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LAND MANAGEMENT, CADASTRE AND LAND MONITORING
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ЕКОНОМІКА ТА ЕКОЛОГІЯ ЗЕМЛЕКОРИСТУВАННЯ

НАУКИ ПРО ЗЕМЛЮ. ГЕОІНФОРМАЦІЙНІ ТЕХНОЛОГІЇ МОДЕЛЮВАННЯ СТАНУ ГЕОСИСТЕМ

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ONTOLOGY OF BOUNDARIES IN THE SYSTEM OF MODERN LAND MANAGEMENT: FROM GEOMETRY TO THE REGIME OF RIGHTS AND VALUES

A. MARTYN,
Doctor of Economic Sciences, Professor,
Corresponding Member of the National Academy of Agrarian Sciences of Ukraine National University of Life and Environmental Sciences of Ukraine
Email: martyn@nubip.edu.ua
ORCID: 0000-0002-6905-2445

L. HUNKO,
Doctor of Economic Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
Email: gunko_l@nubip.edu.ua
ORCID: 0000-0002-9454-744X

A. SYNIEUTSKYI,
PhD student
National University of Life and Environmental Sciences of Ukraine
Email: sai37@ukr.net
ORCID: 0009-0000-4934-2181

Abstract. *The article conceptualizes the notion of a boundary in modern land management as an institutional-regime category that transcends the geometric interpretation of a dividing line. Based on comparative-historical and institutional analysis, norm-oriented modeling, and formal ontologization (LADM), it substantiates the transition from a material-geometric to a regime-based ontology of space, where the boundary functions as an event-relation that constitutes rights, restrictions, responsibilities, and rent flows. Four structural levels of the boundary-material, legal, informational, and ecological-are identified, and their supervenient relations and the causal influence of procedural data validity on the legitimacy of regimes are demonstrated. The principles of ontological boundary design are formulated (procedural* *constitutiveness, multimodality, adaptability, quality metricity, compatibility and priorities, value transparency), which enable the integration of legal norms, spatial data, and mechanisms of land value management. The practical significance lies in the transition from a "register of lines" to a dynamic regime-based model of space for cadastral and planning systems, improving decision quality, minimizing conflicts, and ensuring transparent benefit distribution. The work is positioned as a contribution to the development of modern land management theory as a fundamental discipline; further publications are announced concerning regime formalization, GeoBIM integration, and legitimacy assessment procedures.*

Keywords: *boundary; spatial ontology; land management; LADM; institutional regimes; rights and restrictions; 3D/4D cadastre; interoperability; value capture; spatial governance.*

Problem Statement

The modern system of land management is undergoing a profound theoretical and methodological shift. Historically, its foundation was the geometric paradigm, within which the boundary was regarded as a linear representation of territorial division. Such reduction ensured technical precision but failed to reflect the complex nature of space as a bearer of rights, restrictions, land-use regimes, ecosystem services, and socio-economic values. As a result, a key ontological gap has emerged in the scientific theory of land management—the absence of a holistic understanding of the boundary's nature as a phenomenon irreducible to a physical line or coordinate geometry.

In the contemporary context, a boundary is not merely a material marker but the result of a complex interaction among legal, economic, environmental, and informational processes. It represents the spatial form of legal titles and restrictions, a concentration of social relations of ownership, access, control, and responsibility. In the conditions of cadastral digitalization, the formation of multidimensional (3D and 4D) models of land use, the development of spatial planning systems, and automated management, the classical notion of a boundary as a static geometric line loses its heuristic value. Instead, there emerges a need for a new ontology of boundaries – one that explains them as procedural, multilevel, and relational structures combining materiality, legal status, informational representation, and social legitimacy.

Theoretical indeterminacy in understanding boundaries generates systemic problems: inconsistency of legal regimes, land-use conflicts, difficulty of integrating cadastral, environmental, and urban-planning data, and imperfections in assessing spatial value and constraints. The lack of a comprehensive ontology of the boundary leads to fragmentation in state land policy, legal instability, and discrepancies between physical space and legal reality.

Thus, the scientific problem lies in the need to reconceptualize the essence of boundaries in the modern land management system – to move from a geometric toward an ontological-legal and regime-based understanding of space. This involves the development of a theoretical model in which the boundary appears not only as the result of measurement but as a process of constituting rights, generating value, reconciling interests, and maintaining spatial justice. The development of such an ontology of boundaries is a necessary condition for building a modern scientific theory of land management capable of integrating spatial, legal, economic, and ecological dimensions of land governance.

The purpose of this article is to develop the theoretical and methodological foundations of the ontology of boundaries in the system of modern land management as a fundamental basis for the transition from a geometric to a legal-value-based understanding of space. The research aims to conceptualize the boundary as a multidimensional phenomenon – a procedural, legal, informational, and socio-ecological structure that constitutes regimes of ownership, use, restriction, and management of land resources.

To achieve this purpose, the following objectives are set:

– to substantiate the philosophical and ontological nature of boundaries as a category of modern land management theory;

– to determine the regularities in the evolution of boundary concepts from material-geometric to institutional-regime models;

– to identify the key structural levels of a boundary (material, legal, informational, ecological) and the interrelations among them;

– to formulate the principles for constructing an updated ontology of boundaries capable of integrating spatial data, legal norms, and land value management mechanisms;

– to define the theoretical conditions for further formalization and practical implementation of this ontology in modern land management systems.

The realization of this goal allows the boundary to be reinterpreted not as a technical abstraction but as a key institutional and legal element of spatial organization, determining the efficiency, justice, and sustainability of land relations in contemporary society.

Materials and Methods

The empirical base comprised three classes of materials:

(1) historical and legal corpora and sources concerning the establishment of boundaries and titles from the earliest periods (Ancient Eastern boundary markers such as kudurru; the Roman Corpus Agrimensorum Romanorum; medieval fiscal surveys like the Domesday Book; parliamentary enclosure acts; the Napoleonic cadastre; the Torrens system, etc.);

(2) contemporary normative and standard documents that formalize the ontology of boundaries in data and law (UNECE Land Administration Guidelines, FAO Voluntary Guidelines on the Responsible Governance of Tenure (VGGT), ISO 19152 Land Administration Domain Model (LADM), FIG documents, and national legislation on cadastre and planning, including the provisions of the Law of Ukraine "On the State Land Cadastre");

(3) spatial and registry data relevant to the regime-based interpretation of boundaries (cadastral maps, urban zoning data, property rights registries, and remote sensing datasets based on programs such as Landsat and Copernicus).

The methodology combines multilevel conceptual-institutional analysis with formal data-based procedures. The comparative-historical method was applied to identify invariants of boundaries across legal systems; institutional analysis and property rights theory were used to interpret the boundary as a bearer of regimes of access, exclusion, and responsibility; deontic logic and norm-oriented modeling were employed to describe permitted, prohibited, and obligatory spatial relations; formal ontologization was carried out within the LADM framework by mapping the concepts "object – right/restriction/responsibility – event" onto entities of cadastral and planning databases; systems analysis was used to establish relationships among the material, legal, informational, and ecological levels, among others.

Analysis of Recent Studies and Publications

The ontology of boundaries in land management has developed at the intersection of legal history, the economics of property rights, and cadastral information standards. Ancient Eastern artifacts such as the kudurru demonstrate an early understanding of the boundary as a legal fact: these were monumental royal grants inscribed with sanctions for encroachment, meaning that the boundary functioned as a performative act rather than a purely physical marker [1]. Modern Assyriological studies clarify that the kudurru should be interpreted primarily as legal monuments recording titles and boundary agreements, not as "boundary stones" in the literal sense [1].

The Roman tradition codified the boundary as a synthesis of law, procedure, and technique: the Corpus Agrimensorum Romanorum systematized methods of delimitation, emphasizing that the legal validity of boundary establishment is ensured by a public act and its textual documentation [2].

Medieval fiscal surveys, notably the Domesday Book (1086), illustrate the boundary as a basic unit of taxation, jurisdiction, and proof of title. Historiography consistently interprets the Domesday as an instrument of land value accounting and of legal immunities, granting the boundary the status of an administrative-legal constant [3–4].

Early modern transformations–the parliamentary enclosures in England–shifted the boundary from a mode of "common use" to a regime of private exclusivity. Parliamentary records and academic reviews document thousands of acts and millions of acres restructured under enclosure laws, reflected in detailed plans and a new rent-based logic of the boundary [5-6].

In the nineteenth century, institutions emerged that still define the ontology of the boundary. The Napoleonic Cadastre (1807) established the duality of "plan-register" and the unified parcel as the vehicle of fiscal equity; recent empirical studies confirm the scale and objectives of this reform [7-8]. In parallel, the Torrens system (South Australia, 1858) introduced the principle of indefeasibility of title, whereby the authenticity of boundary and title is guaranteed by the state register [9].

During the twentieth century, cadastral systems transitioned from a "narrow fiscal" to a multifunctional model. Classical works on cadastral evolution showed that these systems transcended fiscal functions to become information infrastructures serving markets, planning, taxation, and environmental protection [10-11]. Simultaneously, GIS and remote sensing emerged: Roger Tomlinson's CGIS project for the Canada Land Inventory inaugurated operational GIS and revealed the potential of thematic layering as a new mode of "seeing" boundaries, as documented in his original publications and subsequent reviews [12-14]. The Landsat program, launched in 1972, provided a continuous record of terrestrial imagery, institutionalizing data as evidence of spatial change and forming a foundational layer for cadastral and planning decision-making [15-16].

In the twenty-first century, the ontology of the boundary was formalized through international guidelines and standards. The UNECE Land Administration Guidelines defined the target functions of land administration systems and emphasized the role of basic spatial units, including those "above and below surface" [17-18]. The FAO Voluntary Guidelines on the Responsible Governance of Tenure (VGGT, 2012) anchored human rights and legitimacy of tenure regimes as criteria of proper land governance, thereby expanding the boundary's scope from geometry to ethics and inclusion [19-20]. The key framework is ISO 19152 (Land Administration Domain Model, LADM): the 2012 edition and the forthcoming 2024–2025 revision unify the "people–land–rights/restrictions/responsibilities" model, transforming the boundary into a formal data entity with explicit semantics and interoperability [21-23]. Parallel to this, the 3D/4D cadastre program conceptualized the boundary as a volume in space–time: FIG publications, thematic reports, and national roadmaps (notably those of the Netherlands) describe models of legal objects, BIM/CityGML integration, and progressive implementation [24-26].

The theoretical foundation of the "regime-based" understanding of boundaries was provided by the economics of property rights and the institutional theory of collective action. The classical works of R. Coase on externalities and transaction costs, H. Demsetz on the evolution of property rights, and E. Ostrom on rules and boundaries in common-pool resources explain why boundaries constitute rents, conflicts, and mechanisms of their resolution; these ideas have been repeatedly incorporated into land policy and cadastral design [27-29].

Synthesis of these research directions yields three robust conclusions from prior studies: 1) the boundary has historically evolved from a sacred-legal act to a digital institution with a verifiable data chain [1-3, 7-9, 21-23]; 2) the market-economic and public-legal functions of the boundary have expanded from fiscal accounting to multifunctional regimes of value and restriction [10–11, 17–20]; 3) 3D/4D cadastral models and interoperability standards have established a foundation for the formal description of boundaries as volumetric-temporal carriers of rights and restrictions [21–26].

This defines the current theoretical gap: the absence of an integrated ontology that unites legal, economic, and data-based interpretations of the boundary into a single regime model.

Presentation of the Main Research Material

In global practice, several types of boundaries are distinguished according to their ontological status and legal effect:

1) Jurisdictional: state borders, administrative divisions, municipal and special districts (water management, forestry, port zones);

2) Cadastral: parcel boundaries, sub-parcels, servitude strips, infrastructure corridors, rights-of-way and access, including 3D rights (surface, subsurface, building volume) and temporal limits of rights;

Table 1. Principles of Ontological Design of Boundaries in Land Management

Principle Name	Essence of the Principle	Example of Application
Procedural Constitutiveness	A boundary exists only insofar as it is created and confirmed by a valid procedure (act, registry, public notice).	A fence placed "by sight" between two plots does not constitute a valid boundary until coordinates are recorded in the cadastre and ownership rights are registered.
Multimodality	A boundary integrates five layers: material, legal, informational, social, and ecological. Failure in any layer reduces legitimacy.	For a coastal protection zone: physical signs (material), council resolution (legal), GIS layer (informational), public hearings (social), and shoreline ecosystem regime (ecological). Only together do they function.
Adaptivity	The boundary regime changes in accordance with predefined risk and data triggers.	For a flood-prone area: if the water level exceeds X cm once every 10 years, new construction is automatically prohibited and/or mandatory land filling is required.
Metric Quality	Boundary quality is measured by open metrics: coordinate accuracy, data provenance, procedural legitimacy.	For example, land management documentation states: boundary point accuracy ±0.10 m; source–survey of 2024; protocol of neighbor agreement. This allows the owner to understand the boundary's reliability.
Compatibility and Priorities	Predetermined rules define overlaps of jurisdictions and special regimes and their hierarchy of precedence.	A power line crosses an area zoned as residential. The rule applies: the power line protection zone takes precedence, so housing cannot be built directly under the wires even if the master plan allows it.
Value Transparency	Gains and losses from boundary or regime changes are disclosed and fairly distributed under value capture/sharing rules.	After construction of a new metro line, nearby land values increase. Part of the gain, through property taxes or infrastructure contributions, returns to the city for public facilities, while the remainder stays with owners.

Note: Author's elaboration.

3) Planning: functional zoning boundaries, protective belts, coastal buffer zones, sanitary and noise buffers, risk zones (flood, landslide), and urban growth boundaries;

4) Environmental and heritage: protected areas, biocorridors, buffer zones of World Heritage sites, archaeological areas;

5) Resource and agrarian: agricultural land masses, reclamation networks and their components, irrigation/drainage zones, shelterbelts;

6) Sectoral and special-purpose: right-of-way and protection zones for power lines, pipelines, transport routes, aerodrome restriction surfaces, military zones, coastal and maritime limits (shoreline, baselines, water areas).

All these boundaries function as regime generators: they define permissible, prohibited, and conditionally permitted uses of space, shaping rents and externalities. Thus, in land management theory, the boundary is neither an object nor merely a "line on the ground" but a category that fixes the mode of existence of space as an ordered field of rights, restrictions, and values. Its ontological type is that of a relation and event, not a substance. The boundary constitutes the difference between spatial regimes and introduces this difference into the institutional order through rules, procedures, and representational artifacts. Ontologically, it is an operational entity–it exists only insofar as it is maintained through procedures of establishment, confirmation, public visibility, and enforcement (see Table 1).

The boundary has a tripartite structure. As an event, it arises through constitutive acts-establishment, agreement, and registration. As a relation, it links at least two regime domains, setting correlatives of permissions and prohibitions. As a rule, it operates as a norm of spatial behavior, organizing expectations, sanctions, and rent flows. Thus, the boundary is not reducible to geometry; its geometry is derivative of its normative form.

In the modal sense, the boundary defines what is possible, permitted, forbidden, and obligatory in space. It is a deontic object: one that structures rights (ownership, use, exclusion), duties (maintenance, access, tolerance of impacts), and responsibilities (compensation, restitution, insurance). A deontic ontology explains why one and the same material plot acquires different values depending on the regime established by its boundary.

The boundary exists simultaneously in several modes:

• material (marker, fence, natural barrier),

• legal (title, restriction, servitude),

• informational (cartographic record, database topology, change log),

• social (agreement, legitimacy, participatory procedure),

• ecological (environmental gradients, impact buffers).

Its ontological stability is a function of supervenience: failure of any mode diminishes the evidential validity and legitimacy of the entire construct.

The boundary may have "thickness" (as a buffer) and volumetric form. It not only separates but also creates transitional spaces with their own regimes of compatibility. Mereologically, it represents a special case of partially overlapping regions, where components may be continuous in law yet discrete in materiality. Topologically, the boundary is a morphism between regime spaces, defining rules of intersection, precedence, and hierarchy.

The legal consequences of a boundary are not confined to the surface. A boundary projects vertically (to subsurface, underground structures, aquifers, air corridors) and temporally (terms of validity, phases, conditional transitions). Its identity lies in persistence through change: it endures not through geometric invariance but through procedural continuity and the version chain of data.

Every boundary representation is, necessarily, an interpretation with uncertainty. Therefore, the ontology of boundaries includes epistemic attributes: accuracy, evidentiality, traceability, stability, and interoperability. A boundary acquires causal power through institutions that guarantee record verifiability, contestability, and enforceability.

The boundary is an operator of spatial value. It endogenizes rents through access scarcity, regulatory rarity, compatibility or incompatibility of uses, network effects, and ecosystem services. Value is not an intrinsic property of "the land itself" but an emergent property of the regime generated by boundary rules.

The normal state of a boundary is tension of interests. Ontologically, conflict is not an anomaly but a mechanism of regime renewal. The legitimacy of a boundary derives from procedural justice, proportionality of restrictions, and fairness in benefit-burden distribution. Without these, the boundary degenerates into a fact of domination, losing its status as a publicly justified norm.

In the digital age, the boundary possesses informational-legal autonomy: a registry entry conforming to semantic and quality standards acquires ontic validity. Algorithmic zoning, control, and monitoring procedures become part of its ontology; hence, transparency, reproducibility, and auditability are not matters of programming ethics but conditions of existence for the boundary as a public fact.

Philosophically and ontologically, therefore, the boundary is an institutionally sustained event-relation that structures space into regime domains, endowing them with deontic, value-based, and spatio-temporal dimensions. Its truth is ensured not by geometry itself but by the linkage rule → representation → procedure → enforceability. Within this framework, the boundary functions as a basic operator transforming territory into an ordered space of rights and values, which constitutes the subject matter of the modern scientific theory of land management.

The evolution of boundary concepts within land management reflects a deep transformation of spatial rationality-from material-geometric to institutional-regime. In the initial model, the boundary was a static spatial marker recording ownership or territorial division, its ontological status determined by physical attributes such as embankment, river, fence, or boundary stone. Geometry, measurement, and physical localization dominated this paradigm. Later, the boundary acquired legal meaning–as a form of securing rights and titles, an element of proof of possession. Gradually, the transition occurred toward an institutional model in which the boundary not only divides space but structures social relations, creates regimes of permission and prohibition, and defines rules of access, responsibility, and value distribution.

In the digital era, this evolution enters the phase of a regime ontology, where the boundary functions as an infrastructure of data, norms, and procedures-a spatial-legal infrastructure rather than a measurement object.

The modern boundary has a multilevel structure integrating four interrelated levels: material, legal, informational, and ecological. The material level defines the physical parameters of space (relief, features, boundary markers). The legal level determines titles, servitudes, restriction zones, and usage norms. The informational level provides representation within cadastral and planning systems, including metadata, accuracy, traceability, and digital signatures. The ecological level reflects the boundary's interaction with natural processes-landscape stability, buffering, and ecosystem functionality.

These levels interact systemically: legal regimes shape the informational structure; informational precision affects ecological adequacy; and physical stability of space constrains the scope of legal norms. This multilevel integration is summarized in Table 2.

From the standpoint of systems analysis, the formation of an updated ontology of boundaries requires three interrelated blocks of principles. The first is integrative: the combination of geospatial data, legal norms, and mechanisms of land value management into a unified ontological model. This involves the unification of the concepts "object," "regime," and "event" in terms of ISO 19152 (LADM) and harmonization with INSPIRE spatial standards. The second is procedural: the creation of procedural logic for the automated determination, verification, and updating of boundaries based on sensor data, governmental decisions, and transactions in registries. The third is val-

Table 2. Levels of Boundaries in Land Management

Boundary Level	Core Content	Function in the Land Management System
Material	Physical representation of space, natural or artificial boundary elements	Ensures localization and topographic determinacy
Legal	System of titles, restrictions, servitudes, and land-use regimes	Establishes the legal regime of space
Informational	Data, models, coordinates, LADM/ INSPIRE standards	Represents boundaries in digital cadastral systems
Ecological	Natural linkages, buffering, influence on landscapes	Maintains ecosystem stability and zonal balance

Note: Author's elaboration.

ue-regulatory: the introduction of mechanisms for transparent assessment of the effects of boundary changes, the consideration of ecological and social value, and the distribution of benefits according to the principle of public justice.

The theoretical conditions for the formalization of this ontology are: 1) recognition of the boundary as a complex event-based entity that possesses modes of material, legal, informational, and ecological existence; 2) use of a data metamodelling framework capable of representing multilayered objects (LADM 2.0, GeoBIM); 3) establishment of unified criteria for accuracy, reliability, and procedural legitimacy; 4) integration of cadastral and planning systems in a mode of semantic interoperability; 5) normative consolidation of the principles of adaptability, compatibility, and value transparency.

The implementation of these conditions will ensure the transition from a "register of lines" to a dynamic regime model of space, where the boundary functions as a systemic interface between law, data, and the environment.

Conclusions from the conducted research

The problem of the ontology of boundaries is a key link in the development of the modern theory of land management as an independent fundamental scientific discipline. It has been determined that under current conditions, the boundary ceases to be merely a geometric attribute of territory and acquires the status of a complex institutional–regime category that integrates the material, legal, informational, and ecological levels of spatial organization. Its existence is defined not by physical localization but by procedural validity, legal legitimacy, informational coherence, and ecological rationality. Thus, the boundary emerges as an active instrument of space construction, not merely its description.

The evolution of boundary concepts-from a material-geometric to an institutional-regime model-demonstrates a regular transition from a descriptive to a normative-procedural type of spatial reasoning. This determines the need to create a new ontology of boundaries based on the principles of procedural constitutiveness, multimodality, adaptability, metric quality, regime compatibility, and value transparency. Such a vision enables the integration of legal norms, spatial data, and land value management mechanisms into a single coherent theoretical system. This integration forms the foundation for the transition from a cadastral-technical to an intellectual-ontological level of land management.

