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MODERNIZATION OF GROUNDWATER MONITORING SYSTEM IN THE CHORNOBYL EXCLUSION ZONE: CHALLENGES AND IMPLEMENTATION OF INTERNATIONAL STANDARDS

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Abstract

The Chornobyl Exclusion Zone remains one of the most radioactively contaminated territories in the world, and the state of its water resources continues to play an important role in long-term radiological impacts on downstream populations in the Pripyat – Dnieper basin. Radiation monitoring of surface and groundwater in the ChEZ is a key tool for assessing radionuclide migration, predicting environmental risks, and supporting decision-making in post-accident management. However, the current monitoring infrastructure was largely established in the early 1990-ies and no longer meets modern scientific, technical, or regulatory demands. This work explores current challenges and opportunities in enhancing the monitoring system for water resources in the Chornobyl Exclusion Zone. Particular attention is paid to the overall need for harmonization with international standards including modernization of the monitoring network, optimization of monitoring program, integration of modern sensor technologies, and introduction of the efficient data management and analysis tools.

Key words: *Chornobyl Exclusion Zone, groundwater monitoring, radioactive contamination, hydrogeological modeling, international standards, environmental safety.*

The Chornobyl Exclusion Zone (ChEZ) encompasses a complex system of radiation-hazardous objects and contaminated environments, resulting from the 1986 nuclear accident at Unit 4 of the Chornobyl Nuclear Power Plant (ChNPP). These include the "Shelter" object (the original "Sarcophagus"), highly contaminated by radioactive fallout terrestrial areas, legacy radioactive waste disposal sites (e.g., the Red Forest), and multiple water bodies containing radionuclide-contanated sediments (e.g., the former ChNPP cooling pond). In addition, the 10-km zone surrounding the ChNPP hosts numerous facilities associated with radioactive waste and spent nuclear fuel (SNF) management, including "Pidlisny", " 3-rd Stage of ChNPP", "Buryakivka" disposal sites, and the "Vector" industrial complex, which includes newly commissioned and planned near-surface waste storage and disposal infrastructure. Many of these facilities, along with the legacy contamination of soils and sediments, constitute actual or potential sources of radionuclide leaching to the hydrogeological system of the ChEZ. Monitoring and understanding the behavior of radionuclides in groundwater is therefore a critical component of radiation safety and long-term environmental management of the area.

The current groundwater monitoring network in the ChEZ [1,2], largely established in the early 1990s, is outdated in both design and functionality. Most wells were constructed using technologies no longer considered adequate by modern hydrogeological standards. A significant number of wells are equipped with long (up to 12 m) screens, producing depth-integrated samples that limit vertical resolution and complicate hydrostratigraphic interpretation. Corroding steel casings introduce geochemical artifacts and may impact the accuracy of measured radionuclide activity concentrations due to redox changes or sorption. The spatial distribution of wells is uneven. While some key infrastructure facilities are surrounded by relatively dense monitoring networks, large intermediate areas lack any observation points, hindering regional assessments of groundwater flow and contaminant transport pathways.

Field sampling remains largely manual and labor-intensive, employing basic tools such as water level popper gauges and bailers. These practices are prone to human error and inconsistent sampling conditions. Moreover, the temporal frequency of sampling is poorly aligned with the time dynamics of critical hydrogeological and radiological parameters.

Another limitation is the restricted range of measured parameters. Monitoring program still focuses almost exclusively on radionuclide activity concentrations, while neglecting essential geochemical indicators such as pH, Eh, major ions, and dissolved organic carbon. Without these data, reliable modeling of radionuclide speciation and mobility remains impossible.

Recent changes in the hydrological landscape of the ChEZ have further complicated the monitoring task. The 2014 drainage of the ChNPP cooling pond led to a dramatic drop in local groundwater levels, desaturating parts of the aquifer and altering flow patterns. This was compounded by the establishment of the Chornobyl Radioecological Biosphere Reserve in 2016, which reclassified much of the Exclusion Zone while preserving a core industrial area around the plant.

