobren” and anolyte “Crystal”. In addition, the quality of flushing of drip outlets with AquaDoctor, Secobren, and Crystal was assessed by opening the drip outlets and analyzing the condition of their components (filters, membranes, main and self-flushing labyrinths, and outlet chambers) before and after flushing (Fig. 4). In total, 5 drip outlets were opened for study on each of the three studied pipelines in each of the farms. That is, the quality of flushing with each of the substances (AquaDoctor, Secobren and Crystal) of ten drip outlets was investigated, and the components of the drip outlets were analyzed to determine which are most susceptible to clogging.

The main structural elements of the studied pipeline drippers are an inlet filter, a main labyrinth with a wide channel, a silicone membrane, a self-flushing pressure compensation labyrinth, and an outlet chamber. As can be seen from Figs. 4 and 5, the inlet filter is cleaned well enough during flushing and cannot be the reason why the drips cannot be restored to their capacity.

Figure 5 shows that the main labyrinth (No.1) is completely cleaned of contaminants after the droppers are washed. Some contaminants that do not affect the performance of the droppers may remain in the outlet chamber of dropper No. 2. It should be noted that, according to the observations of IRRIGATOR UKRAINE LLC specialists,

a b c

Fig. 3. Visual assessment of the quality of flushing of subsurface drip irrigation pipelines in the field: a – in 5-liter containers; b – at the beginning of the pipeline discharge after flushing; c – at the end of the pipeline discharge after flushing

a b c

Fig. 4. The appearance of the drippers from the side of the inlet filter:
a – before flushing; b, c – after flushing

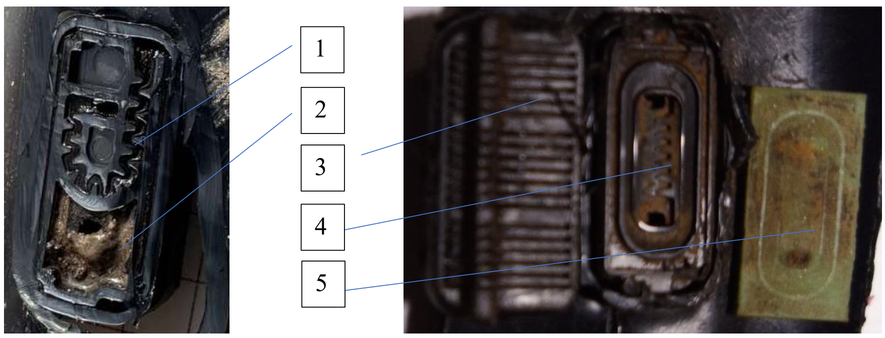


Fig. 5. View of the dropper components after flushing:
1 – main labyrinth; 2 – dropper outlet chamber; 3 – inlet filter; 4 – self-flushing labyrinth; 5 – silicone membrane

contamination of the outlet chamber occurs by dirt entering the dropper from the outlet side during the installation of pipelines when there is no water in them and the anti-siphon systems of droppers are not working. This is typical for underground pipelines. The silicone membrane (No. 5) in all the drippers tested was undamaged, flat and elastic, so it could not have caused the drippers to fail. The most vulnerable component of the droppers, in terms of contamination with particles of organic origin, is the self-flushing labyrinth (No. 4). It is significantly contaminated in all drips, which, in our opinion, is the main reason for the loss of drip capacity. Despite the fact that the studied drips are quite advanced systems with dense filters, pressure stabilizing mechanisms and anti-siphon systems, their design did not take into account the possibility of penetration and further development of a large number and variety of biological microorganisms This makes it necessary to periodically flush them when using recycled water or water from surface sources.

Field studies of domestic environmentally safe, electrochemically activated substances such as Kristal anolyte and Secobrand hypochlorite have confirmed that their cleaning capacity for drip irrigation pipelines and drip outlets from biological contaminants is comparable to the environmentally hazardous foreign product with a high chlorine content that is currently used in Ukraine for these purposes.

**Conclusions.** The results of laboratory and field studies have shown that the washing capabilities of environmentally friendly means of electrochemically activated low-concentrated saline solutions “Crystal” and “Secobren” are comparable to those of environmentally hazardous 15 % hypochlorite “AquaDoctor” and are promising for their further use in drip irrigation systems.

The working concentrations of solutions of “Crystal” and “Secobren” substances required for washing emitters of drip irrigation systems were preliminarily determined and the need for more detailed laboratory and field studies on this issue was substantiated (development of washing technology depending on the nature and intensity of contamination). Given that the use of “Crystal” and “Secobren”, due to their environmental safety, does not impose restrictions on the number and intensity of flushing, as is the case when using the highly toxic 15 % sodium hypochlorite “AquaDoctor”, it is possible to thoroughly clean drip irrigation systems and restore up to 100 % of the throughput capacity of drip outlets, even during the growing season.

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# ОЦІНКА МОЖЛИВОСТІ ПРОМИВКИ СИСТЕМ КРАПЛИННОГО ЗРОШЕННЯ ЕЛЕКТРОХІМІЧНО АКТИВОВАНИМИ НИЗЬКОКОНЦЕНТРОВАНИМИ СОЛЬОВИМИ РОЗЧИНАМИ

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***Анотація.*** *Практика використання систем краплинного зрошення свідчить, що забруднення краплинних водовипусків, у тому числі продуктами органічного походження, є серйозною загрозою їх надійної роботи. В Україні для боротьби з таким забрудненням використовують промивки трубопроводів краплинного зрошення екологічно небезпечним 15 % гіпохлоритом натрію "AquaDoctor" виробництва КНР. Разом з тим, в світовій практиці існують данні про можливість ефективного застосування для таких цілей екологічно безпечних електрохімічно активованих низькоконцентрованих сольових розчинів, зокрема – аноліту. Аналіз вітчизняного ринку дезінфікуючих та бактерицидних засобів і антисептиків дозволив припустити, що аноліт «Кристал» виробництва ПП «Персонал Люкс» (м. Харків), який має високу біоцидну активність при масовій сумарній концентрації АДР 0,1 %, та електрохімічно активований низькоконцентрований гіпохлорит натрію «Секобрен» з вмістом гіпохлориту до 0,06 % виробництва ТОВ «УКРТЕК ПРОДАКТ» (м. Київ), що має може аналогічні властивості, можуть бути використані для промивки краплинних водовипусків. Проведено лабораторні і польові дослідження щодо можливості промивки електрохімічно активованими низькоконцентрованими сольовими розчинами забруднень краплинних водовипусків продуктами органічного походження. Дослідження проведено при промивках трубопроводів краплинного зрошення з інтегрованими крапельницями фірми ASSIF (METZER, Ізраїль) дезінфікуючими засобами "AquaDoctor", «Кристал» та «Секобрен». Лабораторні дослідження проводились в акредитованій в системі УкрСЕПРО лабораторії ІВПіМ НААН, польові – на системах підґрунтового краплинного зрошення Черкаської та Київської областей. Для промивки в польових умовах використовувалась «Примусова установка подачі та змішування ПУПЗ» розробки ТОВ «ІРРІГАТОР УКРАЇНА».*

*Результати лабораторних і польових досліджень засвідчили, що промивні спроможності екологічно безпечних засобів «Кристал» та «Секобрен» є співставні з можливостями екологічно небезпечного гіпохлориту "AquaDoctor". Це робить доцільним проведення подальших досліджень для відпрацювання технології промивки краплинних водовипусків в залежності від характеру та інтенсивності їх забруднення.*

***Ключові слова****: зрошуване землеробство, системи краплинного зрошення, краплинні водовипуски, забруднення біологічного походження, промивки, електрохімічно активовані низькоконцентровані сольові розчини, аноліт, гіпохлорит натрію*

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# TARIFFS FOR WATER SUPPLY SERVICES FOR IRRIGATION AS A TOOL FOR ATTRACTING INVESTMENTS TO IMPROVE WATER USE AND AMELIORATIVE INFRASTRUCTURE

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***Abstract.*** *Conceptual approaches to increasing the investment attractiveness in water resources and land reclamation infrastructure should be adapted to solving the problems facing states and societies, including measures to ensure sustainable economic development and environmental protection. The implementation of investment and infrastructure projects is provided for by the Irrigation and Drainage Development Strategy until 2030 and is becoming relevant in solving the problems of the Ukrainian economy. Implementing a tariff policy will allow for maintaining land reclamation infrastructure in working condition, reducing the energy intensity of water supply for irrigation, establishing technological integrity of water use, etc. Such tasks draw attention to increasing the function of tariffs as one of the sources of covering investments in water infrastructure. A general trend in solving problems can be considered a broad view of problems, lower risk, and higher management reliability.*

*The article critically analyzes the experience of using irrigated lands based on the introduction of tariffs, given the investment component of tariffs and the use of mobilized funds for investment activities. Productive and inefficient principles of tariff formation are shown, and the importance of land reclamation infrastructure and current directions of financing irrigation infrastructure in EU countries are revealed through compliance with the requirement of targeted funds spending for infrastructure facilities.*

*Based on the risk classification, the significance and impact of risks in the operation of land reclamation systems in market conditions are given; the main components of tariff formation in irrigation water supply services, which include investments in improving land reclamation infrastructure, are outlined; contents of the investment component in the activities of water user organizations (WUO) is indicated, and the ways for the return on investment in land reclamation infrastructure in Ukraine are outlined. Ukraine's experience in successfully using the irrigation potential through a tariff policy for water supply can serve as an example for other countries.*

***Keywords:*** *irrigation, investments, land reclamation infrastructure, tariffs*

**Relevance of the study.** Reforming the irrigation industry through a system of tariffs and financing the development of the agrosphere will allow increasing the economic efficiency of irrigation, ensuring its financial sustainability and fiscal transparency [1], the functioning and renewal of irrigation and drainage systems, which is provided for by the tasks of the "Strategy of Irrigation and Drainage in Ukraine up to 2030" [2]. The state and problems of the development and participation of the Ukrainian Water Users Organizations in attracting investments are shown [3]. Tariff formation in irrigation water supply is considered as a means of maintaining irrigation systems in proper condition and a source of formation of capital investments in the restoration and modernization of the land reclamation infrastructure of Ukraine.

**Purpose of the study** The purpose of the study is to determine the main components of tariff formation for irrigation water supply services as a tool for reliable financial support and stimulation of efficient water use by water users of Ukraine, based on the analysis of regulatory acts, the practice of forming and attracting investments in land reclamation infrastructure, and risk assessment.

**Analysis of recent research and publications** The researchers emphasized the importance of irrigation in Ukraine depending on the cost of water and the importance of introducing a transparent tariff system for water supply and wastewater services [4], considered significant aspects of the role of investments and tariffs [1–3, 6, 7, 16, 22, 23, 28, 35–37], summarized and systematized scientific approaches to methods for forming tariffs for irrigation water supply and compensation for funds spent on water supply in EU member states [5]. There is a methodology for calculating the effectiveness of methods and regimes of crop irrigation [6] where applied principles of economic assessment of investments in drip irrigation projects on a modern basis are given. The research results on the trends of loading in the irrigation sector when solving sustainable development problems [7] were considered, including both cautious opinions [33] and positive ideas about investments in the tariff system [28, 31, 32]. Functions, legal principles, and mechanisms of tariffs in world practice were shown, and the problems of reforming the water management system on reclaimed lands were addressed [25]. However, there was no study on tariff formation aspects in Ukraine when supplying water for irrigation with investment in land reclamation infrastructure based on the experience of the EU and other countries.

**Research methods** The following methods were used in the research: historical-logical (the experience of European countries in providing paid services for maintenance of land reclamation systems based on introducing tariffs and investments in land reclamation infrastructure was studied), logical-abstract (regulatory acts, literary sources, and the best practices from 2000 to 2024 were analyzed), analytical-synthetic (processing of the information received and summarizing the results in the form of tables on tariff schemes in water supply services, the role of risks in infrastructure investment, revealing the high potential for return on investment in constructing modern irrigation systems in Ukraine; using the positive activities of the WUO), systemic analysis regarding the study of the experience of EU countries on water tariffs and mobilizing investments in land reclamation infrastructure in Ukraine.

**Research results and their discussion**

**The importance of the chain: water resources → reclamation infrastructure → investments.** Based on the complex and multidisciplinary nature of reclamation systems, attracting investments to the construction/renewal of such systems based on improving water supply services is recognized as an important component of a water use management mechanism in irrigated agriculture. The sense of the investment attractiveness of projects for the efficient use of resources is the presence of transparent political, institutional, environmental, macroeconomic, and business factors that, through risk reduction, contribute to the attraction of financial resources to the irrigation sector and guarantee the return on invested funds.

In Ukraine, the reclamation system is considered as a technologically integrated engineering infrastructure; the powers of the central executive body implementing the state policy in the field of hydrotechnical land reclamation include: participation in the implementation of investment policy, placement of state investments under target programs [8]; attraction of investments and investment attractiveness of irrigation and drainage systems are provided for by the "Strategy for the Development of Irrigation and Drainage in Ukraine for the Period Until 2030" [2], the need to attract investments in the modernization and restoration of state pumping stations, in the formation of a favorable investment climate [9] is also specified, the financial relationships of the categories: tariffs, infrastructure and investments [1] are gaining importance, the close connection between them is noted by the Rules of Ecological and Economic Accounting [10]; the need to take into account the risks associated with climate change is indicated [1], the economic efficiency of investment projects is assessed according to known market indicators: payback period, internal rate of return, profitability index, net discounted income, etc. [6, 11].

Research has identified several market approaches that can affect the economic attractiveness of investments in irrigation infrastructure. They include subsidizing infrastructure, clearly defining water rights, facilitating market-based water transfers, and marginal cost-based irrigation water pricing [12]. However, implementing the specified business approaches is not linear/directive and has its peculiarities when solving the problem of fund returning funds invested in land reclamation in different countries.

According to the analysis published by BofA (Bank of America), there is a growing interest in water as an investment object in the world, although the actual volumes of investment are still far from potential needs. This is confirmed by the investment amount in achieving the Sustainable Development Goals (SDGs) related to water. Thus, achieving SDG 6 "Ensuring water access and sanitation for all" requires an annual investment of 114 billion dollars [7], and achieving SDG 14 "Conservation and rational use of ocean and sea resources" will be possible with an annual investment of 175 billion dollars. Unfortunately, from 2015 to 2019, only $10 billion was invested in achieving SDG 14.

One of the reasons for the insufficient investment in water is the lack of clear mechanisms for using tariffs as a tool for attracting investments in water use projects [1]. Therefore, the further reform of the system of water management and land reclamation in Ukraine, carried out to fulfill the tasks of the “Strategy of irrigation and drainage in Ukraine until 2030” [2] and the Plan of measures for its implementation [9], requires development and implementation in practice the methods of forming tariffs for water supply/removal services in irrigation and drainage as tools for attracting investments in the implementation of projects to increase irrigation and drainage areas [1, 2].

Therefore, it is appropriate to consider the existing approaches to forming tariffs for water supply from the point of view of accumulating funds for investments in reclamation infrastructure as a component of tariffs (Table 1.)

It should be noted that of the 9 options in Table 1, only the first 6 methods of determining water price and water management services meet the requirements of the modern economy, as they provide incentives for rational water use, allow the accumulation of funds for the restoration and modernization of the reclamation infrastructure, and contribute to investments and investment returns. The last 3 should be assessed as unproductive in the conditions of a market economy since they rely on financing current and capital costs from the budget. In practice, a tariff system for water supply services may be flexible depending on the state/forecasts of natural water supply (very wet, moderately wet, or dry year). The condition for cost coverage at the expense of tariffs and investments borne by the contractor for providing services is stipulated by the EU Directive on the conclusion of concession contracts [14].

**Concept and current trends of irrigation infrastructure financing in the EU**. According to the Commission on Technical Guidance regarding the protection infrastructure against climate change in the period 2021-2027 [15], infrastructure is a rather broad concept that includes, in particular, natural infrastructures, such as green roofs, walls, spatial objects, and drainage systems; network infrastructure, which is crucial for the functioning of the modern economy and society, in particular water supply and wastewater use. Infrastructure investments must be aligned with the goals of the Paris Climate Agreement to reduce greenhouse gas emissions in line with the EU’s climate goals up to 2030, climate neutrality up to 2050, and climate-resilient development. In addition, it is noted that investments in infrastructure projects should not cause significant damage to other EU environmental goals, such as sustainable use

1. Options of tariff formation for irrigation water supply

| Main feature | Content |
|---|---|
| Cost principle | It involves all costs for the operation of the infrastructure and a part of investment costs |
| Benefit principle | The procedure for determining the cost of water management services based on increasing the profit of recipients of water management services |
| Marginal principle [12] | It is based on the price of water and water management services that will cover the system costs in the long term, while optimizing the productive use of the system and maximizing the formation of additional value of crop irrigation |
| Block tariff method | It applies block pricing, so that the area charge includes the provision of e.g. 2,000 $m^3$ /hectare, and all water supplied above this incurs the full volumetric charge. [1]. Since under this method the water price changes gradually depending on its consumption, it is aimed at reducing water consumption. |
| Method of water pricing in off-peak and peak periods | It involves a change in the price depending on the period of water withdrawal from the system, and is typical for crop irrigation in arid areas, very similar to the marginal principle. |
| Method of price “discrimination” | It is based on the maximization of the price that the user is ready and willing to pay; the price is determined depending on the user’s ability and willingness to pay a certain price. |
| Socio-political method | It leads to irrational consumption of water resources due to the lack of productivity stimulation. |
| Equal price method (flat rate tarrifs) | It is not directly connected with the quantitative characteristics of water supply. |
| Method of “shadow” pricing | It represents the “protection” of social values and seeks to bring the price of water to the social optimum. |

*Source: created by the authors according to [13]* and protection of water and marine resources, transition to a closed-loop economy, prevention and recycling of wastes, the prevention and control of pollution and the implementation of the ecosystem protection of people's health.

The report of the Audit Chamber of the EU (European Court of Auditors) emphasizes the high importance of targeted spending of funds for land reclamation infrastructure. It is noted that during a systematic study of spending funds for the sustainable use of water in the agricultural sector of the European Union, based on state audit methods, it was established that the irrigation infrastructure, which increases the quantity and improves the quality of water, belongs to the key consumers of these funds. Therefore, the possibility of building new irrigation infrastructure and its improvement is being considered, namely new irrigation installations, water intake infrastructure, wastewater treatment infrastructure for water reuse in irrigation, "green" infrastructure for water conservation; capital expenditures and depreciation deductions from the value of infrastructure facilities, as a component of the costs of water management organizations, provision and administration of water supply services, etc.

The already mentioned Report of the EU Audit Chamber states that various forms of EU financing are available to investment entities to implement irrigation projects, namely EU rural development programs that support the funding of water conservation measures, increasing irrigated areas and establishing wastewater treatment infrastructure for reusing water in irrigation. Certain investments require potential water savings of more than 5 %, and it is problematic to ensure that irrigation investments will benefit water bodies, especially if the irrigated area is within a water-stress area.

When constructing a new irrigation infrastructure, confirmation of land ownership and/or a valid water withdrawal permit is required, Within the framework of the "Common MarketOrganization" (CMO), irrigation infrastructure is financed for three sectors: fruits and vegetables, olives and olive oil and wine, Modernization of existing systems is practiced, besides the olive and olive oil sector, where EU can support only improvements. Irrigation infrastructure may be financed under other programs such as "Production Planning". In general, the state financial audit showed that rural development programs do not sufficiently support water conservation measures and water reuse infrastructure [16].

Many years of experience in introducing paid water use, tariffs, and investments in the Republic of Kyrgyzstan [19] are valuable. The main components of this area in Kyrgyzstan are: establishing fairly high tariffs, establishing tariffs mainly for the irrigated area due to the lack of hydrometric posts on watersheds, introducing the mechanism of flexible regulation of tariff rates, establishing a preferential tariff for electricity for irrigation pumping stations, introducing an effective mechanism for controlling and accounting for water use and supervising of unauthorized water intake from natural water bodies, uninterrupted financing of WUO activities and ensuring timely payment for irrigation services, establishing a fee for irrigation water supply services as mandatory, regulating the mechanisms of responsibility of the primary division of Water Resources Service of Kyrgyzstan and water users for fulfilling contractual obligations regarding the supply of irrigation water, introducing developed mechanisms for ensuring transparency and targeted use of investments in the irrigation sector from the state budget and water users' funds.

An essential element of managing complex reclamation systems in market conditions is the consideration of risks, that is, the danger of uncertainty and failure to get the planned result. Considering the risk factor enables us to choose a risk reduction strategy and achieve the set goals. There are operational risks (can arise during current business activities) and financial risks (related to changes in financial markets, as well as credit and investment risks), short-term (may have an impact on the business activities shortly), and long-term risks (may have a significant impact on business activities in the distant perspective), etc. The risk assessment of irrigation investment projects is regularly considered [6]. The practical development of the permit system, including databases and a risk-based verification system, is envisaged [1]. The significance of the risk factor associated with infrastructure investments for better water use through irrigation tariffs is presented in Table 2.

To overcome macroeconomic risks, management decisions should be based on a clear understanding of the hydrological cycle and reasonable water accounting [23]. So there is a need for a detailed assessment of risks and potential problems, a careful analysis of the costs of functioning and support of water user associations, and the introduction of financial management, investment planning, and risk management [24].

Given the formation of an effective economic mechanism for ensuring the functioning of the

2. Investment risks in water supply infrastructure

| Type of risk | Specifications and examples |
|---|---|
| Macroeconomic and business risks | **Investment risk:**<br>• possible adverse impact on the expected investment income due to disruption of the stability in project implementation;<br>• state guarantees in project implementation.<br>**State support for irrigation based on water supply tariffs:**<br>• determining the amount of state subsidies for expenses<br>• adjustment of the taxation system,<br>**Operational and construction risk**: risks associated with complex technologies and innovative approaches.<br>**Market risk:**<br>• ensuring uninterrupted financing of WUO activities, water users, and water supply operators;<br>• changes in demand for water supply services.<br>**Political risk:**<br>• in case of public procurement (for example, growing cotton and tobacco);<br>• in case of political interference in the process of tariff imposing.<br>**Risk of funds transfer**: in case of discrepancy between the income from the water supply by accounting and the receiving funds from debtors.<br>**Credit risk**: in case a counterparty fails to fulfill his contractual agreements.<br>**Risk of agreement termination in time**: the risk of premature termination of long-term contracts. |
| Regulatory and political risks | **Regulatory risks include:**<br>• changing the principles of tariff formation and improving the tariff policy. Tariffs are imposed depending on the costs of water supplied by irrigation systems, taking into account the type of crops (based on water consumption rates);<br>• economic regulation can be strong, weak, or absent;<br>• provisions on the participation of the private sector in forming and improving infrastructure. |
| Commercial risks | **Industry risks:** risks affecting revenues from a specific project (water availability, water accumulation, payment of services by the tariff);<br>**Risk of creditors' claims**: raising claims for disruption of water supply schedules, low quality of services, violation of environmental protection legislation, and failure to receive the planned yields under irrigation. |
| Environmental risks | • variability in water availability due to climate change may reduce the efficiency of water infrastructure, such as hydropower generation;<br>• potential negative environmental impact of large multipurpose water infrastructure;*<br>• positive impact of using purified wastewater for irrigation;<br>• growing the hazards of depletion and deterioration of water resources. |
| *multipurpose infrastructure covers all constructed water systems, including dams, reservoirs, hydroelectric power plants, and associated irrigation canals and water supply networks, which can have a multipurpose use in economic, social, and environmental activities [17]. | |
| Social risk | • resettlement of households that may be flooded downstream of dams;<br>• limited labor availability associated with tariff increases;<br>• attraction of qualified labor force when expansing irrigated land areas and cultivating crops with high added value;<br>• the positive impact of land reclamation infrastructure on the development of settlements located in reclamation areas [18]. |

*Compiled by the authors according to [6, 17, 18]* reclamation water supply infrastructure for crop irrigation based on water supply tariffs, taking into account regulating investment provision and the impact of investment risks, it is possible to group the basic aspects of tariff formation in water supply services: actual volumes and management of water resources, the essential role of reclamation infrastructure and water management. The factors of attraction and use of investments in infrastructure improvement through introducing tariffs when providing services are shown in the Table 3.

**Investing in irrigation infrastructure and mobilizing sources of return.** The state, as the initiator of land reclamation activities, takes the necessary measures on attracting financial resources and targeted use of investments, ensure the efficient use of water and renewed land, as well as return the invested funds. In many countries, there is the practice of building new irrigation systems at the expense of state budget funds, external borrowings, bank loans, etc., with the subsequent transfer of infrastructure facilities into ownership/management to independent companies or water user associations [19]. At the same time, it is noted that financial resources and technical support of irrigation infrastructure from state or international donors for infrastructure maintenance and management are less available than for initial investments. That can lead to poor maintenance and poor-quality service provision [23]. Therefore, efforts to mobilize their own (private) financial resources for renewing infrastructure facilities are justified.

In particular, the modernization of on-farm and inter-farm irrigation systems in Ukraine will require investments of about 3 billion USD and allow for additional irrigation on a total area of about 1,180,000 hectares [2].

There are known proposals to use the investment component in water supply tariffs as a source of investment financing in the form of paid water use mechanisms, along with reducing subsidies to support irrigation from national/local budgets, increasing the financial burden on direct users of water supply services – water users in the agricultural sector, with mandatory consideration of their actual paying capacity [19]. Such measures meet the requirements of the WFD [26] regarding compliance with the principle of water supply cost recovery.

**The importance of the investment component in tariffs in Ukraine.** It has been established that improving the performance of WUOs in Ukraine will lead to increasing the area fees to cover investment costs, but that will happen at a lower volume fee since the cost of water pumping is reduced about twice. This

3. Main components of tariff formation in irrigation water supply services

| Components of tariff formation | Description of the tariff system |
|---|---|
| Water resources | Availability of water resources, ensuring water supply during the irrigation season, compliance with nature protection requirements, taking measures to save water, and clear water accounting. |
| Land reclamation infrastructure | Ensuring water supply for selected methods of irrigation, maintenance in working condition, and improvement of reclamation infrastructure at the cost of funds obtained for water supply services according to tariffs; ensuring water transportation by water users' orders, compliance with water supply schedules, and using effective irrigation methods. |
| Management of water resources | Separation of management functions of water and land reclamation infrastructure and provision of water supply and drainage services from the water management tasks based on decentralization. A promising direction is the transfer of the functions of reclamation infrastructure management and operation to water users' organizations and associations, ensuring the implementation of the investment project program and monitoring compliance with the rules for operating water objects. |
| Tariff systems for irrigation water supply services | The use of effective principles of tariff formation, covering the costs of infrastructure operation by tariffs, accumulating funds under the investment tariff component, giving priority to the two-rate tariff, stimulating the efficient water use; tariff differentiation depending on irrigation technology, set of crops under irrigation, technical condition of irrigation systems (traditional systems, reconstructed systems, new systems); using the advantages of integrated water management by the basin principle, accounting of costs for supplying water for irrigation (separation of constant and variable costs, application of ecological and economic accounting of water [2]). |

problem will probably be actual for a few years until WUOs upgrade all their pumping stations [1] and bring the irrigation area in line with the capacity of the pumping stations. The full amount of all costs associated with water management on the tariff basis will be shown, an effective tariff policy for WUOs water supply services will be developed, the coverage of economically justified costs and a fair distribution of the financial burden on water users through the introduction of two-rate tariffs with fixed and variable components will be ensured.

There is a fair distribution of costs between water users – "who consumes more water – pays more"; sustainable development of land reclamation systems is ensured by including an investment component in the tariffs [27]. Thus, the tariff rate contributes not only to common but also to the expanded renewal of fixed assets of land reclamation systems.

Including the capital costs for the replacement and construction of engineering infrastructure facilities of a reclamation network (Article 20 "Organization Services" of the Law [3]) in the costs of maintaining the reclamation network of the organization means using tariffs as a source of investment in infrastructure improvement. That is a measure to strengthen responsibility for the targeted use of funds accumulated through tariffs. The implementation of the mechanism for decentralizing irrigation management and transferring on-farm systems to long-term use (ownership) will be facilitated by a legislative solution to create an institute of state-owned reclamation infrastructure operators, etc. [28]. In Ukraine, the investment component has already been included in water supply tariffs as part of municipal services as well as the approved investment program for the relevant year [29].

The problem of insufficient investments in the renewal and maintenance of land reclamation infrastructure facilities, the wear and tear of which reaches 70 %, can be solved through a breakthrough tariff policy. That will contribute to eliminating the deficit of natural water supply in more than 2/3 of the territory of Ukraine, reducing the energy intensity of water supply for irrigation, establishing technological integrity of water use, reducing water loss for filtration, and improving the mechanisms of state support for agricultural producers on irrigated lands [30].

**The world's experience in the formation of investment sources**. It can be hypothesized that the existing administration system of the agricultural sector and the irrigation system corresponds to the allocated funds for capital costs in land reclamation infrastructure. In the EU countries, capital subsidies to irrigators dominate [5], but not the compensation for the costs of maintaining land reclamation systems through tariffs, which entails strict control over the targeted use of funds [16]. Along with "market" options for tariff formation, priorities are given to solving social problems (Table 1).

This approach may be justified in countries with strong economies and the capacity to cover investments in land reclamation infrastructure from budget funds. Along with uncompromising views on the "principled" impossibility of water users' funds participating in covering capital investments in hydro-technical land reclamation, there is no requirement to cover the capital costs associated with these investments. There is no requirement to pay prices compensating for the depreciation costs of "donated" components [33], etc. There are known individual cases of including capital costs in tariffs; for example, in Israel, 40 % of the water tariff is an investment component for water infrastructure development [28]. There are some cost recovery programs under consideration [31]. Regulatory measures and institutional mechanisms (water prices and tariffs) contribute to a stable political environment [32]. There are new initiatives based on water pricing, revision of water rights, water abstraction limits, development of regulated water markets, water reuse, and targeted subsidies for the modernization of irrigation systems. It is noted that water pricing policies would be impossible to implement due to technical and administrative impracticability and the severe social prospect of farmers [34].