The results of the study represent an attempt to form a theoretical framework for the further development of modern land management theory as a fundamental discipline combining legal philosophy, spatial ontology, information sciences, and ecological economics. The proposed approach outlines prospects for the formalization of the regime model of boundaries in digital cadastres, the improvement of spatial governance systems, and the advancement of the normative and value basis of public geospatial policy.

Furthermore, the research results can be applied in the development of sustainable land-use policies, public rent management, and ecosystem service monitoring. The proposed ontological structure of boundaries provides a foundation for building digital “territorial models” that reflect not only physical but also legal, socio-economic, and ecological interrelations. This enables more accurate assessment of land value, equitable distribution of benefits and risks among stakeholders, and the development of value capture/value sharing instruments in public policy. Therefore, the study has practical significance both for the scientific substantiation of spatial development strategies and for applied fields such as land management, cadastre, territorial governance, and ecological planning.

The authors regard the obtained results as the first step toward creating an integrated scientific theory of modern land management. Subsequent publications will focus on the development of a methodology for ontological spatial modeling, the formation of a categorical framework for contemporary land management science, and theoretical aspects of managing regimes of value, risk, and justice within the land management system.

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Мартин А.Г., Гунько Л.А., Синєуцький А.І.

ОНТОЛОГІЯ МЕЖ У СИСТЕМІ СУЧАСНОГО ЗЕМЛЕУСТРОЮ: ВІД ГЕОМЕТРІЇ ДО РЕЖИМУ ПРАВ І ЦІННОСТЕЙ

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Анотація. *Стаття концептуалізує поняття «межа» в сучасному землеустрої як інституційно-режимну категорію, що перевищує геометричне трактування лінії поділу. На основі порівняльно-історичного та інституційного аналізу, нормоорієнтованого моделювання і формальної онтологізації (LADM) обґрунтовано перехід від матеріально-геометричної до режимної онтології простору, де межа функціонує як подія-відношення, що конституює права, обмеження, відповідальності та рентні потоки. Ідентифіковано чотири структурні рівні межі – матеріальний, правовий, інформаційний, екологічний – і показано їх супервенійні зв'язки та причинний вплив процедурної валідності даних на легітимність режимів. Сформульовано принципи онтологічного дизайну меж (конститутивність процедури, багатомодусність, адаптивність, метричність якості, сумісність і пріоритети, ціннісна прозорість), що уможливлюють інтеграцію правових норм, просторових даних та механізмів управління цінністю землі. Практична корисність полягає у переході від «реєстру ліній» до динамічної режимної моделі простору для кадастрових і планувальних систем, підвищенні якості рішень, мінімізації конфліктів і прозорому розподілі вигод. Робота позиціонується як внесок у становлення теорії сучасного землеустрою як фундаментальної дисципліни; анонсовано подальші публікації щодо формалізації режимів, GeoBIM-інтеграції та процедур оцінки легітимності.*

Ключові слова: *межа; онтологія простору; землеустрій; LADM; інституційні режими; права й обмеження; 3D/4D-кадастр; інтероперабельність; value capture; просторове врядування.*

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AN INTEGRATED APPROACH TO PLANNING, ASSESSING AND IMPLEMENTING THE REMOVAL OF TOPSOIL: FROM REGULATIONS TO EVIDENCE-BASED LAND MANAGEMENT PRACTICES

KOSHEL A.,
Doctor of Economics
National University of Life and Environmental Sciences of Ukraine
e-mail:koshelao@gmail.com
KOLHANOVA I.,
PhD in Economics
National University of Life and Environmental Sciences of Ukraine
e-mail: kolganova_i@ nubip.edu.ua
KEMPA O.,
Dr inż. (PhD)
Wroclaw University of Environmental and Life Sciences
e-mail:olgierd.kempa@upwr.edu.pl

Abstract. *Scientific and methodological approaches to the development of land protection measures in modern land management documentation are proposed.*

The article examines the current requirements for the development of working land management projects for the removal and transfer of fertile soil in accordance with the regulatory framework of Ukraine. The main tasks of such projects are outlined, including ensuring the rational use and preservation of soil fertility, minimising the negative effects of economic activity, and restoring disturbed lands. The article analyses the key indicators that determine the feasibility of removing and storing soil layers: humus content, acidity, proportion of exchangeable sodium, and particle size distribution. It is shown that compliance with these parameters is an important factor in environmental safety and sustainable development of agricultural production.

The content of working land management projects includes design tasks, an explanatory note, description of natural conditions, results of soil and geodetic surveys, design solutions to determine a set of land protection measures, plans of agricultural soil groups, and calculations of the estimated cost of work. This structure ensures the scientific validity of decisions and the practical efficiency of their implementation.

The article summarises current knowledge and practices in the field of land management, offering a comprehensive approach to the development of working land management projects. The proposed rules and recommendations can serve as a basis for professionals involved in land management, agronomy and ecology.

Keywords: *land protection, land management, land improvement, land management, land management documentation, removal of fertile soil layer, working draft of land management.*

Actuality

Soil health is a key constraint on agricultural productivity and climate resilience. According to the IPCC, arable soils have lost 20-60% of their organic carbon stocks since the beginning of development, and degradation processes (including erosion) directly reduce fertility and increase greenhouse gas emissions [1]. The UNCCD estimates that up to 40% of the world's land is already degraded, which requires systematic measures to restore and manage soils based on the principles of land degradation neutrality (LDN) [2].

Ukraine is one of the countries with the most fertile black soil, but suffers from significant erosion losses. According to FAO estimates, more than 20% of arable land (≈6.5 million hectares) in Ukraine is degraded or unproductive, with 300-600 million tonnes of soil lost annually and crop losses of up to 50% depending on the level of degradation [4]. National assessments under the LDN initiative document the spread of water and wind erosion over approximately 57% of the country's territory [5]. Separately, significant annual losses of humus due to mineralisation and erosion are recorded [9].

The European Soil Strategy 2030 defines the goal of "healthy soil ecosystems" and requires linking land use, soil protection, and climate policy to reliable indicators of soil ecological status [3]. In Ukraine, since 2022, the Rules for the Development of Working Land Management Projects have been in force, which directly regulate the removal and transfer of fertile soil, storage and use of excavated soil, and reclamation of disturbed land [6]. However, international generalisations show that the effect of topsoil removal depth on yield and degradation risks is quantitatively sensitive and ambiguous, and therefore requires substantiation by specific data. A meta-analysis of topsoil removal experiments shows that yield reduction becomes statistically significant with decreasing thickness of the A-horizon and increases with increasing depth of removal [7]; modern field studies also document an increase in erosion flows, changes in infiltration and moisture after topsoil removal [8].

Thus, the scientifically sound design of topsoil removal and transfer works in Ukraine is critically important for three reasons: 1) the scale of degradation and loss of fertility at the national level [4], [5], [9]; 2) the requirements of European policy on soil restoration and monitoring [3]; 3) the quantitative sensitivity of yields and erosion processes to topsoil removal parameters, which requires local experimental data and standardised methods for assessing effects [1], [7], [8]. It is this framework that creates the basis for the transition from normative description to obtaining reproducible scientific results necessary for adjusting land management practices [2], [6].

Analysis of the latest scientific research and publications

International reviews have documented the causal link between soil degradation, loss of organic carbon and declining agricultural productivity. The IPCC report (SRCCL) summarises the data on SOC losses due to arable land development and shows that degradation reduces yields and increases GHG emissions, which directly addresses the need to minimise topsoil disturbance [1]. The UNCCD in GLO2 assesses the extent of land degradation and formulates the LDN framework for restoration planning, where topsoil removal, relocation and return operations are considered high-risk without proper reclamation and monitoring [2]. The European Soil Strategy 2030 requires quantitative indicators of soil health and alignment of land management practices with ecosystem restoration goals [3].

The Ukrainian regulatory context is structured by the Resolution of the Cabinet of Ministers of Ukraine "On Approval of the Rules for the Development of Working Land Management Projects" No. 86 of 02.02.2022, which regulates the content of working land management projects for the removal and transfer of the fertile layer, including quality parameters, technologies, storage and reclamation [6]. DSTU 4362:2004 "Soil quality. Indicators of soil fertility" defines fertility indicators (humus content, density, granulometry, pH, etc.) that should be the basis for design decisions and monitoring the effects of work [7]. The Law of Ukraine "On Land Protection" sets out the legal framework for preserving soil fertility and reproduction, including through technological requirements for land use [8]. FAO's generalisations about Ukraine confirm the widespread degradation of arable land and the need for restorative practices and monitoring [4], [9].

The quantitative assessment of the effects of topsoil removal is summarised in the 2021 meta-analysis: the effect of erosion "cutting" or experimental removal of the surface layer statistically reduces yields; critical thresholds are associated with the residual thickness of the A horizon (> 25 cm) and the depth of removal (< 5 cm), beyond which the yield drop increases sharply [7]. Field surveys in 2023 recorded an increase in erosion flows, changes in infiltration and moisture, and a restructuring of plant communities after the surface layer was removed, which confirms the need for spatial risk modelling and phased implementation of the work [8].

A separate segment of the literature relates to temporary stockpiling and surface layer transfer. It has been proven that with the increase in storage time and height of the dumps, the viability of the seed bank decreases and the biological integrity of the soil deteriorates; direct prompt return of the removed layer to the reclamation sites provides better results for vegetation restoration than long-term storage [10-13]. Altered geochemical profiles and a decrease in nutrients in the thickness of the dumps, sometimes with accumulation of metals, have also been recorded, requiring control of the composition and stratification of dumps [14]. In different biomes, the results are consistent: the need to minimise the time between removal and placement, limit the height/angle of slopes, and apply protection against drying out and weed germination have been pointed out [10-15].

Ukrainian research emphasises the need for integrated monitoring of agricultural land and the link between degradation and economic losses, which is consistent with international findings on the criticality of topsoil conservation [9]. Taken together, the body of work forms a methodological basis for science-based design: quantitative justification of the depth of removal, storage, storage, monitoring of fertility and erosion risks, as well as alignment with EU requirements for soil health [1-4], [6-15].

The aim of the study is to provide scientific justification for methodological approaches to the development of working land management projects for the removal and transfer of fertile soil layers, taking into account regulatory and legal requirements, soil and environmental parameters, and the practical results of a specific case study – a 11.8-hectare land plot located in the Kyiv region.

Materials and methods of scientific research

The study uses a set of generally accepted scientific methods aimed at analysing the regulatory, agrochemical, and spatial-soil aspects of developing working land management projects for the removal and transfer of fertile soil layers. The basic materials were the provisions of the current regulatory acts of Ukraine (Land Code, Law "On Land Management", Resolution of the Cabinet of Ministers of Ukraine "On Approval of the Rules for the Development of Working Land Management Projects" No. 86 of 02.02.2022), the results of soil and geodetic surveys of a land plot with an area of 11.7981 hectares, as well as agrochemical indicators determined in accordance with DSTU 4362:2004. The following methods were used analysis and synthesis – to systematise legislative requirements; comparative method – to compare national and international approaches to soil protection; systematic method – to assess the interrelationships between standards, soil removal technology and environmental consequences; geoinformation analysis was used to spatially visualise agricultural soil groups and land development plans; generalisation was used to formulate practical recommendations and conclusions on improving the structure of working land management projects.

Research results and their discussion

In accordance with paragraph 28 of Resolution No. 86 of the Cabinet of Ministers of Ukraine dated 2 February 2022 "On Approval of the Rules for the Development of Working Land Management Projects," such working projects are developed to implement measures for the reclamation of disturbed lands, the removal and transfer of fertile soil layers, conservation of land, improvement of the quality of agricultural and forest lands, as well as for their protection against erosion, flooding, waterlogging, salinisation, drying out, landslides, compaction, acidification and contamination with waste, radioactive and chemical substances.

Working projects are developed by business entities that have the right to perform land management work in accordance with the Law of Ukraine "On Land Management", on the basis of a contract with the customer.

The working land management project includes: tasks for its preparation, an explanatory note, a description of the natural and agroclimatic conditions of the territory, materials from soil and geodetic surveys, technical and economic indicators, design solutions for land protection, cost estimates, plans of agricultural production groups of soils and slopes (if necessary), plans of measures and materials for transferring the project to the ground.

The main purpose of developing working projects for the removal and transfer of fertile soil layers is to determine the scope of work involved in removing, transporting and storing soil, and in the case of soil covering, also the scope of its rational use. Such working projects involve developing the technology for performing the work, determining the sequence of operations and calculating costs.

Practical experience in developing working land management projects indicates the advisability of a two-stage approach to their creation.

The first stage involves conducting a soil survey of the land plot to determine the mass fraction of humus at the lower boundary of the fertile layer, which is the basis for establishing the depth of its removal and transfer. The survey should include not only agrochemical analysis, but also a detailed study of the genetic profile of the soil.

The second stage is the direct development of a working land management project in accordance with Article 54 of the Law of Ukraine "On Land Management".

According to the Resolution, a working land management project for the removal and transfer of fertile soil must contain justified decisions on the layer-by-layer removal and separate storage of the most fertile layer.

The object of the study of methods for developing land management documentation was a land plot with an area of 11.7981 hectares. The land plot is located in an agricultural land mass and borders on privately owned land plots.

According to soil survey data, the soil cover of the land plot is represented by an agricultural production group of soils with code 42d (dark grey podzolised, slightly leached, medium loamy soils).

According to the agrochemical characteristics of the soil, the humus content in this agricultural soil group in the 0-100 cm layer varies from 1.80 to 2.10%, which is assessed as slightly hu-

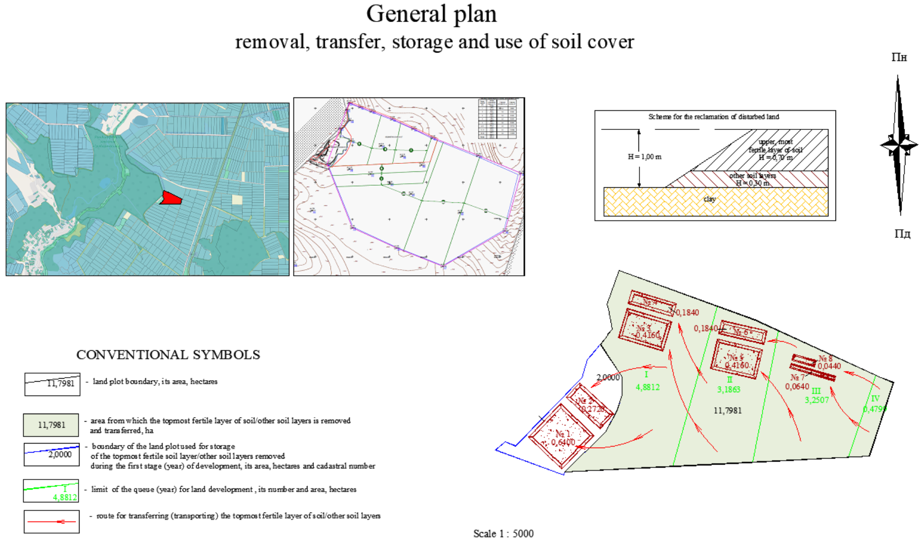

Fig. 1. General plan for removal, transfer, storage and use of topsoil

mus soil (according to DSTU 4362:2004 Soil quality. Soil fertility indicators).

The project solution provides for the layer-by-layer removal of the upper most fertile soil layer to a depth of 0.70 m and other soil layers to a depth of 0.30 m from an area of 11.7981 ha and their separate storage. The soil density is 1.30 t/m^3 (Fig. 1).

General standards for removing soil cover from land plots and standards for removing soil cover in terms of stages (years) of development are given in Tables 1 and 2.

The removal and transfer of topsoil will be carried out in the fourth stage of development. The technological scheme for removing topsoil includes:

- removal of the upper most fertile soil layer to a depth of 0.70 m;
- removal of other soil layers to a depth of 0.30 m.

The topsoil from the first stage of development is to be transferred and stored in temporary dumps No. 1 and No. 2. Subsequently, during the development of the quarry, as the areas of the development stages are freed up,

Table 1. General standards for removing soil cover from land plots

No.	Code agro-choi soil group	Area from which the topmost fertile soil layer/other soil layers are removed, m2	Depth of removal of the topmost fertile soil layer/other soil layers, m	Volume of the upper most fertile soil layer/other soil layers, m3	Density of the upper most fertile soil layer/other soil layers, t/m³	Removal of the topmost fertile soil layer/other soil layers, tonnes
1		117981	0,70	82587		107363
2	42d	117981	0,30	35394	1,30	46013
Total:		-	-	117981		153375

Table 2. Standards for soil cover removal in terms of stages (years) of development

Queue number (year) of development	Area from which the topmost fertile soil layer/ other soil layers are removed, m^2	Depth of removal of the topmost fertile soil layer/other soil layers, m	Volume of the upper most fertile soil layer/other soil layers, m^3	Density of the upper most fertile soil layer/other soil layers, t/m^3	Removal of the topmost fertile soil layer/other soil layers, tonnes
I	48812	0,70	34168	1,30	44419
		0,30	14644		19037
Всього:			48812		63456
II	31863	0,70	22304	1,30	28995
		0,30	9559		12427
Всього:			31863		41422
III	32507	0,70	22755	1,30	29581
		0,30	9752		12678
Всього:			32507		42259
IV	4799	0,70	3359	1,30	4367
		0,30	1440		1872
Всього:			4799		6239
Разом:	117981		117981		153375

the soil cover of the next stage will be transferred (stored) to temporary dumps Nos. 3-8 in the space developed during the previous stage.

In accordance with paragraph 26 of the Resolution of the Cabinet of Ministers of Ukraine "On Approval of the Rules for the Development of Working Land Management Projects" dated 2 February 2022 No. 86, land plots of any intended use may be used for temporary storage of fertile soil with the consent of the owner or user of the land plot.

When the soil cover is removed, it is loosened, resulting in a 5-7% increase in volume, and the volume of temporary dumps for storage also increases by 5-7%. Before laying temporary soil cover dumps, the area is cleared of debris and its surface is levelled with a bulldozer (loader). A complex of works on the arrangement of a temporary dump includes levelling the soil cover, forming the "body" of the dump, approaches and exits from the dump, levelling the slopes and crest of the dumps. Work to protect temporary dumps from denudation processes (washing away, blowing away, weathering, etc.) is carried out by sowing perennial grass seeds on its surface.

The proposed stages (years) of development are generally advisory in nature and determine the general directions for removing and transferring soil cover and the general sequence of actions. They may change (be adjusted) depending on the economic situation and the increase in the number of units of equipment.

In accordance with Article 168 of the Land Code of Ukraine and Article 52 of the Law of Ukraine "On Land Protection", the fertile soil layer/other soil layers will be used for land reclamation. The reclamation scheme is shown in Figure 1.

Conclusions and perspectives

The results of the study confirmed that the effectiveness of developing working land management projects for removing and transferring fertile soil layers directly depends on the scientific validity of the parameters of the work, taking into account agrochemical indicators and spatial characteristics of land plots. The analysis of the regulatory framework, combined with a case study based on a land plot with an area of 11.7981 hectares, proved that the current standards need to be adapted to regional fertility conditions and different soil types, since the actual values of humus, acidity and granulometric composition may differ significantly from the established limits.

It has been determined that a two-stage structure for preparing working projects (preliminary soil survey and development of technical and economic solutions) provides an optimal combination of regulatory requirements and practical implementation of work, but its effectiveness is enhanced by the use of digital mapping methods, automated models for predicting erosion losses, and multifactorial analysis of soil quality indicators. The proposed approach to assessing the suitability of land for topsoil removal based on agrochemical indicators (humus content, pH, exchangeable sodium, granulometry) creates the basis for the formation of national standardised criteria for the environmental safety of these works.

The results confirm that the integration of geoinformation technologies, digital monitoring and regionally adapted standards can significantly reduce the risks of soil degradation and increase the effectiveness of recultivation of disturbed lands. This approach forms a practical basis for the transition from formal implementation of project procedures to systematic soil fertility management, which is consistent with European standards of "soil health" and the goals of land degradation neutrality.

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Кошель А., Колганова І., Кемпа О.

КОМПЛЕКСНИЙ ПІДХІД ДО ПЛАНУВАННЯ, ОЦІНКИ ТА РЕАЛІЗАЦІЇ РОБІТ ІЗ ЗНЯТТЯ РОДЮЧОГО ШАРУ ҐРУНТУ: ВІД НОРМАТИВІВ ДО ДОКАЗОВИХ ПРАКТИК ЗЕМЛЕУСТРОЮ

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Анотація. *Запропоновано науково-методичні підходи щодо розроблення заходів з охорони земель в сучасній документації із землеустрою.*

У статті розглянуто сучасні вимоги до розроблення робочих проєктів землеустрою щодо зняття та перенесення родючого шару ґрунту відповідно до нормативно-правової бази України. Окреслено основні завдання таких проєктів, серед яких – забезпечення раціонального використання та збереження родючості ґрунтів, мінімізація негативних наслідків господарської діяльності та відновлення порушених земель. Проведено аналіз ключових показників, що визначають доцільність зняття й складування ґрунтових шарів: вміст гумусу, кислотність, частка обмінного натрію та гранулометричний склад. Показано, що дотримання цих параметрів є важливим чинником екологічної безпеки та сталого розвитку аграрного виробництва.

Зміст робочих проєктів землеустрою включає завдання на проєктування, пояснювальну записку, характеристику природних умов, результати ґрунтових і геодезичних обстежень, проєктні рішення із визначення комплексу заходів з охорони земель, плани агровиробничих груп ґрунтів та розрахунки кошторисної вартості виконання робіт. Така структура забезпечує наукову обґрунтованість рішень і практичну ефективність їх реалізації.

Стаття узагальнює актуальні знання та практики у сфері землеустрою, пропонуючи комплексний підхід до розроблення робочих проєктів землеустрою. Пропоновані правила та рекомендації можуть служити основою для фахівців, зайнятих у сфері управління земельними ресурсами, агрономії та екології.