Moreover, the 2022 Russian invasion of Ukraine resulted in the temporary occupation of the ChEZ, during which time laboratories and monitoring equipment were looted or destroyed. Restricted access to key areas and a shortage of qualified personnel have only intensified the already critical need for modernization of the monitoring system.

Leading international organizations such as the International Atomic Energy Agency (IAEA), the International Organization for Standardization (ISO), and the American Society for Testing and Materials (ASTM) have developed detailed guidelines and protocols for the design and operation of groundwater monitoring systems. These standards ensure the quality, reproducibility, and comparability of monitoring data and facilitate international collaboration and knowledge exchange. For example, the IAEA's safety guides and technical reports — such as SSG-31 and SRS-35 on monitoring for radioactive waste disposal facilities, TRS-391 and TRS-424 which outline methodologies for site characterization and the design of long-term monitoring systems [3–7].

Similarly, the ISO 5667 series provides detailed procedural guidance for sampling design, field methods, sample handling, and quality assurance in water monitoring, including recent revisions that reflect advances in sensor technology and environmental data management (e.g., ISO 5667-1:2023, ISO 5667-3:2024). These standards help ensure data reliability and long-term comparability, especially important in long-duration environmental monitoring campaigns such as those required in the ChEZ [8–11].

In parallel, ASTM standards offer a technical foundation for the design, construction, and operation of groundwater monitoring wells. Documents such as ASTM D5092/D5092M-16 (2024 revision) address proper well installation methods, while ASTM D4448-01 and ASTM D6089-19 detail procedures for groundwater sampling, sample documentation, and analytical QA/QC protocols [12-14]. The implementation of such internationally validated methods is essential for ensuring that the monitoring system in the ChEZ can serve not only domestic regulatory needs but also align with transboundary water management standards and international environmental safety obligations.

These internationally recognized frameworks—formulated by IAEA, ISO, and ASTM—provide the scientific and regulatory basis for the modernization of environmental monitoring systems at nuclear legacy sites. Their adoption is essential for enhancing the reliability, comparability, and transparency of data, particularly in transboundary contexts. Building on this foundation, the current EU-funded project (INSC/2023/442-544) aims to implement these best practices in the specific context of the Chornobyl Exclusion Zone. By adapting international methodologies to site-specific hydrogeological and institutional conditions, the project seeks to develop a technically sound and future-proof groundwater monitoring system. This modernization effort is not limited to hardware and instrumentation—it encompasses a full-spectrum redesign of monitoring strategies, sampling protocols, data integration, and institutional coordination mechanisms.

One of the core elements of this effort is the design and installation of a new generation of monitoring wells. These wells will use chemically inert and corrosion-resistant materials, such as polyvinyl chloride (PVC) or high-density polyethylene (HDPE), to preserve the integrity of hydrochemical measurements. The screen intervals will be reduced and precisely positioned within the aquifer to enable discrete-depth sampling, thereby improving the vertical resolution of contamination data. Each well will incorporate bentonite seals to prevent vertical flow along the borehole annulus, minimizing cross-contamination between hydrostratigraphic layers.

In parallel, the spatial footprint of the monitoring network is being reassessed and expanded. Current configurations leave critical areas—especially those between major waste management sites like the Vector complex and the ChNPP industrial area—either sparsely monitored or entirely unobserved. New monitoring points will be strategically located to fill these spatial gaps and provide better coverage of suspected radionuclide migration pathways and downgradient discharge zones, including those adjacent to surface water bodies.

To improve the temporal resolution and reduce dependence on manual sampling, the project also envisions a broad deployment of automated sensors, such as TD-Diver-type water level and temperature loggers. These devices will provide high-frequency, autonomous measurements that capture seasonal and event-based hydrodynamic fluctuations. Where warranted by risk or site sensitivity, some locations may be equipped with telemetry-enabled sensors capable of real-time data transmission to central servers.

Equally important is the integration of standardized and scientifically robust groundwater sampling protocols. These include preliminary well purging to remove stagnant water, in-line filtration through 0.45 μm membranes, immediate stabilization of samples to preserve redox and chemical conditions, and on-site measurements of key geochemical parameters such as pH, redox potential (Eh), electrical conductivity, and dissolved oxygen. These additions are vital for understanding the geochemical controls on radionuclide mobility, including sorption/desorption dynamics and colloid-facilitated transport.