The development and implementation of an effective tariff policy for irrigation water supply services, as a component of the state policy of Ukraine in water management, implies the goal of the tariff policy – not to punish water users by increasing the production cost of production, but to increase their interest in efficiency and water saving in water management, increase the participation of the key beneficiaries of irrigation – water users (farmers, households) in implementing effective methods of using reclaimed land and water resources, introduce innovations in irrigated agriculture and irrigation water supply, which in turn will support the full use of irrigation potential.

The attraction of the investments of WUOs is based on tariffs. As of the end of 2023, 33 WUOs have been registered in 10 regions of Ukraine. In 2023 they performed irrigation on an area of 46 thousand hectares, which is 35 % of the total irrigation area in the territory controlled by Ukraine. 7 WUOs submitted information to the State Land Cadastre about the reclamation network serving their territory, and only one WUO got the right to use the property of the reclamation system. The next step in expanding the activities of WUOs is obtaining the land reclamation network (facilities) in ownership [20]. Therefore, the current state of WUO activities in Ukraine does not yet meet the requirements of the Law of Ukraine "On water user organizations and stimulation of hydrotechnical land reclamation" [3] regarding the use of tariffs to attract investments in irrigation infrastructure.

According to the already mentioned Law on WUOs [3], the legal basis for providing water supply services is precisely "determining the tariff for WUOs' services", and this right is the exclusive competence of the general meetings of WUOs [3, Art. 12]. The tariff of the WUOs' services includes the operating costs of the WUOs' reclamation network, costs for water intake and delivery to water users, and the WUOs' organizational costs [3, Article 20]. The participation of WUOS members in introducing investments in the reclamation network of the organization is also regulated [3, Art. 23]. Besides providing services for irrigation water supply, the next step in the WUOs' activities is introducing a tariff system, which must be coordinated with investments.

Such perspectives are evidenced by the calculations of the economic indicators on irrigation use, which show that the methods of soil water regime operation directly affect the total water consumption in the cultivation technological process, which, in turn, depends on crop type, method of watering, and irrigation regime. The highest profit – from 15.8 to 25.5 thousand UAH/ha was obtained for vegetable crops, and the lowest profit – 5.8 and 6.0 thousand UAH/ha, respectively, for winter wheat and spring barley [6]. High economic efficiency (profit from irrigation is 12 thousand hryvnias/ha) provides financial opportunities for reconstruction and modernization of irrigation with an acceptable (no more than 8-10 years) payback period [4].

In Ukraine, it is believed that the payback period for investments in irrigation when growing commercial corn is 6-8 years [21]. The rules of water statistics provide for the accounting of assets and investments in water supply and drainage infrastructure [10]. When forming restoration plans, and preparing investment proposals and projects in Ukraine, first of all, it is necessary to focus on using available water resources and implementing energy-saving principles [22].

In market conditions, using productive principles of tariff formation becomes a key moment in the development of irrigation and drainage in Ukraine. Efficient use and conservation of water and good operational condition of reclamation infrastructure give priority to investment objects. To invest funds, an investor, analyst, consultant, financier, or owner need strong arguments to obtain high economic results from the investment project based on the forecasts. Complex multi-purpose infrastructure when implementing the investments, protects water bodies, develops the agrarian sector, and solves social problems. When considering proposals, the main levers of market approaches to investments are used: providing infrastructure processes with financial resources, solving legal problems, and establishing a tariff system [12].

Implementation of investment projects in irrigation based on tariffs provides future benefits. Despite the significant need for funds, projects on the restoration and development of irrigation systems are attractive for investments due to their short payback period [2]. Due to additional irrigation areas that will be under operation after constructing new intra-farm irrigation systems when applying the most modern technical, technological, and constructive solutions, there is a possibility for the construction of irrigation systems with the highest economic efficiency and ecological safety. At the same time, that will make it possible to minimize the cost of irrigation water supply [2]. According to experts, an appropriate water management system should be based on a combination of water policy and management tools accompanied by introducing feasible institutional reforms and necessary investments from the public and private sectors [35].

After decentralization in Indonesia, many sectors require investments from regional governments. The main obstacles to financing infrastructure are insufficient governance and lack of guaranteeing cost recovery through tariffs. To overcome the obstacles tariff payers are involved in these processes [36]. It is appropriate to introduce "smart irrigation", and involve the state support for innovations, research on improving irrigation productivity, use of alternative sources of water resources for irrigation, and reduction of energy costs in irrigation [37].

**Conclusions.** As foreign experience shows, the tools of tariffs for water supply services should be used to solve the key financial problem in irrigation development. To solve the problem of restoration of irrigation infrastructure in Ukraine, it will be appropriate to use tariffs for irrigation water services. Such tariffs should have an investment component. The load on the effective mechanism of tariff formation is increasing due to the mandatory investment component of tariffs and solving administrative and legal problems of further reforming the Ukrainian irrigation and drainage sector.

When applying a two-rate tariff for water supply services for irrigation, capital costs for the replacement and construction (placement) of engineering infrastructure facilities will be covered by the fee for irrigated areas, and the costs of pumping water are included in the variable part of the tariff. An effective tariff policy will affect macroeconomic, regulatory, political, and business risks. Developments and experience of countries with a market economy regarding the attraction of tariffs as a source of investment in reclamation infrastructure, compliance with the target spending funds and solving prospective problems regarding the shortage of water resources, taking into account the impact of risks, introducing paid water use, tariffs and investments are valuable for Ukraine, especially given the need to deploy the full-fledged activity of the WUOs.

**Areas for further research**: development of legislation regarding the introduction of tariffs for water supply, the study of the current state of reforms on introducing tariffs, in particular, the practice of the WUOs' activities in the condition of transferring the reclamation network into their ownership, research of the impact of the risk factor on the investment component of tariffs for water supply to minimize the negative impact of risks, generalization of the best practices of reclamation infrastructure operation based on tariffs both in Ukraine and overseas; substantiation of tariff components for irrigated systems in the real conditions of using reclaimed land by agricultural enterprises in Ukraine, determination of indicators (criteria) of tariffs, development of a unified principle (methodology) of calculating tariffs (fees) for the services and implementation technical conditions.

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# ТАРИФИ НА ПОСЛУГИ З ПОДАЧІ ВОДИ НА ЗРОШЕННЯ ЯК ІНСТРУМЕНТ ЗАЛУЧЕННЯ ІНВЕСТИЦІЙ ДЛЯ ПОЛІПШЕННЯ ВИКОРИСТАННЯ ВОДИ ТА МЕЛІОРАТИВНОЇ ІНФРАСТРУКТУРИ

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***Анотація.*** *Концептуальні підходи до посилення інвестиційної привабливості вкладень у водні ресурси та меліоративну інфраструктуру мають бути адаптовані до розв'язання завдань, що стоять перед державами і суспільством конкретної країни, зокрема заходи, що забезпечують сталий розвиток економіки та природоохоронної діяльності. Реалізація інвестиційних та інфраструктурних проєктів передбачена Стратегією розвитку зрошення та дренажу до 2030 р. і стає актуальною у розв'язанні проблем економіки України. Запровадження політики тарифів дасть змогу підтримувати меліоративну інфраструктуру у робочому стані, знижувати енергоємність подачі води на зрошення, встановити технологічну цілісність водокористування тощо. Такі завдання зумовлюють увагу до підвищення функції тарифів як одного із джерел покриття інвестицій у водну інфраструктуру. Загальною тенденцією у розв'язанні проблем можна вважати широкий погляд на проблеми, менший ризик та вищу надійність управління.*

*У матеріалі проведено критичний аналіз досвіду використання зрошуваних земель на базі запровадження тарифів через призму інвестиційної складової тарифів та використання мобілізованих коштів для провадження інвестиційної діяльності. Вказано продуктивні та малоефективні принципи формування тарифів, розкрито значення меліоративної інфраструктури й актуальні напрями фінансування інфраструктури зрошення в країнах ЄС через дотримання вимоги цільового витрачання коштів в інфраструктурні об'єкти.*

*На основі класифікації ризиків наведено значення та вплив ризиків в управлінні меліоративними системами у ринкових умовах; окреслено головні складові тарифоутворення у наданні послуг з подачі води на зрошення, до складу яких входять інвестиції в поліпшення меліоративної інфраструктури; зазначено зміст інвестиційної складової у діяльності організацій водокористувачів (ОВК); накреслено орієнтири окупності вкладень інвестицій у меліоративну інфраструктуру в Україні. Досвід України щодо успішного використання потенціалу зрошення через тарифну політику на подачу води може стати прикладом для інших країн.*

***Ключові слова:*** *зрошення, інвестиції, меліоративна інфраструктура, тарифи*

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# OPTIMAL PARAMETERS OF SOIL WATER REGIME DURING CROPS CULTIVATION ON DRAINED LANDS

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***Abstract.*** *The results of the research on determining the optimal parameters of the soil water regime during cultivation of promising agricultural crops on drained lands under modern conditions of farm management and climate changes are presented. It was found that the weather conditions of the vegetation seasons of 2022, 2023, and 2024 on the drained lands of the reclamation system of the Sarny Research Station of IWP&LR of NAAS were very contrasting: periods with excessive precipitation alternated with their prolonged absence, and significant fluctuations in temperature indicators were noted. The assessment of the impact of water regime regulation on the yield of spring wheat, winter rapeseed, grain corn, and soybeans was carried out using an unified fertilization system, applying the same rates of mineral fertilizers, and with an identical plant protection system on the background of 3 options for regulating the groundwater level (GWL) – 75–80 cm, 85–100 cm, and 100–140 cm. On the background of the indicated options for regulating the GWL, the lowest moisture reserves were observed in the summer period, and in areas adjacent to the studied territory, where the GWL was not regulated, moisture reserves in the summer in the soil layer of 0–30 cm dropped to the critical values (8–9 mm). On the experimental plots during this period, thanks to timely sluicing, soil moisture reserves did not fall below 47–50 mm. Based on the analysis of the dynamics of dry mass of growth of spring wheat, winter rapeseed, grain corn, and soybeans according to the options for regulating the soil water regime, the optimal parameters of the soil water regime (GWL, moisture, and moisture reserves) were determined for the phenological phases of the studied crops. It was found that the highest yield increase due to the optimization of moisture supply was observed in spring wheat and soybeans. Spring wheat is the most sensitive to soil water regime and reacts more actively than other crops to a decrease in GWL. The regulation of the GWL contributed to an increase in the yield of spring wheat by 41.6 %, winter rapeseed by 18.3 %, grain corn by 32.5 %, and soybeans by 44,8 %.*

***Keywords:*** *drainage system, drained lands, climate changes, soil water regime, optimal water regulation parameters*

**Relevance of the research**. Modern agricultural production is under the direct influence of climate changes, which is especially felt in the drainage zone, where significant changes have recently occurred in the structure of areas under the crops. Therefore, effective agricultural production is possible only if producers are ensuring the necessary conditions that will allow adapting to climate changes [2, 3, 14].

The current structure of sown areas is subjected to both climate changes and market conditions, which dictate the cultivation of economically attractive crops. Climate changes has made adjustments to the technological flowcharts of crops cultivation and the crop rotation of agricultural enterprises. Such economically attractive crops as corn, sunflower, soybeans, and rapeseed gradually became the main ones, and crops of traditional specialization (long-staple flax, sugar beet, rye, oat, etc.) in the drainage zone ceased to be a priority.

At the same time, the formation of new conditions for agricultural crops cultivation and changes in the use of drained lands requires the expansion of the functional tasks of drainage systems, primarily regarding the optimization of water regulation in the humid zone [4, 5, 10].

The presence of a clear trend towards further increase in the aridity of the climate in Ukraine and, accordingly, the formation of conditions not only for overmoistening of soils, but also for their moisture deficit, during the vegetation season, requires the restoration and expansion of water regulation capabilities on drained lands, which is becoming a mandatory and defining component of modern technologies for the production of economically attractive agricultural crops.

**Analysis of recent research and publications** shows that currently in the drainage zone due to the impact of climate change and at the same time the demand of external and internal markets for certain types of agricultural products, there has been a shift in crop growing areas and significant changes in the production structure of the areas under the crops [3, 8, 9].

From 1990 to 2021, the area under sunflower increased by 4.1 times; under corn for grain – 4,5 times; under rapeseed – 14,6 times; under soybeans – 11,4 times, making their products the basis of export. At the same time, from 42 to 83 % of the areas under these crops are located in the Forest-Steppe and Polissya zones [7].

The total area of cereals and leguminous crops in Ukraine on average has remained almost unchanged over the past five years compared to 1990, but the share of their production by natural and climatic zones has changed. Due to the increase in productivity, 65 % of cereals is grown in Polissya and the Forest-Steppe, although the percentage of areas under those crops in these regions is 53 % [6, 7].

As for the cultivation of corn for grain, today in the Forest-Steppe and Polissya this crop is becoming the main one along with winter wheat [9]. Due to climate changes, corn for grain is now successfully grown in the Polissya zone.

The trend of rapeseed cultivation is confirmed by official statistics: in recent years, the area under rapeseed in Ukraine has increased by 66,7 %: from 0,8 million hectares in 2017 to 1,2 million hectares in 2022, and the leaders in terms of yield are Volyn, Khmelnytskyi, Ternopil, Rivne, and Vinnytsia regions [15, 16].

At the same time, in the last 5 years, there has been a significant increase in soybean yield (2,05–2,64 t/ha). The main areas of soybean cultivation are Zhytomyr, Ternopil, Khmelnytskyi, and Kyiv regions [1, 16].

Considerable attention is paid to the study of soil water regime during the cultivation of sunflower, winter wheat, soybeans, and corn. The researches were mainly conducted within the Southern Steppe, Right-Bank Steppe, and Forest-Steppe of Ukraine [11–13, 17]. The conducted studies have established that soil water regime is formed mainly due to the weather conditions, the amount of moisture reserves in soil, the amount and intensity of precipitation throughout the year, including during the vegetation season. To a large extent, the soil water regime depends on the morphological characteristics of hybrids, the density of the crops, sowing dates, and cultivation technologies. Comprehensive studies on determining the parameters of soil water regime in modern farm management conditions in the area of operation of drainage systems have almost not been conducted.

Thus, taking into account the requirements of modern agricultural production regarding the need to ensure the soil water regime in accordance with the current crop rotation, the problem of determining optimal water regulation parameters on drained lands for cultivation of promising agricultural crops under the modern conditions of farm management and climate changes is relevant.

**The aim of the work** is to determine the optimal parameters of soil water regime during the cultivation of promising agricultural crops on drained lands under the current farm management conditions and climate change.

**The object and research methodology.** The research was conducted on drained lands of the reclamation system of the Sarny Research Station (SRS) of IWP&LR of NAAS, which is located in the western, the most swampy part of Ukrainian Polissya. The reclamation system includes the main canal and a second-order main canal, which flows into the first-order main canal in the eastern part of the massif. The main canals are laid through the lowest points of the swamp massif and the greatest depths of peat. The collecting canals are laid perpendicular to the main canals. Their length is 1–2 km. The distance between the collecting canals is within 1–2 km, depending on the slope of the surface. Upland trapping canals are used to intercept surface and groundwater. The length of the open network of canals is 27,213 km, the main channel (MK-2) and other conducting canals – 18,803 km, and the regulating channels – 8,410 km. In total, the system includes 36 open canals, two of which are the main ones. The length of the closed network is 107,623 km, of the collectors – 11,56 km, of the drains – 96,063 km. Closed drainage network (pottery, plastic, fiberglass, fascia drainage) serves to drain 289 hectares with 327 mouths in total. The system has 49 hydraulic structures and one automobile bridge. The agricultural lands consist of 355 hectares of lowland peat soils, and 115 hectares of mineral soils.

The basis of methodological approaches to conducting field research is the use of generally accepted methods of conducting meteorological observations (temperature, precipitation), determining the groundwater level (GWL), soil moisture, and biometric characteristics (occurrence of main phenological phases, yield) during the vegetation season. The scheme of experimental research on drained lands of the reclamation system of the Sarny Research Station (SRS) of IWP&LR of NAAS is shown in Fig. 1.

**Research results.** Analysis of weather conditions on drained lands of the SRS was carried out based on the observation results made by the weather station of SRS of IWP&LR of NAAS, which has been operating since 1946. The weather station is located directly near the research sites, which makes it possible to objectively assess the influence of the main meteorological factors on the growth and productivity of agricultural crops (Fig. 2).

During the vegetation season of 2022 there was 244,3 mm of rainfalls, which is 155,7 mm less than the long-term norm, in 2023 there was 233,3 mm, which is 166,7 mm less than the long-term norm, in 2024 there was 344,0 mm, which is 56 mm less than the average long-term norm. Precipitation during the 2022, 2023, and 2024 vegetation seasons was extremely uneven. During the summer months, the monthly amount was generally less than the long-term norm.

It should be noted that in recent years there has been a steady trend towards a decrease in precipitation during the summer period.

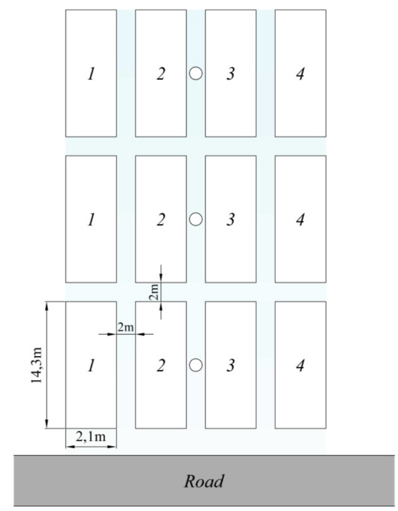


Fig. 1. Scheme of field research on experimental plots of the SRS melioration system, where the following were grown:

1 – winter rapeseed, 2 – corn, 3 – spring wheat, 4 – soybeans

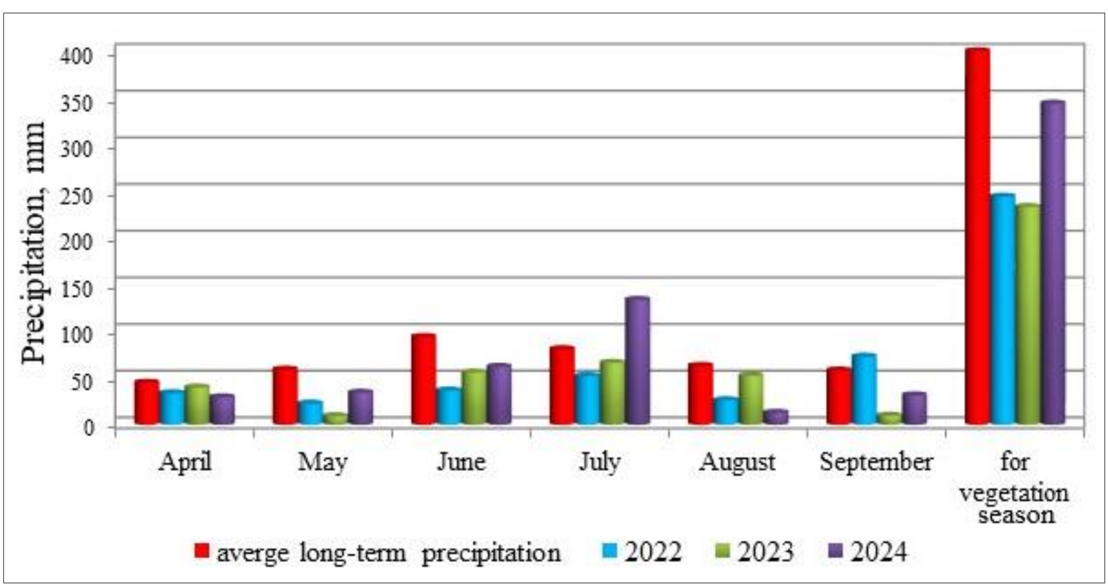


Fig. 2. Precipitations during the vegetation seasons of 2022, 2023, and 2024, SRS melioration system

The temperature regime during the vegetation season of 2022 was characterized by a long and cold spring. May was especially cold, when the average monthly air temperature was 1,4 °C below norm. During June, July, and August, the average monthly temperature was higher by 3,2; 1,2, and 2,6 °C, respectively. At the same time, September was abnormally cold, with the average monthly temperature being 2,6 °C below the long-term norm.

The temperature regime during the vegetation season of 2023 was characterized by a cold period at the beginning of the vegetation season, when the average monthly air temperature in April was 0.6 °C below the long-term norm. The temperature regime was close to the long-term norm during May and June. The average monthly air temperature was significantly higher during July and September.

The temperature regime during the vegetation season of 2024 was characterized by higher average monthly air temperatures comparing to the average long-term indicators. July, August, and September were especially anomalously warm – the average monthly air temperature was higher by 3,9, 3,8, and 4,3 °C compared to the long-term norm (Fig. 3).

Hydrothermal conditions for the active vegetation period on drained lands of the SRS are presented in Table 1.

As can be seen from the data in Table 1, the duration of the active vegetation period (the period of time with an average daily air temperature above 10 °C) for the research period 2022–2024 varied within the range of 146–156 days, and the sum of active temperatures above 10 °C for the same period was 2401–3014 °C,

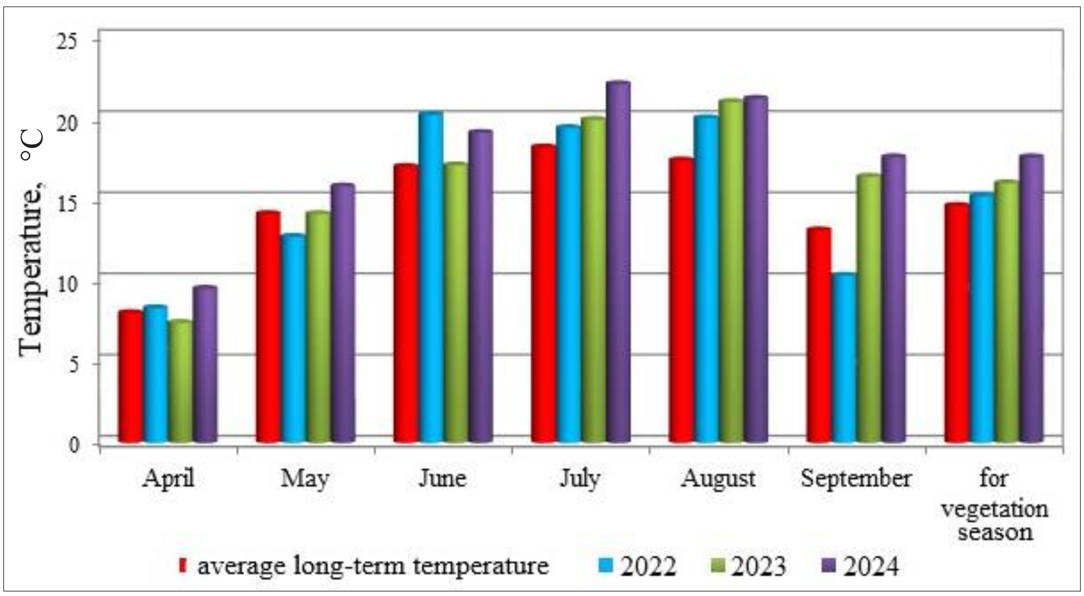


Fig. 3. Average monthly air temperature during the 2022, 2023, and 2024 vegetation seasons, SRS melioration system

1. Hydrothermal conditions for the active vegetation period on the drained peat swamp massif of the Sarny Research Station during 2018–2024.

| Years | Dates | | Amount of days | Σt>10 °C | Σp, mm | HTC | T average, °C | Σt>15 °C |
|---|---|---|---|---|---|---|---|---|
| | beginning | the end | | | | | | |
| 2018 | 8.04 | 24,09 | 169 | 3062 | 246 | 0,80 | 18,1 | 2545 |
| 2019 | 23,04 | 17,09 | 147 | 2643 | 307 | 1,16 | 18,0 | 2356 |
| 2020 | 28,04 | 15,10 | 170 | 2857 | 342 | 1,20 | 16,8 | 2178 |
| 2021 | 10,05 | 17,09 | 130 | 2431 | 220 | 0,90 | 18,7 | 2066 |
| 2022 | 24,04 | 17,09 | 146 | 2401 | 200 | 0,76 | 16,4 | 1871 |
| 2023 | 11,05 | 7,10 | 149 | 2712 | 187 | 0,69 | 18,2 | 2447 |
| 2024 | 11,05 | 30,09 | 156 | 3014 | 274 | 0,91 | 19,3 | 2853 |
| LTN* | 25,04 | 30,09 | 158 | 2498 | 302 | 1,23 | 16,3 | 2356 |

*long-term norm.

the hydrothermal coefficient was 0,69–0,91, and the average monthly air temperature was 16,4–19,3 °C.

Thus, using the generally accepted ranking of the hydrothermal coefficient, it can be said that the vegetation seasons of 2022–2024 can be classified as slightly arid in terms of moisture conditions, which is uncharacteristic for the Western Polissya zone. This is fully consistent with the statements of other scientists who indicate that the climate change in the Western Polissya zone develops towards the aridization of climate [6–7].

The considered agricultural crops (spring wheat, winter rapeseed, corn for grain, and soybeans) were studied on the background of 3 options for regulating the groundwater level (GWL). The soils on the experimental plots are sod-podzolic light loam. A unified fertilization system was used in all 3 options, which provided for the application of the same rates of mineral fertilizers and an identical system of fungicidal and insecticidal plant protection allowing to assess the impact of water regime regulating on the yield of the studied crops.

Before the experiment started, the experimental plot was limed at a rate of 5 t/ha of $CaCO_3$. In the experiment, the following rates of mineral fertilizers were applied to each crop: winter rapeseed and spring wheat – $N_{60}P_{60}K_{60}$ + seed treatment with the phosphorus-mobilizing product Rice Pi; soybeans – $N_{35}P_{60}K_{60}$ + seed treatment with the phosphorus-mobilizing product Rice Pi and seed inoculation with the product Rhizofix; corn – $N_{120}P_{120}K_{120}$ + seed treatment with the phosphorus-mobilizing product Rice Pi. Also, foliar feeding with a 5 % solution of Urea and a 3 % solution of magnesium sulfate was carried out twice during the vegetation season.

Thus, in the technological flowchart of crop cultivation, we created an opportunity to highlight the importance of the water regime in the formation of the yield of cultivated crops and to determine their sensitivity to its formation. The regulation of water regime was carried out using sluicing.

During the vegetation season of 2023, observations of soil moisture and moisture reserves in the 0–30 cm soil layer were conducted at the experimental plots (Fig. 4, 5).

At the site No. 1, the GWL during the active vegetation period (May-August) was within 100–140 cm below the soil surface. The moisture in the arable soil layer (0–30 cm) during this period was observed within 14,1–66,2 % of the full soil moisture capacity, and the moisture reserves were 25,1–99,0 mm.

At the site No. 2, the GWL during the active vegetation period (May-August) was within 85–100 cm below the soil surface. The moisture in the arable soil layer (0–30 cm) during this period was observed within 18,1–68,6 % of the full soil moisture capacity, and the moisture reserves were 30,8–106,7 mm.

At the site No.3, the GWL during the active vegetation period (May-August) was within 75–85 cm below the soil surface. The moisture in the arable soil layer (0–30 cm) during this period was observed within 23,4–73,3 % of the full soil moisture capacity, and the moisture reserves were 46,7–133,9 mm.

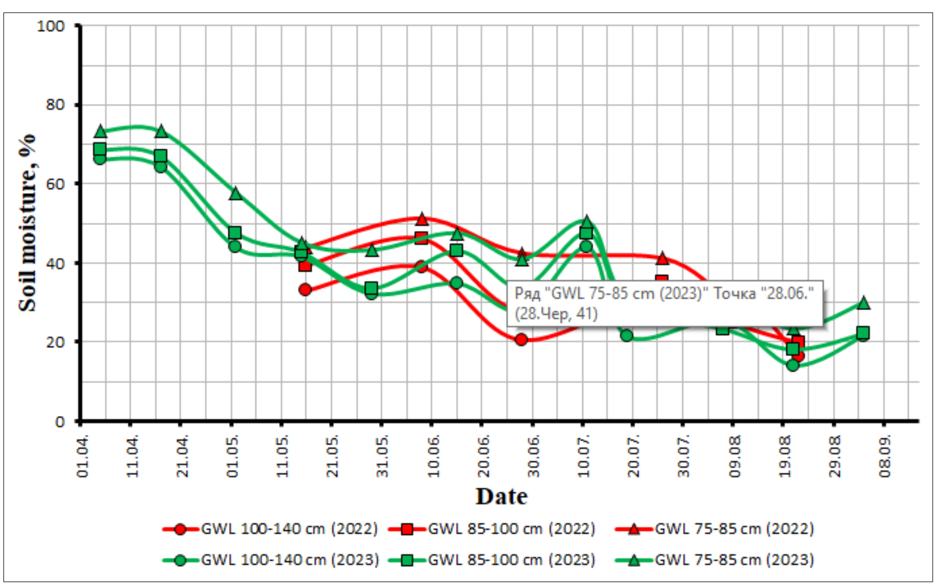


Fig. 4. Dynamics of moisture in the 0–30 cm soil layer within the experimental plots in 2022 and 2023, SRS melioration system

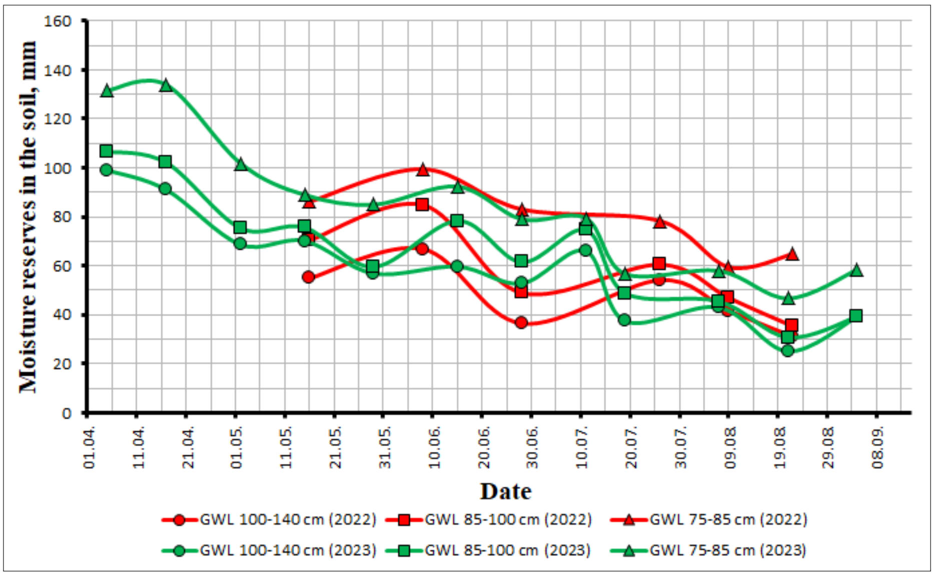


Fig. 5. Dynamics of moisture reserves in the 0–30 cm soil layer within the experimental plots in 2022 and 2023, SRS melioration system

Thus, the GWL in all three variants was located at a depth of maximum 140 cm below the soil surface at plot No. 1, 100 cm at plot No. 2, and 85 cm at plot No. 3. At the same time, the root system of all studied crops at plots No. 2 and No. 3 reached groundwater. The depth of penetration of the corn root system into the soil at plot No. 1 was more than 2 meters.