Ключові слова: *охорона земель, землеустрій, поліпшення стану земель, управління земельними ресурсами, документація із землеустрою, зняття родючого шару ґрунту, робочий проєкт землеустрою.*

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RATIONAL USE OF AGRICULTURAL LANDS: MONITORING THE HUMUS BALANCE ACROSS CROP ROTATIONS

T. ZHYGAILO,
Candidate of Agricultural Sciences, Senior Research Fellow,
https://orcid.org/0000-0002-9580-5922;
Email: Fanenger@gmail.com
Institute of climate-smart agriculture, National Academy of Agricultural Sciences of Ukraine
A. CHUGAI,
Doctor of Science (Technical), Professor
http://orcid.org/0000-0002-8091-8430 ;
Email: avchugai@ukr.net
Odesa Mechnikov National University
O. ZHYGAILO,
Candidate of Geographical Sciences, Associate Professor
https://orcid.org/0000-0002-3552-327X;
Email: elenajigaylo@gmail.com
Odesa Mechnikov National University
A. TOLMACHOVA,
Candidate of Geographical Sciences, Associate Professor
https://orsid.org/0000-0002-9340-5028;
Email: alla.tolmach@ukr.net
Odesa Mechnikov National University

Abstract. *Sustainable land use cannot be achieved without deliberate efforts to preserve and restore soil fertility, with the humus status serving as its key indicator. The challenge of maintaining a stable humus balance has become particularly pressing under the dominance of short-rotation crop sequences in the agricultural practice of the Southern Steppe of Ukraine. The absence of systematic monitoring of soil organic matter complicates the prediction of agroecosystem productivity and threatens the degradation of chernozems, the country's most valuable agricultural resource.*

This study aimed to assess the performance of different short-rotation crop rotations under conditions of complete fertilizer exclusion, to quantify their effects on the humus balance, and to identify the most suitable model for long-term land use. The methodological framework was based on humus balance calculations in a five-field rotation with winter rapeseed and sunflower, conducted during 2020–2024.

The results indicated that technical crops generated a negative humus balance (–0.28 t/ha and –0.77 t/ha, respectively), with the most severe deficit observed after bare fallow (–1.46 t/ha). In contrast, cereals contributed to partial restoration of humus reserves (up to +0.21 t/ha and +0.08 t/ha), while the highest positive effect was obtained from bare fallow (+1.14 t/ha). The overall balance per rotation amounted to –2.22 t/ha in the first sequence and +0.38 t/ha in the second.

These findings highlight the importance of incorporating bare fallow into crop rotations as a natural source of organic matter, essential for sustaining chernozem fertility and ensuring the resilience of agricultural production in the Southern Steppe of Ukraine.

Keywords: *southern chernozems, humus, biomass, balance, short-rotation crop rotation, cover crops.*

Problem Statement

Rational use of agricultural land requires a comprehensive approach to the preservation and reproduction of soil fertility, one of the key indicators of which is the humus status. Under conditions of intensified farming, reduced application of organic fertilizers, disruption of crop rotations, and increased agrochemical load, the risk of soil degradation, particularly humus loss, is significantly increasing [1,2].

The issue of maintaining a sustainable humus balance in short-rotation crop rotations, which currently prevail in farming practice, is especially urgent. The absence of systematic monitoring of organic matter dynamics in agroecosystems limits the possibilities of sound land-use planning and increases the threat of depletion of chernozems – the main resource of productive agriculture [3].

Therefore, there is a need for a scientifically grounded assessment of humus balance within different types of crop rotations in order to develop effective land-use models aimed at the long-term preservation of soil fertility.

Analysis of Recent Research and Publications

Rational use of agricultural land is one of the priority areas of modern land management and agroecological governance. Under conditions of increasing anthropogenic pressure, climate change, and intensive farming, the preservation of soil fertility, particularly its humus status, acquires strategic importance [4].

According to numerous studies, humus serves as the main indicator of soil fertility, influencing the water-physical, chemical, and biological properties of the arable layer. Maintaining a positive humus balance in soils is a necessary condition for sustainable agricultural production, ensuring ecological stability in agro-landscapes, and supporting effective land use [5,6,7].

One of the most effective mechanisms for regulating the humus balance is a rationally organized crop rotation, which influences humus formation processes through the alternation of crops with different biological productivity, root system types, and capacities for symbiotic nitrogen fixation. Long-term field experiments indicate that the inclusion of legumes, green manure crops, catch crops, as well as the application of organic fertilizers, significantly improves the humus status of soils.

The issue of maintaining humus balance in agroecosystems holds a central place in modern scientific research. Results of long-term experiments demonstrate that the main source of humus replenishment in soils is plant residues and the non-commercial part of the harvest. In the absence of fertilization, row crops (such as sunflower and maize) generally form a negative balance, while cereals and crops with continuous sowing methods have greater potential to maintain a positive humus balance. The use of organic and mineral fertilizers, along with green manure crops, contributes to the enrichment of soils with organic matter and ensures their non-deficit condition [8,9].

Regional monitoring studies (Poltava, Kharkiv, and Kirovohrad regions) reveal significant differences in the formation of humus balance, determined both by crop rotation structure and fertilization levels. It has been established that, in most cases, the absence of fertilizers results in a humus deficit, with the greatest losses associated with the cultivation of industrial crops. Conversely, the inclusion of cereals and occupied fallows in crop rotation structures allows for partial or complete compensation of these losses [10,11,12].

Some scientific publications emphasize that the assessment of humus balance should be considered not only in the production aspect but also as an important component of the ecological and economic justification of sustainable land use. This approach makes it possible to form a system of indicators necessary for long-term land resource management and for preventing soil degradation [13].

As a result of long-term studies conducted by scientific institutions in various soil-climatic conditions of Ukraine, scientific approaches to optimizing crop rotation structure have been developed. In particular, the features of crop placement in rotations have been studied, taking into account their growing duration, biological compatibility, return period to the same field, as well as the requirements of modern intensive technologies.

Under current agricultural production conditions, traditional ten-field rotations, characteristic of collective farms in the past, are gradually being replaced by short-rotation crop rotations of various agro-industrial orientations. In this regard, both scientific and practical interest in studying the transformation of soil organic matter in land-use systems dominated by cereals and industrial crops is growing.

Research Aim. The aim of the study is to provide a comparative assessment of the efficiency of different short-rotation crop rotations on chernozems of the Southern Steppe of Ukraine in terms of humus balance formation under conditions of complete abandonment of fertilization, with subsequent identification of the optimal model for sustainable land use.

Materials and Methods

To evaluate the impact of short-rotation crop rotations on the humus status of chernozems in the Southern Steppe of Ukraine, we used the method of humus balance calculation in crop rotations [14], which is based on the ratio between the input and mineralization of organic matter in the soil. The calculations took into account the mass of the main and by-product yields of agricultural crops, humification coefficients of plant residues, as well as the amount of humus losses caused by mineralization processes.

The object of the study was short-rotation crop rotations developed and recommended for the conditions of the southern region of Ukraine [15]. The subject of the study was a five-field crop rotation including winter rapeseed and sunflower, which was investigated during 2020-2024 under production conditions of the Southern Steppe.

The calculations were carried out according to the following indicators: organic matter input into the soil from root and post-harvest residues; the amount of humus formed as a result of the humification of plant residues; humus losses due to mineralization and erosion processes; and the integral humus balance per crop rotation cycle.

Results and Discussion

In recent years, the issue of soil humus balance has attracted increasing attention from researchers, given its key importance for sustainable land use and fertility preservation [8–12].

Our research, conducted under the conditions of the Southern Steppe of Ukraine (Odesa region), was aimed at assessing the efficiency of short-rotation crop rotations in humus balance formation. The analysis was carried out for two variants of crop rotations that differed in the type of preceding crop for winter wheat (bare fallow vs. occupied fallow). The crop rotation included cereal crops (winter wheat and spring barley) and industrial oilseed crops (winter rapeseed and sunflower).

We evaluated the two short-rotation crop rotations in terms of their ability to accumulate or lose humus. Considering the indicators of humus losses per equivalent area (Fig. 1a, 1b), it should be noted that the highest values were recorded under bare fallow (1.46 t/ha) and the row crop sunflower (1.01 t/ha). This allows us to conclude that the greatest humus losses occurred in the first crop rotation (4.43 t/ha), where the preceding crop for winter wheat was bare fallow. The lowest humus losses were observed in the second crop rotation (3.59 t/ha), where bare fallow was replaced by occupied fallow with white mustard as a green manure crop.

Indicators of biomass input into the soil for humus formation are also of great importance. Analyzing the data on biomass input into the soil (Fig. 2a, 2b), we observe that the total amount of by-products was higher in the second crop rotation (3.97 t/ha), which indicates its better potential capacity to replenish organic matter. The highest amount of by-products was observed after the occupied fallow (1.76 t/ha), confirming its significant role as a stabilizer of the humus balance. Cereal crops provide a considerably larger volume of organic residues (0.88…0.70 t/ha) compared to industrial (oilseed) crops (0.39…0.24 t/ha), which demonstrates their advantage in forming the soil's humus potential.

Calculations of the humus balance in short-rotation crop rotations (Table 1) showed that in both rotations, a humus deficit was observed after industrial (oilseed) crops (–0.28 t/ha and –0.77 t/ha, respectively), which is due to the low level of by-product input into the soil. The largest deficit was recorded in the first rotation after bare fallow (–1.46

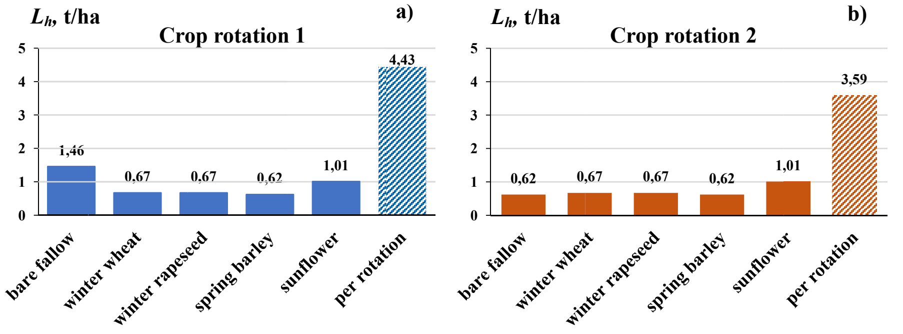

Fig. 1. Dynamics of humus losses in crop rotations. Southern Steppe.

Note: soil type – southern chernozem, heavy loam.

Source: compiled by the authors using the methodology for calculating humus balance in crop rotation [14].

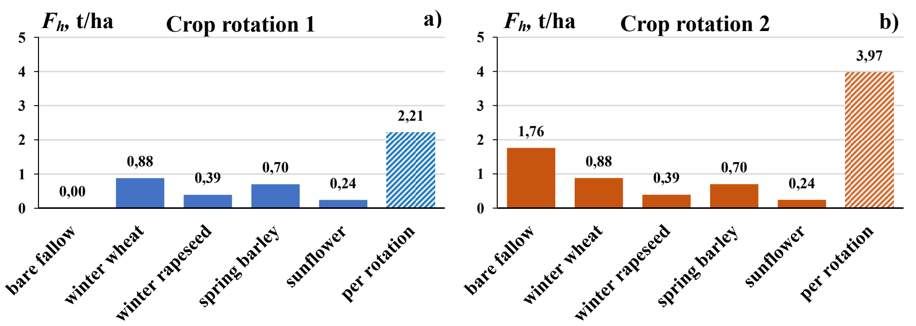

Fig. 1. Dynamics of humus formation in crop rotations. Southern Steppe.

Note: Calculations were made taking into account the yield of agricultural crops in 2020-2024 in the Odessa region.

Source: compiled by the authors using the methodology for calculating humus balance in crop rotation [14].

t/ha), confirming its negative impact on the humus status of the soil.

At the same time, after cereal crops a certain surplus of humus was observed (+0.21 t/ha after winter wheat and +0.08 t/ha after spring barley), which indicates their more favorable role in the humus formation process. Particularly significant is the indicator for the occupied fallow, where the surplus reached its maximum values (+1.14 t/ha), highlighting its effectiveness as a source of replenishing organic matter in the soil.

Summarizing the calculation results for the full rotation, it was established that the first crop rotation is characterized by a considerable humus deficit (–2.22 t/ha), which necessitates the application of organic fertilizers to eliminate soil degradation processes. In contrast, the second rotation showed a slight surplus (+0.38 t/ha), contributing to the stabilization of humus reserves. This indicates the expediency of includ-

Table 1. Balance of humus in short-rotational crop rotations in the Southern Steppe (2020-2024)

№ i/o	Culture	Crop rotation	Loss of humus (L_h), t	Formation of humus (F_h), t	Deficiency of humus (D_h), t
1	Bare fallow	The option 1	1,46	–	-1,46
2	Winter wheat		0,67	0,88	0,21
3	Winter rapeseed		0,67	0,39	- 0,28
4	Spring barley		0,62	0,70	0,08
5	Sunflower		1,01	0,24	-0,77
For the rotation			4,43	2,21	-2,22
1	Occupied fallow	The option 2	0,62	1,76	1,14
2	Winter wheat		0,67	0,88	0,21
3	Winter rapeseed		0,67	0,39	-0,28
4	Spring barley		0,62	0,70	0,08
5	Sunflower		1,01	0,24	-0,77
For the rotation			3,59	3,97	0,38

Note: Humus balance per 1 hectare of crop rotation area in the absence of fertilizer; green manure – white spring mustard.
Source: compiled by the authors using the methodology for calculating humus balance in crop rotation [14].

ing occupied fallow in the crop rotation structure, as it is capable of compensating for organic matter losses and maintaining the ecological balance of the agroecosystem.

Conclusions

The performed calculations of humus balance demonstrated that the cultivation of industrial (oilseed) crops in short-rotation crop rotations is accompanied by a persistent humus deficit (–0.28 to –0.77 t/ha), with the greatest losses recorded after bare fallow (–1.46 t/ha).

Cereal crops, by contrast, contribute to the formation of a certain surplus of humus (+0.08 to +0.21 t/ha), while the greatest positive effect was obtained after occupied fallow (+1.14 t/ha), confirming its expediency in the crop rotation structure.

Over the full rotation, the first crop rotation was characterized by a considerable humus deficit (–2.22 t/ha), indicating a potential threat to the fertility of southern chernozems. In contrast, the second rotation showed a slight surplus (+0.38 t/ha), pointing to its higher ecological and agronomic efficiency.

The obtained results confirm that optimizing the structure of short-rotation crop rotations, particularly by replacing bare fallow with occupied fallow using green manure crops, is an important prerequisite for preserving the humus status and enhancing the sustainability of agroecosystems in the Southern Steppe of Ukraine.

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Жигайло Т.С., Чугай А.В., Жигайло О.Л., Толмачова А.В.

РАЦІОНАЛЬНЕ ВИКОРИСТАННЯ ЗЕМЕЛЬ СІЛЬСЬКОГОСПОДАРСЬКОГО ПРИЗНАЧЕННЯ: МОНІТОРИНГ ГУМУСОВОГО БАЛАНСУ В МЕЖАХ СІВОЗМІН

ЗЕМЛЕУСТРІЙ, КАДАСТР І МОНІТОРИНГ ЗЕМЕЛЬ 3'25: 25-32.
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Анотація. *Раціональне землекористування неможливе без цілеспрямованого збереження та відновлення родючості ґрунтів, ключовим індикатором якої виступає рівень гумусового стану. Особливої актуальності набуває питання підтримання стабільного гумусового балансу в умовах поширеного застосування короткоротаційних сівозмін, що переважають у сільськогосподарській практиці Південного Степу України. Відсутність налагодженого моніторингу вмісту органічної речовини у ґрунті ускладнює прогнозування продуктивності агроекосистем та загрожує виснаженням чорноземів – найціннішого ресурсу вітчизняного землеробства.*

Метою дослідження було здійснити порівняльний аналіз ефективності різних короткоротаційних сівозмін за умов повної відмови від внесення добрив, визначити їх вплив на баланс гумусу та виокремити найбільш раціональну модель для довгострокового землекористування. Методичною основою стали розрахунки гумусового балансу у п’ятипільній польовій сівозміні з ріпаком озимим і соняшником, що вивчалася у 2020–2024 рр.

Результати показали, що після технічних (олійних) культур формується від’ємний баланс гумусу (–0,28 т/га і –0,77 т/га відповідно), а найсуттєвіший дефіцит зафіксовано після чистого пару (–1,46 т/га). Водночас зернові культури сприяють частковому відновленню запасів гумусу (до +0,21 т/га і +0,08 т/га), а найбільший позитивний ефект забезпечує зайнятий пар (+1,14 т/га). Сумарний баланс за ротацію становить –2,22 т/га у першій сівозміні та +0,38 т/га у другій.

Таким чином, наші дослідження підтверджують необхідність включення зайнятого пару до структури сівозмін як природного джерела органічної речовини, що дозволяє зберегти родючість чорноземів та забезпечити сталість агровиробництва у Південному Степу України.

Ключові слова: *чорноземи південні, гумус, біомаса, баланс, короткоротаційна сівозміна, сидерати.*

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DIGITAL AGRONOMY: SMART DECISION-SUPPORT WORKFLOW FOR CLIMATE-RESILIENT FARMING IN THE KYIV AGGLOMERATION

V. NAZARENKO,
Associate Professor in the computer systems, networks, and cybersecurity department
E-mail: volodnz@nubip.edu.ua
ORCID: 0000-0002-7433-2484
National University of Life and Environmental Sciences of Ukraine

Abstract. *Rapid metropolitan growth is reshaping agrarian viability in peri-urban regions. Using the Kyiv agglomeration as a data-rich testbed, this study couples a modular UAV–AI decision-support workflow with empirical constraints emerging from land use, labour markets, logistics, and land rents. Regional evidence shows agricultural land has been squeezed to 0.21% of the area (≈0.18 k ha), against >54% green zones; wage differentials (16,500 UAH food processing vs 14,000 UAH agriculture) and transport costs of 20–250 UAH/km undermine farm margins and labour retention, while prime-zone rents up to 25 million UAH/ha/year intensify conversion pressure (Kyiv & oblast baseline tables and figures). These structural frictions motivate digital agronomy that is explicitly policy- and cost-aware. We therefore prototype a decision-support workflow that fuses UAV/satellite imagery, in-field IoT, and historical climate/crop data with administrative-economic layers (rents, wage gradients, haulage costs). The system translates multisource inputs into actionable stress detection, irrigation timing, and input allocation recommendations. At the same time, a logistics module evaluates route/vehicle choices under peri-urban cost profiles—a stakeholder-co-design process (farmers, processors, and planners) anchors usability and transferability. We report (1) the peri-urban baseline for Kyiv (land, wages, logistics, enterprise distribution), (2) the architecture of the UAV–AI workflow and integration points with farm CRMs and public agri-data, and (3) an evaluation framework linking agronomic KPIs to spatial-economic constraints for resilient adoption. The approach is designed for cross-border replication (Ukraine - Germany) and to inform respectable policy outputs on digital land management and peri-urban agrifood resilience.*

Keywords: *precision agriculture, digital agronomy, UAV, AI decision support, peri-urban farming, land use change, logistics costs, Kyiv agglomeration, resilience, policy integration.*

Introduction

Rapid urbanisation and the digitalisation of economic processes are two defining trends of the 21st century. Together, they drive structural change in both advanced and transitional economies, altering the distribution of land use, enterprise activity, and labour flows. In Eastern Europe, particularly Ukraine, these processes are accelerated by geopolitical and economic shocks that expose vulnerabilities in agrarian and urban sectors.

The Kyiv metropolitan region provides a compelling case study. On the one hand, the area has experienced significant contraction in agricultural land, coupled with rapid growth in non-agricultural enterprises, logistics, and services. On the other hand, the development of innovative city initiatives—from urban transport optimisation to digital governance platforms—illustrates how the digital economy reconfigures how cities manage infrastructure and services.

This article seeks to merge two strands of inquiry: (I) spatial-economic analysis of agrarian-urban dynamics and (II) the development of middleware-driven innovative city architectures (Figure 1). The objective is to examine how digital solutions leveraging IoT, UAVs, and AI-based decision support can address empirical urban pressures.

Analysis of recent research and publications

Aligned with the current Agriculture 4.0 technological innovations, three technology domains - UAV imaging, IoT telemetry, and AI/ML analytics - form a sensor stack for operational agronomy. Review papers on unmanned platforms in precision agriculture record a steady expansion of the range of tasks: from early detection of stresses and water regime monitoring to disease mapping and yield forecasting [1, 2]. The combination of "smart sensors" and machine learning algorithms, summarized in a systematic review with IoT and AI, underpins the shift from point cases to end-to-end decision support solutions, consistent with the platform architecture presented in this article [3].

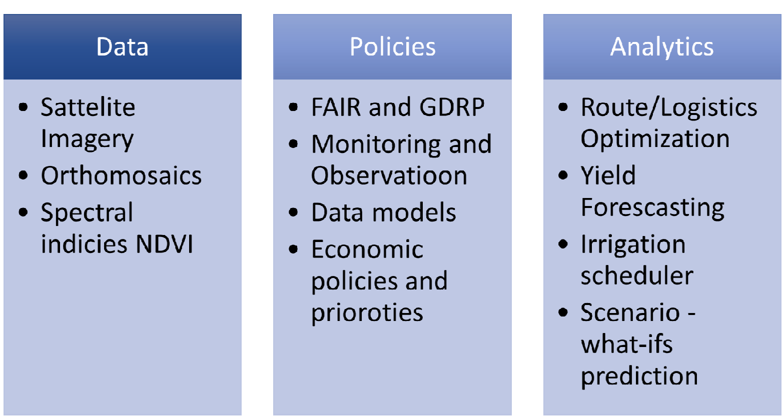

Fig. 1. Main components of an intelligent decision-support system (based on Nazarenko V. research data).