The data collected from the modernized system will be synthesized and interpreted through the development of a regional groundwater flow and radionuclide transport model based on the MODFLOW FLEX 10 numerical framework. This model, incorporating both unconfined Quaternary and confined Eocene aquifers, will be calibrated against recent monitoring data and used to simulate contaminant migration patterns under current and future hydrogeological scenarios. It will also serve as a decision-support tool for optimizing the placement of additional wells and assessing long-term safety and exposure risks.

To ensure data usability and regulatory compliance, a unified, SQL-based monitoring database will be established, complemented by a geographic information system (GIS) interface. This digital platform will enable spatial visualization of groundwater quality, facilitate trend analysis using statistical methods, and streamline reporting to Ukrainian authorities and international partners. The system will be designed to accommodate both manually collected and automatically transmitted data, with provisions for metadata handling, quality control, and secure access.

Institutional coordination is also a central component of the modernization initiative. The project fosters the harmonization of sampling schedules, analyte lists, and laboratory methodologies across the major actors in the zone—namely, SSE "Ecocenter", SSE "Chornobyl NPP", and SSE "CERWM". Provisions are made for inter-laboratory comparison exercises to validate radionuclide measurements, as well as for shared protocols on data formatting and exchange.

Finally, the upgraded groundwater monitoring system is being designed to align with broader national and European radiation monitoring infrastructures. This includes compatibility with Ukraine's Integrated Automated Radiation Monitoring System (IARMS), as well as data export capabilities to EU-level repositories such as the European Groundwater Monitoring (EUGM) platform and the EcoZagroza environmental hazard information system. Such integration not only enhances transparency and interoperability but also positions Ukraine to meet its international environmental monitoring obligations in the context of post-accident legacy site management.

Groundwater monitoring in the Chornobyl Exclusion Zone stands at the intersection of environmental science, nuclear safety, and geopolitical instability. The challenges posed by outdated infrastructure, evolving hydrological conditions, and institutional fragmentation demand a modernized, coordinated, and science-driven monitoring approach. By adopting state-of-the-art field methods, analytical protocols, and modeling tools, the ChEZ can serve as a global reference case for long-term environmental management of nuclear legacy sites.

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МОДЕРНІЗАЦІЯ СИСТЕМИ МОНИТОРИНГУ ПІДЗЕМНИХ ВОД У ЗОНІ ВІДЧУЖЕННЯ ЧОРНОБИЛЬСЬКОЇ АЕС: ВИКЛИКИ ТА ІМПЛЕМЕНТАЦІЯ МІЖНАРОДНИХ СТАНДАРТІВ

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Анотація

Зона відчуження Чорнобильської АЕС залишається однією з найбільш радіаційно забруднених територій у світі, а стан її водних ресурсів і надалі відіграє важливу роль у формуванні довготривалих радіаційних наслідків для населення, що проживає нижче за течією у басейні Прип'яті – Дніпра. Радіаційний моніторинг поверхневих і підземних вод у зоні відчуження є ключовим інструментом для оцінки міграції радіонуклідів, прогнозування екологічних ризиків та підтримки прийняття рішень у післяаварійному управлінні. Водночас наявна інфраструктура моніторингу була здебільшого створена на початку 1990-х років і більше не відповідає сучасним науковим, технічним та нормативним вимогам. У даній роботі розглядаються актуальні виклики та можливості для вдосконалення системи моніторингу водних ресурсів у зоні відчуження Чорнобильської АЕС. Особливу увагу приділено необхідності гармонізації з міжнародними стандартами, включаючи модернізацію моніторингової мережі, оптимізацію моніторингових програм, інтеграцію сучасних сенсорних технологій та впровадження ефективних інструментів управління та аналізу даних.

Ключові слова: зона відчуження Чорнобильської АЕС, моніторинг підземних вод, радіоактивне забруднення, гідрогеологічне моделювання, міжнародні стандарти, екологічна безпека.