The lowest moisture reserves were observed during the summer period. In the areas adjacent to the studied territory, where the GWL were not regulated, moisture reserves during the summer period in the 0–30 cm soil layer dropped to critical values and were less than 8–9 mm. At the experimental plots in the same period, thanks to the timely sluicing, soil moisture reserves did not drop below 47–50 mm.

The optimal parameters of the soil water regime (GWL, soil moisture, and soil moisture reserves) during spring wheat, winter rapeseed, corn for grain, and soybeans cultivation were determined based on the analysis of the dynamics of the increase in dry mass of the specified crops by the phases of their development on the background of 3 options for regulating the level of groundwater. As our studies have shown, soybeans and corn grow and develop quite slowly at the beginning

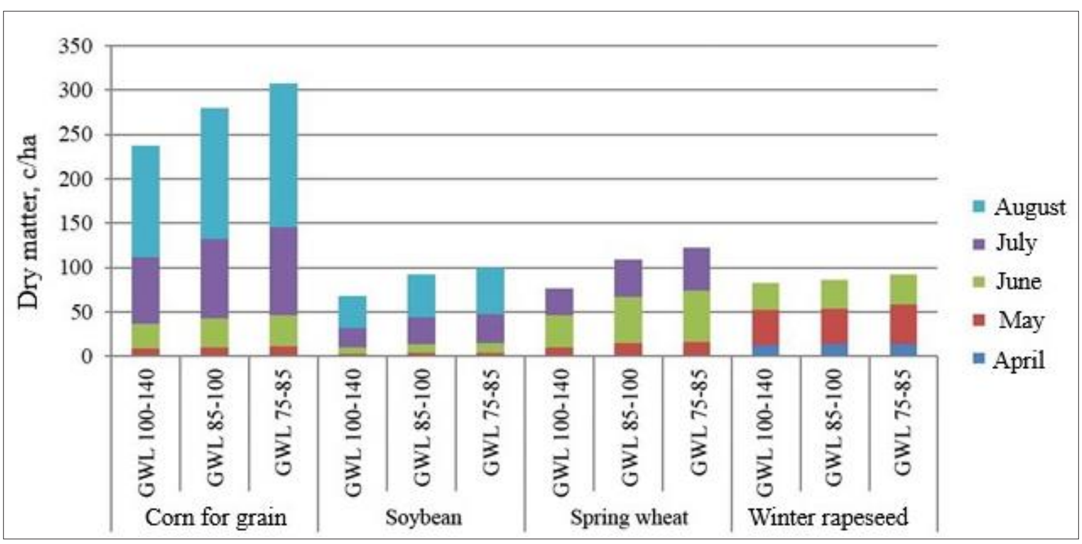


Fig. 6. Dynamics of dry mass increase of promising crops under optimal moisture supply by months of the vegetation season, c/ha

of the vegetation season (from May to the second ten days period of June). Starting from mid-June, growth accelerates significantly and the maximum values of dry mass increase are observed in the second half of the vegetation season (July-August).

The dynamics of the increase in dry mass of spring wheat, winter rapeseed, corn for grain, and soybeans under optimal moisture supply over the ten days period of the vegetation season is shown in Fig. 6.

The optimal parameters of the soil water regime during spring wheat, winter rapeseed, corn for grain, and soybeans cultivation are presented in Table 2.

The yield of cultivated crops on the background of 3 options for regulating the groundwater level on sod-podzolic light loam soils is presented in Table 3 and Figures 7–9.

The analysis of the yield of the studied crops shows that in the context of the 3-year research cycle, depending on the groundwater levels.

2. Optimal parameters of soil water regime during winter rapeseed, spring wheat, corn for grain, and soybeans cultivation

| № | Indicator | Crop | | | |
|---|---|---|---|---|---|
| | | **Winter rapeseed** | **Spring wheat** | **Corn for grain** | **Soybean** |
| 1 | Critical period of moisture availability | 3rd ten days period of April – 1st ten days period of June | 3rd ten days period of May – 1st ten days period of July | 3rd ten days period of June – 2nd ten days period of August | 1st ten days period of July – 2nd ten days period of August |
| | The beginning of vegetation | 1st ten days period of April | 1st ten days period of May | 2nd ten days period of May | 2nd ten days period of May |
| | Dry mass increase per ten days period, c/ha | 0,8–0,9 | 0,8–1,2 | 2,4–3,1 | 0,7–1,0 |
| 2 | GWL, cm | 50–60 | 65–70 | 70–90 | 70–90 |
| | Soil moisture, % of full soil moisture capacity | 66–73 | 44–58 | 42–45 | 42–45 |
| | Moisture reserves in a layer of 30 cm, mm | 990–1320 | 690–1020 | 700–890 | 700–890 |
| | Beginning of the period of intensive vegetative mass increase | 3rd ten days period of April | 3rd ten days period of May | 3rd ten days period of June | 1st ten days period of July |
| | Dry mass increase per ten days period, c/ha | 8,3–9,3 | 6,2–9,8 | 13,2–17,2 | 5,8–8,4 |
| 3 | GWL, cm | 60–70 | 90–100 | 105–115 | 105–120 |
| | Soil moisture, % of full soil moisture capacity | 64–73 | 32–43 | 28–41 | 44–51 |
| | Moisture reserves in a layer of 30 cm, mm | 910–1340 | 570–850 | 530–790 | 660–790 |
| | Mid-period of intensive vegetative mass increase | 2nd ten days period of May | 2nd ten days period of June | 3rd ten days period of July | 3rd ten days period of July |
| | Dry mass increase per ten days period, c/ha | 12,8–14,4 | 12,1–19,3 | 30,0–39,0 | 8,6–12,6 |
| 4 | GWL, cm | 70–90 | 110–115 | 120–125 | 120–125 |
| | Soil moisture, % of full soil moisture capacity | 42–45 | 35–48 | 26–31 | 26–31 |
| | Moisture reserves in a layer of 30 cm, mm | 700–890 | 600–920 | 430–580 | 430–580 |
| | Period of maximum vegetative mass increase | 1st ten days period of June | 1st ten days period of July | 2nd ten days period of August | 2nd ten days period of August |
| | Dry mass increase per ten days period, c/ha | 24,8–27,8 | 17,8–28,4 | 56,9–74,0 | 16,3–23,9 |
| 5 | GWL, cm | 100–110 | 115–120 | 110–115 | 110–115 |
| | Soil moisture, % of full soil moisture capacity | 35–48 | 44–51 | 14–23 | 14–23 |
| | Moisture reserves in a layer of 30 cm, mm | 600–920 | 660–800 | 250–470 | 250–470 |

3. Crops yield subject to the GWL on sod-podzolic light loam soils, vegetation seasons 2022, 2023, and 2024

| Crop | Variety/hybrid | Yield, t/ha GWL, cm | | | Hip $_{0,5}$ t/ha |
|---|---|---|---|---|---|
| | | 100–140 | 85–100 | 75–85 | |
| 2022 | | | | | |
| Winter wheat | Kitri | 5,35 | 5,89 | 6,41 | 0,28 |
| Oat | Zubr | 4,34 | 4,91 | 5,49 | 0,16 |
| Corn for grain | DK 315 | 14,1 | 17,39 | 18,33 | 0,52 |
| Soybean | Astor | 2,81 | 3,63 | 4,11 | 0,22 |
| 2023 | | | | | |
| Winter wheat | Kitri | 3,31 | 4,94 | 5,98 | 0,23 |
| Winter rapeseed | Atlant | 3,44 | 3,63 | 4,07 | 0,19 |
| Corn for grain | Foton | 9,96 | 12,44 | 14,23 | 0,47 |
| Soybean | Astor | 2,52 | 3,44 | 3,81 | 0,27 |
| 2024 | | | | | |
| Winter wheat | Kitri | 2,60 | 2,93 | 3,54 | 0,19 |
| Oil radish | Lybid | 1,42 | 1,76 | 2,01 | 0,13 |
| Corn for grain | R 8834 | 11,73 | 12,76 | 14,87 | 0,45 |
| Soybean | Astor | 2,49 | 3,03 | 3,41 | 0,24 |

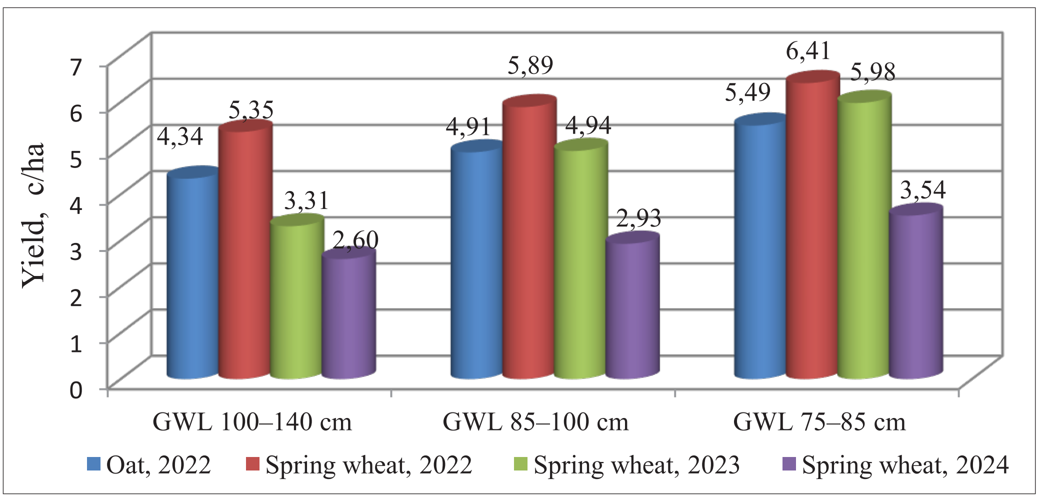


Fig. 7. Yields of spring wheat of the Kitri variety and oat of the Zubr variety subject to the GWL, SRS melioration system

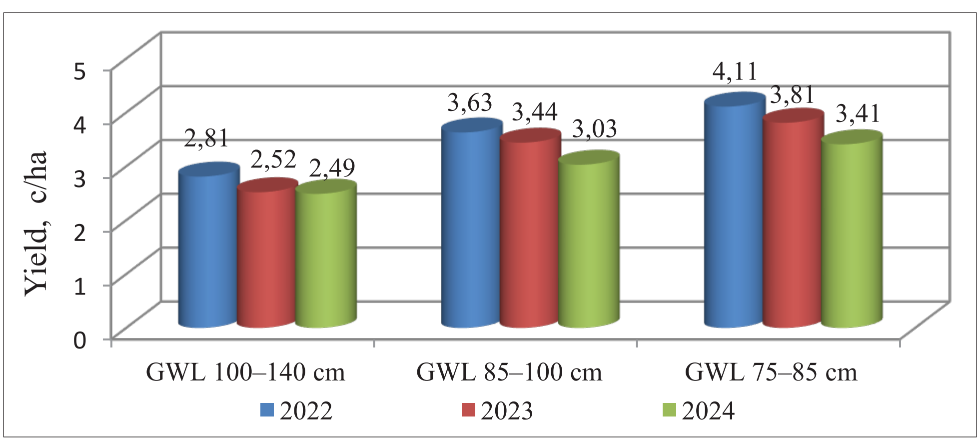


Fig. 8. Yield of soybean variety Astor subject to the GWL, SRS melioration system

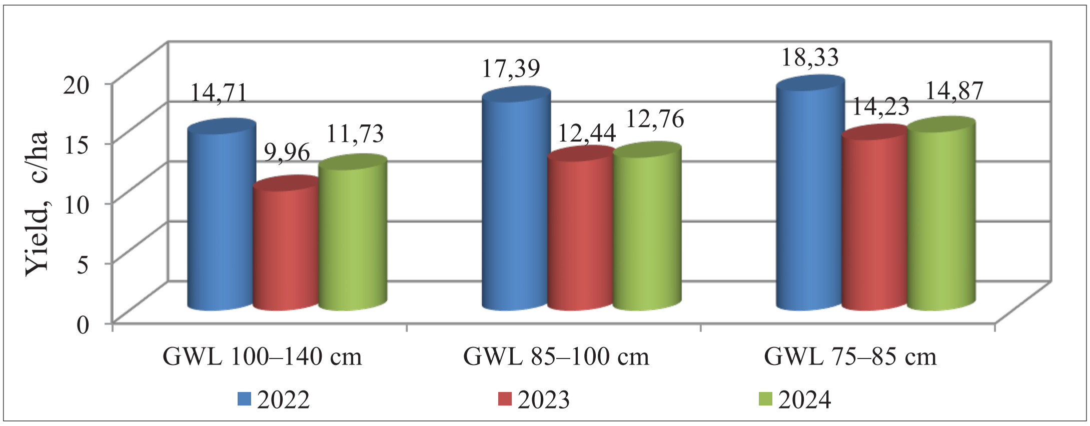


Figure 9. Corn yield subject to the GWL, SRS melioration system

The yield of winter wheat varied in the range of 2,60–6,41 t/ha, of corn – in the range of 9,96–18,33 t/ha, and of soybean – in the range of 2,49–4,11 t/ha. In general, it should be noted that the high yield of corn during the 3-year research cycle indicates the prospects for its cultivation in the Western Polissya zone. This is also confirmed by the results obtained at the Agricultural Polygon of LLC "Zakhidagroprom" in the north of the Rivne region, where under production conditions the yield of individual corn hybrids was over 14 t/ha [18].

It should also be noted that in 2024, compared to the previous 2022 and 2023, during the experiment it was obtained a significantly lower yield of spring wheat – 2,60–3,54 t/ha, which is associated with a prolonged air drought observed in the period from the 3rd ten days period of June to the 2nd ten days period of July (maximum daily air temperatures during this period exceeded 30 °C). Prolonged air drought during the period of intensive spring wheat grain filling led to the formation of grain with a low mass of 1000 seeds, which led to a significant decrease in yield.

As the research results show, over a 3-year research cycle, the difference in yield between the plot where the GWL was at the depth of 100–140 cm below the soil surface and the plot with the GWL at 85–100 cm was 0,84 t/ha for spring wheat, 2,27 t/ha for corn for grain, and 0.76 t/ha for soybeans. The yield increase was 22,4 % for spring wheat, 19,0 % for corn for grain, and 29.1 % for soybeans.

The highest yields values were obtained on plot No. 3, where the GWL during the vegetation season was within the optimal range for the studied crops (75–85 cm below the soil surface). The difference in yields between the plot with the GWL at 100–140 cm was 1,56 t/ha for spring wheat, 3,88 t/ha for corn for grain, and 1,17 t/ha for soybeans. Due to the regulation of the GWL, the yield increase was 41,6 % for spring wheat, 32,5 % for corn for grain, and 44,8 % for soybeans. That is, an increase in the GWL by 30–40 cm leads to a significant increase in crops yield.

The other crops (oat, winter rapeseed, and oil radish) were studied in this experiment only during one year. However, it was found that winter rapeseed was the least sensitive among them to the depth of groundwater levels. Thus, the difference in yield between the plot where the GWL was at the depth of 100–140 cm below the soil surface and the plot where the GWL was at the depth of 85–100 cm was 0,57 t/ha or 13,1 %, and between the plots where the GWL was at the

4. Crops yield subject to the GWL on sod-podzolic light loam soils, average for 2022, 2023, and 2024 vegetation seasons

| **Crop** | **Yield, t/ha** | | | **Yield increase by the GWL options, cm** | | | |
|---|---|---|---|---|---|---|---|
| | | | | **t/ha** | | **%** | |
| | **GWL, cm** | | | **85–100 to 100–140** | **75–85 to 100–140** | **85–100 to 100–140** | **75–85 to 100–140** |
| | **100–140** | **85–100** | **75–85** | | | | |
| Winter wheat | 3,75 | 4,59 | 5,31 | 0,84 | 1,56 | 22,4 | 41,6 |
| Soybean | 2,61 | 3,37 | 3,78 | 0,76 | 1,17 | 29,1 | 44,8 |
| Corn | 11,93 | 14,2 | 15,81 | 2,27 | 3,88 | 19,0 | 32,5 |

depth of 75–85 and 100–140 cm – 1,15 t/ha or 26,5 %. The weaker response of winter rapeseed to the depth of groundwater levels is explained by the fact that the period of intensive accumulation of vegetation mass for this crop is April-May, when the soil has sufficient moisture reserves accumulated during the winter period.

Among the studied crops over the 3-year research cycle, the highest yield increase due to the optimization of moisture availability was observed in soybean and spring wheat. While analyzing the yield increase of the studied crops in terms of individual years, spring wheat turned out to be the most sensitive to moisture availability and reacted more actively than other crops to a decrease of the GWL due to a relatively weak root system compared to the rest of the studied crops.

**Conclusions.** It was found that the weather conditions of the vegetation seasons of 2022, 2023, and 2024 on the drained lands of the melioration system of the SRS of IWP&LR of NAAS were very contrasting: periods with excessive precipitation alternated with their prolonged absence. Significant fluctuations in temperature values were also noted.

On the background of the 3 options for regulating the GWL, the lowest moisture reserves were observed during the summer period. In the areas adjacent to the study area, where the GWL were not regulated, moisture reserves in the 0–30 cm soil layer during the summer dropped to critical values (8–9 mm). In the study areas during this period, due to timely sluicing, soil moisture reserves did not drop below 47–50 mm. Based on the analysis of the dry mass increase dynamics of spring wheat, winter rapeseed, corn for grain, and soybeans according to the options for regulating the soil water regime, the optimal parameters of the soil water regime (GWL, soil moisture, and moisture reserves) were determined for the phases of development of the studied crops.

The highest yield increase due to the optimization of moisture availability was observed for spring wheat and soybeans. Spring wheat is the most sensitive to soil water regime and reacts more actively than other crops to a decrease in the GWL. Regulation of the GWL contributed to an increase of the yield of spring wheat by 41,6 %, winter rapeseed by 18,3 %, corn for grain by 32,5 %, and soybeans by 44,8 %.

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УДК 624.131.6

## ОПТИМАЛЬНІ ПАРАМЕТРИ ВОДНОГО РЕЖИМУ ҐРУНТУ ПРИ ВИРОЩУВАННІ СІЛЬСЬКОГОСПОДАРСЬКИХ КУЛЬТУР НА ОСУШУВАНИХ ЗЕМЛЯХ

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***Анотація.*** *Наведено результати досліджень щодо визначення оптимальних параметрів водного режиму ґрунту при вирощуванні перспективних сільськогосподарських культур на осушуваних* *землях у сучасних умовах господарювання та змін клімату. Встановлено, що погодні умови вегетаційних періодів 2022–2024 рр. були дуже контрастними: чергувалися періоди з надмірною кількістю опадів, тривалою їх відсутністю та відмічалися значні коливання температурних показників. Досліджувані сільськогосподарські культури (яра пшениця, ріпак озимий, кукурудза на зерно та соя) вивчали на фоні 3-х варіантів регулювання рівня ґрунтових вод (РҐВ). У технологічній схемі вирощування культур створена можливість виокремити значення водного режиму у формуванні урожайності вирощуваних культур та визначити їх чутливість до його формування. Регулювання водного режиму здійснювали за допомогою шлюзування. На фоні регулювання рівня ґрунтових вод (РҐВ) найнижчі показники вологозапасів відмічались у літній період, а на прилеглих до досліджуваної території ділянках, де РҐВ не регулювався, вологозапаси влітку у шарі ґрунту 0–30 см опускались до критичних значень (8–9 мм). На дослідних ділянках у цей період завдяки вчасно проведеному шлюзуванню вологозапаси грунту не опускалися нижче 47–50 мм. На основі аналізу динаміки наростання сухої маси пшениці ярої, ріпаку озимого, кукурудзи на зерно та сої за варіантами регулювання РҐВ визначено оптимальні параметри водного режиму грунту (РҐВ, вологість та вологозапаси) за фазами розвитку досліджуваних культур. Визначено, що найвищий приріст урожайності за рахунок оптимізації вологозабезпечення відмічено у пшениці ярої та сої. Пшениця яра є найбільш чутливою до водного режиму ґрунту і активніше інших культур реагує на зниження РҐВ. Регулювання РҐВ сприяло зростанню урожайності ярої пшениці – на 41,6 %, озимого ріпаку – на 18,3 %, кукурудзи на зерно – 32,5 % та сої – 44,8 %.*

***Ключові слова:*** *дренажна система, осушувані землі, зміни клімату, водний режим ґрунту, оптимальні параметри водорегулювання*

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# SOIL DAMAGE AND RECOVERY IN UKRAINE: LESSONS FROM GLOBAL POST-WAR EXPERIENCES

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***Abstract.*** *The russian invasion of Ukraine has resulted in extensive environmental damage, significantly affecting the country's soil quality and raising concerns about long-term agricultural sustainability and environmental health. The war has resulted in soil degradation through contamination by military operations, destruction of farmland, and disruption of natural ecosystems. The objective of the research is to evaluate the environmental consequences of the war in Ukraine, with a particular emphasis on soil degradation and the development of strategies for post-war restoration. The manuscript will entail a comprehensive review of existing literature on soil degradation and post-war environmental restoration, with a particular focus on case studies from conflict zones such as Vietnam, the Balkans, and post-Second World War Europe. Furthermore, an analysis of data from Ukrainian government agencies, environmental organisations, and international bodies will be conducted to assess the extent and nature of soil damage caused by the war. To achieve effective recovery of its soils and ecosystems, Ukraine can draw on global experiences and implement long-term strategies combining modern decontamination technologies, sustainable agricultural practices and policy reforms that promote ecological resilience. It is imperative that environmental, social, and economic factors be integrated into the country's post-war recovery strategy. It is imperative that international cooperation and investment in environmental restoration, in conjunction with community involvement, are pursued in order to guarantee the success of these endeavours and to provide Ukraine with the support it requires in order to achieve a sustainable and resilient agricultural future. The research provides a foundation for the development of integrated strategies that leverage global lessons, thereby ensuring long-term recovery for Ukraine's soil and agricultural systems.*

***Keywords:*** *agriculture, pollution, soil damage, erosion, heavy metal, oil spill, landmine*

**Relevance of the research**. Soil pollution represents a significant environmental issue with global repercussions, frequently resulting from industrial, agricultural, and urban activities. However, one lesser-known yet impactful source of soil pollution arises from war and military conflicts. The deployment of hazardous substances, such as explosives, chemicals, heavy metals, and oil spills, during warfare inevitably results in soil contamination. The destruction of ecosystems during armed conflicts often leads to long-term degradation of arable land, thereby impeding post-war recovery for affected populations and the country in general [24].

As the global economy was beginning to recuperate from the effects of the pandemic, a new crisis emerged with the invasion of Ukraine by russia, resulting in a war in Europe [41]. The russian invasion of Ukraine which intensified in February 2022 precipitated the most significant armed conflict in Europe since the Second World War. The consequences of this situation have not been confined to the countries directly affected; they have also had an impact on Europe and the broader global community indirectly, through the issue of food security [11, 17].

In addition to the human toll, the conflict has resulted in considerable environmental damage, with a particular impact on Ukraine's soil, agricultural sector, and ecosystems [23]. The war has served to exacerbate the pre-existing environmental challenges, while simultaneously introducing novel and acute risks associated with military operations.

**Analysis of the latest research and publications.** The profound impact of war on human lives is well documented. However, the natural environment, which encompasses soil, water, air, and living organisms, is frequently overlooked amidst the devastation. This is despite the fact that human lives are inextricably linked to the natural environment.

The latest research and publications on the environmental impact of armed conflicts have revealed the extensive damage inflicted by war on ecosystems, with soil degradation evoking significant concern [19, 35]. The war has caused extensive environmental destruction and soil contamination in Ukraine. Of particular concern is the damage to the country's fertile agricultural soils, which constitute a critical component of its economy. Ukraine is renowned as the "breadbasket of Europe", with its expansive tracts of fertile black soil (Chernozem) ranking among the most productive in the world [23].

Ukrainian and international environmental agencies and research organizations have commenced the documentation of the effects of the war on the country's natural resources [4, 17, 26]. These include soil contamination from heavy metals and fuel residues, erosion from disturbances on the battlefield, and the disruption of agricultural systems.

It has been demonstrated that military operations, including the utilisation of explosives, the transportation of heavy machinery, and the contamination of the environment with chemical substances, have a considerable impact on the structure of the soil, the composition of nutrients, and biodiversity [16].

Global case studies on post-conflict soil restoration, including those from post-Second World War in Europe offer valuable insights into the rehabilitation of conflict-affected soils [28]. Furthermore, recent publications have examined the role of sustainable agricultural practices in post-conflict recovery as the efficacy of terracing, crop diversification, and organic farming in restoring soil health and ensuring food security in the aftermath of war. Research also underscores the importance of involving local communities and stakeholders in the recovery process, a lesson that Ukraine could benefit from in its restoration efforts [12].

**The purpose of this research** is to examine the environmental impacts of the war in Ukraine, with a particular emphasis on soil quality, and to investigate potential strategies for post-war soil restoration. By analysing global experiences in post-conflict soil recovery, the research aims to provide insights and recommendations for restoring Ukraine's damaged landscapes, ensuring sustainable land use, and supporting long-term ecological resilience.

**Methods and objects of the research.** A review of the existing literature on the subject based on cited publications will be conducted. A comprehensive review of existing literature on soil degradation and post-war environmental restoration will be conducted, with a particular focus on case studies from conflict zones such as Vietnam, the Balkans, and post-Second World War Europe.

The data will then be subjected to analysis. An examination of data collected from Ukrainian government agencies, environmental organisations and international bodies will be conducted to determine the extent and types of soil damage resulting from the war.

**Research results and discussion.** As of September 2024, the Ministry of Environmental Protection and Natural Resources of Ukraine [26] has estimated the financial and environmental impact of military actions to be UAH 2.596 trillion. This figure was calculated by the State Environmental Inspection in accordance with the approved methodology and represents the estimated damage resulting from the aforementioned actions. A total of 5,909 cases of environmental damage resulting from the armed aggression of russian federation have been recorded and documented.

In terms of land resources, the estimated financial loss is UAH 1.15 trillion, based on 2,912 documented cases of damage. The total area of land affected by littering is more than 19.8 million m$^2$, while the contaminated soil area is estimated at more than 945,140 m$^2$, with an estimated financial loss of more than UAH 18.25 billion.

In the context of an ongoing armed conflict in part of Ukraine, soil contamination with lead and fluoride has been identified as a significant environmental concern, warranting further investigation. For instance, in Dnipro region, the concentration of lead has been found to exceed the maximum permissible concentration (MPC) by three times, while in Mykolaiv, the concentration of lead has been found to exceed the MPC by five. The concentration of zinc, copper, fluoride, and oil products has decreased by a quarter; in Zaporizhzhia region, the concentration of lead has increased by 11.17 times the MPC, the concentration of zinc and fluoride has increased by half, the concentration of petroleum products has increased by 35 %, and the concentration of phosphates has increased by 30 % [9].

At this stage, the analysis is limited to a broad overview of the conflict and its consequences. Subsequently, the focus will shift to the immediate and long-term challenges Ukraine is confronted with in its recovery process. This will include an examination of the necessity for environmentally conscious strategies to address the multitude of environmental issues that have been exacerbated by the war.

A substantial body of research has demonstrated the significant and enduring impact of armed conflict on soil quality and ecological systems. The environmental consequences of warfare are manifold and context-specific. Nevertheless, a number of pivotal findings have emerged from studies examining the impact of warfare on soil, including the following: heavy metal contamination, erosion and land degradation, oil and fuel spills, unexploded ordnance and landmines.

*Heavy metal contamination.* Research has demonstrated that war can result in significant heavy metal contamination of soils in conflict zones, for instance, Iraq, Syria [25], and the Balkans [34]. Elevated concentrations of metals such as lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), and depleted uranium (DU) have been identified in soils affected by military action. These metals originate from munitions, military vehicles, and destroyed infrastructure.

Soil samples from conflict zones in Iraq [1] exhibited elevated concentrations of lead and cadmium, exceeding the threshold levels deemed safe for agricultural and residential use.

The utilisation of depleted uranium (DU) munitions in military conflicts, such as the Gulf War, has resulted in the residual presence of radioactive materials in soil, which presents long-term risks to ecosystems and human health [15].

The impact of heavy metal contamination on soil fertility can be considered to have twofold consequences: firstly, it renders land unsuitable for agricultural use, and secondly, it poses a risk to the food chain and water supplies.

The phytoremediation method makes use of plants to absorb, accumulate and detoxify heavy metals from soil. Specific plant species, designated as hyperaccumulators, have the capacity to concentrate metals such as lead, cadmium, and arsenic within their tissues. Subsequently, the plants are harvested and safely disposed of. Notable examples include sunflowers and Indian mustard, which have demonstrated efficacy in soil detoxification in contaminated war zones such as Iraq [14].