The second cluster of literature emphasizes the interoperability and role function of the middleware layer in cross-linking domain services and data. Work on aligning digital agricultural platform architectures and "pragmatic interoperability" in supply chains shows that standardized APIs, model schemes, and event-driven connectors provide scalability and manageability to complex ecosystems [4, 5]. The OGC SensorThings API standards and their industry enhancements demonstrate practical mechanisms for the interoperability of sensor data streams. The next-generation frameworks for "data spaces" and OPC UA automations outline the infrastructure for the secure exchange and reuse of agricultural data [6-8].

Finally, the latest directions—digital twins of farms, life cycle metrics, and technology adoption issues—shift the emphasis from purely technical efficiency to systemic effectiveness and sustainability. Reviews from digital twins and "smart" farming outline the potential of virtual replicas for simulating scenarios and optimizing resources. At the same time, LCA estimates point to the environmental and cost implications of implementing precision farming [9, 10]. In parallel, research on DSS and barriers to adoption highlights the importance of clear interfaces, transparent quality indicators, and economic feasibility for different manufacturers [11, 12]. This confirms the feasibility of the middleware architecture chosen in the article, with weighting criteria (time-cost-risk-quality) and contextual economic adjustment for the periurban conditions of the Kyiv agglomeration, where logistics costs and competition for land significantly affect operational decision-making.

Purpose. This study aims to develop and demonstrate a modular decision-support workflow that integrates geospatial and economic data to enhance the resilience and competitiveness of peri-urban agriculture under the pressures of rapid metropolitan growth. Using the Kyiv agglomeration as an applied case, the research aims to establish a robust empirical baseline of land use, labour, logistics, and rent dynamics that shape the viability of farming systems; design and prototype a UAV–AI–IoT platform capable of fusing multi-source spatial, climatic, and operational data with administrative-economic indicators; and evaluate how weighted routing and cost-sensitive analytics can inform stress detection, irrigation scheduling, and logistics optimization.

Methods and research data

The study draws on statistical data for the Kyiv region between 2000 and 2022, including land cadastre records, wage statistics, enterprise distribution, and transportation costs (Figure 2). Baseline findings include agricultural land reduction, green zone distribution, prime-zone land rent prices, average monthly wages, transport costs for logistics, and other data (Table 1).

A three-layer middleware architecture for bright city service orchestration was modelled: Application Layer (services for mobility, governance, energy, and environmental monitoring); Middleware Layer (event-driven routing, weighted decision parameters, API gateways); Core Services (data storage, IoT device management, security, and redundancy mechanisms). The parametric routing model applies weights to service requests to optimize real-time response time and resource allocation.

1. Key research data findings for Kyiv and Kyiv region (Kyiv agglomeration zone)*

Category	Data (2022)
Agricultural land	reduced to 0.21% of the total area
0.18 k ha	0,21
Green zones	Green zones account for 54% of the land.
Prime-zone land rents	25 million UAH/ha/year
Average monthly wages in food processing	16,500 UAH
Average monthly wages in agriculture	14,000 UAH in agriculture
Transport costs for logistics	20–250 UAH/km.

* prepared by Nazarenko V. based on the research data [13-14]

A comparative method was used to connect empirical urban pressures with middleware capabilities. Interviews with local stakeholders (farmers, IT providers, municipal planners) informed usability considerations. The research interview was conducted via personal communication and an interview, as well as an online form. The full survey results have not yet been disclosed to the general public.

It is important to note the current limitations on using uncrewed aerial vehicles (UAVs) in Ukraine under wartime conditions. Due to security restrictions, regulatory controls, and risks of interception, large-scale UAV deployment for agricultural monitoring and data collection is not always feasible. Therefore, while UAVs remain a crucial component of digital agronomy and long-term sustainability measurement, their application in the near term should be considered cautiously. In such cases, alternative sources such as satellite imagery, ground-based IoT sensors, and administrative-economic datasets can partially compensate for the limited aerial data. This reservation emphasizes the need for flexible, multi-source architectures to maintain decision-support functions despite temporary technological constraints.

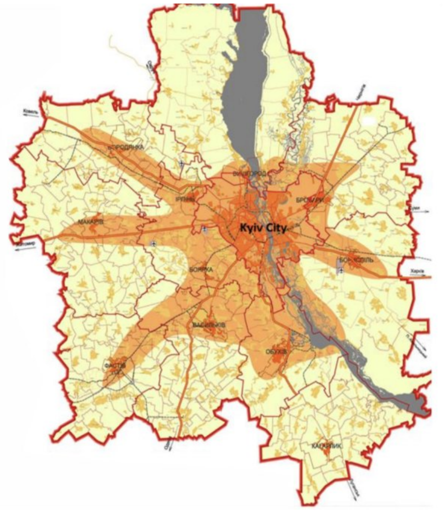

Fig. 2. Boundaries of the Kyiv agglomeration (based on Nazarenko V. research data) [16]

Results

The contraction of agricultural land and the steep increase in land rents have undermined the viability of peri-urban farming. Wage disparities further reduce the attractiveness of agricultural employment, while logistics costs undermine competitiveness. The result is a structural shift toward service and logistics enterprises in peri-urban zones.

The growth of innovative city initiatives has been driven by demand for more efficient governance and citizen services. Pilot projects in Kyiv include traffic monitoring systems, digital municipal services, and environmental IoT deployments. The middleware frame-

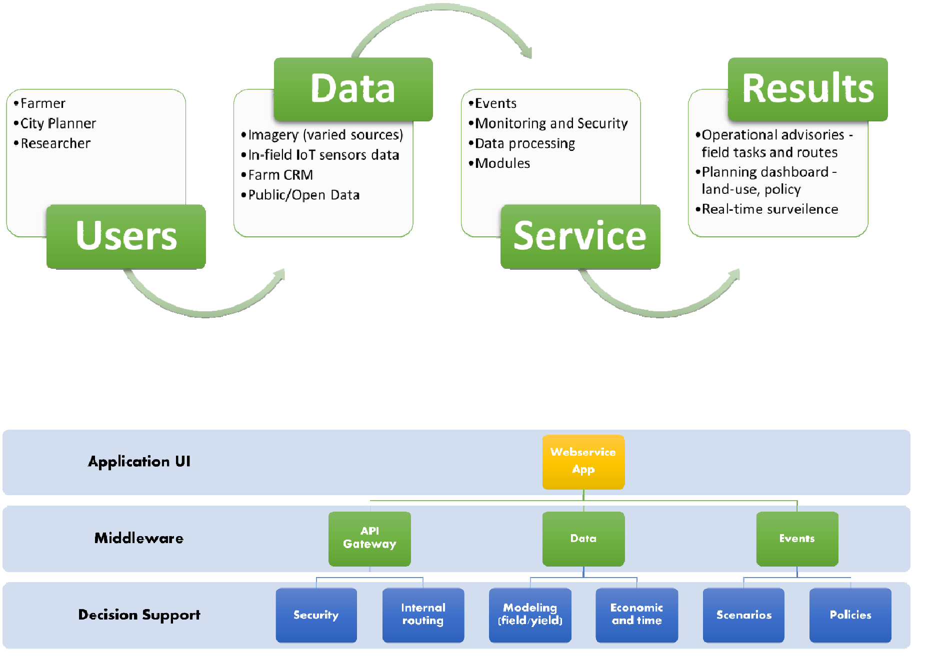

Fig. 3. Smart decision support system architecture, the main functions of the software system – top image, the three-level architecture of the software – bottom image (based on Nazarenko V. research data)

work addresses challenges such as scalability, interoperability, and resilience.

The middleware framework addresses three central challenges in innovative city service management: scalability, interoperability, and resilience. Scalability is achieved by supporting the growing volume of IoT devices and data streams that must be processed in real time [15]. Interoperability ensures that diverse services and platforms can communicate effectively by adopting common data standards. At the same time, resilience guarantees that operations can continue despite technical failures or external shocks. These features create a robust foundation for integrating complex urban systems within a single, adaptive digital environment.

The simulation of routing scenarios further demonstrates how middleware optimisation improves logistics and service delivery (Figure 3). The system enhances performance across multiple domains by applying weighted parameters to balance cost, time, and resource constraints. In logistics, this translates into reduced costs per kilometre and more efficient routing under congestion conditions. In governance, the model enables faster and more effective responses to citizen requests, improving service delivery and public trust. In agriculture, integrating UAV and sensor data into urban planning processes supports more precise land-use decisions and strengthens the resilience of peri-urban farming systems.

The findings illustrate how innovative city solutions can partly mitigate urbanisation challenges. For example, integrating UAV data into the middleware

2. Middleware routing algorithm for smart city and smart agriculture platform design *

Category	Details
System events	UAV tile ready sensor threshold breach farmer CRM ticket batch model retrain route-planning request policy/KPI query
System services	image pre-proc crop-stress model irrigation scheduler yield forecaster route optimizer data mart writer policy dashboard API
Main data parameters (input)	peri-urban cost profiles (e.g., 20–250 UAH/km) wage differentials (e.g., 16,500 versus 14,000 UAH) land-use pressure (agricultural land = 0.21%) used to weight economic risk/time sensitivity for Kyiv agglomeration pilots
Weights and algorithm data	time (latency) cost (CPU or UAH) per request accuracy range (%) economic data task/step priority

* prepared by Nazarenko V. based on the author's research data and materials

system provides real-time visibility of land use changes, allowing planners to anticipate and manage peri-urban expansion. Similarly, optimised logistics can reduce food system vulnerabilities by lowering transportation costs.

The smart agriculture and city middleware platform must orchestrate heterogeneous agricultural data flows (UAV imagery, in-field IoT, cadastral/administrative datasets, climate and market feeds) and route requests to the optimal analytic or storage microservice under explicit cost–time–risk–quality constraints. We adapt the three-layer architecture (Applications <-> Middleware <-> Core Services) with an event-driven dispatcher and weighted messages, proven in the Smart-City context, to agricultural use cases and peri-urban Kyiv conditions (logistics costs, wage/rent gradients, land-use pressure). The base presentation of the middleware systems' parameters and functions is outlined in Table 2 (we omitted technical details, as it is outside the topic of the present research, but they will be presented in future research publications). Algorithm usage scenario- peri-urban Kyiv farm requests optimal harvest-day routing (event - route-planning request) during congestion, 80 km round-trip, current band = 120–250 UAH/km. The system picks an optimal route planning path based on weights, and the route choice is based directly on economic criteria (set up in advance), resulting in faster/cheaper computation when transport is expensive.

From a practical standpoint, the resilience of the proposed data-centric architecture lies in its distributed and adaptive design. Each layer of the middleware platform—data ingestion, processing,

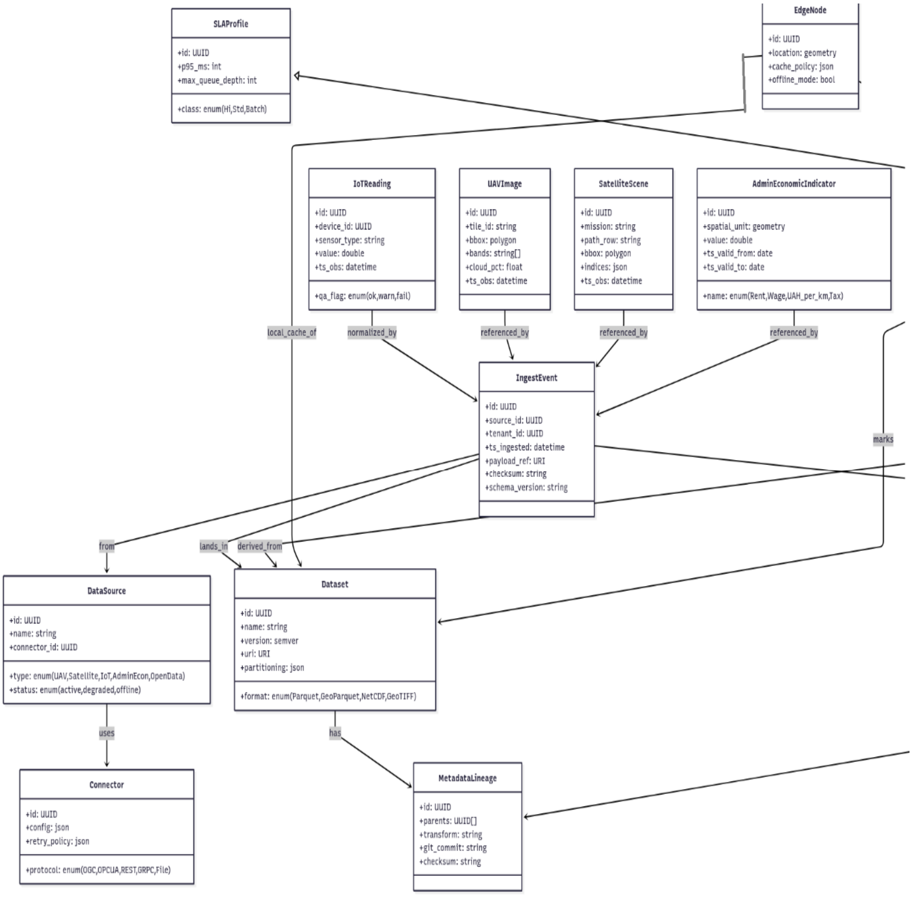

Fig. 4. Class diagram of Data-Centric Resilience Model (based on Nazarenko V. research data)

and service orchestration—operates under modular redundancy, allowing system components to remain functional even if parts of the infrastructure are temporarily degraded. Edge computing nodes can execute essential analytics locally when connectivity to central servers is interrupted, while asynchronous message queues ensure incoming data is cached and synchronized once the network stabilizes. Adopting open standards (OGC SensorThings, ISO, OPC UA) enables quick substitution of data sources and services without rewriting the core logic. Furthermore, using multi-source inputs - satellite imagery, IoT telemetry, administrative datasets, and economic indicators - ensures continuity of decision-support functions when specific data channels (such as UAV imagery) are unavailable (Figure 4). Collectively, these mechanisms maintain operational stability, safeguard data integrity, and preserve analytical continuity under transient conditions, confirming the platform's applicability for resilience planning and crisis-adaptive agriculture.

However, deploying such systems

requires careful attention to several critical factors. Data governance must be ensured through adherence to FAIR data principles and compliance with GDPR, guaranteeing transparency, accessibility, and protection of sensitive information. Equally important is user adoption, which depends on designing interfaces that are intuitive and accessible to a wide range of stakeholders, from municipal administrators to farmers and citizens. Interoperability also plays a decisive role, requiring local platforms to align with international standards such as ISO and OGC to facilitate integration across systems and borders. These considerations position the study within broader debates on innovative city development and the digital economy, underscoring the importance of cross-sector integration and international collaboration.

Discussion

Urbanisation in Kyiv illustrates the pressures of metropolitan growth on agriculture and regional sustainability. Digital economy tools, particularly middleware-driven innovative city platforms, offer viable pathways to manage these challenges. By combining empirical urban-economic data with algorithmic service orchestration, this research demonstrates how data-centric architectures can support resilience and sustainability in transitional contexts.

Future research should extend platform testing across borders (e.g., Ukraine–Germany), incorporate UAV-based precision agriculture, and evaluate policy implications for urban-rural governance. The study advances SDGs 9, 11, 12, and 17 by promoting innovation, sustainable cities, responsible production, and global partnerships (SDG 9 - Industry, Innovation, and Infrastructure; SDG 11 - Sustainable Cities and Communities; SDG 12 - Responsible Consumption and Production; SDG 17 - Partnerships for the Goals) [17].

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Назаренко В.А.

ЦИФРОВЕ ЗЕМЛЕРОБСТВО: ПРОЦЕС ПІДТРИМКИ ПРИЙНЯТТЯ РОЗУМНИХ РІШЕНЬ ДЛЯ СТІЙКОГО ДО ЗМІНИ КЛІМАТУ СІЛЬСЬКОГО ГОСПОДАРСТВА В КИЇВСЬКІЙ АГЛОМЕРАЦІЇ

ЗЕМЛЕУСТРІЙ, КАДАСТР І МОНІТОРИНГ ЗЕМЕЛЬ 3'25: 33-42.
http://dx.doi.org/10.31548/zemleustriy2025.03.04

Анотація. *Швидке зростання мегаполісів суттєво змінює життєздатність аграрного сектора економіки у приміських регіонах. Використовуючи Київську агломерацію як багатий на дані випробувальний полігон, це дослідження поєднує модульний робочий процес підтримки прийняття рішень за допомогою БПЛА та штучного інтелекту з емпіричними обмеженнями, що виникають у сфері землекористування, ринків праці, логістики та земельної ренти. Регіональні дані свідчать, що сільськогосподарські угіддя* *скоротилися до 0,21% площі (≈0,18 тис. га), проти >54% зелених зон; різниця в оплаті праці (16 500 грн харчова промисловість проти 14 000 грн у сільському господарстві) та транспортні витрати на рівні 20–250 грн/км підривають маржу фермерських господарств та утримання робочої сили, тоді як орендна плата в прайм-зоні до 25 млн грн/га/рік посилює тиск на конверсію (базові таблиці та цифри Києва та області). Ці структурні розбіжності мотивують розвиток цифрового землеробства, яка явно враховує політику та витрати. Тому запропоновано створити прототип робочого процесу підтримки прийняття рішень, який поєднує аналіз знімків БПЛА/супутників, польовий Інтернет речей та історичні дані про клімат/врожай з адміністративно-економічними рівнями (орендна плата, градієнти заробітної плати, витрати на перевезення). Інформаційна система перетворює вхідні дані з кількох джерел у швидке та результативне виявлення проблемних моментів, час поливу та рекомендації щодо розподілу вхідних даних. У той же час, системний (програмний) модуль бізнес-логіки оцінює вибір маршруту/транспортного засобу відповідно до профілів витрат у приміському регіоні — процес спільного проектування зацікавленими сторонами (фермери, переробники та планувальники) визначає зручність використання та передачу. В дослідженні представлено (1) базовий рівень приміського розвитку Києва (земля, заробітна плата, логістика, розподіл підприємств), (2) архітектуру робочого процесу БПЛА-штучного інтелекту та точок інтеграції з CRM-системами для ферм та публічними даними аграрного виробництва, а також (3) систему оцінювання, яка пов'язує KPI аграрного сектору та промисловості з просторово-економічними обмеженнями для стійкого впровадження. Цей підхід розроблений для транскордонного реплікації (Україна – Німеччина) та для інформування про ефективні результати політики щодо цифрового управління земельними ресурсами та стійкості приміських агропродовольчих фондів.*

Ключові слова: *точне землеробство, цифрове землеробство, БПЛА, підтримка прийняття рішень штучним інтелектом, приміське землеробство, зміна землекористування, логістичні витрати, Київська агломерація, стійкість, інтеграція політик.*

НАУКИ ПРО ЗЕМЛЮ. ГЕОІНФОРМАЦІЙНІ ТЕХНОЛОГІЇ МОДЕЛЮВАННЯ СТАНУ ГЕОСИСТЕМ

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DESIGNING A CONCEPTUAL MODEL OF THE GEOSPATIAL DATABASE FOR HAZARDOUS ANIMAL BURIAL SITES AFFECTED BY ANTHRAX

A. MOSKALENKO,
PhD in Technical Sciences, Associate Professor
The National University
of Life Resources and Environmental Sciences of Ukraine
E-mail: moskalenko_a@nubip.edu.ua
T. IEVSIUKOV,
Doctor of Economic Sciences, Professor
The National University
of Life Resources and Environmental Sciences of Ukraine
E-mail: ievsiukov_t@nubip.edu.ua

Abstract. *The article presents the author's approach to the systematization and accumulation of geospatial and attributive data on dangerous burials of animals that died from anthrax. Anthrax is a zoonotic disease, the spores of which can remain viable in the soil for decades, posing a potential threat. Burials of animals not carried out in biothermal pits (mainly before 1954) do not provide an adequate level of safety. In the event of a shift in the soil cover, spores can reach the surface and cause new cases of the disease among wild and domestic animals, as well as infection of people. A significant part of such burials does not have clearly established boundaries of land plots and established regimes of limited use of adjacent territories, which complicates control over their condition.*

As part of the study, the available geospatial and attributive data on dangerous burials were structured, and a conceptual model of a geospatial database was developed, which ensures the accumulation, structuring, and systematization of data. The model is built using UML notation and is presented in the form of a class diagram that reflects the main structural elements of the database and their attributes.

The results obtained can be used to create a physical model of a geospatial database for the registration (register) of lands with dangerous burials of animals that died from *anthrax, as well as for the further development of the monitoring system, planning of sanitary and protective measures, establishing regimes of limited land use, etc.*

Keywords: *geospatial database, conceptual model, anthrax*

Relevance

Human economic activity is one of the key factors influencing the state of the environment and determining its safety for the population. As a result of anthropogenic impact, various objects are formed, some of which can exert a negative influence on surrounding areas, wildlife, and human health for decades. Among such hazardous regime-forming objects are livestock burial sites containing animals that died from anthrax, particularly those burials conducted without the use of biothermal pits. According to research findings [1], the main cause of new anthrax outbreaks lies in the inadequate protection of old burial sites, which are often simple earthen pits and do not meet biological safety standards. Several scientific studies [1-2] emphasize the exceptional resilience of anthrax spores: they withstand boiling, dry heat, conventional disinfectants, and can persist in soil for decades. Meanwhile, data [3] show that between 1999 and 2022, 35 human cases of anthrax were recorded in Ukraine. Similar cases are reported across European countries, as reflected in weekly and annual reports of the European Commission – for instance, five cases were registered during a single week (18–24 September 2025) [4].

Existing burial sites of animals that died from anthrax remain a potential source of biological hazard. Disturbance of the soil cover in such locations may lead to the release of spores to the surface, posing a risk of infection for both wild and domestic animals, and representing a threat to humans, as anthrax is a typical zoonotic disease. Beyond the direct biological hazard, several additional factors contribute to elevated risk levels. These include the absence of clearly defined boundaries and appropriate informational signage, discrepancies between spatial data and the actual location of burial sites, loss of records regarding such sites, various types of surveying or excavation activities, and military actions that cause mechanical disruption of the soil cover.

Previous scientific developments, including [5], have focused on creating geospatial database models for the registration and monitoring of anthrax cases. However, these efforts have primarily concentrated on recording confirmed cases of the disease, without accounting for local territorial characteristics and associated risks. At the same time, European Union legislation [6] outlines the general principles for the prevention, detection, surveillance, and control of infectious animal diseases, including anthrax. Given Ukraine's status as an EU candidate country, it is necessary to harmonize national legislation with European standards, particularly regarding systems for registering and documenting the course of infectious animal diseases.

In this context, the creation of a geospatial database acquires particular significance and relevance, as it enables not only the registration of new disease cases but also the accumulation, structuring, and systematization of spatial and attribute data related to territories containing hazardous animal burial sites. Such a database will serve as a foundation for further spatial analysis, risk assessment of disease spread, planning of sanitary protection measures, and the development of land-use management decisions. The first step in this process is the development of a conceptual model of the geospatial database, which defines its structure, key elements, and interrelationships.

Review of Recent Studies and Publications

The challenges of geospatial database modeling across various sectors, as well as the study of risks associated with zoonotic infections, have been the subject of numerous scientific investigations and publications. For instance, study [2] provides a detailed analysis of anthrax pathogen strains and their virulence characteristics. Research [7] offers an overview of the epizootic situation regarding anthrax in Ukraine and the condition of burial sites for animals that died from the disease.

Makovska I. and her co-authors [8] explored the potential of geographic information systems (GIS) for analyzing rabies spread in Vinnytsia Oblast. Study [9] presents findings on the identification of anthrax-prone areas in Kenya. Similarly, research [10] examines the current status and spatial patterns of anthrax outbreaks across geographic regions of Zimbabwe, taking into account climatic factors.

Issues of conceptual modeling of geospatial data are addressed in [11], which presents a catalog of object classes for the cadastral geodata database. Article [12] outlines the specific features of conceptual modeling tailored to the needs of ecotourism. Study [13] examines a conceptual model for geoinformation-based assessment of the impact of hazardous animal burial sites – specifically those related to anthrax – on adjacent territories.

Particular attention should be given to practical developments, such as the interactive map [14] designed for reporting suspected and confirmed anthrax cases in Ukraine. The European Commission [15] regularly publishes consolidated statistics on recorded cases of this disease. However, these initiatives are primarily focused on quantitative indicators and do not account for local territorial characteristics, levels of transmission risk, or potential sources of contamination.

Consequently, recent studies and publications have insufficiently addressed the issue of developing a geospatial database structure for recording and registering territories containing hazardous animal burial sites related to anthrax. This gap highlights the need for further research and practical solutions.

Research aim

This study aims to provide a scientific rationale for the key components and structure of a geospatial database designed to record and register territories containing hazardous animal burial sites related to anthrax. The relevance of this issue stems from the high level of biological hazard that persists for decades in such locations, as well as the lack of up-to-date, reliable, and systematized information regarding their location, condition, and the legal status of the land plots involved.

At this stage, conceptual modeling plays a crucial role, as it enables the formation of a logical structure for the future database, including the definition of object classes, their attributes, and interrelationships. Thus, the objective of the study is not only to document existing hazardous burial sites but also to develop an effective tool for ongoing monitoring, risk forecasting, and support for management decision-making.

Materials and Methods

The methodology is based on a combination of scientific literature review and analysis of regulatory documents, along with the application of modern conceptual modeling techniques for geospatial data. To describe the structure and logic of object interactions, the Unified Modeling Language (UML) was used. The class diagram developed within the study reflects not only the key informational elements but also the types of relationships between them, allowing for the consideration of potential data incompleteness or absence. This approach ensures the systematization, flexibility, and scalability of the geospatial database.

The application of the conceptual model is the first and essential step in developing a physical database model, which can subsequently be implemented within a GIS environment. This will enable spatial analysis, risk assessment of anthrax spread, mapping of hazardous areas, and improve the effectiveness of planning sanitary and environmental protection measures.

Results and Discussion

During the course of the study, a conceptual model of the geospatial database of hazardous animal burial sites related to anthrax was developed. It accounts not only for the spatial location of burial sites but also for their safety status, characteristics of the surrounding area, and the presence of warning signs and fencing (Fig. 1).

At the conceptual level, the model represents the structure of the entire geospatial database, including feature classes, their attributes, and the relationships between them.

In the developed model, the classes Region, District, and Community ensure the linkage of burial sites to the corresponding administrative-territorial units. The model accounts for temporal changes in administrative boundaries, including dissolutions, mergers, enlargements, and name changes. The Settlements class describes existing populated places within each community. Within an administrative-territorial unit, a burial site can be represented in two ways: via the LandParcel class — if the land parcel has been formally registered and its boundaries are defined in legal documents; or via the TerritorialPart class – in cases where no cadastral information is available in the State Land Cadastre.

The AnimalBurial class is central to the developed model and serves as the primary spatial object for assessing the risk of anthrax spore dissemination. The attribute functionality defines the burial site's status (closed or active). The BurialType and BurialClass classes perform a classification function, reflecting the type of animals, disease name, burial type, and the level/class of potential hazard.

The Restrictions class represents sanitary protection zones surrounding hazardous animal burial sites affected by anthrax. Safety measures – such as informational signs, fences, barriers, and other visibility elements – are modeled through the MarkingMeasures class. Additionally, the Soil class reflects the properties of the soil cover, which may either facilitate or inhibit the spread of dangerous spores. The Catchment class accounts for the location and area of the

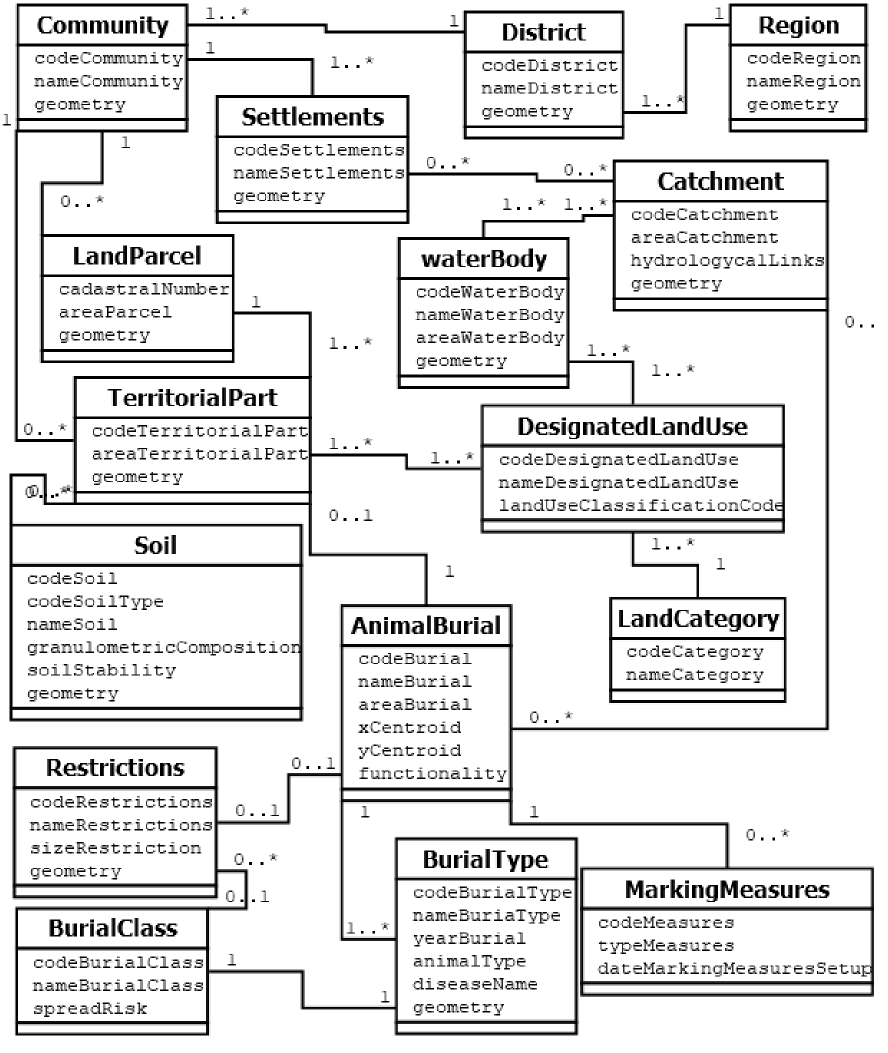

Figure 1. Conceptual model of the geospatial database for hazardous animal burial sites that died from anthrax

watershed, as well as hydrological links between the burial surface and aquifers.

Overall, the developed model provides a foundation for the subsequent creation of a physical database and enables the systematic organization of information required for monitoring and assessing the risks of anthrax dissemination.

Conclusions and prospects

The development of a conceptual model of a geospatial database of dangerous burials of animals that died from anthrax is an important step towards creating an effective system for monitoring and managing land use risks. The proposed model provides structuring and integration of both spatial and attributive information, which allows forming a holistic register of such objects and increasing the efficiency of their accounting and analysis.

A key scientific value of the model lies in its consideration of a complex set of factors that determine the likelihood of anthrax emergence and spread: soil types, hydrological conditions, burial characteristics and types, land categories, the presence of sanitary restrictions, visibility and marking measures, among others. This comprehensive approach provides a foundation for constructing a physical database model that will enable rapid spatial risk analysis and forecasting of hazardous situations.

The practical significance of the study lies in enhancing the effectiveness of land-use planning and supporting evidence-based decision-making in the fields of public health, environmental protection, and agricultural production. Future research prospects include the development of a methodology for spatial zoning of anthrax risk areas and the automation of thematic map generation to support management decisions.

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Москаленко А.А., Євсюков Т.О.

РОЗРОБЛЕННЯ КОНЦЕПТУАЛЬНОЇ МОДЕЛІ БАЗИ ГЕОПРОСТОРОВИХ ДАНИХ НЕБЕЗПЕЧНИХ ПОХОВАНЬ ТВАРИН, ЯКІ ЗАГИНУЛИ ВІД СИБІРКИ

ЗЕМЛЕУСТРІЙ, КАДАСТР І МОНІТОРИНГ ЗЕМЕЛЬ 3'25: 43-50.
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Анотація. *У статті представлено авторський підхід до систематизації і накопичення геопросторових та атрибутивних даних щодо небезпечних поховань тварин, які загинули від сибірки. Сибірка є зоонозним захворюванням, спори якого здатні зберігати життєздатність у ґрунті протягом десятків років і залишатись джерелом потенційної загрози. Поховання тварин, здійснені не у біотермічних ямах (головним чином до 1954 року), не забезпечують належного рівня безпеки: у разі зміщення ґрунтового покриву спори можуть потрапити на поверхню і стати причиною нових випадків захворювання серед диких і свійських тварин, а також інфікування людей. Значна частина таких поховань не має чітко встановлених меж земельних ділянок і встановлених режимів обмеженого використання прилеглих територій, що ускладнює контроль за їхнім станом.*

У межах дослідження було структуровано наявні геопросторові та атрибутивні дані про небезпечні поховання і розроблено концептуальну модель бази геопросторових даних, що забезпечує накопичення, структурування й систематизацію даних. Модель побудована з використанням нотації UML та представлена у вигляді діаграми класів, що відображає головні структурні елементи бази даних та їхні атрибути.

Отримані результати можуть бути використані для створення фізичної моделі бази геопросторових даних з обліку (реєстру) земель з небезпечними похованнями тварин, що загинули від сибірки, а також для подальшого розвитку системи моніторингу, планування санітарно-захисних заходів, встановлення режимів обмеженого землекористування та ін.

Ключові слова: *база геопросторових даних, концептуальна модель, сибірка.*

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APPLICATION OF GIS TECHNOLOGIES TO ASSESS THE IMPACT ON THE SURROUNDING ENVIRONMENT OF THE LOCATION OF WIND POWER PLANTS USING THE EXAMPLE OF "POLONYNA RUNA" OF THE TURYE-REMETIVSKAYA AH COMMUNITY

V. PERESOLIAK,
Candidate of Sciences in Public Administration,
Associate Professor Uzhhorod National University
E-mail: v.peresolyak@gmail.com;
ORCID:0000-0002-6255-1559
I. RADISH,
Candidate of Technical Sciences, Associate Professor
E-mail: ihor.radysh@uzhnu.edu.ua;
ORCID: 0000-0003-0187-4183
I. KRYLYO,
Master, Lecturer
Natural Sciences and Humanities Professional College
Uzhgorod National University
E-mail: ihor.krylo@uzhnu.edu.ua

Abstract. *In the current conditions of the development of renewable energy, which includes wind energy, the most important task is to minimize the environmental impact of wind power plants (WPPs) on the environment in the context of decarbonization of economic sectors. The use of geographic information systems (GIS) allows for effective analysis and modeling of the impact of wind farm placement, taking into account: environmental, landscape, economic, climatic and social factors that affect the sustainable development of territories. The article considers the use of geographic information systems (GIS) to assess the environmental impact of the location of a wind farm (WPP), which is planned to be built on the territory of the "Polonyna Runa" tract of the Turye-Remetivska rural territorial community of the Uzhhorod district of the Transcarpathian region.*

The study involves the collection and processing of spatial data, including relief, wind speed and direction, the presence of protected areas, and habitats of sensitive species of flora and fauna. GIS will be used to analyze visual and noise impacts, assess risks to biodiversity and public health, and model alternative locations for the station's wind turbines.

The assessment results contribute to making informed design decisions regarding the location of wind farms, reducing negative environmental impacts and ensuring a *balance between the sustainable development of wind energy in the region and the preservation of the natural environment.*

Keywords: *wind energy, environmental impact assessment, geographic information systems, spatial planning, sustainable development of territories, renewable energy sources, decarbonization, CO_2 emissions.*

Introduction

In today's climate of global warming and the growing need for renewable energy sources, wind energy occupies an important place among environmentally friendly technologies. Wind farms (WPPs) contribute to the reduction of greenhouse gas emissions and the reduction of dependence on traditional energy resources. However, their placement can have a significant impact on the environment, including biodiversity, landscape, noise pollution and the quality of life of local populations.

To assess the impact of wind farms on the environment, it is important to use the latest analysis methods, among which geographic information systems (GIS) occupy a special place. GIS technologies allow for spatial analysis, modeling the potential impact of wind turbines, evaluating alternative options for their location, and minimizing environmental risks.

Ukraine has favorable conditions for the development of wind energy:

- land free from industrial, residential and intensively used agricultural land for the construction of wind power plants (WPP);
- high capacity of factories capable of producing modern wind turbines, especially in regions with potential for the use of WPP;
- many years of observation data and the availability of highly qualified personnel for the construction of high-tech structures, such as wind farms.

According to various estimates, the industrial potential of wind power in Ukraine is about 500 billion kWh per year [1]. Based on the experience of most European countries in implementing wind power plants in Ukraine, electricity production can be increased by using more powerful wind turbines and commissioning new onshore wind power plants up to 17,455 GWh in 2030 (with a total capacity of 6.214 GW) [16]. According to the Regulation on Approval of the National Renewable Energy Action Plan for the Period Until 2030 and the Action Plan for its Implementation [17], it provides for the construction of wind power plants with a total capacity of 16,000 MW, therefore the importance of site selection and development of wind power plant construction has not changed. In December 2024, Elementum Energy successfully closed a deal to acquire a 200MW wind power project in western Ukraine. The new wind farm is expected to generate approximately 700GWh of electricity annually, equivalent to the annual electricity consumption of approximately 600,000 people.

Wind energy plays a leading role in the decarbonization of the Ukrainian economy. In addition, wind power plants replace traditional energy sources that burn fossil fuels to produce electricity. Thanks to wind energy technologies, CO_2 emissions into the atmosphere have been reduced by 835 million tons.

The popularization of small wind turbines has a rapid and tangible impact on the national economy. The installation of small wind turbines can be widely used not only for electricity generation, but also to facilitate mechanical processes (mills, deep well pumps, pumping water from wells, pumps, etc.).

Analysis of recent research and publications

In the field of assessing the impact of wind farm (WFP) siting on the environment using geographic information systems (GIS), a number of studies have been conducted that emphasize the importance of an integrated approach to planning and implementing renewable energy projects.

Certain ecological, economic and technical aspects of wind energy use were considered in their works by such scientists as Y. Bashynska, V. Didyk, S. Kudrya, O. Sukhodolya and others. In legal science, the issues of legal regulation of relations in wind energy were studied in their works by O. Sushik, H. Grigoriev, K. Karakhanyan, M. Kuzmina, E. Rybnikova, Y. Rud, T. Kharitonova, I. Chumachenko, V. Peresoliak, M. Lopushanska and others proposed a methodology for assessing the environmental impact of renewable energy facilities, tested on the example of the Polonyna Runa wind farm in the Turye-Remetivska rural territorial community of the Uzhhorod district of the Transcarpathian region. This methodology covers all stages of the project life cycle and takes into account environmental, economic and social aspects of the impact. The use of GIS allows for detailed analysis of spatial data and modeling of potential environmental risks.

The purpose of the study is to use GIS technologies to assess the impact of wind farm (WPP) location on the environment, taking into account the following factors: environmental, landscape, economic, climatic, social and special studies of regulatory and legal requirements for the construction and operation of wind power plants with an emphasis on their impact on the environment in the natural resource management system.

Materials and research methods

The research methods used to study the topic were: cartographic analysis, spatial analysis, modeling, visualization, logical generalization, and information presentation. Namely: for the creation and analysis of planning and cartographic materials that represent spatial data in a graphical form - the method of cartographic analysis; for the relationships between project objects and existing ones, such as distance, direction, adjacency, interpenetration - a spatial analysis method; for predicting the impact on the environment and ecological features of the territory - a modeling method; for creating and presenting the results of the analysis for a wide range of users - a method of presenting information.

Results and their discussion

For the environmentally efficient use of wind energy, comprehensive information about its characteristics is necessary. When analyzing the wind energy potential of a region, a wind energy cadastre is compiled.

A wind energy inventory is an objective, reliable and necessary set of quantitative data characterizing wind as an energy source. Based on long-term observations, a wind energy inventory presents all wind characteristics in tabular or graphical form.

The main source of initial data for wind energy cadastres is the organization of wind speed observations using a reference network of hydrometeorological stations [13]. Such observations are made a certain number of times per day, cover a period of several decades, and provide the raw data for analysis. The advantage of such observations is that they are collected in a unified manner.

The average annual wind speed is the first characteristic of the overall level of wind energy. This value can be used to determine the efficiency of a wind turbine in a specific sector or in a region as a whole. It should be noted that wind speed depends on the terrain, especially the roughness of the surface, the presence or absence of shading elements and the height above ground level at the selected site. These conditions vary greatly from station to station. Therefore, for comparison, they need to be converted to average wind speed. These conditions are usually referred to as open, flat terrain and a height of 0 meters above the ground.

Energy resources are usually assessed on the basis of potential, technical and economic resources. Technical resources of wind energy are considered as part of the potential resources that can be exploited using existing technical means. Technical resources of wind energy are part of the potential resources that can be used using existing technical means and are determined taking into account inevitable losses when using wind energy. According to the theory of an ideal wind turbine, only a portion of the energy that is used and converted, i.e. passes through the cross-section of the wind turbine, is useful work. The maximum amount of useful energy is estimated as the wind energy utilization factor (WEF) limited by a constant of 0.593. The best wind turbine models today maintain this parameter in the range of WEF- 0.45-0.48.

It should be noted that modern wind turbine designs do not fully utilize the entire range of wind speeds. At minimum wind speeds, the amount of electricity produced is below the minimum operating power of the wind generator, which is insufficient to overcome the friction forces of the wind generator components. Only in the range from the minimum operating speed to the design speed can the wind turbine use its installed capacity and wind energy can be used with the greatest benefit. If the wind speed continues to increase to the maximum operating speed, the wind turbine output power is maintained at the level set by the controller. If the wind speed exceeds the maximum operating speed, the wind turbine is shut down and stopped to prevent technical breakdowns.

Modern wind turbines are large technological structures (megawatt wind turbines have a diameter of 60-120 m and a tower height of 60-100 m or more), built using the latest developments in aerodynamics, electrical engineering, electronics, and computer technology. Currently, the installed capacity of a wind turbine is 1 kW, and its cost is 800-1000 USD. In the future, this figure is expected to decrease to 600 USD.

Estimates of wind energy potential for a narrow area are based on general climate maps covering a country or region and measurements from meteorological stations located tens, and in some cases hundreds, of kilometers from the study area, therefore, very approximate results can be obtained, which, of course, describe only the current circulation process and the background wind field. To obtain more accurate estimates, it is necessary to consider the surrounding landscape conditions and topography at a distance of several kilometers from the study area. Only such desk-based methods can assess the potential for local air current activity at low altitudes.

When selecting sites for energy facilities, it is necessary to take into account a number of different parameters, such as meteorological observations, topographic data, and local economic development plans [7,11].

Areas with the following characteristics may be suitable for the construction of wind farms:

- optimal average annual wind speed;
- absence of high-altitude obstacles on the leeward side;
- there are no uneven terrain, buildings and structures, vegetation in a certain proximity to the wind turbine;
- the site on the top of the hill should be flat with gentle slopes or the site should be located on a plain, shallow water or island;
- the presence of local landforms that affect the phenomena of "push" and acceleration of the wind flow is not found (among them are high valleys and flat peaks of heights;
- a mountain tunnel-like gorge, which has an orientation in space parallel to the prevailing wind directions (Fig. 1).