Bioremediation employs the use of microbial organisms to facilitate the degradation of contaminants or the transformation of these substances into less harmful compounds. Specific bacteria and fungi are capable of metabolising heavy metals or reducing their mobility in the soil. For example, the use of Pseudomonas bacteria has been demonstrated in post-conflict regions as a means of addressing lead and cadmium pollution [8].

The replanting of trees and the implementation of erosion control measures serve to stabilise the soil, thereby reducing the potential for the spread of contaminants through wind or water runoff. Furthermore, trees and vegetation can assist in the sequestration of heavy metals, thereby preventing their entry into the broader ecosystem [7].

Soil washing is a process whereby the contaminated soil particles are physically separated through the use of water or chemical solutions. This method has the potential to reduce metal concentrations to safer levels and has been employed in regions that have been heavily polluted by conflict, including Kosovo and Serbia [13].

An alternative approach involves the addition of chemical agents, such as lime, phosphate, or biochar, to the soil. These agents bind heavy metals, preventing their absorption by plants or leaching into groundwater. The stabilisers immobilise the metals, reducing their bioavailability. This technique is frequently employed in regions affected by industrial and military contamination [7].

*Erosion and land degradation.* It has been demonstrated that military activities disrupt the physical, chemical, and biological properties of soil, leading to significant degradation [8, 18]. For example, the movement of heavily tracked military vehicles has been observed to increase soil compaction [32], while disturbances caused by tanks have been shown to negatively affect soil quality, resulting in harm to invertebrate populations and vegetation [3].

The research of Almohamad [2] was to identify the characteristics and variations of soil erosion in the context of armed conflicts in the Northern Al-Kabeer River basin in Syria. The mean soil erosion rate is 4 t $ha^{-1}$ per year, with a standard deviation of 6.4 t $ha^{-1}$ per year. Approximately 10.1 % of the basin is subject to a tolerable soil erosion rate, while 79.9 % of the study area has experienced erosion at varying degrees. In areas affected by armed conflict, forest fires tend to result in the dominance of land cover types such as coniferous forest, transitional woodland, and scrub on steeper slopes. In the upper part of the basin, these land cover types exhibited average post-fire soil loss rates that were 200 % to 800 % higher than in the pre-fire situation.

It is frequently the case that military conflicts result in the destruction of forests and other forms of natural vegetation, which in turn gives rise to severe soil erosion. The use of bombs, artillery shelling, and chemical defoliants during conflicts has been documented as a cause of widespread deforestation in research conducted in Afghanistan and Vietnam. In Afghanistan [36], soil erosion has increased significantly in areas that were subjected to intensive bombing during decades of conflict. This has resulted in the desertification of former agricultural land, thereby rendering recovery more challenging.

In Vietnam [37], researchers observed that extensive deforested areas, particularly those treated with herbicides, continue to experience difficulties in regenerating, which has led to soil degradation and a reduction in agricultural productivity.

Furthermore, combat-related activities have been demonstrated to result in a reduction of essential soil components, including total carbon (C), nitrogen (N), microbial biomass, and soil respiration rates [10]. The flux of soil carbon dioxide ($CO_2$) is particularly susceptible to the level of disturbance [33], thereby underscoring the impact of military actions on soil health. Even foot traffic during military training exercises has been demonstrated to compact the soil, decrease water infiltration rates, reduce above-ground biomass, and exacerbate soil erosion [40].

On-site observations at Ar. the Rimam depression of the Sabah Al-Ahmad Nature Reserve in Kuwait [30] demonstrated that the damage to this site was caused by three primary factors: munition disposal pits (11,3 % of the area), compacted areas between pits (36,4 %), and compacted road tracks (3,6 %). The results of the field investigations of soil profiles and laboratory characterisation of soil samples indicated a significant disruption of pedogenic processes, a loss of topsoil, severe soil compaction, a reduction in the infiltration rate, contamination with munition materials, and alterations in chemical properties. Despite the presence of higher vegetation cover in the pits compared to the adjacent compacted areas, the percentage of vegetation cover was found to be significantly lower than that observed during the pre-disturbance period. The soil and vegetation assessment also indicated that the natural recovery process did not fully restore the land and vegetation to their pre-disturbance status.

For example, research from Vietnam highlights the significance of extensive reforestation and the utilisation of bioremediation techniques to detoxify soils contaminated by chemical agents [29]. Similarly, studies from the Balkans emphasise the critical role of erosion control measures and landscape restoration in preventing further environmental degradation [7].

The impact of erosion is the stripping away of the fertile topsoil that is necessary for plant growth, which has the effect of severely reducing agricultural potential and exacerbating food insecurity in post-war areas.

*Oil and fuel spills.* In numerous contemporary armed conflicts, military vehicles, tanks, and aircraft have been identified as a significant source of environmental degradation, largely due to fuel and oil spills. The contamination of soil by hydrocarbons, heavy metals, and toxic chemicals resulting from such spills has been demonstrated to cause long-term damage to biodiversity, agricultural productivity, and water resources. For instance, during the Gulf War, extensive oil spills and the destruction of oil wells resulted in the release of considerable quantities of petroleum into the soil [15]. The soil in Kuwait was significantly contaminated by oil spills and soot from burning oil wells, which resulted in notable alterations to the soil's physical and chemical properties. The contamination of soil with petroleum has resulted in a reduction in soil fertility and the introduction of toxic hydrocarbons, which persist in the environment and are challenging to remediate [27].

The contamination of soil with petroleum disrupts the chemical composition of the soil, kills vegetation, and renders the land unsuitable for agricultural or natural regeneration. For instance, the rate of biodegradation of oil products for different levels of pollution in Chernozem was determined over a period of 24 months [22]. The content of hydrocarbons decreased by 85–87 % and 60–64 %, respectively. One of the key mechanisms for the loss of hydrocarbons from the soil surface is microbiological decomposition. Studies have demonstrated that in the oil concentration range of 6,4–24,6 l/m², there was a notable increase in the intensity of carbon dioxide release from the soil, which is 60 % higher than in the control option. This indicates an intensification of the processes of its biodegradation. The impact of soil pollution with oil on diagnostic indicators such as soil pH and the content of water-soluble potassium and sodium was found to be less significant than the influence of the time factor. The phytotoxicity of oil-contaminated soil was also demonstrated to have a negative impact on seed germination in field conditions. The research results indicate a gradual self-purification of the soil from petroleum hydrocarbons during the observation period.

A variety of methods, including physical, chemical, and biological, are available for addressing oil spills. The initial two methods are constrained by factors such as elevated costs, inefficacy, and disruption to the natural ecosystem [39]. As an alternative, bioremediation offers an environmentally friendly process for the removal or reduction of petroleum pollutants in the environment through the use of selective microbial flora [31].

Baniasadi & Mousavi [5] proposed that bioremediation represents a more environmentally friendly approach than physicochemical methods, which are more cost-effective and cause less disruption to the environment.

In 1991, Kuwait oil fires resulted in the combustion of numerous oil wells, leading to the release of millions of barrels of oil into the surrounding desert environment. This incident caused significant contamination of the soil. Large-scale bioremediation and soil washing efforts were undertaken with the objective of restoring the land. The Iraq conflict (post-2003) resulted in substantial damage to oil infrastructure, with spills contaminating both land and water. Bioremediation was employed as a means of cleansing soil that had been rendered polluted by oil and fuel spills. In this method, natural or genetically modified microorganisms are applied to the polluted site, and/or the polluted environment is enriched with nutrients. These processes are known as bioaugmentation and biostimulation, respectively. The primary focus of attention is due to the fact that these methods have been the subject of scientific investigation by the research community with regard to their potential for the treatment of oil spills, primarily at the laboratory scale, with less extensive investigation in real-world settings.

*Unexploded ordnance (UXO) and landmines.* The presence of unexploded ordnance and landmines in the aftermath of armed conflicts continues to present a significant risk to soil quality and land use. The presence of UXO can result in soil contamination with explosive residues and heavy metals.

The results of studies conducted in Cambodia [21] and Bosnia [20] indicate that soils contaminated with explosive residues have undergone alterations in microbial communities and have exhibited disrupted plant growth. The presence of UXO precludes the safe utilisation of land for agricultural and developmental purposes, resulting in the underutilisation of vast tracts of arable land due to concerns regarding potential detonation.

The impact of UXO on the environment can be significant. The presence of UXO and landmines impedes the post-war recovery and development of agricultural activities. Furthermore, the detonation of ordnance results in the release of toxic chemicals into the soil, thereby exacerbating the pollution.

The identification of unexploded ordnance and landmines can only be addressed through the utilisation of a stochastic-deterministic model but the eventual creation of risk-hazard maps requires preliminary work involving laboratory experiments and field surveys. Baselt et al [6] put forward a novel approach to the problem within the context of an international research project. The objective is to produce risk-hazard maps that can be employed by elected decision-makers, administrative authorities, and emergency personnel in affected municipalities.

Unpiloted aerial systems featuring advanced remote sensing capabilities represent a significant technological advancement with the potential to significantly impact the resolution of the explosive ordnance crisis. In particular, recent developments in hardware engineering have facilitated the effective deployment of compact, lightweight, and less power-consuming hyperspectral imaging (HSI) systems from small unpiloted aerial vehicles (UAVs). The results demonstrate that the analysis of hyperspectral imaging (HSI) data sets can yield spectral profiles and derivative data products, which are capable of distinguishing between multiple ERW and mine types in a range of host environments [38].

**Conclusions.** The research on war-affected soils has revealed the significant environmental degradation that follows military conflicts, particularly in relation to heavy metal contamination and soil erosion. These issues can impede recovery for decades. The implementation of remediation strategies necessitates the formulation of long-term plans, encompassing the utilisation of contemporary decontamination technologies, the adoption of sustainable land use practices, and the allocation of substantial financial resources to facilitate the restoration of ecosystems and to bolster agricultural and economic recovery in post-conflict societies.

The United Nations Environment Programme (UNEP) has highlighted the necessity for integrated strategies that address both environmental and social concerns, advocating for policy frameworks that ensure sustainable land management and ecological recovery. The research emphasises the importance of considering environmental, social, and economic factors in soil restoration, offering insights that can inform the recovery process in Ukraine, drawing on global examples of successful post-war remediation strategies.

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# ПОШКОДЖЕННЯ ТА ВІДНОВЛЕННЯ ҐРУНТІВ В УКРАЇНІ: УРОКИ СВІТОВОГО ПОВОЄННОГО ДОСВІДУ

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***Анотація.*** *Російське вторгнення в Україну призвело до значної шкоди навколишньому середовищу, суттєво вплинувши на якість ґрунтів країни та викликавши занепокоєння щодо довгострокової стійкості сільського господарства та здоров'я довкілля. Війна призвела до деградації ґрунтів через забруднення внаслідок військових дій, знищення сільськогосподарських угідь та порушення природних екосистем. Метою дослідження є оцінка екологічних наслідків війни в Україні, з особливим акцентом на деградацію ґрунтів та розробку стратегій післявоєнного відновлення. Рукопис передбачає всебічний огляд існуючої літератури з питань деградації ґрунтів та повоєнного відновлення довкілля, з особливим акцентом на тематичних дослідженнях із зон конфліктів, таких як В'єтнам, Балкани та Європа після Другої світової війни. Крім того, буде проведено аналіз даних українських урядових установ, екологічних організацій та міжнародних організацій для оцінки масштабів і характеру ґрунтових пошкоджень, спричиненних війною. Щоб досягти ефективного відновлення ґрунтів та екосистем, Україна може використати світовий досвід і впровадити довгострокові стратегії, що поєднують сучасні технології знезараження, стійкі сільськогосподарські практики та політичні реформи, які сприяють екологічній стійкості. Вкрай важливо, щоб екологічні, соціальні та економічні фактори були інтегровані в стратегію післявоєнного відновлення країни. Міжнародне співробітництво та інвестиції у відновлення довкілля у поєднанні із залученням громадськості є запорукою успіху цих зусиль та надання Україні підтримки, необхідної для досягнення сталого та життєздатного сільськогосподарського майбутнього. Дослідження створює основу для розробки комплексних стратегій, які враховують глобальний досвід, забезпечуючи тим самим довгострокове відновлення ґрунтів та сільськогосподарських систем України.*

***Ключові слова:*** *сільське господарство, забруднення, пошкодження ґрунтів, ерозія, важкі метали, розлив нафти, наземні міни*

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# ASSESSMENT OF THE ACCURACY OF METEOROLOGICAL DATA OBTAINED FROM VIRTUAL AND AUTOMATIC WEATHER STATIONS FOR THE CONDITIONS OF UKRAINIAN POLISSYA

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***Abstract.*** *The article presents a comprehensive assessment of meteorological data obtained from the virtual Visual Crossing Weather Data (VCWD) and the automatic (iMetos Base) meteorological station for the Polissya region of Ukraine. For this purpose, were selected the meteorological data which are included in the formula for calculating the reference evapotranspiration ($ET_0$) according to the Penman-Monteith method (FAO56-PM), namely average (Tmean), maximum (Tmax) and minimum (Tmin) air temperature, dew point temperature (Tdew), average relative humidity (Rhmean), average water vapor pressure deficit (Damean), total solar radiation (Rs), average wind speed at a height of 2 m ($u_2$) and daily precipitation (P). The results of the regression analysis and the calculation of the mean absolute percentage error (MAPE), root mean square error (RMSE), and standard error (SEE) demonstrate that the data on mean and maximum air temperature, as well as dew point temperature, were obtained with a high degree of accuracy from the virtual VCWD weather station. The MAPE errors are 5,6, 2,8, and 8,3 %, respectively (MAPE < 10 %). For the minimum air temperature and average relative humidity, good accuracy is inherent, with MAPE errors of 20,0 and 13,6 %, respectively (MAPE =10-20 %). The data on solar radiation and water vapor pressure deficit were obtained with satisfactory accuracy, with MAPE errors of 25,0 and 45,2 %, respectively (MAPE = 20–50 %). The data on wind speed at a height of 2 m, total monthly and daily precipitation were obtained with unsatisfactory accuracy, with MAPE errors of 62,3, 52,6, and 40103 % (MAPE >50 %), respectively. It has been established that the values of daily precipitation (RMSE = 6,0 mm) obtained from VCWD are not accurate. It is possible to use only the total precipitation for the month (RMSE = 11,6 mm) or its annual values (RMSE = 47,9 mm). The application of a correction factor to the obtained meteorological data increases their accuracy and reduces the errors of MAPE, RMSE and SEE. The use of various errors made it possible to comprehensively verify the obtained meteorological data. For example, the MAPE error calculates the accuracy of the meteorological indicator, while the RMSE and SEE errors indicate how the obtained value differs from the average value. In the future, the obtained meteorological indicators from the Visual Crossing Weather Data virtual meteorological station will be used to calculate the reference and actual evapotranspiration using the Penman-Monteith method (FAO56-PM) in the conditions of Polissya of Ukraine.*

***Keywords:*** *virtual weather station, meteorological data, air temperature, precipitation, accuracy, MAPE, RMSE and SEE errors*

**Relevance of the study.** Meteorological data are useful for a variable applications, such as weather and climate forecasting, landscape planning, and disaster management. However, the availability of these data requires a good network of stationary meteorological stations and other supporting systems for their collection, recording, processing, archiving, communication, and dissemination [1]. Weather-based forecasting models play an important role in agricultural decision support systems, but they are usually computed at the regional level due to the limited number of weather stations. Farmers have to contact the nearest weather station, but the recommendations are not always adapted to their situation [2, 3]. Currently, virtual weather stations (VWS) are widely used [2, 4] and the demand for spatial climate data in digital form has increased [5]. A VWS is the integration of algorithms for downloading meteorological data, processing it, and using it to obtain data in the nearest places where there are no meteorological stations. To develop a VWS, it is necessary to evaluate the accuracy of various interpolation methods and the original meteorological data [2, 4]. Evaluation of meteorological data obtained from different sources is a fundamental task of meteorological analysis [6]. Studies conducted in Kenya [1], Belgium [2], the United States [3], Ecuador [7, 8], New Zealand [9], Brazil [10], Albania [11], Poland [12], Canada [13], and Ukraine [14] determined the accuracy of available meteorological data for individual points of the landscape obtained from the Virtual Climate Station Network by comparing them with measurements at independent meteorological stations.

To establish the accuracy of meteorological data obtained from virtual weather stations, we chose Visual Crossing Weather Data (VCWD). VCWD provides easy access to hourly or daily climate data for the entire world, including forecast data for the next 15 days. Its archive includes more than 50 years of global weather history. In addition to the usual meteorological indicators, such as temperature and relative humidity, wind speed and precipitation, powerful features such as solar radiation and energy, degree days, evapotranspiration reference and weather forecast are available. All data from the site is available for download via the weather data request page and the weather API. The datasets are displayed in a table, which is available in several formats. One of the powerful features of VCWD is the ability to import data into most business intelligence systems, including Excel, for further processing [18].

Although meteorological parameters are measured regularly and are widely available on weather forecasting services on the Internet, they need to be checked for accuracy in each region separately. Previous studies have examined one or more meteorological indicators. № comprehensive verification of all meteorological data measured by an automatic weather station has yet been conducted. Therefore, this study was conducted to verify the accuracy and quality of the meteorological data obtained from the virtual climate station for the conditions of Polissya in Ukraine.

**Analysis of recent research and publications.** Studies conducted around the world confirm the reliability of meteorological data obtained from virtual weather stations (VWS) [2, 9, 13]. As stated in [2, 4, 5], in order to develop VWS and GIS-compatible climate maps, it is necessary to evaluate the accuracy of various interpolation methods and source meteorological data. To validate VWS, a randomly selected weather station is removed from daily datasets and the interpolated values are compared to the actual values. From a practical point of view, the meteorological data obtained from VWS can be used to control crop irrigation. To develop the VWS in the United States, the authors of [15] used the PRISM (Parameter-elevation Relationships on Independent Slopes Model) interpolation method, which was compared with the WorldClim and Daymet climate data sets. The comparison showed that the use of a relatively dense set of station data and the PRISM interpolation method led to a significant improvement in climate data compared to WorldClim and Daymet.

Often, meteorological data are not used independently, but as input data in various climate models, so their quality affects the accuracy of calculations [17]. Many studies have been devoted to the statistical comparison of meteorological data, some of which are more than 100 years old [16]. Studies by the authors of [7, 8] demonstrate the importance of using high-quality meteorological data to calculate the reference evapotranspiration. The verification of the results of meteorological data obtained from VWS and automated weather stations (AWS), which was performed by the authors of [3] in the western United States, showed their reliability and they can serve as input data for landscape environmental modeling. Studies conducted in New Zealand [9] determined the accuracy of available meteorological data for individual points of the landscape obtained from the Virtual Climate Station Network (VCSN) by comparing them with measurements at independent meteorological stations. It was found that the average monthly global radiation, average daily maximum and minimum air temperature are obtained from the VCSN with reasonable accuracy and a small margin of error. However, the amount of precipitation was calculated inaccurately. The authors' research [12] on air temperature observations in Warsaw (Poland) showed that the statistical ML (machine learning) model can serve as an alternative approach to traditional kriging and numerical modeling, characterized by lower complexity and higher computing speed in the field of urban meteorological research (RMSE = 1,06 °C and $R^2$ = 0,94, compared to AWS). The authors of [13, 17] note that air temperature obtained from

VWS is an attractive source of data for predicting water temperature due to the reduced cost of instrumental equipment and the availability of long-term historical records over large areas of North America.

Studies conducted in Brazil (Paraíba State) [10] comparing global horizontal irradiation obtained from automated meteorological stations and satellite images showed good correlation of data. It was confirmed that the calculated data from satellite images slightly exceed those obtained by ground-based meteorological stations. Comparison of solar radiation data provided by NASA's Solar Radiation Database with available ground measurements in Albania [11] shows that the ground-based solar radiation data are in all cases underestimated compared to the data provided by the NASA database. The conversion factor is 1,149. Work [14] compared the average daily air temperature in the Odesa region obtained from a field monitoring station with data from the weather forecasting service (Meteo.Farm) and the weather site of the Odesa State Agricultural Station of the Institute of Food and Agriculture of the National Academy of Agrarian Sciences of Ukraine. The standard deviations showed the closeness of the air temperature data between all three data sources: RMSE (weather site) = 1,38 °C and RMSE (weather site) = 1,63 °C.

**The purpose of the research** was to conduct a comprehensive verification of meteorological data obtained from the virtual (Visual Crossing Weather Data) and automatic (iMetos) meteorological stations for the conditions of Polissya in Ukraine.

**Materials and methods.** The daily meteorological data for this study were obtained from VWS Visual Crossing Weather Data (VCWD) [18] for the period May-September 2023-2024 and from the iMetos Base weather station from Pessl Instruments [19], which is located at the experimental site in LLC "Agrofirma Kyivska", Makovyshche village, Bucha district, Kyiv region (50.4574°, 29.8949°).

For the comprehensive verification, we selected meteorological data that are included in the formula for calculating the reference evapotranspiration (ET) according to the Penman-Monteith method (FAO56-PM) [20], namely, mean (Tmean), maximum (Tmax) and minimum (Tmin) air temperature, dew point temperature (Tdew), average relative humidity (Rhmean), average water vapor pressure deficit (Damean), total solar radiation (Rs), average wind speed at a height of 2 m ($u_2$), and daily precipitation (P).

To verify the obtained meteorological data, we used regression analysis and the graph analytical method, for which the actual values obtained from AWS iMetos were plotted on the abscissa axis and the actual values obtained from VWS Visual Crossing Weather Data on the ordinate axis. The resulting linear relationship was compared with a 1:1 line [1, 7]. To assess the accuracy of the obtained meteorological data, the mean absolute percentage error MAPE [21, 22], root mean square error RMSE [23], and standard error of estimate SEE [24] were determined:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{x-y}{x}\right|\cdot 100\% . \qquad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x-y\right)^2} . \qquad (2)$$

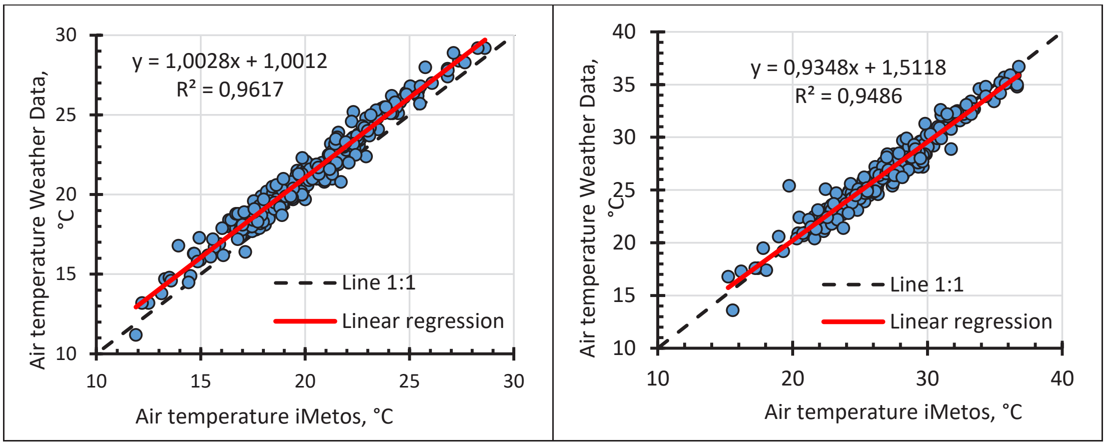
$$E = \sqrt{\frac{1}{(n-2)}\left[\left(y-\bar{y}\right)^2 - \frac{\left[\Sigma\left(x-\bar{x}\right)\left(y-\bar{y}\right)\right]^2}{\Sigma\left(x-\bar{x}\right)^2}\right]} \qquad (3)$$

where $x$ – the value of the meteorological indicator obtained from AWS iMetos; $y$ – from VWS VCWD; $\bar{x}$. – is the average value of the meteorological indicator obtained from AWS iMetos; $\bar{y}$ – from VWS VCWD; $n$ – sample size ($n = 306$).

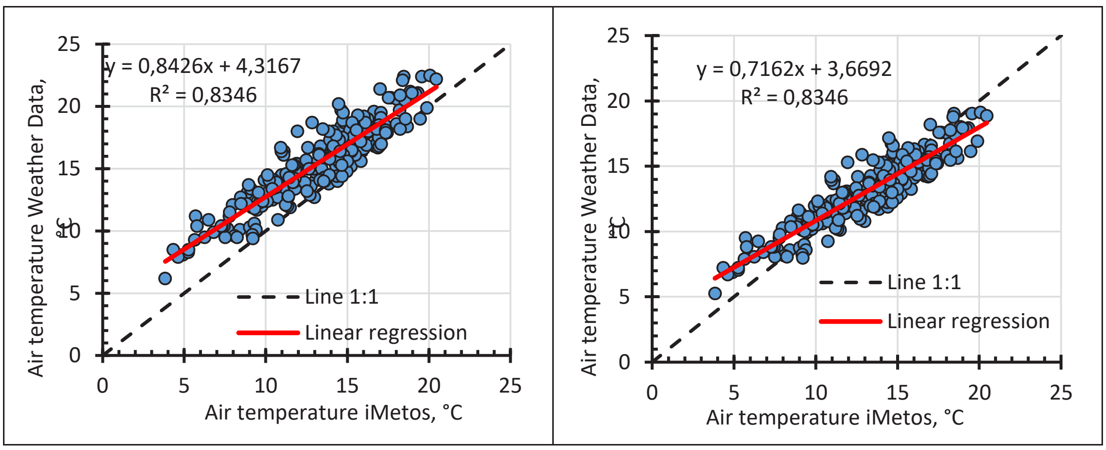
The use of various errors makes it possible to comprehensively verify the obtained meteorological data. For example, the MAPE error calculates the accuracy of the meteorological indicator. The RMSE and SEE errors indicate how the obtained value differs from the average value. The lowest errors indicate the best accuracy of the obtained meteorological indicator.

**Research results and discussion.** According to the results of a comprehensive check of air temperature, which was obtained from VMS Visual Crossing Weather Data and from the iMetos automatic meteorological station, it was found that the most reliable data are obtained for the average and maximum air temperature. As can be seen from the graph (Fig. 1a, 1b), the obtained linear dependencies almost coincide with the 1:1 line, and the coefficients of determination are 0,9617 and 0.9486, respectively. Less accurate data are obtained for the minimum air temperature, the linear dependence is above the 1:1 line (Fig. 1c), and the coefficient of determination is 0,8346. This indicates an overestimation of the minimum air temperature relative to the actual temperature.

The results of the error calculations (Table 1) also confirm that the most reliable data are obtained for the average and maximum air temperature. For example, for the maximum air temperature, on average over the years of research, the errors of MAPE, RMSE, and SEE




a) average air temperature, °C b) maximum air temperature, °C




c) minimum air temperature, °C d) minimum specified air temperature, °C

Fig. 1. Regression analysis for checking air temperature

were 2,8 %, 1.0, and 0,9 °C, respectively, which corresponds to the high accuracy of the result [22]. For 2023–2024, the MAPE, RMSE, and SEE errors for the maximum air temperature were 2,4–3,1 %, 0,8–1,1, and 0.75–1.04 °C, respectively. In terms of months of research, the errors of MAPE, RMSE, and SEE for the maximum air temperature were within 2,6–3,4 %, 0,8–1,1, and 0,66-1,00⁰ C, respectively. The minimum error values were observed in May, and the maximum in July and September. Such a small range of errors indicates their stability over time.

For the minimum air temperature, the errors of the MAPE, RMSE, and SEE were 20,0 %, 2,6, and 1,29 °C, respectively, which corresponds to the good accuracy of the result [22]. To improve the accuracy of the minimum air temperature, we calculated the ratio of the actual minimum temperature to the one obtained from VCWD, which averaged 0.85 over the years of research. Multiplying the obtained minimum air temperature data by the correction factor of 0,85, we obtained the revised minimum air temperature. As a result, the errors of the MAPE, RMSE, and SEE decreased and amounted to 10,4 %, 1,5, and 1,10 °C, respectively (Table 1), which corresponds to the high accuracy of the result (Fig. 1d).

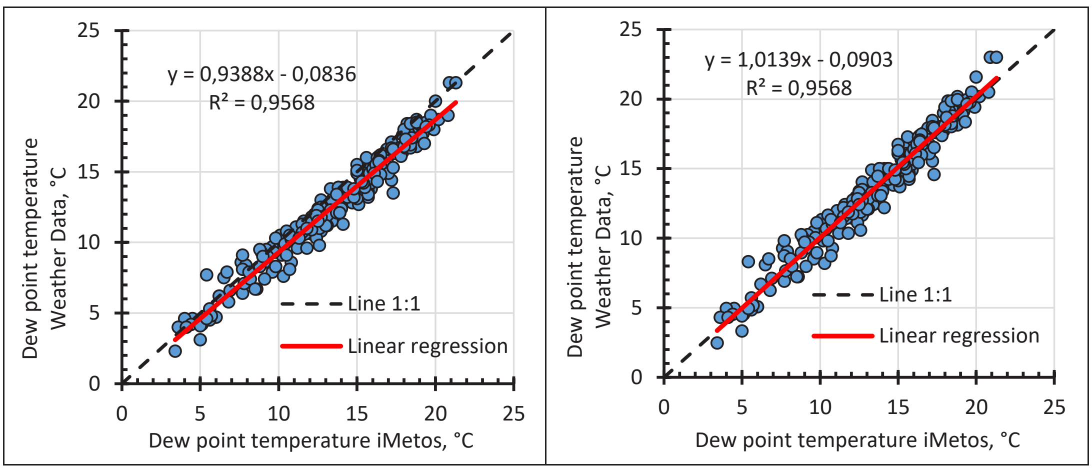
According to the analysis of the graph (Fig. 2a), it was found that the obtained linear dependence for the dew point temperature almost coincides with the 1:1 line, and the coefficients of determination are 0.9568, which indicates the high accuracy of the results [24].

The results of the error calculations (Table 2) also confirm the high accuracy of the dew point temperature obtained from VCWD. Thus, on average, over the years of research, the errors of MAPE, RMSE, and SEE, respectively, were 8,3 %, 1,2, and 0,79 °C, which corresponds to the high accuracy of the result [22]. For the years 2023–2024, the errors of MAPE, RMSE, and SEE were 6,8–9,7 %, 0,9–1,5, and 0,68–0,72 °C, respectively. In terms of months of research, the errors of MAPE, RMSE and

1. MAPE, RMSE and SEE errors for air temperature, °C (by observation periods)

| Observation period | Air temperature, °C | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | aver | max | mine | min* | aver | max | mine | min* | aver | max | mines | min* |
| | MAPE error | | | | RMSE error | | | | SEE error | | | |
| average | 5,6 | 2,8 | 20,0 | 10,4 | 1,2 | 1,0 | 2,6 | 1,5 | 0,63 | 0,90 | 1,29 | 1,10 |
| 2023 | 5,5 | 2,4 | 20,0 | 9,3 | 1,2 | 0,8 | 2,4 | 1,2 | 0,57 | 0,75 | 1,07 | 0,91 |
| 2024. | 5,6 | 3,1 | 20,1 | 11,4 | 1,3 | 1,1 | 2,8 | 1,7 | 0,69 | 1,04 | 1,42 | 1,21 |
| May | 4,6 | 2,6 | 25,3 | 13,3 | 0,9 | 0,8 | 2,3 | 1,4 | 0,67 | 0,66 | 0,77 | 0,65 |
| June | 4,7 | 2,6 | 12,5 | 8,3 | 1,1 | 0,8 | 1,7 | 1,3 | 0,57 | 0,80 | 0,97 | 0,82 |
| July | 5,4 | 2,9 | 17,2 | 7,4 | 1,3 | 1,1 | 2,6 | 1,3 | 0,59 | 1,00 | 1,15 | 0,98 |
| August | 6,1 | 2,4 | 22,6 | 8,5 | 1,4 | 0,9 | 3,2 | 1,4 | 0,43 | 0,77 | 1,06 | 0,90 |
| September | 6,5 | 3,4 | 28,7 | 18,9 | 1,3 | 1,0 | 2,8 | 1,9 | 0,67 | 0,85 | 1,08 | 0,92 |

min* – specified minimum air temperature.




a) dew point temperature b) specified dew point temperature

Fig. 2. Regression analysis to check the dew point temperature

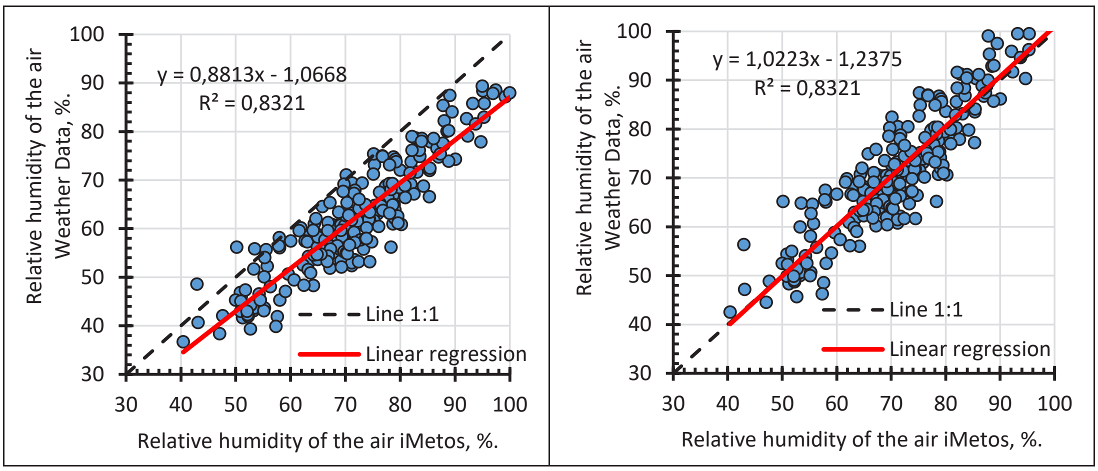
SEE for dew point temperature were in the range of 11,4–7,1 %, 1,4–0.9 and 0,93–0,53 °C, respectively. The minimum error values were observed in the summer months, and the maximum in May and September. To improve the accuracy of the dew point temperature, we calculated the ratio of the actual dew point temperature to the one obtained from VCWD, which averaged 1.07 over the years of research. Multiplying the obtained dew point temperature data by the correction factor of 1,07, we obtained the corrected dew point temperature. As a result, the MAPE and RMSE errors decreased by 2,5 % and 0,3 °C, and the SEE error increased by only 0,06 °C. The refined dew point temperature also corresponds to the high accuracy of the result (Fig. 2b).

According to the analysis of the graph (Fig. 3a), it was found that the obtained linear dependence for relative humidity is below the 1:1 line, the coefficients of determination of the obtained dependence are 0,8321. This indicates that the relative humidity is underestimated relative to the actual one.

On average, over the years of research, the MAPE, RMSE, and SEE errors for relative humidity obtained from VCWD were 13.6 %, 10.7 %, and 4.62 %, respectively (Table 3), which corresponds to the good accuracy of the result [22]. For the years 2023–2024, the errors of the MAPE, RMSE, and SEE were 11,5–15,7 %, 9.0–12.1, and 4,24–4,39 %, respectively. In terms of months of research, the errors of MAPE, RMSE and SEE for relative humidity were in the range of 16,1–8,9 %, 12,2–5,6 and 4,38–2,39 %, respectively. The minimum error values were observed in May, and the maximum – in the summer months. To improve the accuracy of relative humidity, we calculated the ratio of actual relative humidity to that obtained from VCWD,

2. Errors of MAPE, RMSE and SEE for dew point temperature, °C (by observation periods)

| Observation period | Dew point temperature, °C | | | | | |
|---|---|---|---|---|---|---|
| | average | refined | average | refined | average | refined |
| | MAPE error | | RMSE error | | SEE error | |
| average | 8,3 | 5,8 | 1,2 | 0,9 | 0,79 | 0,85 |
| 2023 | 6,8 | 6,5 | 0,9 | 0,8 | 0,68 | 0,74 |
| 2024 | 9,7 | 5,2 | 1,5 | 0,9 | 0,72 | 0,78 |
| May | 11,4 | 15,8 | 0,9 | 1,2 | 0,93 | 1,00 |
| June | 7,1 | 4,7 | 1,1 | 0,7 | 0,62 | 0,67 |
| July | 7,1 | 4,3 | 1,4 | 0,9 | 0,77 | 0,83 |
| August | 7,8 | 4,0 | 1,3 | 0,7 | 0,53 | 0,58 |
| September | 10,9 | 8,4 | 1,2 | 1,0 | 0,76 | 0,83 |




a) relative humidity b) clarified relative humidity

Fig. 3. Regression analysis for checking relative humidity

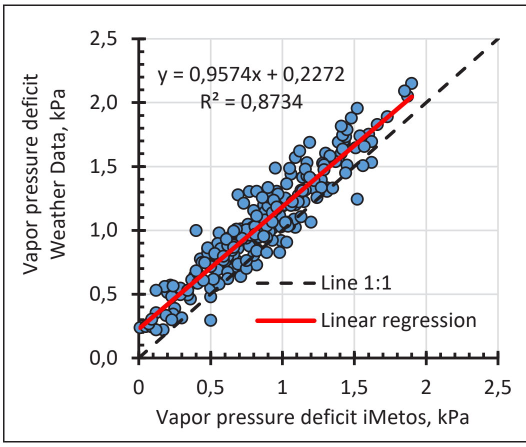
which averaged 1.16 over the years of research. Multiplying the obtained relative humidity data by the correction factor of 1,16, we obtained the corrected relative humidity. As a result, the MAPE and RMSE errors decreased by 7,4 % and 5,3 %, and the SEE error increased by 0,74 %. The accuracy of the result of the refined relative humidity increased to high (Fig. 3b).

Based on the analysis of the graph (Fig. 4a), it was found that the obtained linear dependence for the water vapor pressure deficit is above the 1:1 line, the $R^2$ of the obtained dependence is 0,8734. This indicates an overestimation of the water vapor pressure deficit relative to the actual values.

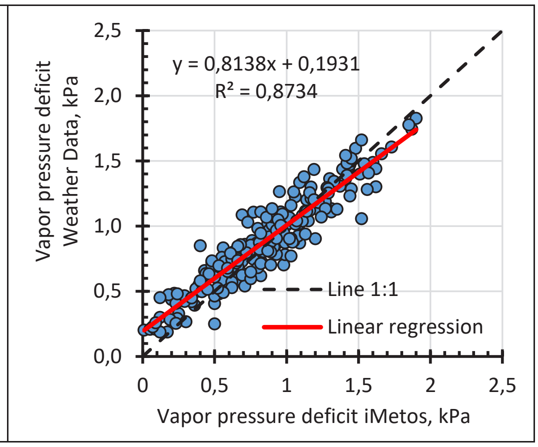
On average, over the years of research, the MAPE, RMSE, and SEE errors for the water vapor pressure deficit obtained from VCWD were 45,2 %, 0,24, and 0,14 kPa, respectively (Table 4), which corresponds to satisfactory accuracy [22]. For the years 2023–2024, the errors of MAPE, RMSE, and SEE, respectively, were 47,8–42,6 %, 0.21–0,26, and 0,14–0,13 kPa. In the context of months of research, the errors of MAPE, RMSE, and SEE for the water vapor pressure deficit were in the range of 82,7–9,8 %, 0,28–0,13, and 0,14–0,07 kPa, respectively. The minimum error values were observed in May, and the maximum in the summer months. It should be noted that the MAPE error in July was very high, amounting to 82,7 %, which corresponds to the unsatisfactory accuracy of the result [22]. To improve the accuracy of the water vapor pressure deficit, we calculated the ratio of the actual water vapor pressure deficit to the one obtained from VCWD, which averaged 0,80 over the years of research. Multiplying the obtained data on the water vapor pressure deficit by the correction factor of 0,80, we obtained the refined water vapor pressure deficit. As a result, the errors of MAPE, RMSE, and SEE decreased by 7,4 %, 0,1, and 0,03 kPa. The accuracy of the result of the refined water vapor pressure deficit remained satisfactory (Fig. 4b). In July, the MAPE error

3. Errors of MAPE, RMSE and SEE for relative humidity, % (by observation periods)

| Observation period | Relative air humidity, %. | | | | | |
|---|---|---|---|---|---|---|
| | average | refined | average | refined | average | refined |
| | MAPE error | | RMSE error | | SEE error | |
| average | 13,6 | 6,2 | 10,7 | 5,4 | 4,62 | 5,36 |
| 2023 | 11,5 | 6,2 | 9,0 | 5,3 | 4,24 | 4,92 |
| 2024 | 15,7 | 6,2 | 12,1 | 5,4 | 4,39 | 5,09 |
| May | 8,9 | 11,7 | 5,6 | 7,4 | 2,39 | 2,77 |
| June | 11,6 | 6,2 | 9,5 | 5,7 | 4,38 | 5,08 |
| July | 14,4 | 5,3 | 11,6 | 5,1 | 4,12 | 4,77 |
| August | 16,1 | 5,3 | 12,2 | 4,6 | 4,35 | 5,05 |
| September | 13,4 | 6,7 | 9,9 | 5,2 | 2,76 | 3,20 |




a) water vapor pressure deficit




b) specified water vapor pressure deficit

Fig. 4. Regression analysis for checking the water vapor pressure deficit

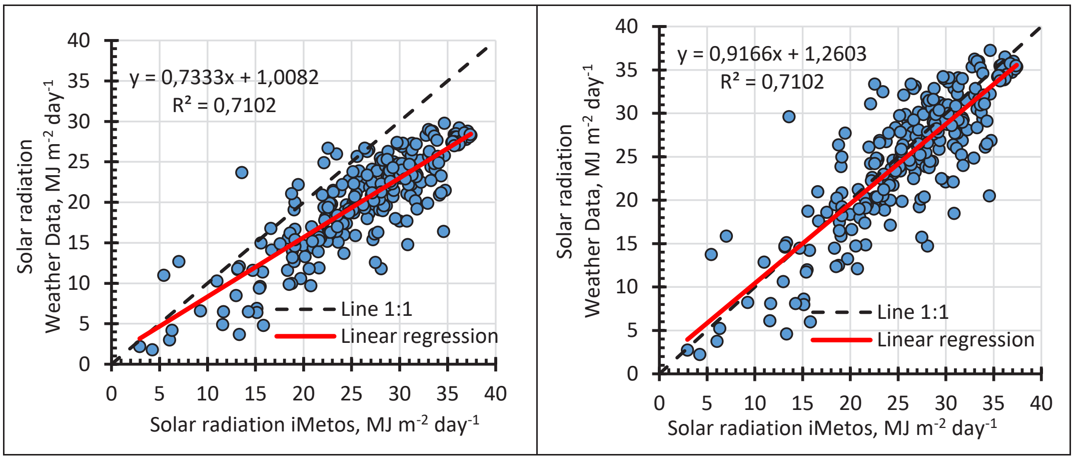
4. MAPE, RMSE and SEE errors for water vapor pressure deficit, kPa (by observation periods)

| Observation period | Water vapor pressure deficit, kPa | | | | | |
|---|---|---|---|---|---|---|
| | average | refined | average | refined | average | refined |
| | MAPE error | | RMSE error | | SEE error | |
| average | 45,2 | 27,7 | 0,24 | 0,14 | 0,14 | 0,11 |
| 2023 | 47,8 | 32,2 | 0,21 | 0,15 | 0,14 | 0,11 |
| 2024 | 42,6 | 23,3 | 0,26 | 0,14 | 0,13 | 0,11 |
| May | 9,8 | 17,0 | 0,13 | 0,22 | 0,07 | 0,05 |
| June | 40,3 | 22,8 | 0,23 | 0,13 | 0,14 | 0,11 |
| July | 82,7 | 53,8 | 0,28 | 0,14 | 0,14 | 0,12 |
| August | 34,7 | 16,6 | 0,25 | 0,14 | 0,09 | 0,07 |
| September | 26,9 | 17,4 | 0,19 | 0,14 | 0,11 | 0,09 |

decreased to 53,8 %, which brings the accuracy of the results obtained in this month almost to satisfactory.

Based on the analysis of the graph (Fig. 5a), it was found that the obtained linear dependence for solar radiation is below the 1:1 line, the coefficients of determination of the obtained dependence are 0,7102. This indicates an underestimation of solar radiation values relative to the actual ones.

On average, over the years of research, the errors of MAPE, RMSE, and SEE for solar radiation obtained from VCWD were 25,0 %, 7,0, and 3,26 MJ/m$^2$ /day, respectively (Table 5), which corresponds to the satisfactory accuracy of the result [22]. For 2023–2024, the errors of




a) solar radiation b) refined solar radiation

Fig. 5. Regression analysis to check solar radiation

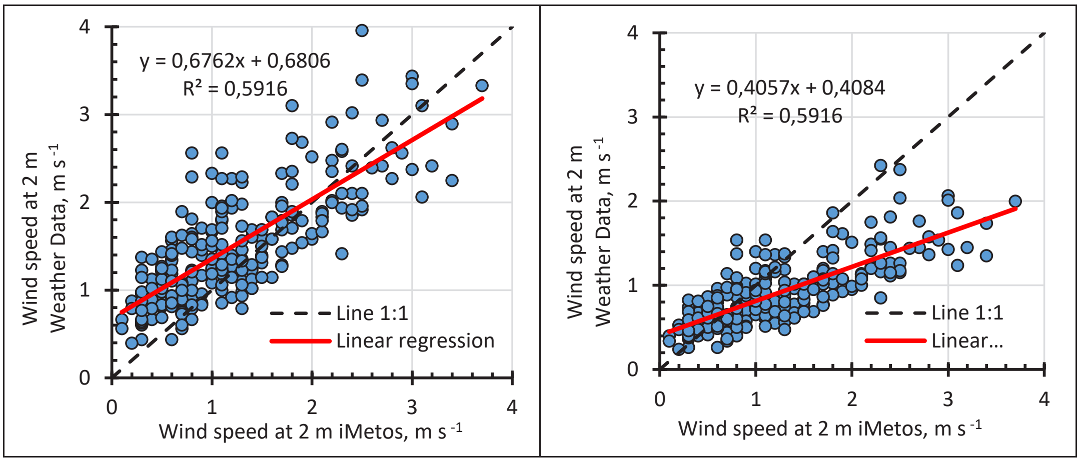
MAPE, RMSE, and SEE, respectively, were 24,5–25,6 %, 6,7–7,3, and 3,49–2,99 MJ/m$^2$/day. In the context of the study months, the errors of MAPE, RMSE and SEE for solar radiation were in the range of 28,9–22,7 %, 7,3–6,0 and 7,48–1,97 MJ/m$^2$ /day, respectively. The minimum values for the MAPE error were observed in the summer months, and the maximum values were observed in May and September. For the RMSE error, on the contrary, the maximum values were observed in the summer months, and the minimum values were observed in May and September. The maximum values of the SEE error were in May and the minimum values were in September. To improve the accuracy of solar radiation, we calculated the ratio of actual solar radiation to that received from VCWD, which averaged 1,25 over the years of research. Multiplying the obtained solar radiation data by the correction factor of 1,25, we obtained the corrected solar radiation. As a result, the MAPE and RMSE errors decreased by 10,5 % and 2,8 MJ/m$^2$ /day, and the SEE error increased by 0,82 MJ/m$^2$/day. The accuracy of the result of the refined solar radiation increased to good (Fig. 5b).

The largest deviations of the obtained meteorological data from the actual ones were found for wind speed, with a determination coefficient of 0,5916 for the established dependence (Fig. 6a). According to the analysis of the graph, it was found that the obtained linear dependence for wind speed crosses the 1:1 line at the point 2.1. Up to the value of 2,1, the linear dependence passes above the 1:1 line, and after crossing it, it passes below. This indicates that the wind speed is overestimated up to a value of 2.1 m/s, and then it is underestimated.

On average, over the years of research, the MAPE, RMSE, and SEE errors for the wind speed at a height of 2 m obtained from VCWD were 62,3 %, 0,56, and 0,43 m/s, respectively (Table 6), which corresponds to the unsatisfactory accuracy of the result [22]. For the years 2023–2024, the errors of the MAPE, RMSE,

5. MAPE, RMSE and SEE errors for solar radiation, MJ/m$^2$ /day (by observation periods)

| **Observation period** | **Solar radiation, MJ/m /day$^2$** | | | | | |
|---|---|---|---|---|---|---|
| | **total** | **refined** | **total** | **refined** | **total** | **refined** |
| | **MAPE error** | | **RMSE error** | | **SEE error** | |
| average | 25,0 | 14,5 | 7,0 | 4,2 | 3,26 | 4,08 |
| 2023 | 24,5 | 15,0 | 6,7 | 4,4 | 3,49 | 4,36 |
| 2024 | 25,6 | 14,0 | 7,3 | 4,0 | 2,99 | 3,74 |
| May | 26,1 | 19,5 | 6,6 | 5,3 | 7,48 | 9,35 |
| June | 24,5 | 17,5 | 7,3 | 4,8 | 3,82 | 4,77 |
| July | 24,9 | 14,5 | 7,6 | 4,4 | 3,27 | 4,09 |
| August | 22,7 | 10,4 | 6,9 | 3,7 | 2,72 | 3,40 |
| September | 28,9 | 14,4 | 6,0 | 3,1 | 1,97 | 2,46 |




a) wind speed b) updated wind speed

Fig. 6. Regression analysis to check wind speed

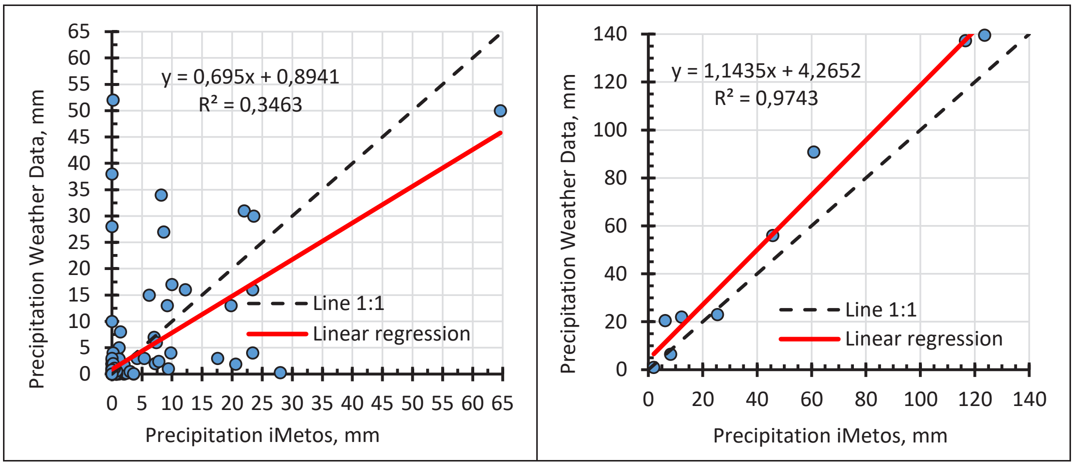
and SEE, respectively, were 25,8–98,7 %, 0,36–0,71, and 0,32–0,45 m/s. In the context of the study months, the MAPE, RMSE, and SEE errors for wind speed were in the range of 124,3–23,6 %, 0,68–0,35, and 0,39–0,27 m/s, respectively. The minimum values for the errors were observed in May and June, and the maximum values were observed in July and August. It is worth noting the very high error of the MAPE in August, which amounted to 124,3 %. To improve the accuracy of wind speed determination, we calculated the ratio of the actual wind speed to the one obtained from VCWD, which averaged 0,6 over the years of research. Multiplying the obtained wind speed data by the correction factor of 0,6, we obtained the refined wind speed. As a result, the MAPE and SEE errors decreased by 23,3 % and 0,19 m/s, and the RMSE error increased by 0,05 m/s. The accuracy of the data obtained increased to satisfactory (Fig. 5b). At the same time, despite the decrease in average errors over the years of research, in May and June, the MAPE and RMSE errors increased. Thus, in May, these errors increased by almost 2,5 times.

Based on the results of comparing the daily precipitation obtained from the VCWD and the actual values, a moderate relationship between them was established [24], with a determination coefficient of 0,3463 (Fig. 7a). The obtained linear dependence for daily precipitation falls below the 1:1 line. Based on the analysis of total precipitation for the month obtained from VCWD and actual precipitation, a close relationship between them was established. The coefficients of determination are 0,9743 (Fig. 7b). The resulting linear relationship for total precipitation per month is above the 1:1 line. This indicates an overestimation of total precipitation for the month relative to the actual precipitation.

On average, over the years of research, the errors of MAPE, RMSE, and SEE for daily precipitation obtained from VCWD were 40103 %, 6,0, and 5,7 mm/day, respectively (Table 7), which corresponds to a very unsatisfactory accuracy of the result [22]. Such high error values are observed

6. MAPE, RMSE and SEE errors for wind speed, m/s (by observation periods)

| **Observation period** | **Wind speed, m/s** | | | | | |
|---|---|---|---|---|---|---|
| | **average** | **refined** | **average** | **refined** | **average** | **refined** |
| | **MAPE error** | | **RMSE error** | | **SEE error** | |
| average | 62,3 | 39,0 | 0,56 | 0,61 | 0,43 | 0,26 |
| 2023 | 25,8 | 38,0 | 0,36 | 0,72 | 0,32 | 0,19 |
| 2024 | 98,7 | 40,0 | 0,71 | 0,48 | 0,45 | 0,27 |
| May | 18,6 | 50,2 | 0,48 | 1,13 | 0,39 | 0,23 |
| June | 23,6 | 36,7 | 0,35 | 0,77 | 0,25 | 0,15 |
| July | 48,3 | 31,3 | 0,55 | 0,58 | 0,33 | 0,20 |
| August | 124,3 | 53,8 | 0,68 | 0,35 | 0,27 | 0,16 |
| September | 63,1 | 28,1 | 0,67 | 0,37 | 0,25 | 0,15 |




a) daily b) the amount for the month

Fig. 7. Regression analysis for precipitation verification

7. Errors of MAPE, RMSE and SEE for precipitation, mm (by observation periods)

| **Observation period** | **Precipitation, mm** | | | | | |
|---|---|---|---|---|---|---|
| | **daily** | **amount for the month** | **daily** | **amount for the month** | **daily** | **amount for the month** |
| | **MAPE error** | | **RMSE error** | | **SEE error** | |
| average | 40103 | 52,6 | 6,0 | 11,6 | 5,7 | - |
| 2023 | 18295 | 72,7 | 6,4 | 12,6 | 6,3 | - |
| 2024 | 61912 | 32,5 | 5,4 | 10,7 | 5,1 | - |
| May | 4367 | 50,0 | 5,0 | 10,0 | 4,8 | - |
| June | 52911 | 33,5 | 6,2 | 25,3 | 6,0 | - |
| July | 74467 | 17,6 | 9,9 | 13,1 | 9,0 | - |
| August | 23264 | 120 | 2,8 | 8,3 | 2,7 | - |
| September | 10941 | 50,5 | 4,4 | 9,8 | 4,3 | - |

both by years of research and by months, which indicates that it is impossible to use the obtained values of daily precipitation from VCWD [9].

Based on the analysis of total monthly precipitation obtained from VCWD, their unsatisfactory accuracy was found. Thus, on average, over the years of research, the MAPE and RMSE errors for the amount of precipitation per month were 52,6 % and 11,6 mm/month, respectively (Table 7). For the years 2023–2024, the MAPE and RMSE errors were 72,7–32,5 % and 12,6–10,7 mm/month, respectively. In terms of months of research, the MAPE and RMSE errors for the amount of precipitation per month were in the range of 120,0–17,6 % and 25,3–8,3 mm/month, respectively. The minimum values for the MAPE error were observed in July, and the maximum values were observed in August. For the RMSE error, the minimum values were observed in August, and the maximum values were observed in June.

For the amount of annual precipitation obtained from VCWD, their satisfactory accuracy was found (MAPE = 23,9 %, RMSE = 47,9 mm/year). For 2023–2024, the errors of the MAPE and RMSE were 28,7–19,2 % and 57,6–38,3 mm/year, respectively.

**Conclusions.**

1. Based on the results of the analysis of meteorological data obtained from the Visual Crossing Weather Data virtual meteorological station, their accuracy was established. Thus, the data on the average, maximum air temperature and dew point temperature are received with high accuracy, with the MAPE errors of 5,6, 2,8 and 8,3 %, respectively (MAPE < 10 %). The minimum air temperature and average relative humidity are characterized by good accuracy, with the MAPE errors of 20,0 and 13,6 %, respectively (MAPE = 10–20 %). The data on solar radiation and water vapor pressure deficit are obtained with satisfactory accuracy, with MAPE errors of 25,0 and 45,2 %, respectively

(MAPE = 20–50 %). Data on wind speed at a height of 2 m, total monthly and daily precipitation were obtained with unsatisfactory accuracy, with MAPE errors of 62,3, 52,6, and 40103 % (MAPE > 50 %), respectively.

2. According to the results of the research, it was found that the values of daily precipitation (RMSE = 6.0 mm) obtained from VCWD are not correct. It is possible to use only total monthly precipitation (RMSE = 11,6 mm/month) or annual values (RMSE = 47,9 mm/year).

3. The application of the correction factor to the obtained meteorological data increases their accuracy and reduces the errors of MAPE, RMSE and SEE.

4. In the future, the meteorological data obtained from the Visual Crossing Weather Data virtual meteorological station will be used to calculate the reference and actual evapotranspiration using the Penman-Monteith method (FAO56-PM) in the Polissya region of Ukraine.