GIS can be used to more accurately determine the environmental impacts of wind farms and make informed decisions about siting, ensuring a balance between the needs of the energy sector and the protection of natural ecosystems.

In summary, we can say that modeling the construction of future wind farms requires the analysis of large amounts of

Fig. 1. Location of a wind turbine in a tunnel-like valley

information, the collection of which can be effectively organized using geoinformatics methods. There are numerous examples of using geographic information systems (GIS) to solve the problem of selecting sites for the construction of wind farms. In particular, it is assumed that digital topographic maps can be used to identify areas that are flat or have a slight slope in the direction of the wind flow, taking into account the absence of surrounding obstacles (hills, trees, buildings, etc.) [12].

A comprehensive approach to site selection for wind turbines requires a qualitative assessment of local characteristics that can contribute to high wind speed and stability, and therefore potential energy production (Fig. 2). When lower-height towers are used for wind turbines, especially those below 20 m, it is more accurate to calculate wind protection zones relative to objects in specific areas and buffer zones that limit potential turbulence zones. This data can also be used to identify areas where wind speeds may slow down.

One of the most important conditions for successful investment in wind energy is a good understanding of the typical wind conditions for a given microregion. As noted above, the power

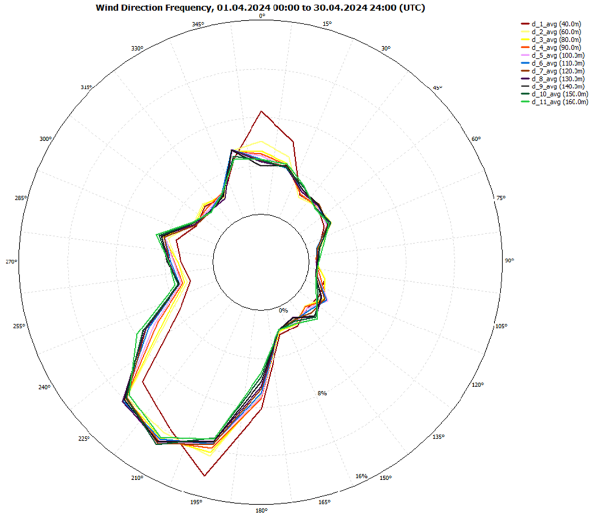


Fig. 2. Wind frequency and direction "Polonyna Runa" from 01.04.2024 to 30.04.2024

of the air flow passing through the rotor of a wind farm is proportional to the cube of the wind speed. Even in regions with good wind conditions, the location of future power plant sites must be carefully selected taking into account the geometry of the site, including the potential presence of obstacles. These factors are often underestimated, but their impact on the performance of each individual power plant is crucial. As a result, choosing a project location between favorable and unfavorable zones can easily compensate for the two- to three-fold difference in energy efficiency and, consequently, in electricity costs between similar power plants [8].

The potential wind energy depends on the roughness of the ground surface at a given location, including sports facilities, buildings, trees, damage to wind turbine cages, and other tall obstacles. Wind tunnel experiments have been conducted in Sweden to determine the minimum distance between wind turbines to avoid interference. The experiments have shown that the distance should be at least six wind turbines in diameter. There is also evidence that this distance should be 8-12 cm in diameter.

The results of wind shadow simulation calculations for different types of obstacles are shown in Fig. 7 [4]. The main methods of geoinformation modeling and analysis necessary for the implementation of the above schemes are:

- proximity analysis, construction of buffer zones;

- terrain surface analysis, determination of visibility between objects, calculation of slope gradients and exposures;

- 3D modeling and web mapping of terrain and wind farm objects.

Wind farms produce energy with little or no chemical impact on the environment, but they have many consequences, such as changing the landscape due to land allocation for construction, noise impact, and radio interference. In this document, the main environmental impacts of wind turbines are analyzed from a land management perspective: determining the degree of noise impact from the operation of wind turbines - noise zone Wind turbines generate noise, which is usually divided into infrasound and noise that affects humans and other living organisms.

Infrasound is acoustic vibrations in the air with a frequency below 20 Hz, i.e. below the threshold of human hearing. Sources of infrasound in nature include wind noise, ocean waves, waterfalls, storms and earthquakes. At the same time, infrasound is widespread in everyday life, for example through the use of heaters, compressors, and automobiles. Urban infrastructure, such as tunnels, bridges, and high-rise buildings, is also a source of infrasound propagation. The infrasound range is considered safe for human health if its level is within 130 dB.

In other words, researchers from the USA and France stated that low-frequency noise from wind turbines negatively affects the human body, causing persistent depression, severe irrational anxiety, and disruption of vital functions, that is, the area around wind farms is not suitable for a comfortable life for people, animals, and birds. At the same time, according to a study commissioned by the German Federal Office of Health, low-frequency vibrations from wind turbines do not have a negative impact on the environment or human health, as the noise level is below the detection threshold of 30 dB.

The problem of reducing the noise impact of wind turbines is solved by locating wind turbines at a certain distance from residential buildings, where the noise level does not exceed 40-50 dB. For different wind turbine capacities, there are general recommendations for impact ranges ranging from 150 to 350. However, the Danish Wind Energy Manufacturers Association [3] recommends a minimum of seven rotor diameters or a distance of 300 meters.

The Association's website (www.Windpower.org) has a freely available calculator that calculates noise levels from a wind turbine at various distances, which is visualized as a raster map.

As is known, protective and sanitary protection zones are established around all industrial enterprises. In order to assess the impact of wind turbines on the environment, it is necessary to calculate protective zones.

In the study of wind energy systems, protection zones are used to assess the impact of wind turbine noise on the environment, for example, to determine the impact of restrictions on the sanitary protection zone around hazardous facilities. The impact of tall objects on the landscape on wind flows is also assessed. Examples of protection zones around objects are shown in Figures 3-6. For example, Fig. 3 shows a polygonal object whose boundaries are equidistant from the object boundary by a certain value, in this case the radius R.

The buffer radius can be a numeric constant or the value of an attribute of a specific spatial object. In the first case, all protected areas have the same radius; in the second case, a buffer area with a unique radius is defined around each object. Additionally, you can use multiple buffers, i.e. an array of radii that can form an array of buffer zones. If the radius is negative (the radius is smaller than the selected area), the buffer zone is created inside the polygonal object.

When solving many applied geoinformatics problems, it is necessary to determine the so-called proximity zones. These zones are also called Voronoi diagrams or proximity zones. Al-

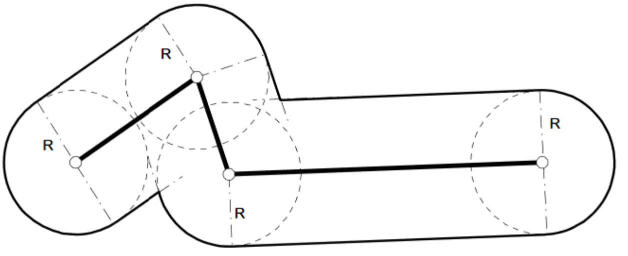
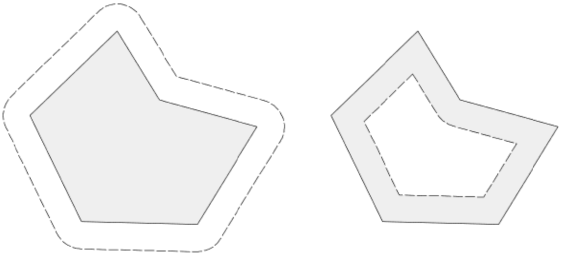


Fig. 3. Scheme of construction of the security zone



a b

Fig. 4. Protection zones with positive (a) and negative (b) radius

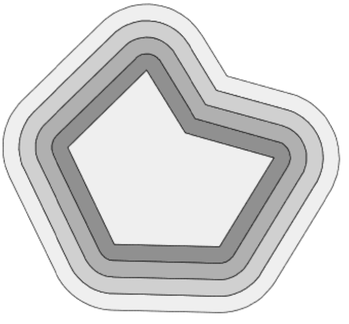


Fig. 5. Ring security zones

gorithms that calculate the slope and exposure of the terrain allow the creation of new regularized grids based on raster DEMs, where each node corresponds to the angle of slope and exposure.

In accordance with the above requirements, the noise impact of the operation of a large-capacity wind turbine was assessed by creating a buffer zone in the GIS. A minimum distance of 450 m from the installation site is considered sufficient to ensure that the noise impact is negligible. The recommended distance from a powerful wind turbine to a permanent human presence area (noise zone) is 350 m.

The next step uses a line-of-sight algorithm to calculate the points that can be observed along a given line on the terrain surface. This calculation also requires the height of the observer above the ground (HA) and the height of the object above the ground (HB) [5]. The algorithm for calculating line of sight consists of several stages. In the first stage, a profile is created along a given line. In the next stage, a segment AB is created for each point of the profile, where point A corresponds to the observer's position and point B corre-

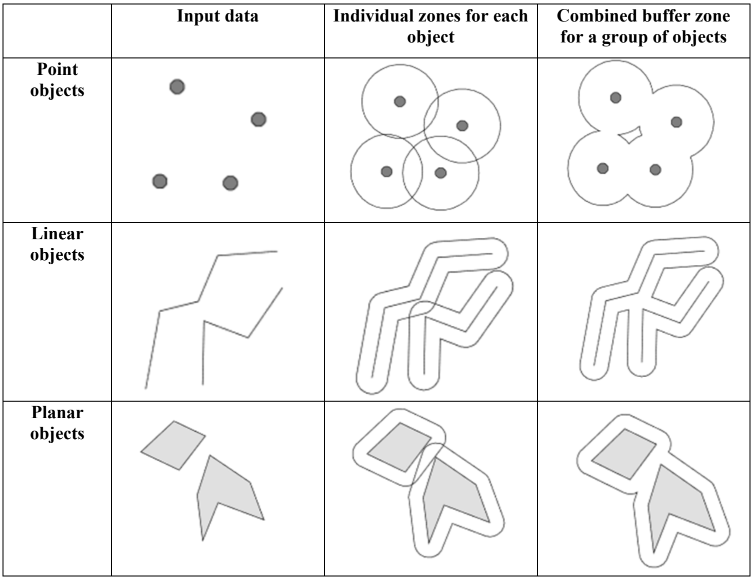


Fig. 6. Scheme of security zones for objects of different localization

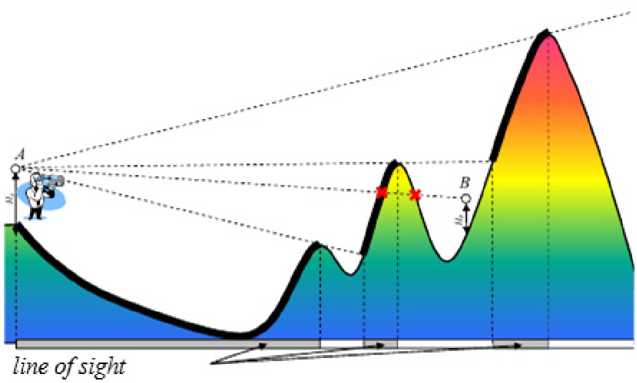


Fig. 7. Scheme for determining lines of sight

sponds to the observation point (the next point of the profile). Note that point A is at a height HA above the ground surface and point B is at a height HB. The third step is to check whether this segment intersects with the previously created elevation profile. If there is no intersection, point B is visible from point A. In Fig. 7, point B is not visible because segment AB intersects the profile line at the point marked in the figure. The thick line shows the part of the profile where the point is visible from point A at HB = 0.

The results of the algorithm can be visualized as line-of-sight segments on electronic GIS maps or as polygons representing visible areas projected onto a 3D terrain model. If the calculations involve significant distances, it is necessary to take into account the curvature of the earth's surface.

A continuation of the previous calculations is the calculation of visible or invisible zones. In this task, the area in which all points are visible from a given observation point is determined. In geoinformatics, there are two approaches to solving this problem: the authors chose the most effective one, which consists in creating radial, linear lines of visibility centered at the observation point. Sight lines are plotted on the map at an angle through a certain angular value, for example, 5 degrees (Fig. 8). The advantage of this method is the high speed of calculations, but the disadvantage is the difficulty of detailing visible and invisible areas.

This study of the spatial characteristics of wind farms assesses the spatial location of wind turbines in relation to landscape elements such as topography, settlement contours, and forests. The topographic conditions of the study area were obtained from the OpenStreetMap service in the form of FerGIS shape files. This data was corrected and supplemented with a master plan and high-resolution satellite imagery. Additions were made regarding the city's administrative boundaries, the current state of the road network, power lines, and development.

The topographic data for this area was the global SRTM model (NASA, USA). These versions were obtained from the SRTM 90m Digital Elevation Databases ev4.1 website (Fig. 8).

We take into account the mutual location of the wind turbine towers using the GenerateNearTable tool in ArcToolBox. Create a position table (Fig. 9) (calculated distances and orientations between all objects in all combinations).

Assuming that the diameter of the wind turbine is 50 m, the shortest distance is 201 m, i.e. the diameter of the wind turbine is 4 m. The directions to the nearest wind turbine show that the towers do not block each other with respect to the wind flow.

This is explained by the fact that the direction to the nearest tower is 53°, which is close to the winter wind direction of 45°. However, the distance between these towers is 424 m, which eliminates the “parking effect”. Accord-

Fig. 8. Lines of sight

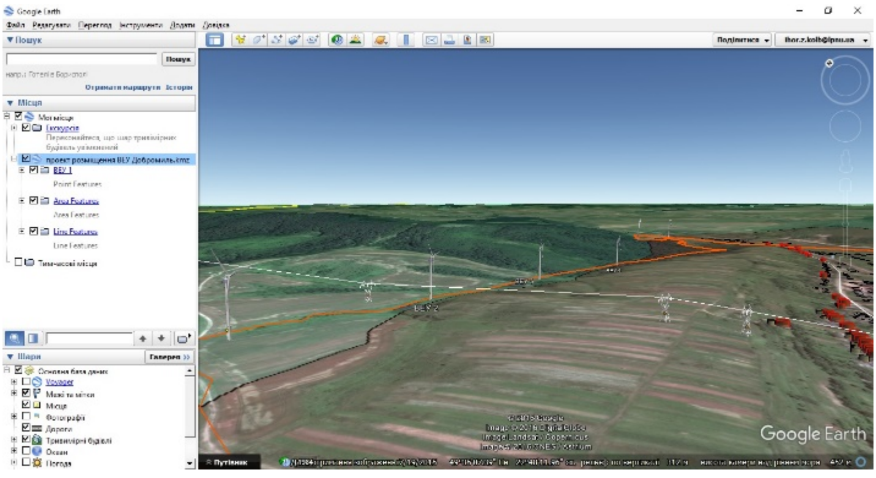


Fig. 9. Topographic data from the SRTM 90m Digital Elevation Databases ev4.1 website

Fig. 10. Result of three-dimensional modeling of the wind farm in Polonyna Runa in the Google Earth service

ing to the modeling results, the site is generally suitable for the construction of a wind farm with 6 towers with a height of 80–100 m.

In this work, the popular and, perhaps, well-known web mapping service Google Earth was used as a means of three-dimensional modeling of the designed wind farm.

To achieve a natural image of the terrain model, 3D models of wind turbines and high-voltage power line towers were used.

The cartographic layers that form the digital map of the area in ArcMap were exported to a KMZ format file, which is readable in the Google Earth service (Fig. 10).

The result of the modeling is a high-quality, textured three-dimensional terrain model. The model is fully controllable, you can change the scale, viewing angle, measure areas, directions, distances. The controls are easy to learn for a wide range of Internet users.

Polonyna Runa

The feasibility of developing a detailed plan of the territory is due to investment proposals for the construction and operation of a wind power plant within the Polonyna Runa area outside settlements. A detailed plan of the territory is being developed for land plots of communal property of the Turye-Remetiv village council of the Uzhhorod district of the Transcarpathian region, which are located outside the boundaries of settlements, for the placement of a separate construction object on Polonyna Runa street - wind energy facilities - in accordance with current legislation using materials from the urban planning and land cadastre. The development of a detailed plan of the territory included the entire mountain range, except for the top part, where the ruins of the Bars military complex are located.

The figure below shows a copy of the Planning Scheme of the Transcarpathian region, which indicates the boundaries of the territory of the mining and recreational complex centered in the village of Lumshory.

According to this cartographic material and data from the land cadastre of Ukraine, the development of a detailed plan of the territory within the project boundaries does not contradict the Planning Scheme of the Transcarpathian region.

The project proposes to place 30 wind turbines, type WTU 5.2, with a nominal capacity of up to 5.2 MW, with a mast height of 100 meters and a blade span of 151 meters on Polonyna Runa. That is, the maximum height of the structure can reach 175 meters.

According to the calculation of the wind rose of the territory, a decision was made to place 30 wind farms at the highest points of the Polonyna territory - on its

Fig. 11. Location of the design area on Google Maps

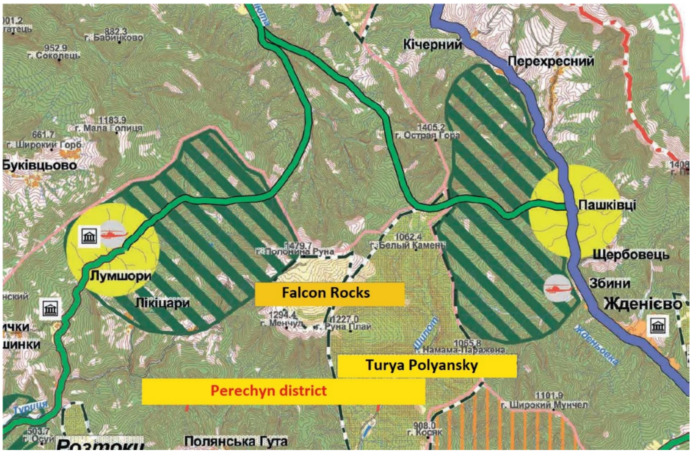


Fig. 12. Copy from the Territorial Planning Scheme of the Transcarpathian region

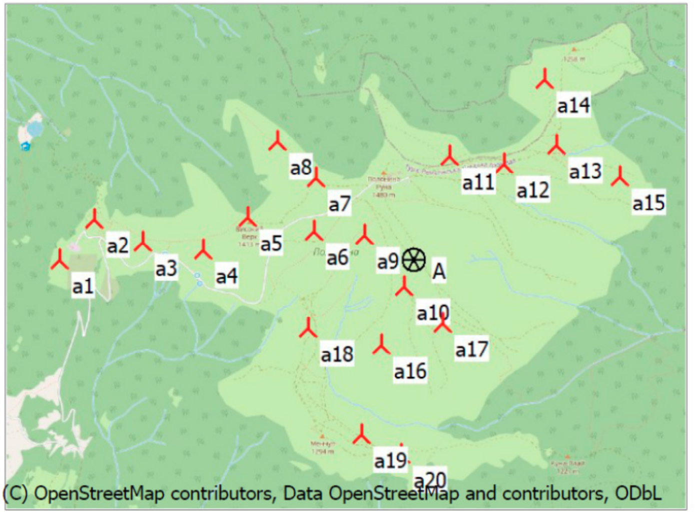


Fig. 13. The best places for placing wind turbines in the Polonyna Runa area

conditional watersheds (Polonyna ridges), since according to the calculations, the wind in these places is quite good.

Wind turbines (WTGs) are variable speed power plants powered by inverters with a three-blade rotor in a headwind configuration. Variable speed is achieved by frequency control of the phase winding of the stator of a synchronous generator.

A significant feature of modern wind turbine models is the low rotor rotation speed. Due to innovations in the design of power transmissions, the rotor rotation speed has been reduced. This significantly reduces the noise level from the wind turbine and, in addition, significantly reduces the risk of birds colliding with the moving blades of the wind turbine.

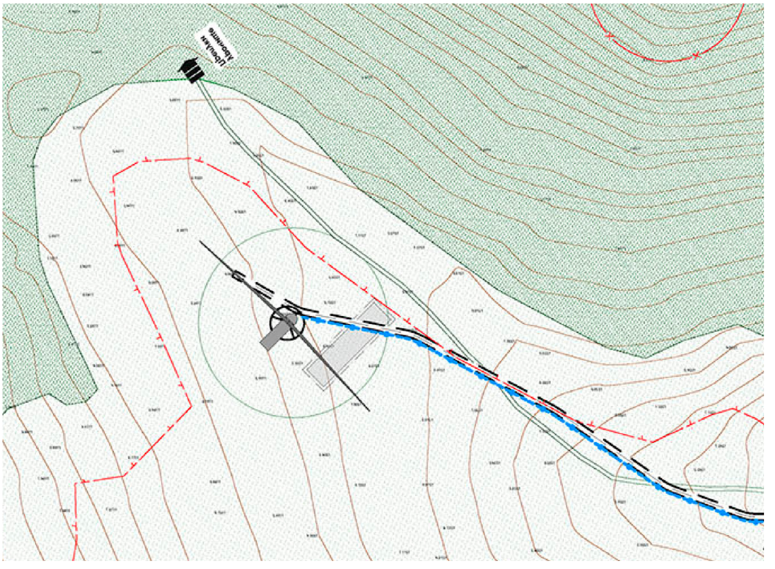


Fig. 14. Typical wind turbine site

In general, each wind turbine has a typical site after construction is completed, and in this case, the area will be completely landscaped, even the maintenance area is proposed to be kept landscaped, to ensure the preservation of the area and prevent fragmentation and reduce negative environmental impacts.

The main structure is the wind turbine mast, the transformer located inside the mast (to provide open access to the territory), and the maintenance platform. A typical platform for a wind turbine is shown in Fig. 14.

Structurally, a wind turbine is a cone-shaped tower, on top of which is a nacelle with a rotor and blades.

The wind turbine is equipped with an automated safety system that ensures safe operation of the wind turbine in the event of a control system failure, component or system failure. To identify errors in the operation of the drives of the main components of the wind turbine, a condition monitoring system is provided. The installation is equipped with a highly efficient lightning protection system.

Conclusions

Assessing the impact of a wind farm's location on the environment using geographic information systems is an important tool in the planning and implementation of renewable energy projects. The use of GIS allows for comprehensive analysis of spatial data, modeling of environmental risks, and taking into account factors such as terrain, biodiversity, noise exposure, and possible socio-economic impacts.

The results of the study show that integrating GIS into the process of selecting a wind farm location helps minimize negative environmental impacts and ensures a balance between wind energy development and environmental conservation. Spatial analysis can identify optimal areas for installing wind farms that will ensure maximum efficiency of energy production and at the same time not harm ecosystems and local populations. The possibility of effective analysis of identifying problems and advantages in the spatial location of wind power plants is shown.

So, the construction of wind farms is an alternative and environmentally sound form of using inexhaustible and renewable energy resources, practically requiring no active and deep exploitation of the territory.

In addition, the construction of wind power plants will increase the stability of electricity supply to industrial and municipal enterprises in the context of energy shortages in Ukraine.

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Пересоляк В. Ю., Радиш І. П., Крильо І. В.

ЗАСТОСУВАННЯ ГІС ТЕХНОЛОГІЙ ОЦІНКИ ВПЛИВУ НА НАВКОЛИШНЄ СЕРЕДОВИЩЕ МІСЦЯ РОЗТАШУВАННЯ ВЕС НА ПРИКЛАДІ «ПОЛОНИНА РУНА» ТУР'Є-РЕМЕТІВСЬКОЇ ОТГ

ЗЕМЛЕУСТРІЙ, КАДАСТР І МОНІТОРИНГ ЗЕМЕЛЬ 3'25: 51-67.
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Анотація. *У сучасних умовах розвитку відновлюваної енергетики, до якої відноситься і вітроенергетика найважливішим завданням є мінімізація екологічного впливу вітроелектростанцій (ВЕС) на навколишнє середовище в контексті декарбонізації галузей економіки. Використання геоінформаційних систем (ГІС) дозволяє ефективно аналізувати та моделювати вплив щодо розміщення ВЕС враховуючи: екологічні, ландшафтні, економічні, кліматичні та соціальні фактор, які впливають на сталий розвиток територій. У статті розглядається застосування геоінформаційних систем (ГІС) для оцінки впливу на навколишнє середовище місця розташування вітроелектростанції (ВЕС), яка планується будувати на території урочища «Полонина Руна» Тур'є-Реметівської сільської територіальної громади Ужгородського району Закарпатської області.*

Дослідження передбачає збір та обробку просторових даних, включаючи рельєф, швидкість та напрямок вітру, наявність природоохоронних територій та місць проживання чутливих видів флори та фауни. За допомогою ГІС проводитиметься аналіз візуального та шумового впливу, оцінка ризиків для біорізноманіття та

здоров'я населення, а також моделювання альтернативних варіантів розміщення вітрогенеруючих турбін станції.

Результати оцінки сприяють прийняттю обґрунтованих проектних рішень щодо вибору місця розташування ВЕС, знижуючи негативний екологічний вплив та забезпечуючи баланс між сталим розвитком вітрової енергетики в регіоні зі збереженням навколишнього природного середовища.

Ключові слова: вітроенергетика, оцінка впливу на довкілля, геоінформаційні системи, просторове планування, сталий розвиток територій, відновлювані джерела енергії, декарбонізація, викиди CO_2.

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USE OF ARTIFICIAL INTELLIGENCE IN PHOTOGRAMMETRIC PROCESSING OF DIGITAL DATA

YE. BUTENKO,
Candidate of Economic Sciences, Associate Professor
E-mail: butenko@nubip.edu.ua
https://orcid.org/0000-0002-5923-5838
National University of Life Resources and Environmental Management of Ukraine
A. VOLONTYR,
Senior Lecturer
E-mail: a.volontyr@chdtu.edu.ua
https://orcid.org/0000-0001-5609-4569
Cherkasy State Technological University
O. KUTSENKO,
Third Educational and Scientific Level Higher Education
E-mail: kutsenkijob@gmail.com
https://orcid.org/0009-0008-5814-8389
National University of Life Resources and Environmental Management of Ukraine

Abstract. *The article considers the impact of artificial intelligence neural network algorithms on the process of photogrammetric processing of digital images and the formation of dense point clouds.*

It is noted that the integration of machine learning algorithms, in particular deep learning, allows you to automate key processing stages, increase the accuracy of object classification, optimize geometric correction of images and improve the quality of final geospatial products in the form of an orthophotomap of the terrain.

The main stages of the photogrammetric process are described: from collecting primary data to forming orthophotomaps and three-dimensional terrain models. Particular attention is paid to the role of the neural network in improving the density of the point cloud due to the correct interpretation of points on digital images, object classification and reducing the influence of the human factor.

The challenges associated with the need for large volumes of high-quality training data are identified. The prospects for the application of artificial intelligence neural networks in photogrammetry and the need for further research in this direction are substantiated.

Keywords: *neural network, artificial intelligence, photogrammetry, machine learning, point cloud, orthophotomap, 3D model, digital image.*

Problem statement

In the modern digital environment, artificial intelligence plays a key role in transforming many areas of human activity.

One of the current problems is to increase the efficiency of photogrammetric processing of digital images and 3D scanning data of the territory. Traditional algorithms have limitations in terms of productivity, accuracy, speed and automation of processes. At the same time, the integration of artificial intelligence elements, such as neural networks and deep machine learning methods, allows to significantly improve the classification, interpretation, determination of shapes, sizes and spatial position of terrain objects [10].

This opens up new opportunities for creating high-precision orthophoto maps of the terrain and 3D models, reducing errors and optimizing the processing of large volumes of remote sensing data [7,9].

Analysis of recent research and publications

Modern scientific research demonstrates the active use of unmanned aerial vehicles in photogrammetric work in the process of obtaining digital images and their further processing.

Domestic authors, in particular Butenko E.V. and Krasnosilska A.A. [12] , focus on the integration of neural networks for automating the classification and interpretation of terrain objects. The works of Shevchenko A.I. [13] and Guralyuk A. [14] consider the role of artificial intelligence in the digital transformation of geoinformation technologies.

The team of authors Butenko and Kulakovskyi devoted their research to studying the issue of the effectiveness of using unmanned aerial vehicles to solve various problems of geodesy and land management [1].

Analysis of scientific works of foreign scientists demonstrates active introduction of artificial intelligence in photogrammetric processes of digital data processing, in particular in automated 3D modeling, object classification and processing of point clouds.

The work of Rongjun Qin and Armin Gruend considers the application of machine learning for semantic interpretation of spatial data, which allows to increase the accuracy of digital terrain models, namely the application of machine learning at different stages of the photogrammetric process: from data collection and camera calibration to the generation of digital surface models and semantic interpretation. The authors analyze how artificial intelligence can automate traditionally manual processes, increasing the accuracy and efficiency of 3D modeling [16].

Shahad Abbood [15] and colleagues analyze deep learning algorithms that optimize image reconstruction and calibration processes in the process of digital sensor calibration. Their research opens up new opportunities for multisensor integration and intelligent image analysis.

The article by Mi Wang [18] substantiates the theoretical basis for the transition to intelligent geographic information systems, where large models play a key role in 3D reconstruction, semantic analysis and automation of photogrammetric processes.

The article by Fabio Remondino [17] confirms that artificial intelligence is able to automate complex photogrammetric tasks, reducing the need for manual intervention. Overall, these studies indicate the transformation of photogrammetry towards intelligent geographic information systems.

Hlotov and Hunina analyze the possibilities of using unmanned aerial vehicles in various types of aerial survey work and their effectiveness [2].

The works of Irschara et al. [3], Remondino et al. [5] and Sauerbier et al. [6] justify the need for full automation of photogrammetric processing of digital images obtained from unmanned aerial vehicles.

Particular attention should be paid to the studies of the authors Butenko and Poshtar [7] and Pokatayev [9], who investigate the integration of neural networks into photogrammetric software algorithms and focus on the role of artificial intelligence in the management of territorial complexes in Ukraine, especially emphasizing their potential for the digital transformation of urban infrastructure.

Practical aspects of the use of artificial intelligence in the process of analyzing digital data are given in the publications Probesto [10] and Gigacloud [11], which describe the principles of machine learning and its application in geographic information systems.

Thus, a review of scientific sources confirms the relevance of the chosen direction of scientific research on the use of artificial intelligence for automation, increasing the accuracy and efficiency of photogrammetric processing of digital data.

Research objective. The purpose of the article is to study the prospects for using artificial intelligence to automate, increase the accuracy, and optimize the processes of photogrammetric processing of digital images.

Materials and methods of scientific research

In the course of scientific research on the application of artificial intelligence in photogrammetric processing of digital data, the following methods of scientific research were used: analytical, abstract-logical, structural-functional and comparative.

The analytical method investigated modern technologies for photogrammetric processing of digital images used to create orthophotomaps, digital terrain models and three-dimensional terrain models.

The abstract-logical method allowed us to assess the prospects for integrating artificial intelligence into photogrammetric software, in particular deep learning algorithms that help automate the processes of classification, geometric correction and interpretation of objects.

The structural-functional method analyzed the stages of photogrammetric processing: image improvement, point cloud formation and classification, and creation of the final product in the form of an orthophotomap of the terrain.

The comparative method was used to assess the effectiveness of using artificial intelligence in photogrammetry compared to traditional approaches, taking into account accuracy, processing speed, and quality of the final data.

Research results and their discussion

In information technology, artificial intelligence is a neural network of hardware or software systems, built on the principle of neurons in the human brain. In fact, it is a computational system of gradual actions, based on a set of connected nodes that are interconnected.

In turn, modern technology of photogrammetric processing of digital images, the formation of dense point clouds is a key stage for creating high-precision geospatial and cartographic products, such as orthophotomaps, digital terrain models and three-dimensional terrain models, which are widely used in various industries, including cartography, land management, environmental monitoring, agriculture and urban planning [2,3].

The essence of photogrammetric processing is the use of digital images to create planning and cartographic materials. Its main stages are: image collection and enhancement, dense point cloud formation, its classification, creation of orthophotomap and digital models.

One of the most promising areas in this context is the integration of artificial intelligence technologies into software for photogrammetric data processing. Rapid progress in the field of machine learning, in particular deep learning methods, opens up fundamentally new opportunities for automating complex processes, increasing the accuracy of object recognition and classification, optimizing geometric correction of images and generally increasing the efficiency of photogrammetric production [1,10].

The main stages of integrating artificial intelligence into photogrammetric data processing programs include: improving the original digital images; forming a point cloud and its improvement; classifying a dense point cloud; forming the final processing product, an orthophotomap [6,7].

Photocorrection of digital images is an important stage in the process of processing visual materials, aimed at improving their quality and eliminating various defects. This process consists of several sequential steps, each of which plays a role in achieving the desired result.

1. Image analysis: At the initial stage, it is necessary to carefully examine the image to identify existing shortcomings. These may include:

2. Exposure errors: insufficient or excessive illumination of the image.

3. White balance errors: incorrect display of colors, which leads to their unnaturalness.

4. Low contrast: insufficient difference between light and dark areas, which makes the image dull.

5. Digital noise: the presence of grain or other artifacts.

6. Geometric distortions: distortion of the image caused by the peculiarities of the optics or the shooting angle.

7. Exposure correction: In case of insufficient illumination of the image, its brightness should be increased. If the image is too bright, this indicator should be reduced [19].

One example of the application of artificial intelligence in the field of photogrammetry is the Luminar Neo software from Skylum. This program uses the capabilities of artificial intelligence to improve the quality of images and edit photos [12]. At the initial stage, the necessary raw data is collected, such as digital images obtained from unmanned aerial vehicles. The key requirements for the images are their high quality, the absence of smears, shadows and the presence of sufficient mutual overlap to ensure the possibility of further processing (Fig. 1).

The next stage is to search for corresponding points in the images based on the identification of common characteristic points that are displayed on differ-

Fig. 1. Fragment of a non-uniform digital image that requires correction

ent images, to establish mutual relationships between them, to perform a set of geometric calculations to determine the three-dimensional coordinates of each point based on its projections on different images, which can be improved by an artificial intelligence algorithm [7,11].

At this stage, the spatial orientation of the images relative to each other and their binding to a defined coordinate system is performed. Parameters characterizing the position and angle of inclination of each image in three-dimensional space are determined. To perform this task, reference points whose coordinates are known with high accuracy can be used.

Formation of a dense point cloud, based on previously oriented images, occurs through pixel analysis of digital images. The number of points in the cloud determines the level of detail (cloud density) and the accuracy of the 3D terrain model created from it [2,7].

The resulting dense cloud of three-dimensional points is subject to further analysis and processing. At this stage, procedures for removing unwanted noise (Fig. 2.), refining the spatial coordinates of points, as well as other operations aimed at improving the quality of the final model can be performed [1,4,9].

Based on the processed dense point cloud, a three-dimensional model of the studied area is created. This model can be used for a wide range of tasks, including visualization, conducting various simulations of geodetic and land management works [1,4].

The use of machine learning also contributes to the creation of more detailed and informative orthophotomaps. The ability of artificial intelligence algorithms to analyze complex spectral characteristics of objects and take into account contextual information allows you to identify patterns and dependencies that may not be noticeable with traditional processing methods. This opens up opportunities for obtaining not only geometrically accurate, but also seman-

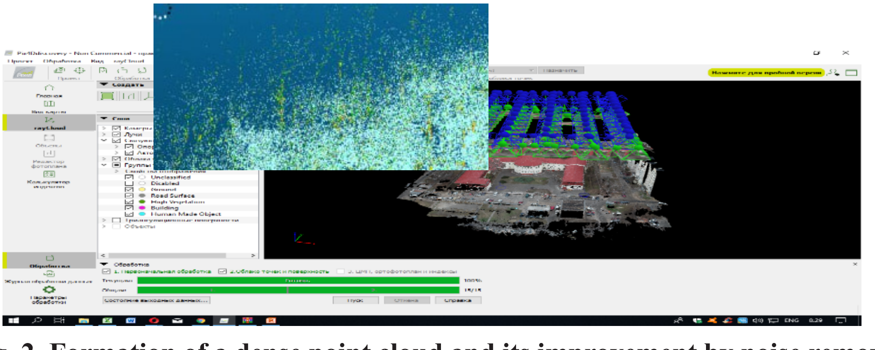

Fig. 2. Formation of a dense point cloud and its improvement by noise removal

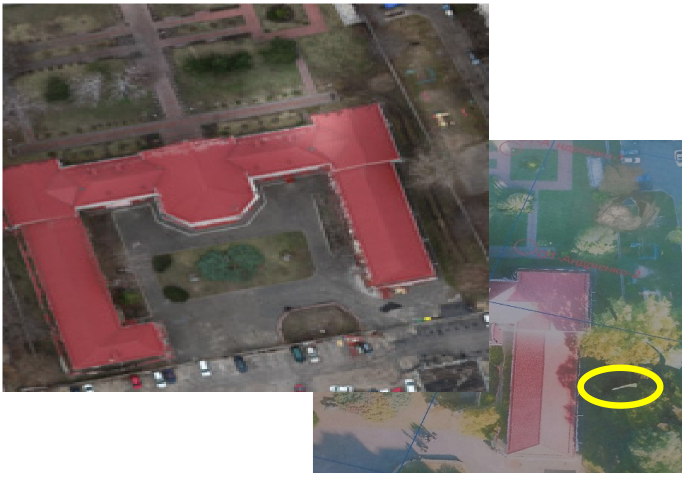

Fig. 3. "Breaks" of the orthophotomap image when using different algorithms for its construction

tically enriched orthophotomaps, which can contain additional information about the properties and characteristics of objects in the area.

Despite significant advantages, the use of machine learning in the creation of orthophotomaps is also associated with certain challenges. For effective training of algorithms, large volumes of high-quality spatial data are required, as well as high-quality cloud classification with detailed division of the cloud into different classes of objects (Fig. 3).

The quality of the obtained results directly depends on the quality and representativeness of the data, as well as on the correctness of the choice and configuration of the machine learning model architecture [11].

It is also worth noting that the automation of a significant part of the process of creating orthophotomaps using machine learning leads to a significant reduction in data processing time and a reduction in the need for manual labor. This is especially important when working with large areas or when it is necessary to promptly update cartographic information.

Analyzing the advantages of using artificial intelligence in photogrammetric data processing programs, it is advisable to highlight the following: detection of specific objects in images, which can be useful for identifying specific landscape features or structures in digital images; improving image quality by removing noise, improving contrast, or restoring lost details; rapid creation of orthophotomaps and 3D models based on point clouds; classification of images based on their content for automatic determination of the type of terrain or identification of specific objects; semantic segmentation of images, which allows you to determine which type each pixel of the image belongs to.

Conclusions

The integration of artificial intelligence into photogrammetric technologies opens up new opportunities for increasing the efficiency and accuracy of digital data processing. The use of neural networks allows you to automate key stages of the process that previously required significant human resources, and also significantly improves the accuracy of object detection in images. This has a positive effect on the quality of final geospatial products, such as orthophotomaps and 3D models. Artificial intelligence provides the ability to analyze large volumes of data, classify objects and correct geometric distortions, which increases the overall efficiency of photogrammetric production. At the same time, to achieve high results, it is necessary to ensure sufficient volumes of high-quality data and the correct architecture of machine learning models.

Despite significant achievements, it should be noted that the integration of artificial intelligence into photogrammetric data processing is still at the stage of active development and requires improvement.

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Бутенко Є. В., Волонтир А. В., Куценко О. О.
ВИКОРИСТАННЯ ШТУЧНОГО ІНТЕЛЕКТУ ПРИ ФОТОГРАММЕТРИЧНОМУ ОПРАЦЮВАННІ ЦИФРОВИХ ДАНИХ
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Анотація. *У статті розглядається вплив алгоритмів нейромереж штучного інтелекту на процес фотограмметричного опрацювання цифрових знімків та формування щільних хмар точок.*

Зазначено, що інтеграція алгоритмів машинного навчання, зокрема глибокого навчання, дозволяє автоматизувати ключові етапи опрацювання, підвищити точність класифікації об'єктів, оптимізувати геометричну корекцію зображень та покращити якість кінцевих геопросторових продуктів у вигляді ортофотоплана місцевості.

Описано основні етапи фотограмметричного процесу: від збору первинних даних до формування ортофотопланів та тривимірних моделей місцевості. Особлива увага приділяється ролі нейромережі у покращенні щільності хмари точок за рахунок правильної інтерпретації точок на цифрових знімках, класифікації об'єктів та зменшенні впливу людського фактора.

Визначено виклики, пов'язані з потребою у великих обсягах якісних навчальних даних. Обґрунтовано перспективність застосування нейромереж штучного інтелекту у фотограмметрії та необхідність подальших досліджень у цьому напрямку.

Ключові слова: *нейромережа, штучний інтелект, фотограмметрія, машинне навчання, хмара точок, ортофотоплан, 3D-модель, цифровий знімок.*

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DESIGN OF COASTAL PROTECTION STRIPS OF WATER PROTECTION ZONES USING GIS TOOLS

B. ZAYACHKIVSKA,
Candidate of Economic Sciences, Assistant
ORCID: 0009-0003-0962-5998
Email: b_zayachkivska@nubip.edu.ua
B. DENYSIUK,
Senior Lecturer
Email: denysiuk_b@nubip.edu.ua
ORCID: 0000-0003-1692-8551
YA. BURBYHA,
student of 1st year Master's degree, Faculty of Land Management
Email: etoyanok@gmail.com
National University of Life Resources and Environmental Management of Ukraine

Abstract. *The regulatory and legal principles of designing water protection zones and their role in protecting the natural environment, determined the boundaries of coastal protection strips and the influence of relief on the size of restriction zones is analyzed. The territory of the Kamianopotokivska territorial community in the Kremenchuk district of the Poltava region is studied. The water bodies of the study area were classified, and the normative values of coastal protection strips were determined according to their sizes in accordance with the requirements of current legislation. Based on open data on the relief of the territory, slopes were calculated and doubling of coastal protection strips within slopes exceeding 3 degrees was provided.*

A geospatial dynamic model for designing coastal protection strips of water protection zones, taking into account legislative norms and relief, and their impact on types of activities, has been developed. The model was created and tested using the Model Builder software module in ArcGIS Pro.

As a result of the study, the model was applied to the collected input data and coastal protection strips of water protection zones were designed within the studied area. The territories were identified and analyzed, the ownership rights of which are encumbered in accordance with the designed water protection zones. This model is dynamic and suitable for use for production purposes at the local level (within territorial communities).

Keywords: *water protection zone; coastal protection strip; territorial community; water bodies; design of water protection zones; GIS technologies; geographic information systems.*

Relevance

Conservation and rational use of water resources is the key to the sustainable development of any territory. In the context of the growing impact of climate change, active land use and urban expansion (urbanization), the design of water protection zones based on the provision of coastal protection strips (CPS) is becoming critically important. These strips (CPS) act as natural filters, effectively counteract soil erosion, and, accordingly, significantly improve water quality.

To ensure spatial planning and make the right management decisions regarding the design of water protection areas, geographic information systems (GIS) are an indispensable tool. They allow taking into account multi-criteria features.

In particular, the Kamianopotokivska territorial community in the Poltava region has significant natural wealth and an extensive network of water bodies. This requires the implementation of special, well-thought-out measures to protect its coastal zones. Only taking into account local features – such as topography, hydrological conditions, and the current land use structure – will allow building a realistic and ecologically balanced model for designing water protection zones using GIS tools.