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УДК 631.67

# ОЦІНКА ТОЧНОСТІ МЕТЕОДАНИХ, ОТРИМАНИХ З ВІРТУАЛЬНОЇ ТА АВТОМАТИЧНОЇ МЕТЕОСТАНЦІЙ ДЛЯ УМОВ ПОЛІССЯ УКРАЇНИ

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***Анотація.*** *У статті проведено комплексне оцінювання метеорологічних даних, отриманих з віртуальної Visual Crossing Weather Data (VCWD) та автоматичної (iMetos Base) метеорологічної станції для умов Полісся України. З цією метою було обрано метеорологічні дані, які входять до формули розрахунку еталонної евапотранспірації ($ET_0$) за методом Пенмана-Монтейта (FAO56-PM) а саме: середня (Tmean), максимальна (Tmax) та мінімальна (Tmin) температури повітря, температура точки роси (Tdew), середня відносна вологість повітря (Rhmean), середній дефіцит тиску водяної пари (Damean), сумарна сонячна радіація (Rs), середня швидкість вітру на висоті 2 м ($u_2$) та щодобові опади (P). На основі регресійного аналізу та розрахунку середньої абсолютної відсоткової похибки (MAPE), середньоквадратичної похибки (RMSE) та стандартної похибки (SEE) обґрунтовано, що з високою точністю з віртуальної VCWD-метеостанції отримано дані щодо середньої та максимальної температури повітря, а також температури точки роси. Похибки MAPE відповідно* *становлять 5,6, 2,8 та 8,3 % (MAPE < 10 %). Для мінімальної температури повітря та середньої відносної вологості повітря притаманна добра точність, похибки MAPE яких відповідно становлять 20,0 та 13,6 % (MAPE = 10 – 20 %). Із задовільною точністю отримано дані про сонячну радіацію та дефіцит тиску водяної пари, похибки MAPE яких відповідно становлять 25,0 та 45,2 % (MAPE = 20 – 50 %). Дані про швидкість вітру на висоті 2 м, сумарні місячні та щодобові опади отримано з незадовільної точністю, похибки MAPE яких відповідно становлять 62,3, 52,6 та 40103 % (MAPE > 50 %). Встановлено, що значення щодобових опадів (RMSE = 6,0 мм), отриманих з VCWD використовувати не коректно. Можливо використовувати тільки сумарні опади за місяць (RMSE = 11,6 мм) або їх річні значення (RMSE = 47,9 мм). Застосування коригуючого коефіцієнту до отриманих метеорологічних даних підвищує їх точність, та зменшує похибки MAPE, RMSE та SEE. Застосування різних похибок дало можливість комплексно перевірити отримані метеорологічні дані. Так, за допомогою похибки MAPE розраховується з якою точністю отримується метеорологічний показник, похибки RMSE та SEE вказали наскільки отримана величина відрізняється від середнього значення. Надалі отримані метеорологічні показники з віртуальної метеорологічної станції Visual Crossing Weather Data будуть використані для розрахунку еталонної та фактичної евапотранспірації за методом Пенмана-Монтейта (FAO56-PM) в умовах Полісся України.*

***Ключові слова:*** *віртуальна метеостанція, метеорологічні дані, температура повітря, опади, точність, похибки MAPE, RMSE та SEE*

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# INFLUENCE OF NITROGEN NUTRITION AND NITRIFICATION INHIBITOR ON THE YIELD OF CEREAL CROPS

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***Abstract.*** *The article presents the results of experimental studies to determine the effect of using different rates of nitrogen fertilizers in the form of KAS-32 and the nitrification inhibitor 3,4-dimethylpyrazol phosphate on the yield of winter wheat, winter rape and corn. Field studies were conducted during 2018–2021 in the research department of Druzhba Nova LLC in Varvynskyi district of Chernihiv region (a branch of the Kernel agricultural holding). Analytical and mathematical-statistical methods were used to process the experimental data. The scheme of the one-factor field experiment included the use of variants with different norms of nitrogen fertilizers ($N_{100}$, $N_{120}$ and $N_{130}$), as well as the use of the nitrification inhibitor 3,4-dimethylpyrazol phosphate when added to KAS-32. The control variant was conditionally without nitrogen fertilizers $N_{10}P_{30}K_{40}$. The results of experimental studies have been proven. Thus, in winter wheat, on average, over the four years of research in 2019–2021, the yield increased from 3,74 t/ha in the control variant $N_{10}P_{30}K_{40}$ to 6,27 t/ha and to 6,30 t/ha in the variants background + $N_{100}$ + NI and background + $N_{120}$ + NI and then slightly decreased in the experimental variant with the maximum rate of nitrogen fertilizers but without the use of NI (background + $N_{120}$) to 5,85 t/ha. For winter rape, on average over the three years of research in 2018–2021, the yield also increased from 2.48 t/ha in the control variant $N_{10}P_{30}K_{40}$ to 3,06 t/ha and 3,16 t/ha in the variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI and further slightly decreased to 2,79 t/ha in the variant with the maximum rate of nitrogen fertilizers but without the use of NI (Background + $N_{130}$).*

*For maize, on average, over 4 years of research in 2019–2021, is fixed an increase in yield from 8,14 t/ha in the control variant $N_{10}P_{30}K_{40}$ to 9,75 t/ha and to 9,52 t/ha in the variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI and a slight decrease in yield in the experimental variant with the maximum rate of nitrogen fertilizers, but without the use of NI (Background + $N_{130}$) to 8,7 t/ha.*

***Keywords:*** *nitrification inhibitor, 3,4 dimethylpyrazol phosphate, urea-ammonia mixture, normalized differential vegetation index, yield, winter wheat, winter rape, corn*

**Relevance of the study.** A number of factors, such as climatic conditions, soil type, growing zone, crop rotation and fertilizer use, influence the formation of sustainable crop yields, but nitrogen fertilizers, first of all, play one of the main factors [1–5]. In turn, nitrogen fertilizers are in constant processes of transformation in the soil from amide form to ammonium form and finally to nitrate form, these processes have a negative effect on the environment, ecosystem and soil as nitrogen losses occur during such transformations [6, 7]. Therefore, it is natural that the effectiveness of nitrogen fertilizers is reduced due to its losses, such as nitrate leaching due to nitrification and evaporation in gaseous forms during denitrification, such losses can be up to 2530 % of the applied amount of nitrogen [8, 9]. Some researchers believe that the so-called inhibitors can reduce nitrogen losses in nutrition systems by up to 50 %, depending on the specific inhibitor and the rate of its use, as well as other conditions such as meteorological conditions and soil type [10, 11].

Taking all of the above into account, we can conclude that the study of the impact of different rates of nitrogen fertilizers in the form of KAS-32 in combination with the nitrification inhibitor (NI) 3,4-dimethylpyrazol phosphate (DMPP) on the yield of winter wheat, winter rape and corn is a relevant area of work.

**Analysis of recent research and publications.** A nitrification inhibitor is a chemical substance of selective action that can inhibit the processes of nitrification in the soil by inhibiting the development of *Nitrosomonas* bacteria without destroying it, namely by suppressing its activity for a certain period of time. The mechanism of action of the nitrification inhibitor is to prolong the conversion of some forms of nitrogen into others compared to the application of soluble mineral fertilizers: urea, ammonium sulfate, ammonium nitrate [12, 13]. In order to reduce nitrogen losses, namely during the nitrification process, nitrogen application rates are regulated and so-called nitrification inhibitors are used, and today 3,4-dimethylpyrazol phosphate is one of the most effective nitrification inhibitors [14, 15, 16]. In the European Union, nitrification inhibitors are regulated by law, including the inhibitor 3,4-dimethylpyrazol phosphate, and the decision of the European Union Regulatory Commission No. 1257/2014 amending Regulation (EC) No. 2003/2003 of the European Parliament and of the Council as regards fertilizers and amending Annexes I and IV of 24.11.2014 was introduced [17].

Thus, the **aim of the study** was to determine the effect of using different rates of nitrogen fertilizers in the form of KAS-32 in combination with the nitrification inhibitor 3,4-dimethylpyrazol phosphate on the yield of winter wheat, winter rape and corn.

**Materials and methods of the study.** The study was conducted at the research site of Druzhba Nova LLC in Varvynskyi district of Chernihiv region (a branch of the Kernel agricultural holding) within the Uday drainage system without groundwater level regulation. The soil of the experimental site is a typical low-humus chernozem, the topsoil of which is characterized by the following main indicators humus content – 3,4 %, pH neutral and close to neutral – 5,7–7,0, mobile phosphorus content – from high to very high – 15,4–26,3 mg/100 g of soil, exchangeable potassium – from medium to high – 7,1–16,2 mg/100 g of soil, easily hydrolyzed nitrogen – from high to high – 5,7–7,9 mg/100 g of soil. The research was conducted according to the scheme of a one-factor experiment. The sown area of the experimental plot was 0,6 hectares, the alternation of variants was sequential. The field experiments were laid out and performed according to the methodology of field experiments (Dospekhov B.A., 1985). Harvest accounting was carried out by continuous harvesting and weighing of the bunker mass from each plot with subsequent conversion to standard moisture and weediness according to DSTU 2240-93 in 3 replications. Mathematical and statistical data were proceeded using the Agrostat software and information complex.

In accordance with the regulation of the European Union Regulatory Commission, a minimum rate of 0,8 % of NI DMPP was used on amide $NH_2^-$ and ammonium $NH_4^+$ forms of nitrogen. According to this minimum calculated rate of 0,8 %, the rate of use of NI DMPP on KAS- 32 -is 7,02 liters per 1000 kg of KAS-32.

**Research results and discussion**.

The analysis of data on the yield of winter wheat, winter rape and corn shows that this indicator varied significantly over the years of research depending on the fertilizer background. Thus, the yield of winter wheat in all experimental variants was higher in two years of research in 2018 in the range of 3,72–8,14 t/ha and in 2020 in the range of 3.77–7.25 t/ha. Yields in the other two years of research, namely in 2019 and 2021, fluctuated at a relatively lower level in the range of 3,63–5,10 t/ha in 2020 and 3,83–4,81 t/ha in 2021, respectively. The average yield of winter wheat in all experimental variants in 2018–2021 ranged from 3,74–6,30 t/ha (Table 1).

In turn, the yield of winter rape in all experimental variants was higher in 2018, ranging from 3,12–3,85 t/ha. Yields in 2020 and 2021 were lower and ranged from 2,21–2,98 t/ha in 2020 and 2,11–2,70 t/ha in 2021. No winter rapeseed trials were conducted in 2019 due to unfavorable weather conditions. The average yield of winter rape in all experimental variants in 2018–2021 ranged from 2.48–3,16 t/ha.

Corn yields also varied depending on the years of research in 2018–2021. Thus, corn yield in all experimental variants was higher in 2018 in the range of 8,60–11,02 t/ha and in 2021 in the range of 8,57–11,19 t/ha. Yields in 2019 and 2020 fluctuated at a lower level in the range of 7,20–8,89 t/ha in 2019 and 8,17–8,66 t/ha in 2020, respectively. The average yield of corn in all experimental variants in 2018–2021 ranged from 8,14–9,75 t/ha.

There is a clear pattern for all studied crops of winter wheat, winter rape and corn and for the four years of research in 2018, 2019, 2022 and 2021 as an increase in yields in the experimental variants depending on the increase in nitrogen rates and the use of NI, followed by a slight decrease in yields in the experimental variant with the maximum nitrogen fertilizer rate but without the use of NI.

Investigating the data of winter wheat yield by years of research and by experimental variants in 2018, the control variant $N_{10}P_{30}K_{40}$ yielded 3,72 t/ha, it increased in the experimental variants with increased rates of nitrogen fertilizers and

1. Yield of winter wheat, winter rape and corn depending on the use of different rates of nitrogen fertilizers with the addition of a nitrification inhibitor (2018–2021), t/ha

| **Option** | **Yield, t/ha** | | | | **Average yield 2018–2021, t/ha** |
|---|---|---|---|---|---|
| | **2018** | **2019** | **2020** | **2021** | |
| Winter wheat | | | | | |
| $N_{10}$ $P_{30}K_{40}$ (background) | 3,72 | 3,63 | 3,77 | 3,83 | 3,74 |
| Background+$N_{100}$+NI | 8,00 | 5,05 | 7,20 | 4,81 | 6,27 |
| Background+$N_{120}$+NI | 8,14 | 5,10 | 7,25 | 4,72 | 6,30 |
| Background+$N_{120}$ | 7,40 | 4,64 | 6,85 | 4,50 | 5,85 |
| $NIR_{05}$ | 0,133 | 0,186 | 0,203 | 0,249 | - |
| Winter rape | | | | | |
| $N_{10}$ $P_{30}K_{40}$ (background) | 3,12 | - | 2,21 | 2,11 | 2,48 |
| Background+$N_{120}$ +NI | 3,70 | - | 2,79 | 2,70 | 3,06 |
| Background+$N_{130}$ +NI | 3,85 | - | 2,98 | 2,66 | 3,16 |
| Background+$N_{130}$ | 3,45 | - | 2,31 | 2,60 | 2,79 |
| $NIR_{05}$ | 0,312 | - | 0,266 | 0,363 | - |
| Corn | | | | | |
| $N_{10}$ $P_{30}K_{40}$ (background) | 8,57 | 7,20 | 8,17 | 8,60 | 8,14 |
| Background+$N_{120}$ +NI | 11,19 | 8,27 | 8,51 | 11,02 | 9,75 |
| Background+$N_{130}$ +NI | 9,95 | 8,89 | 8,66 | 10,59 | 9,52 |
| Background+$N_{130}$ | 9,77 | 7,75 | 8,38 | 9,97 | 8,97 |
| $NIR_{05}$ | 0,275 | 0,335 | 0,291 | 0,887 | - |

the use of NI, namely, Background + $N_{100}$ + NI and Background + $N_{120}$ + NI to 8,00 t/ha and 8,14 t/ha, respectively, and slightly decreased in the experimental variant with the maximum rate of nitrogen fertilizers but without the addition of NI Background + $N_{120}$ to the level of 7,40 t/ha. The same trend was observed in the other 3 years of research in 2019, 202 and 2021. Thus, in 2019, there was an increase in yield from 3,63 t/ha in the control variant $N_{10}P_{30}K_{40}$ to 5,05 t/ha and to 5,10 t/ha in the variants Background + $N_{100}$ + NI and Background + $N_{120}$ + NI with a slight decrease to 4,64 t/ha in the variant Background + $N_{120}$. In 2020, fixed an increase in yield from 3,77 t/ha in the control variant $N_{10}P_{30}K_{40}$ to 7,20 t/ha and to 7,25 t/ha in the variants Background + $N_{100}$ + NI and Background + $N_{120}$ + NI and a slight decrease to 6,85 t/ha in the variant Background + $N_{120}$, and in 2021, an increase in yield from 3,83 t/ha in the control variant $N_{10}P_{30}K_{40}$ to 4,81 t/ha and to 4,72 t/ha in the variants Background + $N_{100}$ + NI and Background + $N_{120}$ + NI and a slight decrease to 4,50 t/ha in the variant Background + $N_{120}$. The $NIR_{05}$ was 0,133 t/ha in 2018, 0,186 t/ha in 2019, 0,203 t/ha in 2020 and 0,249 t/ha in 2021.

On average, over the 4 years of research in 2019–2021, the yield of winter wheat also increased from 3,74 t/ha in the control variant $N_{10}P_{30}K_{40}$ to 6,27 t/ha and to 6,30 t/ha in the variants Background + $N_{100}$ + NI and Background + $N_{120}$ + NI and then slightly decreased in the experimental variant with the maximum rate of nitrogen fertilizers but without the use of NI (Background + $N_{120}$) to 5,85 t/ha.

For winter rape, as well as for winter wheat, in all years of research 2018–2021, an increase in yields was observed in the experimental variants with an increase in the rate of nitrogen and the use of NI on the experimental variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI and a subsequent slight decrease in yields on the experimental variant with the maximum rate of nitrogen fertilizers but without the use of NI (Background + $N_{130}$). Thus, in 2018, the control variant $N_{10}P_{30}K_{40}$ yielded 3,12 t/ha, it increased in the experimental variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI to 3,70 t/ha and 3,85 t/ha, respectively, and slightly decreased to 3,45 t/ha in the experimental variant Background + $N_{130}$. The same trend was observed in the other 2 years of research in 2020 and 2021. Thus, in 2020, an increase in yield was observed in the control variant $N_{10}P_{30}K_{40}$ from 2,21 t/ha to 2,79 t/ha and 2,98 t/ha in the variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI respectively, and a slight decrease in yield to 2,31 t/ha in the variant Background + $N_{130}$. And in 2021, the yield increased from 2,11 t/ha in the control variant $N_{10}P_{30}K_{40}$ to 2,70 t/ha and 2,66 t/ha in the variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI, and a slightly decreased to 2,60 t/ha in the variant Background + $N_{130}$. The $NIR_{05}$ for winter rape was 0,312 t/ha in 2018, 0,266 t/ha in 2020 and 0,363 t/ha in 2021.

On average, over the years of research, the yield of winter rape also increased from the control variant $N_{10}P_{30}K_{40}$ from 2,48 t/ha to 3,06 t/ha and to 3,16 t/ha in the variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI and then slightly decreased in the experimental variant with the maximum rate of nitrogen fertilizers but without the use of NI (Background + $N_{130}$) to 2,79 t/ha.

A similar trend was observed in corn yield data. Thus, in 2018, the control variant $N_{10}P_{30}K_{40}$ yielded 8,60 t/ha, it increased in the experimental variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI to 11,02 t/ha and 10,59 t/ha, respectively, and slightly decreased in the experimental variant Background + $N_{130}$ to 9,97 t/ha. In 2019, the yield of the control variant $N_{10}P_{30}K_{40}$ increased from 7,20 t/ha to 8,27 t/ha and to 8,89 t/ha in the variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI, respectively, and a slight decrease in yield to 7,75 t/ha in the variant Background + $N_{130}$. Similarly, in 2020, corn yields increased from the control variant $N_{10}P_{30}K_{40}$ from 8,17 t/ha to 8,51 t/ha and 8,66 t/ha in the variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI and decreased slightly to 8,38 t/ha in the variant Background + $N_{130}$. And in 2021, the yield of corn also increased from the control variant $N_{10}P_{30}K_{40}$ from 8,57 t/ha to 11,19 t/ha and to 9,95 t/ha in the variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI and decreased to 9,77 t/ha in the variant Background + $N_{130}$. The $NIR_{05}$ was 0,887 t/ha in 2018, 0,335 t/ha in 2019, 0,291 t/ha in 2020 and 0,275 t/ha in 2021.

Summarizing the corn yield data for the average of 4 years of research in 2019–2021, there is also an increase in yield from the control variant $N_{10}P_{30}K_{40}$ from 8,14 t/ha to 9,75 t/ha and to 9,52 t/ha in the variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI and a slight decrease in yield in the experimental variant with the maximum rate of nitrogen fertilizers, but without the use of NI (Background + $N_{130}$) to 8,97 t/ha.

In addition to fertilization, the amount and mode of productive precipitation had a significant impact on the productivity of all crops. Thus, during 2018–2020, in the spring period (from March to May), there was insufficient precipitation – 68,2, 87,6 and 130,0 mm, respectively, which had an extremely negative impact on both the period of spring renewal of winter crops and the conditions for sowing early spring crops. At the end of the growing season, in September 2018, the total amount of precipitation was the lowest in the years of research and amounted to 309,0 mm (Table 2).

The analysis showed that from 2019 to 2020, the amount of precipitation and the amount of productive moisture in the root layer of the soil from March to May remained below optimal values for all crop groups (198,4–222,8–258,2 mm in 2019 and 133,0–168,0–252,0 mm in 2020). At the end of the growing season, in September 2019 and 2020, the total amount of precipitation was almost at the same level and amounted to 341,8 mm and 343,8 mm. In 2021, during the spring growing season, the amount of precipitation was slightly higher compared to previous years and ranged from 196,3–241,7–327,1. Also, the amount of precipitation at the end of the growing season in September 2021 was the highest in the years of research and amounted to 509,9 mm.

The calculations show that the highest correlation between the amount of productive precipitation and crop yields was for grain corn – 0,74. For example, the corn grain yield in the wettest year of 2021 exceeded the drier years of 2019 and 2020 by 1,6 and 2,0 t/ha, respectively. In turn, for the group of winter crops (wheat, rapeseed), the impact of precipitation was less significant (correlation coefficient 0,42 and 0,47, respectively).

2. Dynamics of productive precipitation (cumulative total) by years of research during the growing season (March-September) (2018–2021), mm

| **Months** | **Cumulative rainfall, mm** | | | |
|---|---|---|---|---|
| | **2018** | **2019** | **2020** | **2021** |
| March | 68,2 | 198,4 | 133,0 | 196,3 |
| April | 87,6 | 222,8 | 168,0 | 241,7 |
| May | 130,0 | 258,2 | 252,0 | 327,1 |
| June | 208,6 | 275,4 | 286,4 | 359,3 |
| July | 261,8 | 315,2 | 322,0 | 444,7 |
| August | 269,4 | 325,2 | 329,8 | 499,1 |
| September | 309,0 | 341,8 | 343,8 | 590,9 |

**Conclusions.** The results of experimental studies have shown that the use of different norms of nitrogen fertilizers in the form of KAS-32 in combination with the nitrification inhibitor (NI) 3,4-dimethylpyrazol phosphate (DMPP) significantly affects the yield of winter wheat, winter rape and corn.

In winter wheat, on average, over the four years of research in 2019–2021, the yield increased from 3,74 t/ha in the control variant $N_{10}P_{30}K_{40}$ to 6,27 t/ha and 6,30 t/ha in the variants – Background + $N_{100}$ + NI and Background + $N_{120}$ + NI and then slightly decreased in the experimental variant with the maximum rate of nitrogen fertilizers but without the use of NI (Background + $N_{120}$) to 5,85 t/ha.

In winter rape, on average over the three years of research in 2018–2021, the yield also increased from 2,48 t/ha in the control variant $N_{10}P_{30}K_{40}$ to 3,06 t/ha and 3,16 t/ha in the variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI and then slightly decreased in the variant with the maximum rate of nitrogen fertilizers but without the use of NI (Background + $N_{130}$) to 2,79 t/ha.

For corn, on average, over 4 years of research in 2019–2021, fixed an increase in yield from 8,14 t/ha in the control variant $N_{10}P_{30}K_{40}$ to 9,75 t/ha and 9,52 t/ha in the variants Background + $N_{120}$ + NI and Background + $N_{130}$ + NI and a slight decrease to 8,97 t/ha in yield in the experimental variant with the maximum rate of nitrogen fertilizers but without the use of NI (Background + $N_{130}$).

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## ВПЛИВ АЗОТНОГО ЖИВЛЕННЯ ТА ІНГІБІТОРА НІТРИФІКАЦІЇ НА ВРОЖАЙНІСТЬ ЗЕРНОВИХ КУЛЬТУР

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***Анотація.*** *У статті наведено результати експериментальних досліджень із визначення впливу використання різних норм азотних добрив у вигляді КАС-32 та інгібітора нітрифікації 3,4-диметилпіразолфосфат на урожайність пшениці озимої, ріпаку озимого та кукурудзи. Польові дослідження проведено протягом 2018–2021 рр. в науково-дослідному відділі СТОВ «Дружба Нова» Варвинського району Чернігівської області (відділення агрохолдингу «Кернел»). Для обробки експериментальних даних використано аналітичні та математично-статистичні методи. Схемою однофакторного польового досліду було використання варіантів з різними нормами азотних добрив ($N_{100}$, $N_{120}$ та $N_{130}$), а також використання інгібітора нітрифікації 3,4-диметилпіразолфосфат при додаванні в КАС-32. Контрольним був варіант умовно без азотних добрив $N_{10}P_{30}K_{40}$. Результатами експериментальних досліджень доведено. Так, по пшениці озимій в середньому за чотири роки досліджень 2019–2021 урожайність збільшувалась від контрольного варіанту $N_{10}P_{30}K_{40}$ з 3,74 т/га до 6,27 т/га та до 6,30 т/га на варіантах фон + $N_{100}$ + ІН та фон + $N_{120}$ + ІН та в подальшому дещо знижувалась на варіанті досліду із максимальною нормою азотних добрив але без використання ІН (фон + $N_{120}$) до 5,85 т/га. По ріпаку озимому в середньому за три роки досліджень 2018–2021 урожайність також збільшувалась від контрольного варіанту $N_{10}P_{30}K_{40}$ з 2,48 т/га до 3,06 т/га та до 3,16 т/га на варіантах Фон + $N_{120}$ + ІН та фон + $N_{130}$ + ІН та в подальшому дещо знижувалась на варіанті досліду із максимальною нормою азотних добрив але без використання ІН (Фон + $N_{130}$) до 2,79 т/га.*

*По кукурудзі в середньому за 4 роки досліджень 2019–2021 так само спостерігається збільшення урожайності від контрольного варіанту $N_{10}P_{30}K_{40}$ з 8,14 т/га до 9,75 т/га та до 9,52 т/га на варіантах Фон + $N_{120}$ + ІН та Фон + $N_{130}$ + ІН та несуттєве зниження врожайності на варіанті досліду із максимальною нормою азотних добрив, але без використання ІН (фон + $N_{130}$) до 8,97 т/га.*

***Ключові слова:*** *інгібітор нітрифікації, 3,4 диметилпіразолфосфат, карбамідно-аміачна суміш, нормалізований диференційний вегетаційний індекс, урожайність, пшениця озима, ріпак озимий, кукурудза*

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# ASSESSMENT OF NATURAL MOISTURE CONDITIONS ON THE EXAMPLE OF THE SOUTHWESTERN PART OF KYIV REGION

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***Abstract.*** *The sustainability of agriculture in Ukraine directly depends on the level of natural soil moisture supply, which is significantly deteriorating under the influence of climate change. The article investigates the impact of these changes on the value of potential evapotranspiration (ETo) in the southwestern part of the Kyiv region (Central Forest-Steppe of Ukraine) based on the data from the Bila Tserkva weather station for the period from 1991 to 2020. The research methodology is based on the assumption that the assessment of the impact of climate change on the state of natural moisture supply can be performed provided that climate change itself is assessed according to the long-term dynamics of air temperature and precipitation in the period from 1991 to 2021 with the values of the same indicators in the period from 1961 to 1990 – the climatic norm. The potential evapotranspiration (ETo) was chosen as the criteria for assessing the impact of climate change on the state of soil moisture supply. The assessment results showed that the annual value of potential ETo increased by 9 %, which may indirectly indicate a deterioration in the conditions of natural soil moisture supply. This has important implications for agriculture, as an increase in ET can lead to a decrease in available moisture for plants, which will negatively affect crop yields. The study covers changes in average annual and average monthly air temperature, as well as precipitation by season and month. It has been established that over the past thirty years, Ukraine has been experiencing a deterioration in moisture conditions, which requires the adaptation of agricultural practices. Sustainable development of the agricultural sector is possible only if changes in the natural moisture supply are taken into account when developing management models and cultivation technologies. The results obtained indicate the need to introduce innovative agronomic technologies that adapt to current climate change.*

***Keywords:*** *forecasting of moisture reserves, modeling, factors of influence, hydrothermal conditions, agriculture, climate change*

**Relevance of the research.** The sustainability of farming in Ukraine directly depends on the level of natural soil moisture supply. According to numerous studies conducted by various authors, Ukraine is one of the countries where climate change is characterized by the highest rates of increase in average annual air temperature in Europe. This so-called “hot” phase of climate change began in Ukraine in the late 70s and early 90s of the last century and continues today. Depending on the region of Ukraine, the rate of growth of the average annual temperature ranges from 0,6 to 0,8 °C (over 10 years).

The rapid increase in average annual temperature leads to a corresponding increase in total evaporation and potential evapotranspiration. And given that the amount of annual precipitation remains unchanged, climate change has led to the development of a progressive dehydration process throughout Ukraine, which is primarily manifested through the deterioration of natural soil moisture conditions and sustainable farming practices. In this regard, it is important for almost every business entity, regardless of ownership, to assess the state of natural soil moisture supply and trends in its changes under the influence of climate change as a basis for developing measures to minimize the negative impact of this process on the efficiency and sustainability of management.

**Analysis of recent research and publications.** In recent years, Ukraine's climate has been changing intensively: since 1991, each subsequent decade has been warmer than the previous one: 1991–2000 by 0,5 °C, 2001–2010 by 1,2 °C, 2011–2019 by 1,7 °C. In 10 regions of Ukraine, precipitation in 2014–2018 was 7–12 % less than normal [1–4].

In addition, there is a tendency to increase the area with insufficient precipitation (less than 400 mm) in the warm season. The climate has already become drier throughout the country. In particular, there were droughts in the following periods: spring drought in 2002, 2003; spring and summer drought in 2007, 2009 and 2012; autumn drought in 2011; winter and early spring drought in 2019; autumn drought in 2020 [5–6] .

Scientists both in Ukraine and globally are talking about climate change and the threat it poses to humanity. There are many different forecasts, and they are all disappointing for agricultural producers, since in most of the scenarios, from the most optimistic to the pessimistic, in regions where there is a significant shortage of water resources, changes will lead to a decrease in yields [7–10].

Average annual air temperature is one of the main parameters for assessing climate change. In Ukraine, it has risen by 1,2 °C over the past thirty years, and by 1,7 °C over the past 10 years. However, for effective agricultural management, it is important to know how not only the average annual air temperature is changing, but also the trends in average monthly and seasonal temperatures [11] .

The period of active vegetation of crops has already been extended by 10 days or more. These are additional opportunities for growing all types of heat-loving crops. The effectiveness of precipitation decreases as the air temperature rises, and a 1 °C increase in temperature threatens Ukraine with the disappearance of the already small zone of sufficient moisture (Polissya and the western Forest-Steppe) and the transition of this zone to unstable and insufficient moisture. For several years in a row, the Polissya and Western Forest-Steppe regions have experienced extremely low precipitation.

In recent years, there has been a tendency to increase the area with insufficient rainfall in the warm season (less than 400 mm), which is necessary for growing all crops. The climate has already become more arid throughout the country [12]. Some of the benefits of warming are likely to be short-lived, and within 15–20 years, there will be a significant reduction in yields of most crops due to an increase in the frequency and intensity of droughts [13–14].

The rapid growth of thermal resources and almost unchanged amount of precipitation, both in summer and in spring and summer, is already leading to an increase in the frequency of droughts and their spread to the western and northern regions. Therefore, assessing the conditions of natural moisture supply in the regions that used to be classified as sufficiently moist and provided a stable high productivity of major field crops, but now are increasingly experiencing prolonged droughts and other climate risks is an urgent issue.

**The study aims** to assess the impact of climate change on the growth of potential evapotranspiration in the southwestern part of the Kyiv region.

**Materials and methods.** The research was conducted at the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine by analyzing information obtained from the database of meteorological indicators, followed by their statistical processing.

The research is based on the assumption that the impact of climate change on the state of natural moisture supply can be assessed by evaluating climate change itself based on the long-term dynamics of air temperature and precipitation. The basis for such an assessment is archival data from the State Meteorological Station on the average monthly, seasonal, and annual air temperature, as well as the average monthly, seasonal, and annual precipitation. In our case, we used data from the weather station in Bila Tserkva (49 °48` N, 30 °7` E) for the period from 1961 to 2021. The choice of this observation period is based on the World Meteorological Organization (WMO) recommendations to use data from thirty-year periods for comparison. Climate change assessment is carried out by comparing the above data on temperature and precipitation in the period from 1991 to 2021 with the values of the same indicators in the period from 1961 to 1990 – the climate norm.

It is known that the only factors that affect potential evapotranspiration are climatic parameters. Therefore, ETo is a climatic parameter and can be calculated based on meteorological data. ETo expresses the maximum potential evapotranspiration loss in a specific area and for a specific time of year and is independent of crops or soil type.

The potential evapotranspiration (ETo) was chosen as the criteria for assessing the impact of climate change on the state of soil moisture supply. In the absence of solar radiation data at the meteorological station, we chose the alternative Hargreaves equation to estimate ETo [15]. For the calculation, we used the minimum set of input data and the maximum and minimum air temperatures.

$$ETo = 0,0023\left(T_{mean} + 17,8\right) \times \times \left(T_{max} - T_{min}\right)^{0,5} \times Ra \text{ mm}, \quad (1)$$

where $ETo$ is the reference evapotranspiration, mm; $T_{mean}$ is the average monthly air temperature, °C; $T_{max}$ is the maximum monthly air temperature, °C; $T_{min}$ is the minimum monthly air temperature, °C; Ra is extraterrestrial solar radiation, mm.

$$Ra = \frac{1}{\lambda} \cdot \frac{24(60)}{\pi} \times \times G_{sc} d_r \left[\omega_s \sin(\varphi) + \cos(\varphi)\cos\left(\delta\cos(\omega_s)\right)\right] \text{ mm}, \quad (2)$$

where $Ra$ is extraterrestrial solar radiation, mm; $G_{sc}$ is the solar constant, MJ-m$^{-2}$·day$^{-1}$; $d_r$ is the inverse relative distance of the Earth-Sun, $\omega_s$ is the angle at sunset, rad; $\phi$ is latitude, rad; $\delta$ is solar declination, rad; $\lambda$ is latent heat of vaporization, MJ·m$^{-2}$·day.

The $Ra$ value was taken on the 15th day of each month from Appendix 2 of Table 2.6 [15].

**Research results and discussion.** The air temperature regime was assessed for the period from 1961 to 2021, according to the dynamics of changes in its absolute values and deviations from the norm (1961–1990). The results of this assessment are shown in Fig. 1.

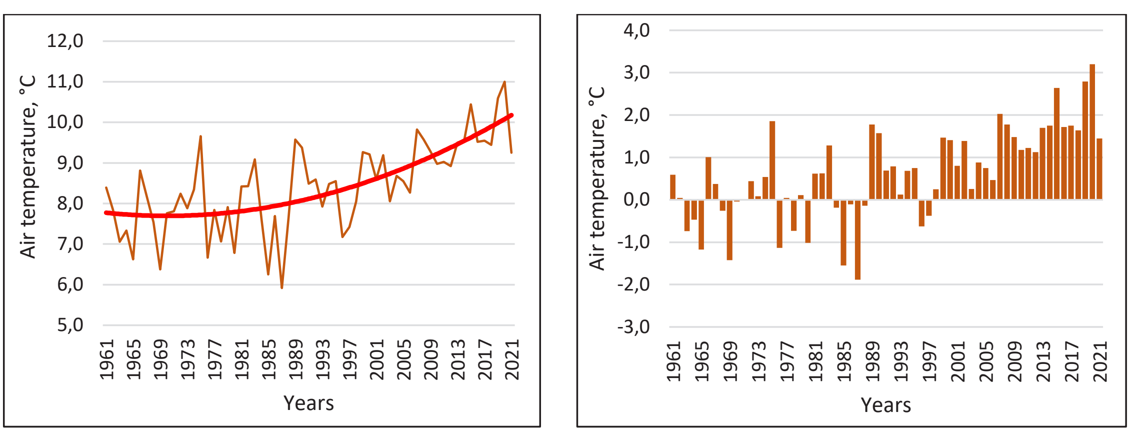
Fig. 2 shows the results of the assessment of the dynamics of seasonal air temperature values, and Table 1 shows the values of average monthly, seasonal and annual air temperature values for the entire assessment period (1961–2021).

The analysis of the data on temperature changes presented in Figures 1, 2 and Table 1 shows that the average annual air temperature for the period 1991–2020 increased by 1,2 °C, in winter by 1,6 °C, in spring by 1,1 °C, in summer by 1,5 °C and in autumn by 0,6 °C, i.e. the most intense temperature increase is in summer.

As for precipitation, the assessment of changes in which was made by the values of annual (Fig. 3), seasonal (Fig. 4) and monthly (Table 2) precipitation amounts for the same period as for the temperature, namely from 1961 to 2021, unlike the temperature, which is increasing, the amount of precipitation in both annual and seasonal (except for autumn) decreases. A slight increase in precipitation in the fall (up to 12 %) does not compensate for the decrease in annual precipitation.

The decrease in precipitation in the rest of the year against the backdrop of a clear increase in temperature is evidence of an increasingly arid climate, and, accordingly, a deterioration in the conditions for growing crops.

The value of potential evapotranspiration can be used to estimate the potential moisture consumption for a certain period (day, month, season, year) and its comparison with the moisture supply for the same period makes it possible to assess the moisture supply of the production process in crop cultivation [16]. In this case, there are several methods for determining potential evapotranspiration, which can be generally divided into calculated and experimental [17–22]. In our study, we used the Penman-Monteith method recommended by FAO as a reference method, which, according to many data on its use in different weather and climatic conditions, allows obtaining data close enough to the values




a) absolute values b) deviations from the norm

Fig. 1 – Dynamics of the average annual air temperature for 1961–2021, °C

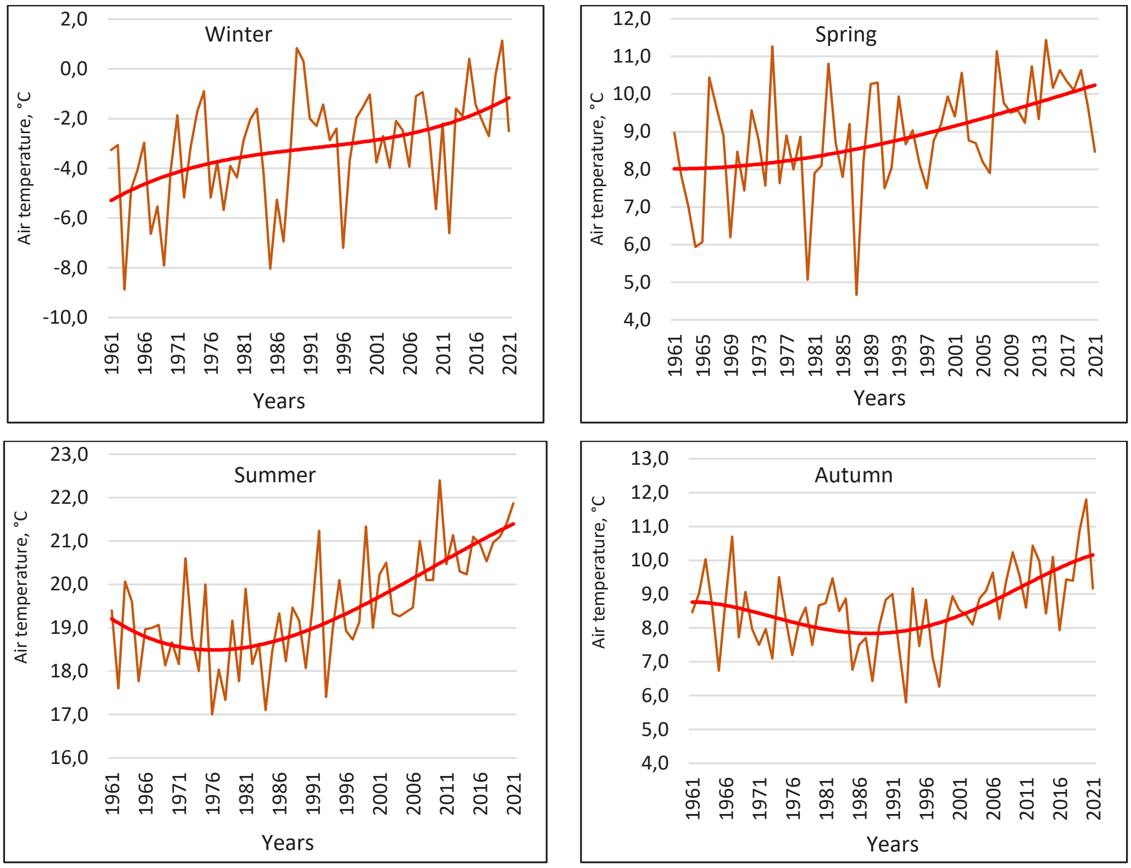
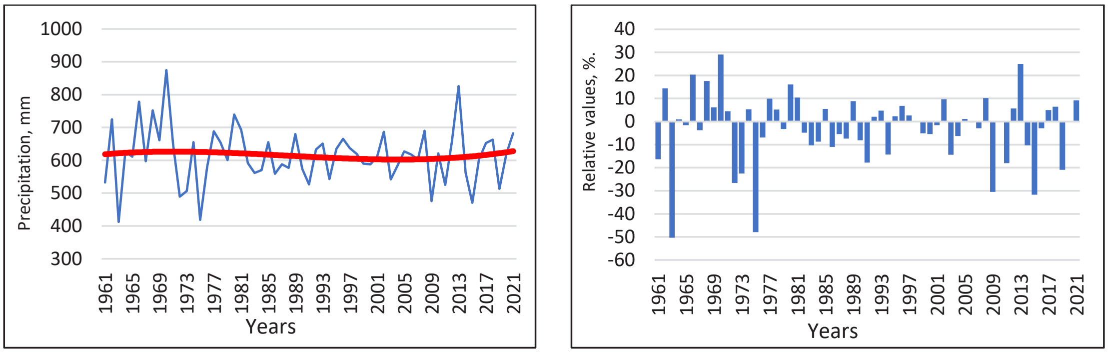



Fig. 2 – Dynamics of seasonal air temperature values for 1961–2021, °C

1. Changes in average monthly, seasonal and annual air temperature values for 1991–2020 compared to 1961–1990, °C

| **Months/seasons** | **Years** | | | |
|---|---|---|---|---|
| | **1961–2021** | **1961–1990** | **1991–2020** | **± to 1961–1990** |
| January | −4,5 | −5,6 | −3,3 | 2,2 |
| February | −3,1 | −4,1 | −2,1 | 2,0 |
| March | 1,8 | 0,9 | 2,7 | 1,8 |
| April | 9,5 | 8,9 | 10,0 | 1,1 |
| May | 15,3 | 15,0 | 15,5 | 0,5 |
| June | 18,7 | 18,2 | 19,2 | 1,1 |
| July | 20,0 | 19,1 | 20,9 | 1,8 |
| August | 19,5 | 18,7 | 20,3 | 1,6 |
| September | 14,6 | 14,2 | 14,9 | 0,7 |
| October | 8,5 | 8,3 | 8,7 | 0,4 |
| November | 2,6 | 2,3 | 2,9 | 0,5 |
| December | −2,2 | −2,4 | −1,9 | 0,5 |
| Winter | −3,2 | −4,0 | −2,4 | 1,6 |
| Spring | 8,9 | 8,3 | 9,4 | 1,1 |
| Summer | 19,4 | 18,7 | 20,1 | 1,5 |
| Autumn | 8,6 | 8,3 | 8,8 | 0,6 |
| Year | 8,4 | 7,8 | 9,0 | 1,2 |




absolute values, mm relative values, % to the norm

Fig. 3. Dynamics of annual precipitation for 1961–2021

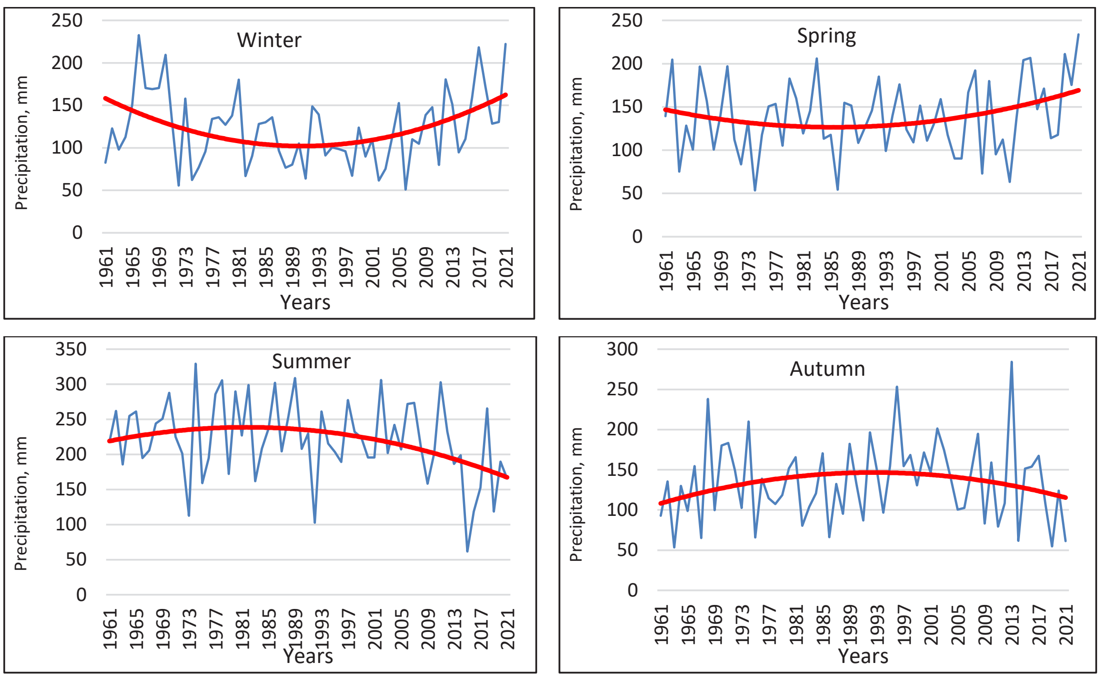



Fig. 4. Dynamics of seasonal precipitation for 1961–2021, mm

2. Changes in monthly, seasonal and annual precipitation over 1991–2020 compared to 1961–1990, mm

| **Months/seasons** | **Years** | | | |
|---|---|---|---|---|
| | **1961–2021** | **1961–1990** | **1991–2020** | **± to 1961–1990, %, %.** |
| 1 | 2 | 3 | 4 | 5 |
| January | 40 | 41 | 38 | −3 |
| February | 37 | 38 | 35 | −3 |
| March | 36 | 34 | 38 | 4 |
| April | 42 | 45 | 40 | −5 |
| May | 60 | 54 | 62 | 8 |
| June | 77 | 76 | 79 | 3 |
| July | 83 | 91 | 76 | −15 |
| August | 61 | 68 | 53 | −15 |
| September | 52 | 47 | 57 | 10 |
| October | 37 | 34 | 42 | 8 |
| November | 45 | 47 | 44 | −3 |
| December | 45 | 45 | 44 | −1 |

Table 2 (ending)

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| Winter | 122 | 124 | 117 | −7 |
| Spring | 138 | 133 | 140 | 7 |
| Summer | 220 | 235 | 208 | −27 |
| Autumn | 135 | 128 | 143 | 15 |
| Year | 615 | 620 | 608 | −12 |

of actual evapotranspiration, but it requires a significant amount of input data, some of which should be obtained from direct measurements. Given this circumstance, an attempt was made to find a simpler method for determining potential evapotranspiration, namely, using only the value of the average monthly temperature. The dependence of the potential evapotranspiration on the average monthly air temperature obtained using this approach is shown in Fig. 5.

Comparison of the values of potential evapotranspiration calculated by the Penman-Monteith method and the dependence shown in Fig. 5 (Fig. 6) made it possible to calculate the correction factors (Table 3) to the experimental dependence of potential evapotranspiration on the average monthly air temperature (Fig. 5). Further comparison of the values of potential evapotranspiration calculated with their use with the data of calculation by the Penman-Monteith method (Fig. 7) showed a sufficient level

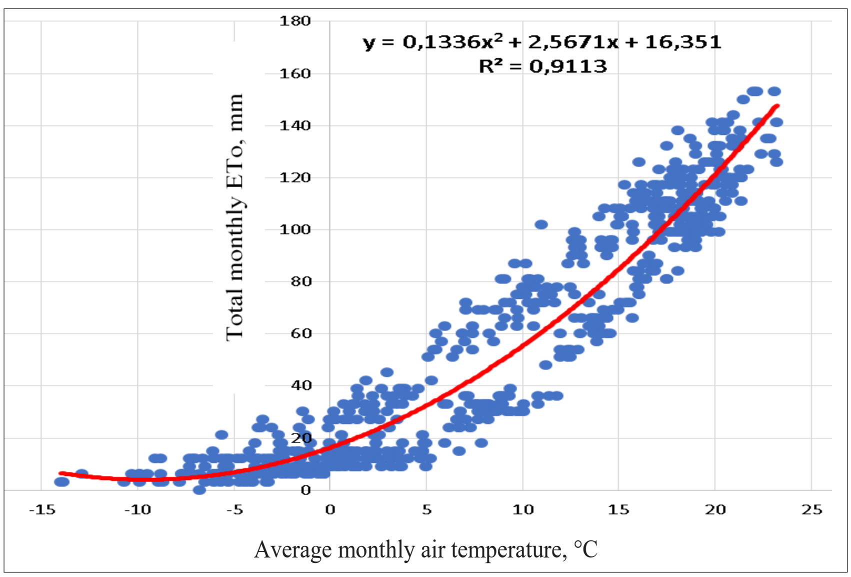



Fig. 5. Dependence of total monthly potential evapotranspiration on the average monthly air temperature, mm

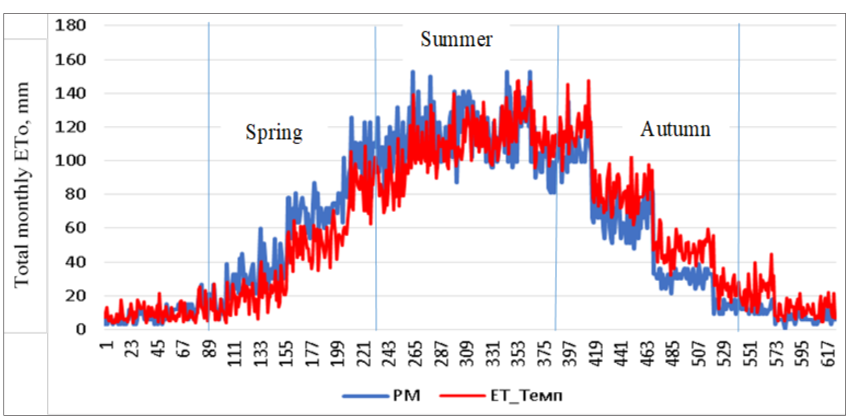



Fig. 6. Potential evapotranspiration calculated by the Penman-Monteith method and based on the average monthly air temperature, mm

of coincidence of the calculation results for practical purposes, which led to the conclusion that it is possible to use the dependence shown in Fig. 5 in combination with the correction factors (Table 3) in conducting forecast calculations of potential evapotranspiration for their further use to assess the level of soil moisture supply.

Using this methodological approach, the dynamics of the annual potential evapotranspiration for the period 1961–2021 was assessed (Fig. 8) and changes in monthly values of potential evapotranspiration for the period 1991–2020 compared to the period 1961–1990 (Table 4).

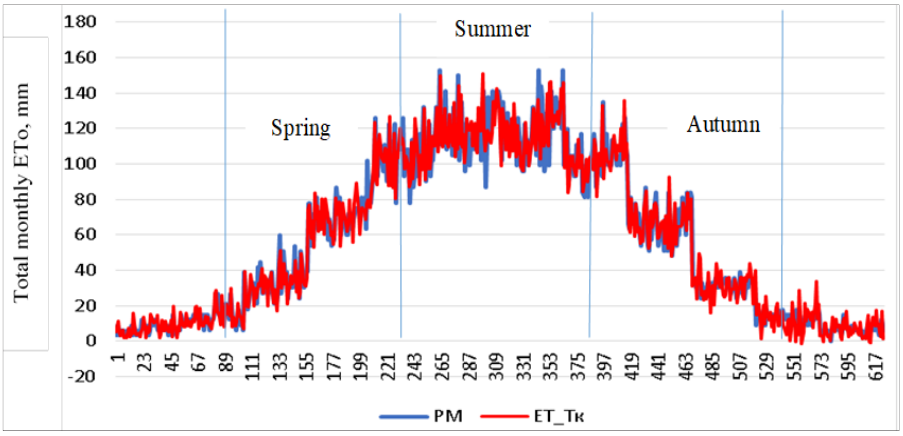



Fig. 7. Potential evapotranspiration calculated by the Penman-Monteith method and based on the average monthly air temperature with a correction factor, mm

3. Correction factors for calculating potential evapotranspiration based on average monthly air temperature

| Months | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
| −2 | 3 | 11 | 19 | 18 | 11 | −1 | −12 | −14 | −16 | −11 | −5 |

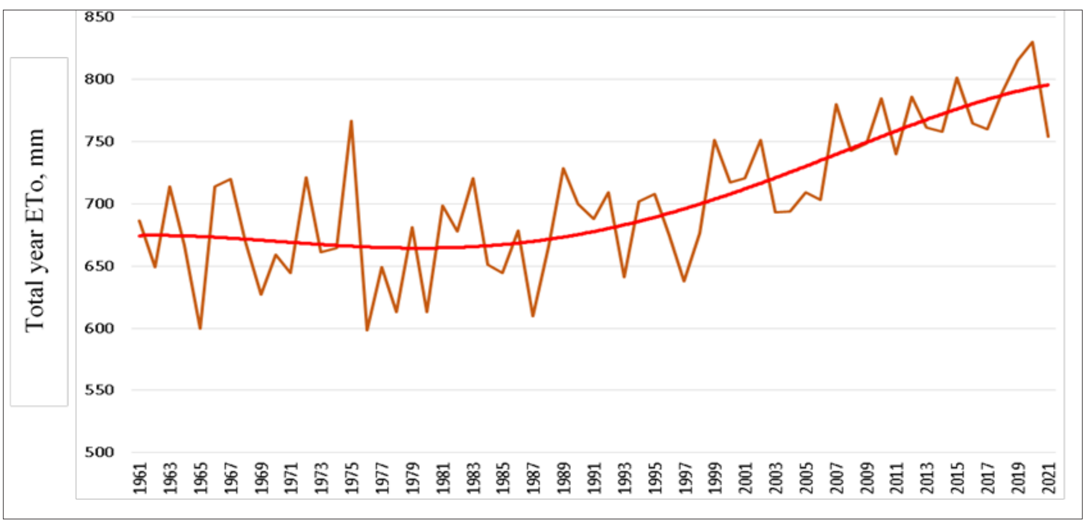



Fig. 8. Dynamics of annual potential evapotranspiration for 1961–2021, mm

4. Changes in monthly values of potential evapotranspiration for 1991–2020 compared to 1961–1990, mm

| Years | Months | | | | | | | | | | | | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | |
| 1961–2021 | 7 | 14 | 34 | 72 | 105 | 123 | 121 | 106 | 68 | 32 | 14 | 7 | 703 |
| 1961–1990 | 6 | 13 | 31 | 69 | 103 | 119 | 113 | 99 | 66 | 31 | 13 | 7 | 670 |
| 1991–2020 | 8 | 16 | 36 | 75 | 107 | 127 | 128 | 112 | 71 | 33 | 15 | 8 | 735 |
| ±1961–1990 | 2 | 3 | 5 | 6 | 4 | 8 | 14 | 12 | 5 | 2 | 2 | 2 | 65 |

The analysis of the results of this table shows that the growth of potential evapotranspiration occurs in all months of the year, but the largest increase is observed in the summer months – by 8 mm in June, 15 mm in July and 13 mm in August. In general, the growth rate of potential evapotranspiration is 65 mm per year.

**Conclusions.** Temperature changes show that the average annual air temperature over the period 1991–2020 increased by 1,2 °C, in winter by 1,6 °C, in spring by 1,1 °C, in summer by 1,5 °C, and in autumn by 0,6 °C, i.e. the most intense temperature increase is in summer.

Regarding precipitation over the same period of research, it was found that, unlike temperature, which is increasing, precipitation is decreasing in annual and seasonal (except for autumn) terms. A slight increase in precipitation in the fall does not compensate for its decrease in the annual context.

There is an increase in potential evapotranspiration throughout the year, with the largest increase in the summer months. In general, the growth of potential evapotranspiration is 65 mm per year.

Summarizing the results of the assessment of climate change on the growth of potential evapotranspiration, it should be noted that climate change has caused a significant (9 %) increase in the annual value of potential evapotranspiration, and, accordingly, a deterioration in the conditions of natural moisture supply of soils in the Central Forest-Steppe of the Ukraine. This circumstance must be taken into account when growing crops.

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УДК 504.4;631.4

# ОЦІНКА УМОВ ПРИРОДНОГО ВОЛОГОЗАБЕЗПЕЧЕННЯ НА ПРИКЛАДІ ПІВДЕННО-ЗАХІДНОЇ ЧАСТИНИ КИЇВСЬКОЇ ОБЛАСТІ

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***Анотація.** Сталість ведення землеробства в Україні безпосередньо залежить від рівня природного вологозабезпечення ґрунтів, що значно погіршується під впливом кліматичних змін. У статті*

*досліджується вплив цих змін на величину потенційної евапотранспірації (ETo) в південно-західній частині Київської області (Центральний Лісостеп України) на основі даних метеостанції м. Біла Церква за період з 1991 по 2020 роки. В основу методології досліджень покладено припущення, що оцінку впливу змін клімату на стан природного вологозабезпечення можна виконати за умови оцінки самих змін клімату за даними багаторічної динаміки температури повітря та опадів в період з 1991 по 2021 рр. зі значеннями цих же показників в період з 1961 по 1990 рр. – кліматична норма.. В якості критеріїв оцінки впливу змін клімату на стан вологозабезпечення ґрунтів обрано потенційну евапотранспірацію (ETo). Результати оцінки показали, що річна величина потенційної ETo зросла на 9 %, що опосередковано може свідчити про погіршення умов природного вологозабезпечення ґрунтів. Це має важливі наслідки для сільського господарства, оскільки зростання ETo може призвести до зменшення доступної вологи для рослин, що негативно вплине на врожайність культур. Дослідження охоплює зміни середньорічної та середньомісячної температури повітря, а також кількість опадів в розрізі сезонів і місяців. Встановлено, що протягом останніх тридцяти років в Україні спостерігається тенденція до погіршення умов вологозабезпечення, що потребує адаптації сільськогосподарських практик. Сталий розвиток аграрного сектору можливий лише за умови врахування змін в природному вологозабезпеченні при розробці моделей господарювання та технологій вирощування. Отримані результати свідчать про необхідність впровадження інноваційних агрономічних технологій, які адаптуються до актуальних змін клімату.*
***Ключові слова:*** *прогнозування вологозапасів, моделювання, фактори впливу, гідротермічні умови, сільське господарство, зміни клімату*

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# THERMODYNAMIC AVAILABILITY OF PLANT NUTRITION FROM SOIL DEPENDING ON CHANGES IN WEATHER FACTORS IN THE DAILY CYCLE

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*Soil is a form of existence of dispersed systems.*
O.E. Fersman

***Abstract.*** *The weather is one of the determining factors in crop productivity. The purpose of this publication is to experimentally confirm and highlight the mechanism of the emergence of the dynamics of pore solution's chemical composition and its thermodynamic accessibility to plants during the interaction of black soil with thermodynamic weather factors in the daily cycle. It has been established that the dynamics of availability should be sought precisely in the daily cycle of soil interaction with the environment. The basis of experimental laboratory research was the thermodynamic hydrophysical method. Samples of typical light loamy black soil of undisturbed structure from the Obukhiv district of the Kyiv region were studied. The studies have found that the emergence of the dynamics of thermodynamic accessibility of the pore solution and its chemical composition is ensured by subordinate processes that occur in the soil under the influence of cyclic environmental factors – temperature, atmospheric pressure, and moisture saturation. During the laboratory experiments, reproducible dynamics of the chemical composition of the pore solution were obtained in the daily range of changes in the specified factors. It is likely that the formation of such dynamics in three cycles of desorption – sorption is provided by all five categories of soil absorption capacity. The chemical composition of the pore solution is functionally related to the heterogeneity parameter of soil environment, which is determined by the thermodynamic potential of moisture. Among the components of the chemical composition, the dynamics of the content of nitrate ions ($NO_3^-$), as one of the most important biogenic compounds, deserves an increased attention. The unique dynamics of $NO_3^-$ content consists in its increase as the heterogeneity (desorption) of the soil (soil moisture) increases, approximately to the values of field capacity. This is explained by the specific behavior of these ions, which have a negative adsorption capacity (physical absorption capacity), between the two surfaces: solid particles-liquid and liquid-air, namely their concentration near the surface of separation in contact with the atmosphere. For structured soil with the presence of trapped air in macropores, nitrate ions are protected from leaching by the flow of moisture and are released into the pore solution in a volley when the macropores open, which is important for the conditions of nitrogen nutrition of plants. The conducted research outlines a whole section of thermodynamic research of soils with undisturbed structure, the implementation of which will result in parametric models for ensuring the production process of plants.*

***Keywords:*** *thermodynamic system of soil, thermodynamic weather factors, heterogeneity, hysteresis, dynamics of moisture availability, dynamics of pore solution's chemical composition, nitrates*

**Relevance of the research.** The soil fertility is understood as the property of soil to satisfy the needs of plants for the nutritional components necessary for the production process [1]. Despite the existing of its various forms and types, the concept of fertility remains unspecified due to the consideration of soil as a container with nutrients, which can be controlled by adding or consuming nutrients, in accordance with the agricultural law of return [2].

However, the sacred phenomenon of fertility has a much more complex nature. In particular, the productivity of the same soil can vary significantly from year to year, although according to agrochemical indicators, the nutrient content in it remains practically unchanged. This difference is believed to be due to the weather conditions of each year. However, the real mechanism of the influence of weather conditions on productivity is not considered in this case. According to chemists' calculations, the gross reserves of biogenic elements in a 20 cm layer of typical black soils will be enough for obtaining a wheat yield of 3 t/ha during 60–150 years regarding nitrogen, during 85–250 years regarding phosphorus, and during 530–870 years regarding potassium [3]. But this can be only under the condition of their full mobilization. It is obvious that weather conditions affect the availability of nutrients from the soil and the optimality of their provision for the production process. At the same time, they affect both the transpiration capacity of the plants and the availability of nutrients from the soil, from those the plants choose the most optimal in space and time for their own production process. After all, it is an axiom that plants have followed the path of adapting and harmonizing their production cycle with the functional cyclical dynamics of the interaction of the soil, as a heterogeneous system, with the cyclicity of external weather disturbances. At the same time, attention should be paid to the predominantly daily cyclical nature of the production process of plants, and therefore the dynamics of the availability of nutrition from the soil to them, as adaptive systems, should be sought precisely in the daily functional cycle of soil condition.