Analysis of recent research and publications

The main ecological purpose of CPS is to protect water bodies from pollution and minimize the negative impact of economic activity. Scientific studies, in particular the work of American scientists (M.G. Dosskey et al.), confirm that the vegetation cover along water bodies significantly reduces the concentration of chemical pollutants coming from the sloping areas. This process occurs due to natural filtration: plants retain harmful substances, decompose organic compounds, and, importantly, slow down surface runoff, ensuring better water penetration into the soil. In addition, buffer vegetation effectively acts as a barrier for heavy metals and pathogenic microorganisms, delaying them on their way to the river bed [1].

CPS are of particular importance for reducing the nitrogen content in water, which is critically important for preventing eutrophication of water bodies (excessive enrichment with nutrients). A meta-analysis (P.M. Mayer et al.) showed that buffer strips can retain up to 85% of nitrates originating from agricultural lands. Given the widespread excessive application of nitrogen-containing fertilizers in Ukraine, the function of CPS to stabilize the ecological state of rivers becomes vital [2].

Along with the water protection function, CPS performs an important anti-erosion role. Dense vegetation reliably strengthens the shoreline, which leads to a decrease in landslides, soil erosion, and siltation of riverbeds. Studies (Osborne та Kovacic) emphasize that coastal vegetation slows down water flows, thereby reducing hydrodynamic pressure on the banks. This prevents the destruction of the shoreline even during floods, which makes this function a priority in flood-prone regions [3].

In addition, CPS is a key element in the preservation of biodiversity. They serve as habitats for many species of birds, amphibians, fish and insects, as confirmed by the conclusions of the European Environment Agency. Coastal protection strips also serve the role of ecological corridors, ensuring the migration of animals and maintaining the genetic diversity of populations. In the context of the fragmentation of natural environments caused by intensive land use, these strips remain the only connecting link between isolated natural areas [4].

Coastal protection strips also have significant social significance: they are recreation areas (rest), improve the microclimate in settlements, reduce noise levels, absorb dust, and improve the quality of life in general. As the EPA report notes, coastal protection strips provide important ecosystem services for communities and contribute to the popularization of environmental education [5].

For the full realization of the ecological potential of coastal protection strips, their spatial continuity and proper legal regulation are necessary. Although Ukrainian legislation establishes requirements (for example, a ban on plowing land, using chemicals, and erecting buildings), violations often occur in practice. This not only reduces the effectiveness of water body protection, but also creates environmental threats. The existing control system requires modernization, expansion of the powers of local environmental inspections, and the introduction of public monitoring.

A feasible step is the introduction of a single state standard for environmental assessment of the WPA, which would integrate European experience. Protective strips should be integrated into river basin management plans, in accordance with the European Green Infrastructure policy. Success requires coordination at the level of interagency cooperation and increased control by state environmental structures. Equally important is the participation of public organizations in initiating environmental measures, conducting information campaigns, and monitoring compliance with requirements.

The effectiveness of water protection zones depends on the quality of spatial planning, legal control, and community involvement in the protection of water resources. Butenko, E., Vovna, M., & Prykhodko, M. Define spatial planning as an effective tool for managing land resources in territorial communities [8]. Modern environmental policy should be based on the integration of scientific data, legal mechanisms, and international experience.

The purpose of this study: the geospatially modelling of coastal protection strips of water protection zones of the territory based on GIS technologies.

Materials and methods of scientific research

This work was developed in accordance with regulatory legal acts, norms and rules on land valuation: the Land Code of Ukraine, the Water Code of Ukraine, Resolution of the Cabinet of Ministers of Ukraine dated May 8, 1996 No. 486, the Law of Ukraine "On Environmental Protection" dated June 25, 1991 No. 1264-XII, the Law of Ukraine "On Regulation of Urban Development Activities" dated February 17, 2011 No. 3038-VI. Open-access data, information from the State Land Cadastre, Google Hybrid, OpenStreet Map, and SRTM were also used in the development. Among the methods used were analytical methods, cartographic geoinformation, graphic, and statistical.

Research results and their discussion

The object of the research is the territory of the Kamianopotokiv territorial community of the Poltava region. According to Article 58 of the Land Code of Ukraine, "to create a favorable regime along the seas, around lakes, reservoirs and other water bodies, water protection zones are established, the boundaries of which are indicated in land management documentation, urban planning documentation at the local and regional levels. Information about the boundaries of water protection zones is entered into the State Land Cadastre. The procedure for determining the size and boundaries of water protection zones and the regime for conducting economic activities in such zones are established by the Cabinet of Ministers of Ukraine."

Water protection zones include CPS as well as additional territories on which restrictions also apply, but are less stringent. Within the boundaries of water protection zones, lands of coastal protection strips and diversion strips with a special regime for their use are allocated. The procedure for determining the size and boundaries of water protection zones and the regime of economic activity in them was approved by the Resolution of the Cabinet of Ministers of Ukraine of May 8, 1996, No. 486.

According to the above Resolution, "the internal boundary of the water protection zone coincides with the minimum water level in the water body", and "the external boundary of the water protection zone, as a rule, is tied to the existing contours of agricultural lands, roads, forest belts, floodplain boundaries, floodplain terraces, slope edges, beams and ravines and is determined by the line furthest from the water body: flooding at the maximum flood (flood) water level, which is repeated once in ten years; bank erosion, meandering; temporary and permanent flooding of lands; erosion activity; coastal slopes and severely eroded lands". That is, to accurately determine the outer boundaries of water protection zones, periodic studies of changes in the shorelines of water bodies are required.

In most cases, water protection zones coincide with coastal protection strips; that is, they are minimized. Within the coastal protection strips (CPS), a number of strict rules have been established that restrict economic activity. Information about the boundaries of coastal protection strips and beach zones is entered into the State Land Cadastre as information on restrictions on land use. The legislation prohibits:

• plowing land (with the exception of areas used for haymaking or grazing livestock);

• storage and application of agrochemicals, including mineral fertilizers and pesticides;

• construction of capital structures (residential, industrial, or other) that may potentially threaten the aquatic environment;

• arrangement of landfills and placement of warehouses with toxic substances;

• mining;

• organization of parking lots and car washes.

The legal mechanism for regulating the CPS is strengthened by the provisions of the Law of Ukraine "On Environmental Protection". This Law emphasizes that the preservation of water resources is a priority task of the state's environmental policy.

It establishes that any activity related to the use of natural resources must comply with the principles of sustainable development and strictly comply with environmental requirements. The Law obliges all business entities (regardless of the form of ownership) to comply with environmental standards, emphasizing the priority of environmental protection interests over purely economic expediency. Thus, the environmental component is decisive in the formation and provision of the legal regime for the use of coastal territories.

An important role in the legal system is played by the Law of Ukraine "On regulation of urban planning activities". It obliges to take into account the CPS when developing master plans for settlements and other urban planning documentation. This requirement ensures the integration of environmental restrictions directly into the processes of spatial planning and development of territories. Establishing requirements for coastal protection at this level allows for effective avoidance of violations at the stage of construction project implementation.

One of the key regulatory documents that determines the parameters of coastal protection zones (CPS) is the Resolution of the Cabinet of Ministers of Ukraine No. 486 of May 8, 1996. This document establishes the Procedure for determining the size and boundaries of water protection zones and the management regime in them.

The width of the CPS depends on the category of water body:

• for large rivers, it must be at least 100 meters;

• for medium-sized rivers - 50 meters;

• for small rivers, streams, and ponds - 25 meters.

Within settlements, these minimum indicators can be reduced, but not lower than the limit established by law. When developing project documentation, hydrological characteristics, terrain relief, the current type of land use, and environmental load are necessarily taken into account. However, in practice, the lack of a clear procedure for drawing the boundaries of CPS in nature (on the terrain) creates significant difficulties in their implementation.

The process of establishing water protection zones and water protection zones is implemented through the preparation of land management documentation. Currently, Ukrainian legislation does not provide for the creation of a separate, specialized document solely for fixing these boundaries. In fact, the boundaries of CPS and WPZ are determined as an integral part of:

• documentation on the development of the territory;

• technical materials on the establishment of restrictions on land use;

• land management projects that directly relate to the formation of water protection zones.

According to Article 26 of the Law of Ukraine “On Land Management”, any restrictions on land use must be introduced on the basis of technical documentation, which includes scientific justification, spatial schemes, plans, and a detailed description of the territory use regime.

The State Standard OSU SCLR 00032632-005:2009 “Land Management. Land Management Projects for the Creation of Water Protection Zones. Development Rules” serves as an important methodological source for land managers. It provides a structured approach to collecting initial information, analyzing the ecological state, the nature of the riverbed, coastal vegetation, and existing infrastructure. The standard also defines the stages of coordination of documentation with executive authorities, local communities, and state cadastral authorities.

The implementation of these requirements is clearly illustrated by the practice of developing community master plans. Here, CPS are necessarily considered as zones with a special land use regime. Their spatial representation is critically important for the formation of functional zoning plans for the territory, which meets the requirements of the State Building Standards of Ukraine State Building Codes B.2.2-12:2019 "Planning and Development of Territories".

A modern and effective solution is the use of geographic information systems (GIS) for modeling and designing the boundaries of water protection zones and coastal protection strips. GIS allows you to automate the consideration of natural conditions (relief, catchment, surface runoff) and quickly analyze the compliance of design solutions with the real situation. Thanks to remote sensing data and geospatial databases, it has become possible to create high-precision interactive CPS maps.

At the first stage of geospatial modeling, water bodies are classified by type: polygonal and linear, and standards for designing coastal protection strips are determined. After the construction of buffer coastal protection zones, their unification is envisaged. At the second stage, the relief was used, slopes were constructed, and slopes were classified by steepness. For those territories that exceeded 3 degrees, they were separated, and those territories that are included in the coastal protection zones and have slopes that exceed the permissible values were determined. Such territories are doubled and combined with those territories that are defined by the limit norms of the current legislation at the first stage to avoid duplication of the areas of restrictions. Thus, the final completed model takes the form, Fig. 1.

In Fig. 1, blue circles indicate the input files, namely the vector format of data on the boundaries of water bodies and a raster image of the relief. Yellow rectangles are the applied tools, in particular, data selection, buffer creation, intersection, extraction, reclassification, data extract, raster model to vector conversion, and union. Green circles that come out of the yellow rectangles are intermediate files, the result of each result. For example, the resulting image of this model is a vector format file called Output Feature Class.

The result of executing the GIS geospatial model using ArcGIS Pro made it possible to design the territories of the coastal protection strips of the Kamianopotokivska community, Fig. 2.

The total area of the territory included in the coastal protection zone is a significant 3706.01 hectares. The analysis revealed that a significant part of this territory is not typical for zones that should be directly adjacent to water bodies. In particular, 204 agricultural land plots were identified within the coastal protection zone, the total area of which exceeds 47 hectares.

This fact is of concern, since for such plots located in the coastal protection zone, the legislation establishes strict restrictions. According to Article 61 of the Land Code of Ukraine, in the coastal protection zone of rivers and water bodies, it is strictly prohibited:

- plowing of land;
- application of mineral fertilizers and pesticides;
- creation of dumps;
- carrying out any other activity that may cause water pollution.

The following categories of land fell within the boundaries of the coastal protection strips of water protection zones:

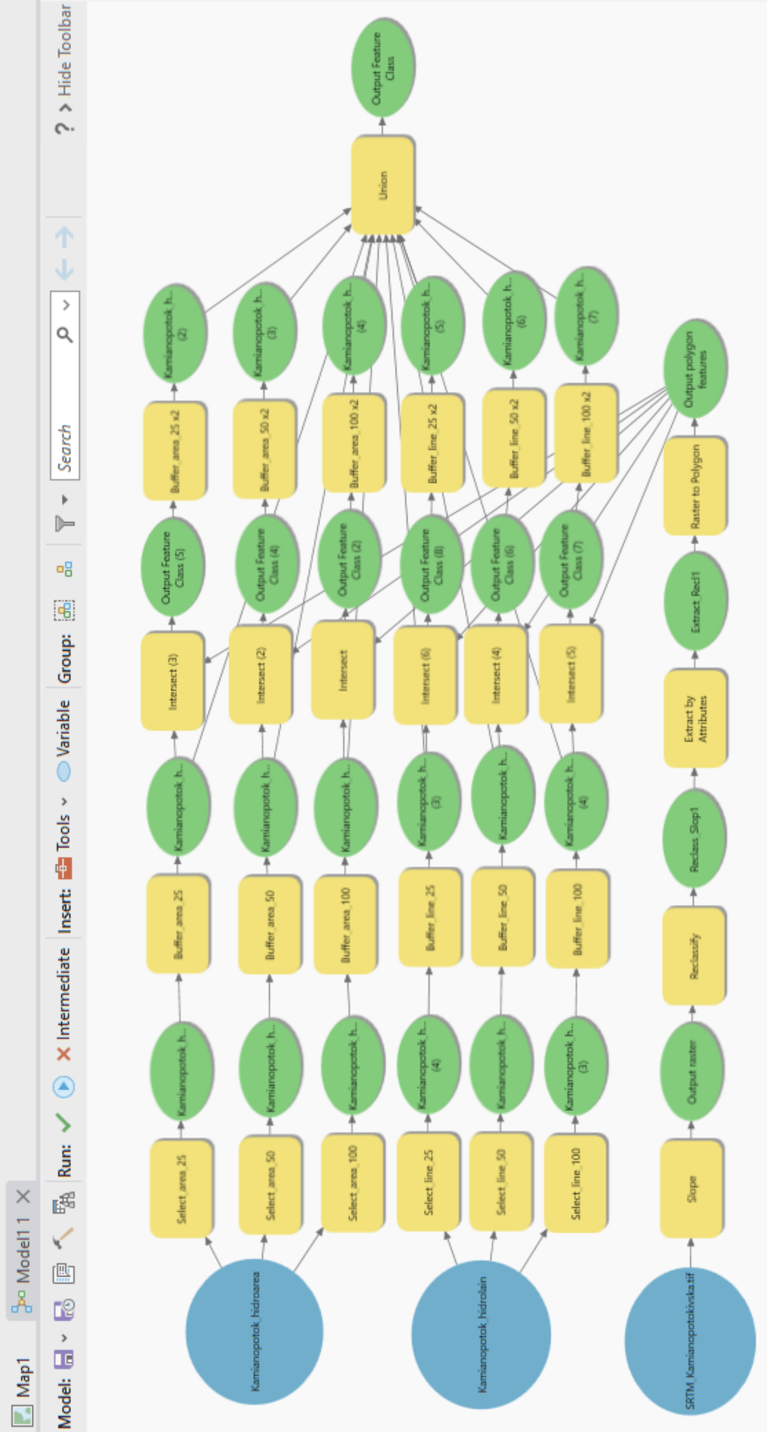

Fig. 1 Final automated model for designing coastal protection strips of water protection zones

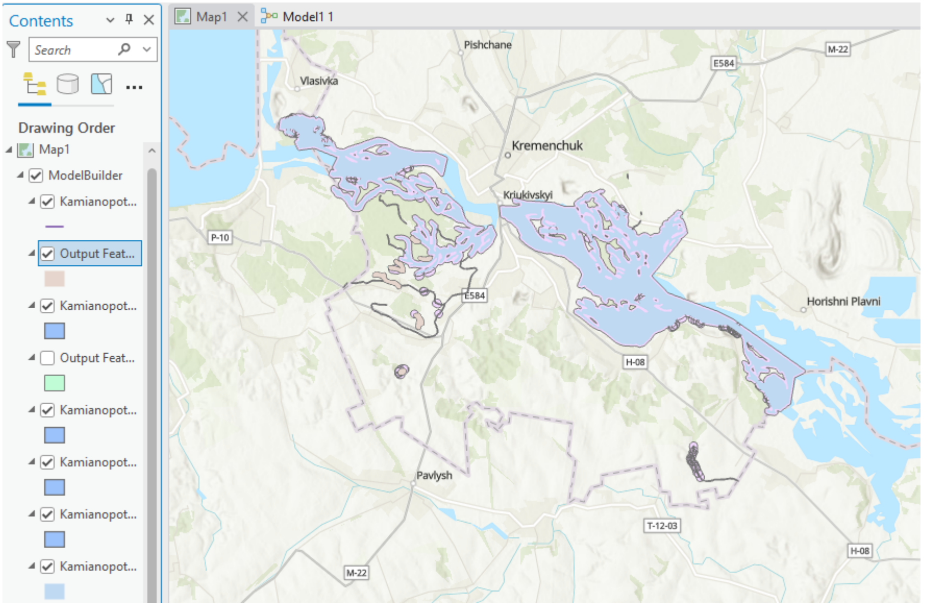

Fig. 2 The border of the Kamianopotokivska community with the designed coastal protection strips of water protection zones

Table 1. Distribution of land within the coastal protection zones of water protection zones by category

№	Category	Number of land parcels	Area, hectares
1	Water fund lands	2	0,51
2	Residential and public development land	10	0,49
3	Lands of forestry purpose	74	3564,86
4	Lands of agricultural purpose	204	47,02
5	Land of industry, transport, communications, energy, defense, and other purposes	10	91,10
6	Lands of recreational purpose	3	2,03
total			3706,01

forestry lands (3564.86 ha), water fund lands (0.51 ha), and recreational lands (2.03 ha). In accordance with Articles 60 and 63 of the Land Code of Ukraine, these lands are either already part of the natural protection belt or perform the function of supporting the hydrological and ecological balance. Their inclusion in the CPS not only does not contradict the protection regime, but also enhances the environmental efficiency of the territory. For example, forest plantations stabilize soils, prevent erosion, and absorb part of the surface runoff. The water fund is naturally an element of the CPS, and recreational lands, as a rule, have minimal technogenic impact and contribute to the formation of an ecological culture. At the same time, more than 91 hectares of land classified as industrial, transport, communications, energy, defense, and other purposes were identified in the CPS. According to Articles 60 and 61 of the Land Code of Ukraine, it is strictly prohibited to place facilities in these territories that may negatively affect the state of the water environment, including warehouses, gas stations, and storage facilities for harmful substances. All existing engineering structures must be operated only under strict compliance with environmental standards, with all protective measures and constant monitoring. Failure to comply with these requirements creates a risk of pollution of surface and groundwater, which is especially dangerous in densely populated regions.

Ten residential and public development sites with a total area of 0.49 hectares have also been recorded within the protective strip. Article 61 of the Land Code of Ukraine prohibits the construction of capital structures in the CPS, except for hydraulic engineering and facilities specially provided for by law. It is also forbidden to arrange cesspools, septic tanks, and sewage systems without proper treatment. These restrictions are aimed at protecting water bodies from pollution and preserving the natural drainage balance. The presence of even small areas of development within the boundaries of the CPS creates potential environmental threats [6].

Article 88 of the Water Code of Ukraine and Article 60 of the Land Code of Ukraine clearly regulate that the boundaries of coastal protection strips for all water bodies without exception must be established on the basis of individual land management projects [7]. Within settlements, these projects must take into account the requirements of urban planning documentation. According to the explanations, existing facilities already located in the CPS may continue to be operated if they do not violate the established regime. However, such facilities are subject to all restrictions, including the prohibition of any new construction on the relevant land plots. These restrictions are effective from the moment the relevant regulatory legal acts enter into force (Article 111 of the Land Code of Ukraine).

Based on the results of the study, a student research paper was written, which took 3rd place in the 1st round of the All-Ukrainian competition of student research papers in the specialty "Geodesy and Land Management".

Conclusions and prospects

The results of spatial analysis revealed both areas registered in the State Land Cadastre (SLC) that comply with the environmental protection regime, and a significant amount of land that falls under the restrictions established by the Land Code of Ukraine. Namely, over 91 hectares of land classified as industrial, transport, communications, energy, defense, and other purposes, and ten areas of residential and public development, the total area of which was 0.49 hectares. This confirms the critical need to use GIS technologies in planning the development of territories to ensure compliance with environmental requirements when forming land use boundaries. The designed CPS model of water protection zones not only identified conflict areas, but also outlined opportunities for further spatial planning in accordance with environmental standards. This geospatial model can be supplemented with multiple studies of changes in the shorelines of water bodies to accurately determine the outer boundaries of water protection zones or dynamically update them according to an established algorithm.

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Заячківська Б.Б., Денисюк Б.І., Бурбига Я.С.

ПРОЄКТУВАННЯ ПРИБЕРЕЖНО-ЗАХИСНИХ СМУГ ВОДООХОРОННИХ ЗОН ЗАСОБАМИ ГІС

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Анотація. *Проаналізовано нормативно-правові засади проєктування водоохоронних зон та їх роль для охорони природного середовища, визначення меж прибережно-захисних смуг та вплив рельєфу на розміри зон обмежень. Досліджено територію Кам'янопотоківської територіальної громади Кременчуцькому районі Полтавської області. Проведено класифікацію водних об'єктів території дослідження, визначено нормативні значення прибережно-захисних смуг відповідно до їх розмірів згідно вимог чинного законодавства. На основі відкритих даних про рельєф території здійснено розрахунок схилів та передбачено подвоєння прибережно-захисних смуг в межах схилів понад 3 градуси.*

Розроблено геопросторову динамічну модель проєктування прибережно-захисних смуг водоохоронних зон з урахуванням законодавчих норм та рельєфу та їх вплив на види діяльності. Модель створено та апробовано за допомогою програмного модуля Model Builder в ArcGIS Pro.

Як результат дослідження, застосовано модель до зібраних вхідних даних та запроєктовано прибережно-захисні смуги водоохоронних зон в межах досліджуваної території. Визначено території та проведено їх аналіз, право власності на які обтяжуються відповідно до запроєктованих водоохоронних зон. Дана модель є динамічною та придатною до застосування у виробничих цілях на локальному рівні (в межах територіальних громад).

Ключові слова: *водоохоронна зона; прибережно-захисна смуга; територіальна громада; водні об'єкти; проєктування водоохоронних зон; ГІС технології; геоінформаційні системи.*