In a heterogeneous system of soil, the thermodynamic moisture potential is an indicator of dynamics status [4]. After all, the most plant nutrients are obtained from the pore solution, the availability of which is determined by the value of the moisture potential. Agrochemists also pay attention to the thermodynamic nature of the biogenic elements availability for plants [5].

ecently, agrochemists have also started paying increasing attention to determining the content of readily available forms of biogenic elements: available forms of nitrogen (N), mobile potassium (K), and mobile phosphorus (P) [6].

However, it is not entirely correct to determine such availability only by agrochemical methods. After all, according to K.K. Gedroits [7], the absorption capacity of the soil is divided into five categories: mechanical, physical, physicochemical, chemical, and biological, which differ in their strength of stabilization of the components of soils' thermodynamic system and the degree of conservatism or dynamism for the each of indicator categories. By considering only the level of chemical absorption capacity, which to a greater extent characterizes the gross content of elements, we effectively exclude the participation of available nutritional components of other categories of absorption capacity. And the nature of these different categories and their intertransitions are determined by the heterogeneity of the four-phase soil system, where the fourth phase, in addition to solid particles, liquid and gas, is an alive matter [8]. However, when conducting agrochemical analyses, this heterogeneous soil structure, which depends on moisture content and other factors, is completely ignored: the soil is dried, ground, sieved, and treated with certain chemicals, after which the resulting solution is analyzed [9]. In due time, V.I. Vernadsky has very critical opinion regarding the analysis of "air-dry" soils, devoid of moisture, gases, and organic matter, believing that such soils do not exist in nature [10]. Insisting on the need to study soils in their natural state, Vernadsky focused on the complete lack of knowledge of soil solutions, which, in his opinion, represent the "substrate of life", an extremely complex and dynamic system of equilibrium. Supporting the life and enabling terrestrial vegetation to exist, soil solutions, as V.I. Vernadsky pointed out, are obviously "the main element of the biosphere mechanism" [11]. Therefore, agrochemical indicators, although they are the most conservative, do not fully characterize the availability of nutrients from the soil. Above we draw attention to the predominantly daily cycle of the bioproduction process. Therefore, the basis for the dynamics of the indicators, which are the least stabilized in the soil's absorption capacity of biogenic elements, should be sought precisely in the daily cycle of the dynamics of nutritional components stabilization. And, first of all, it is necessary to establish the cause and possible mechanism of the emergence of the daily dynamics of the availability of biogenic elements in natural pore solutions as a result of the interaction of all categories of soil absorption capacity as a integral system. After all, plants, as adaptive systems, react sensitively by concentrating fast-growing root hairs precisely in the direction of horizons where nutrition is most accessible to them [12].

Plants have mechanisms, which vary subject to the intensity for providing their own production process with nutrients – from the slowest chemical leaching from crystalline rocks, e.g., as performed by lichens, to the most intense thermodynamic availability based on the dynamics of the potential pore solution in the soil. The latter mechanism can provide the highest intensity of the production process, which, e.g., is required by steppe cereal ecosystems. After all, the vegetation season of steppe forbs is quite short requiring a high intensity of the production process to form biomass and reproductive organs of grasses during the short vegetation season, in which the decisive role is assigned to moisture reserves in the Steppe soils.

We consider it appropriate to first study this specific intensive mechanism for ensuring the availability of nutrients for agricultural crops for the most productive soils from the black soils' variety. After all, the preservation of these soils is a priority task for Ukraine, where the largest area of black soils is located. And it is in Ukraine, as the successor of one of the most ancient agricultural civilizations – Trypillia, where the conditions are created and the highest motivation is present for revealing the sacred phenomenon of fertility, and accordingly, the ways of preserving and effectively managing the productive function of the national heritage of Ukraine – black soils.

*Therefore, it is in Ukraine, where there is the highest motivation to reveal the mechanism of the influence of weather cyclicity on ensuring the dynamics of the availability of nutrients from black soils, which is an element of the strategy of conscious preservation and management of the productive function of this national heritage, which is being actualized by modern global climate changes. Accordingly, the very mechanism of the emergence of the dynamics of availability of nutrients from the soil for plants should be sought in the daily cycle of soil-environment interaction when considering the soil as a complete thermodynamic system, in which a dynamic equilibrium of the chemical composition of natural pore solutions arises in the heterogeneous structure of soil framework.*

**The purpose of the conducted research** is to experimentally confirm and highlight the probable mechanism of the emergence of the dynamics of pore solution’s chemical composition and the availability of plant nutrition components from black soils, as an integral heterogeneous thermodynamic system of natural composition, in interaction with weather factors of the external environment, which ensures its productive function.

**Materials and research methods.** The basis of this scientific research is thermodynamic methods of laboratory and field experimental studies of the natural soils and their regimes, a systematic analysis of functional parameters of soils based on the proposed dynamic functional model in interaction with the external environment [13]. This dynamic model is based on the principles of synergetics, which consider the soil as a thermodynamically non-equilibrium system and a dissipative active kinetic environment, in which self-stabilization and self-organization processes are constantly present, ensuring their evolution in accordance with the cyclicity of external weather conditions [13]. It is the permanent thermodynamic disequilibrium of the soil that provides local and periodically increasing thermodynamic availability of nutritional components for plants, taking into account local phase transitions of matter. Research was conducted for over thirty years on various types of soils belonging to the sites in the drainage and irrigation ones. The most large-scaled agro-landscape studies were conducted in the Forest-Steppe zone in the Obukhiv district of the Kyiv region at the experimental agro-ecological polygon during 1989–2005, where typical light loamy black soils of varying degrees of washout are spreaded and a soil conservation system of agriculture with contour-ameliorative organization of the territory was implemented [14].

It was for these soils that in-depth laboratory studies of the dynamics of availability and the dynamics of the chemical composition of pore solutions were conducted under the conditions of targeted management of soil heterogeneity. Chemical analyses of pore solutions were carried out in the certified hydrochemical laboratory of the Geological Faculty of Taras Shevchenko National University of Kyiv under the leadership of PhD in Chemical Sciences T.V. Gerbunova.

**Research results and their discussion.** The first stage in achieving the goal of the study was to consider the regularities of the specific structure of a real dispersed soil system. When considering the structure, the traditional assessment of soil structure for agrophysics, which is based on the principle of reductionism, i.e. the assessment of soil fragments, into which it breaks down when its integrity is violated, was abandoned. After all, the plants, climatic factors, and moisture interact with the soil as an integral dispersed thermodynamic system, where many microprocesses of transformations of matter, energy, and information occur, and those processes are characterized by the structure of the pore space. At the same time, its heterogeneity is decisive, and it is characterized by the surface of the solid-liquid and liquid-air interfaces, as well as the biomembranes of organisms. And it is the structure of the soil’s pore space that determines the dynamics of interface surfaces when moisture saturation changes. To characterize the pore space, a new physical model was created in the form of a corrugated equivalent of capillary [15]. This model takes into account the irregularity of the intersection of imaginary capillaries, which is characterized by the well-known model of the Jamin capillary [16]. Another, also well-known, model of the so-called equivalent capillary of A.V. Lykov integrally takes into account the combination of imaginary capillaries of all sizes [16]. The new model of the corrugated equivalent capillary combines the benefits of both of these physical models of soil pore space and thereby acquires a new quality. It is used to substantiate the existence of air bubbles trapped by liquid membranes in the pore space of the soil. The main condition for the equilibrium existence of this air is the equality of the radii of curvature of the liquid membrane from the outside, in contact with the atmosphere ($r_a$), and inside this bubble of trapped air ($r_{ta}$), i.e. the equilibrium condition $r_a = r_{ta}$. Since the real dispersed soil system can be characterized, according to the Jamin model, by two characteristic dimensions $r_{min}$ and $r_{max}$, in the model of a corrugated equivalent capillary, a segment is determined, where the condition $r_{min} \leq r_a \leq r_{max}$ is fulfilled, which is the justification for a certain group of pores, where air trapped by liquid membranes exists in an equilibrium state. It is the presence of this air that is the main factor in the occurrence of capillary hysteresis in the soil. The famous scientist O.O. Rode drew attention to this unique phenomenon back in the previous century and emphasized that, despite the fact that in the thermodynamic interpretation of soil-hydrological phenomena, hysteresis is quite deliberately not taken into account, it is actually a phenomenon of extreme importance not only in theoretical terms, but also in solving quite practical problems [15]. Thus, capillary hysteresis is one of the fundamental properties of soil, which is directly related to its other fundamental property – heterogeneity [18].

Thermodynamic potential dynamics. The use of the physical model of a corrugated equivalent of capillary allowed to create a "Method for Determining the Structure of the Pore Space of Soils (Dispersed Media)" [19], which became an applied aspect of the use of the hysteresis phenomenon. The patented utility model is based on the study of the capillary hysteresis loop obtained in a special mode: desorption from full capacity as quickly as possible when there is practically no trapped air in the soil, and sorption as slowly as possible when equilibrium is established in the soil in the expansion of pores with trapped air. The difference in moisture saturation between the fast desorption and slow sorption branches for fixed values of capillary potential characterizes the moving average value of the total volume of trapped air in the group of pores, where the equilibrium condition $r_{min} \leq r_a \leq r_{max}$ is satisfied. The graph aggregates points with different values of capillary potential ($P_i$ and different volumes of trapped air $V_{ta} = f(P_i)$ is called a structural characteristic of the soil pore space). In fact, the curve, graphically plotted as the difference in moisture content between the branches of the hysteresis loop, represents a differential curve of the distribution of pore space by radii. As the pore radii are related to the Jurin's functional dependence on the capillary potential: $P \approx -0{,}15/r$ or $r \approx -0{,}15/P$ [16]. Air trapping in pore expansions increases the overall heterogeneity by the amount of the total internal surface area of the bubbles. Therefore, it is necessary to distinguish between the area of the liquid-air surface interface in contact with the soil atmosphere, which was called extra-heterogeneity (external) [20], and the area of the liquid-air surface interface in the trapped air bubbles themselves, which was called intra-heterogeneity (internal). It is the intra-heterogeneity that most actively responds to the changes in external thermodynamic conditions, because air separated from the atmosphere by liquid membranes reacts sensitively to the changes in external thermodynamic conditions – temperature ($T^oC$), atmospheric pressure ($P_{atm}$), and moisture saturation ($\theta$) – by changing gas pressure and moisture saturation of the pore's body. In this case, a change in gas pressure in the bubble leads to the displacement of the liquid, or its entry into the pore's body, depending on the direction and combination of directions of change in external thermodynamic parameters. The cooperativity of such microprocesses in the pore space of the soil leads to the redistribution of moisture in it and a change in the thermodynamic state of the soil at the level of the macroparameter of the system of unsaturated soil, and, accordingly, to a change in the availability of moisture for plants. The presence of such a dynamics of capillary potential has been experimentally studied under the changes in temperature [20], humidity, and gas pressure in the range, which corresponds to the daily cycle of their variability. It has been found that a rapid change in any external parameter causes a self-oscillating process of capillary potential dynamics in the soil [20].

Therefore, the combination of two fundamental properties – the heterogeneity and hysteresis – ensures the dynamics of pore solution availability during soil interaction with changing external environmental conditions.

Naturally, such processes develop in the time and space of the soil environment, to which plants and plant communities and biota in general, have been adapted. Therefore, the overall response of the thermodynamic state of moisture to changes in external conditions depends not only on the absolute amplitude of changes in thermodynamic parameters, but also on the speed of their changes [15]. And it is the daily cycle that provides the highest speeds, and, accordingly, the highest amplitude of the reaction of the soil thermodynamic system to external changes, which coincides with the daily bioproduction cycle of plants. Therefore, it is the hysteresis of the soil that provides the dynamics of stabilization of the pore solution, within the capillary hysteresis loop, when interacting with the daily variability of external thermodynamic (weather) parameters.

*Analysis of soil structure through the structure of its pore space based on the thermodynamic methods allows us to differentially consider the spatial continuum of pore space, quantitatively characterize the dynamics of soil heterogeneity, and also identify specific local subordinate (internal) processes of the microgradient structure of the soil environment, which ensure local transportation and phase transitions of matter.*

Chemical composition dynamics. One of the most important issues is the assessment of the influence of the daily cyclicity of weather factors on the chemical composition of the pore solution, since both its thermodynamic availability and its chemical composition are the results of the same internal (subordinate) soil processes. In particular, the reaction of trapped air bubbles to the cyclical variability of external thermodynamic environmental conditions leads, in addition to intra-pore moisture redistribution, to the emergence of gas saturation dynamics of the pore solution, which has local nature around the bubbles and provides gas concentration gradients in the liquid of around the pores with trapped air. The carbon dioxide ($CO_2$), which has the highest solubility in the pore solution among atmospheric gases, deserves special attention in these processes. But the main thing is that, when it dissociates, it increases the concentration of hydrogen ions, that is, it lowers the pH. In fact, trapped air becomes a local source of carbonic acid in the soil environment [20]. In turn, radial acidity gradients become a factor in phase transitions of matter, primarily for compounds that cement soil particles. In particular, the dissolution of these compounds, which have predominantly carbonate composition, releases cemented soil particles, which can enable their relative movement under the action of external forces. It is likely that this mechanism ensures the self-development of the soil in the direction of its decompression by increasing the volume of elementary pores and transforming them into structural macropores.

The influence of capillary potential on the dynamics of the chemical composition of the pore solution for a typical light loamy black soils, which is shown in Fig. 1, has been experimentally confirmed. The experimental setup was as follows: a cylindrical soil sample of undisturbed structure with a diameter of 12 cm and a height of 10 cm, located in a plastic cutting ring and waterproofed from above and below with paraffin-bitumen caps, was equipped with two ceramic probes of control tensiometers on the side surface of the soil cylinder and a central working probe, through which the moisture saturation of the soil sample was changed according to the hydrophysical tests methodology [21]. The experimental methodology provides for the sampling of 10 ml portion-wise microsamples of pore solution through a central working ceramic probe during the desorption process of a soil sample, which is saturated to full moisture capacity. The decrease in soil moisture saturation during the sampling was equal to the 1–2,5 % of the volume. The extraction of pore solution in the radial space of the sample actually simulated the extraction of solution from the soil by plants' roots. Semi-microhydrochemical standard analyses was performed on the selected samples to determine the main macrocomponents $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $HCO_3^{-}$, $SO_4^{2-}$, $Cl^{-}$, $NO_3^{-}$, and pH when diluting the sample to the volume required for the analyses. The results of the determinations are shown in Fig. 1, where the concentration of each macrocomponent, presented in mg.eq./l, and pH are functionally related to the capillary potential expressed in absolute values (|P|), kPa, at which the samples were taken. Thus, it has been shown that there is a dynamic change in the chemical composition of the pore solution as the soil desorption progresses, which may be associated with a decrease in the radii of curvature of the liquid-air interface in a heterogeneous soil system, that is, in fact, with an increase in its heterogeneity. Three desorption cycles were carried out and after each cycle the soil monolith was saturated with distilled water through the central working ceramic probe.

According to the results of chemical analysis of pore solution samples, a certain reproducible regular dynamics of the chemical composition components content is visible, although the

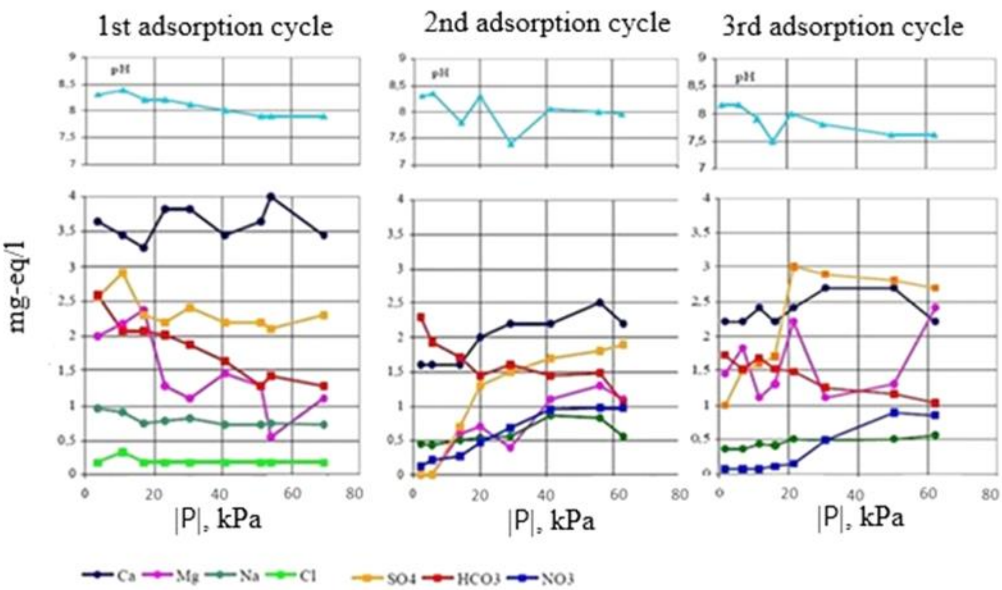


Fig. 1. Dynamics of the chemical composition of the pore solution for a typical light loamy black soil, interval 0,0–0,1 m (placore)

small volume of samples reduces the accuracy of their determination, which sometimes violates the monotony of the obtained dependences. In particular, the following regularities are noteworthy:

– the acidity of the pore solution tends to increase by almost an order of magnitude (a decrease in pH of 1) in each of the three desorption cycles;

– the content of hydrocarbons ($HCO_3^-$) naturally decreases as desorption (decrease in soil moisture) occurs in all three cycles;

– the content of sulfates ($SO_4^-$) decreased in the first cycle, however, in repeated cycles there is a clear tendency towards an increase in their content;

– chlorine ions ($Cl^-$), which have a negative adsorption capacity and can only be found in solution without a replenishment source, were recorded only in the first desorption cycle, and were no longer detected in repeated cycles;

– unfortunately, nitrate ions ($NO_3^-$) were not determined in the first cycle, however, in repeated cycles, a clear tendency towards an increase in their content in the solution as desorption proceeds is observed;

– the dynamics of the content of $Ca^{2+}$, $Mg^{2+}$ and $Na^+$ cations have common features: at the first stage, their content decreases from the highest absolute values, but during repeated desorption cycles, a tendency towards an increase in their content is recorded as the soil is desorbed.

The obtained patterns were reproduced on other soil samples, so their trend has important consequences. In particular, the increase in nitrate content as desorption proceeds can be explained by the fact that nitrate ions have a negative adsorption capacity, which is a manifestation of the physical absorption capacity of the soil [22], therefore, in unsaturated soil they gravitate towards the surface of the liquid-air interface. That is, they concentrate directly below the surface of the liquid-air interface, acquiring the ability to slide and flow along this surface when a moisture potential gradient appears. It is likely that this mechanism of pulling nitrates to the roots operates during pore solution extraction. Under the conditions of air compression, nitrate ions concentrate near the inner surface of this bubble (intra-heterogeneity) and when it opens or a plant roots penetrates it, a volley of these ions occurs, which is a source of one of the most important biogenic elements for plants – nitrogen.

This is the way how we see the experimentally found mechanism of increasing the content of nitrate ions in the pore solution due to their volley ejection during the opening of pores with trapped air during the soil drying process, which directly affects the availability for plants of the nitrogen from the pore solution. The reproducibility of this extremely important pattern is experimentally confirmed by the results of tests of a typical black soil's sample from the depth interval of 0,20–0,30 m of the same soil profile on the plateau (Obukhiv district, Kyiv region). Table 1 contains the absolute values of the capillary potential |P|, kPa, at which samples of the pore solution were taken, and the corresponding values of the nitrate ion content (mg-eq/l) for the II and III desorption cycles for two samples of typical black soil taken from two depth intervals. Figure 2 presents the graphs of the dynamics of the nitrate ions content in the drained pore solution and a graph of the water retention curve of sample No. 1 in the second desorption cycle with the designation of the points of micro-sampling of the pore solution on this curve (see Table 1).

The common nature of the nitrate content dynamics during the soil desorption process is noteworthy: this is an almost monotonic increase in their content to absolute values of capillary potential of 30–45 kPa, after which a certain decrease in their content is observed. This decrease is most likely related to the nature of the pore space structure of the studied soil and gives grounds for concluding that further soil desorption will worsen the conditions for providing plants with the nitrate form of nitrogen.

In the heterogeneous environment of unsaturated soil, there is likely to be an uneven distribution of nitrate ions in the pore solution, as they are under the influence of both solid-liquid

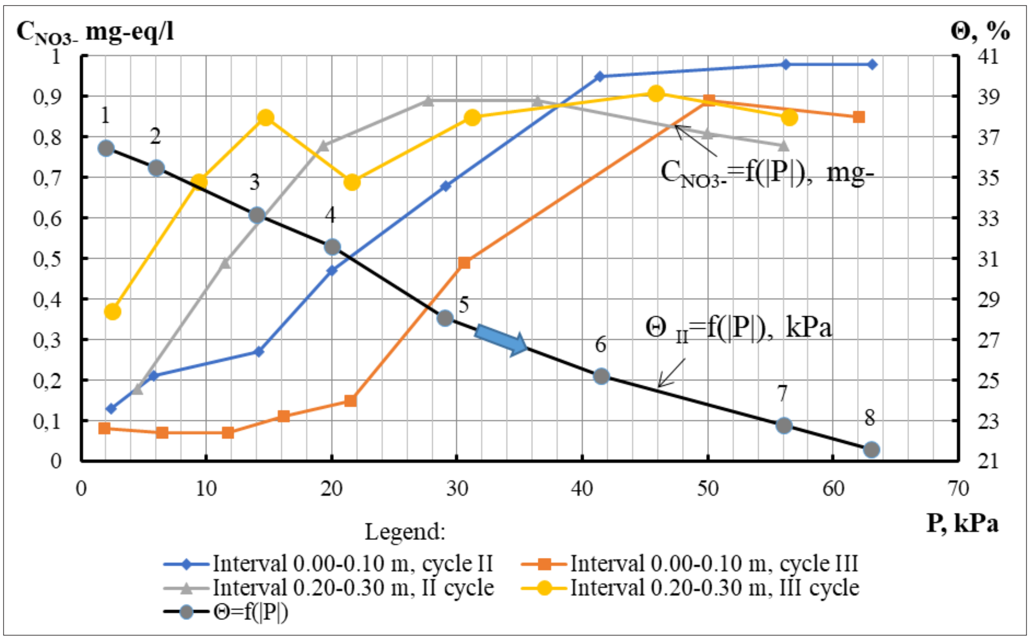


Fig. 2. Graph of repeated desorption of a sample of the typical light loam black soil (placor) from depth intervals of 0,00–0,10 m and 0,0–0,30 m with designations on the , kPa, curve of average moisture values of pore solution sampling and the curves of the dynamics of the nitrate nitrogen content in the drained solution over two desorption cycles , mg-eq/l

1. Nitrate nitrogen ($NO_3^-$) content (mg-eq/l) in drained pore solution depending on absolute values of capillary potential (|P|, kPa) for typical black soil samples from two depth intervals on the second and third desorption cycles

| № | Sample 1, interval 0,00–0,10 m | | | | Sample 2, interval 0,20–0,30 m | | | |
|---|---|---|---|---|---|---|---|---|
| | 2nd cycle | | 3rd cycle | | 2nd cycle | | 3rd cycle | |
| | \|P\|, kPa | $C_{NO3^-}$ mg-eq/l | \|P\|, kPa | $C_{NO3^-}$ mg-eq/l | \|P\|, kPa | $C_{NO3^-}$ mg-eq/l | \|P\|, kPa | $C_{NO3^-}$ mg-eq/l |
| 1 | 2,4 | 0,13 | 1,9 | 0,08 | 4,5 | 0,18 | 2,5 | 0,37 |
| 2 | 5,8 | 0,21 | 6,5 | 0,07 | 11,5 | 0,49 | 9,4 | 0,69 |
| 3 | 14,2 | 0,27 | 11,7 | 0,07 | 19,3 | 0,78 | 14,7 | 0,85 |
| 4 | 20,0 | 0,47 | 16,2 | 0,11 | 27,7 | 0,89 | 21,6 | 0,69 |
| 5 | 29,1 | 0,68 | 21,5 | 0,15 | 36,4 | 0,89 | 31,2 | 0,85 |
| 6 | 41,4 | 0,95 | 30,6 | 0,49 | 49,9 | 0,81 | 45,8 | 0,91 |
| 7 | 56,2 | 0,98 | 50,1 | 0,89 | 56,0 | 0,78 | 56,5 | 0,85 |
| 8 | 63,1 | 0,98 | 62,1 | 0,85 | – | – | – | – |

and liquid-air interfaces. Therefore, these ions, "repelling" from solid particles, gravitate to the surface of the liquid-air interface, due to negative adsorption capacity, therefore, these ions will experience the least the influence of the solid soil skeleton in the most powerful zones of capillary moisture, which are usually observed in the form of joint cuffs at the contact of dispersed soil particles or in water-filled pores. Therefore, it is possible to assume that the distribution of nitrate ions is extremely uneven in the heterogeneous soil environment and may have a network structure, also taking into account the intra-heterogeneity of macropores with trapped air and the presence of a constant source of nitrification of organic matter in the soil. It is these macropores that play a role of a storage, a reserve of nitrate ions, preventing their migration and leaching by the free pore solution.

An important point is the interpretation of the dynamics of the cation content in the pore solution, in particular their almost monotonic decrease in the first desorption cycle and increase in repeated desorption cycles.

**Conclusions.** The influence of weather thermodynamic factors in the daily cycle, namely temperature, atmospheric pressure, and precipitation, on the emergence of the dynamics of thermodynamic availability for plants of soils' pore solution and the dynamics of its chemical composition has been experimentally confirmed. The general formula for the influence of weather looks like the following: the dynamics of weather factors – the dynamics of soil heterogeneity – the dynamics of moisture potential and its chemical composition, which determines the dynamics of nutrient availability.

The dynamics of the soil pore solution's chemical composition is determined by the dynamics of heterogeneity (soil moisture), which occurs under the influence of external thermodynamic disturbances and leads to the destabilization of all categories of soil absorption capacity.

The amplitude of the soil heterogeneity dynamics under the influence of weather is determined by the rate of variability of thermodynamic factors, and their greatest influence on the degree of soil heterogeneity is provided by daily fluctuations in weather factors.

The different distribution of ions – components of nutrition in the pore solution – between the two interfaces of solid particles – liquid and liquid-air – is significantly different from their distribution in the free solution, which is due to the property of different adsorption capacity (physical absorption capacity), which leads to their uneven spatial distribution and a certain selection in the structure of the soil pore space.

A unique phenomenon of an increase in the nitrate content ($NO_3^-$) in the pore solution as the heterogeneity (desorption) of the soil increases, which is determined by the structure of the pore space, in particular the presence of structural macropores with trapped air, has been experimentally found. This phenomenon is of a great importance for the conditions of nitrogen nutrition of plants and requires further studies.

Without providing ready-made management solutions for regulating the nature of fertility, the conducted studies outline the direction of thermodynamic microgradient studies of soils of undisturbed structure based on the miniaturization of sensors and the priority of *in-situ* and *on-line* real-time studies, which will allow combining in parametric models the cyclical nature of external weather factors with the cyclical dynamics of the plant production process.

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# ТЕРМОДИНАМІЧНА ДОСТУПНІСТЬ ЖИВЛЕННЯ РОСЛИН З ҐРУНТУ ЗАЛЕЖНО ВІД ЗМІНИ ФАКТОРІВ ПОГОДИ В ДОБОВОМУ ЦИКЛІ

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*Ґрунт – це форма існування дисперсних систем.*
О.Є. Ферсман

***Анотація.*** *Погода є одним із визначальних чинників продуктивності сільськогосподарських культур. Метою публікації є експериментальне підтвердження і висвітлення механізму виникнення динаміки хімічного складу порового розчину та його термодинамічної доступності для рослин при взаємодії чорноземного ґрунту з термодинамічними факторами погоди в добовому циклі. Встановлено, що динаміку доступності слід шукати саме в добовому циклі взаємодії ґрунту з довкіллям. Основою експериментальних лабораторних досліджень був термодинамічний гідрофізичний метод. Досліджували зразки чорнозему типового легкосуглинкового непорушеної структури з Обухівського району Київської області. Дослідженнями встановлено, що виникнення динаміки термодинамічної доступності порового розчину і його хімічного складу забезпечують субординаційні процеси, що виникають у ґрунті за впливу на нього циклічних факторів довкілля – температури, атмосферного тиску і вологонасичення. У лабораторних експериментах отримана відтворювана динаміка хімічного складу порового розчину в добовому діапазоні змін вказаних факторів. Вірогідно формування такої динаміки у трьох циклах десорбції – сорбції, забезпечують усі п'ять категорій вбирної здатності ґрунту. Хімічний склад порового розчину функціонально пов'язується з параметром гетерогенності ґрунтового середовища, яку визначає термодинамічний потенціал вологи. Серед компонентів хімічного складу найбільшої уваги заслуговує динаміка вмісту іонів нітратів ($NO_3^-$), як однієї з найважливіших біогенних сполук. Унікальна динаміка вмісту $NO_3^-$ полягає у його зростанні по мірі зростання гетерогенності (десорбції) ґрунту(вологості ґрунту) орієнтовно до значень НВ. Це пояснюється особливою поведінкою цих іонів, що мають від'ємну адсорбційну здатність (фізична вбирна здатність), між двома поверхнями розділу тверді частки-рідина та рідина-повітря,а саме їх концентрацією біля поверхні розділу на контакті з атмосферою. Для оструктуреного ґрунту із наявністю затиснутого повітря у макропорах нітрат-іони захищені від вимивання потоком вологи і залпово викидаються у поровий розчин при відкритті макропор, що має важливе значення для умов азотного живлення рослин. Проведені дослідження окреслюють цілий напрямок термодинамічних досліджень ґрунтів непорушеної структури результатом реалізації якого стануть параметричні моделі забезпечення продукційного процесу рослин.*

***Ключові слова:*** *термодинамічна система ґрунту, термодинамічні фактори погоди, гетерогенність, гістерезисність, динаміка доступності вологи, динаміка хімічного складу порового розчину, нітрати*

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