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Assessment of the Barrier Properties of the Vadose Zone at the Radioactive Waste Disposal Sites in the Chornobyl Exclusion Zone

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Оцінка бар’єрних властивостей зони аерації на ділянці пунктів захоронення радіоактивних відходів у Чорнобильській зоні відчуження

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Ключові слова: інфільтраційне живлення, ПЗРВ «Буряківка», КВ «Вектор», Чорнобильська зона відчуження, радіоактивне забруднення, захищеність підземних вод, гідрогеологічне моделювання.

The paper presents estimates of groundwater recharge rate from precipitation and evaluates the potential of the vadose zone to retard and attenuate radionuclides at the “Buryakivka” radioactive waste disposal facility (RWDF) and the “Vector” industrial complex (IC) within the Chornobyl Exclusion Zone. Understanding the patterns of groundwater recharge, groundwater flow, and radionuclide migration in the vicinity of these facilities is crucial for conducting safety assessments for waste disposal and storage. The study area is situated within the Chystogalivska moraine ridge and is characterized by the presence of an unconfined aquifer in Quaternary deposits, which is mainly recharged by atmospheric precipitation. A combination of methods was applied to assess groundwater recharge rate. Analysis of groundwater level dynamics and chloride-ion balance in groundwater and precipitation yielded consistent groundwater recharge rate estimates in the range of (55–65) ± 15 mm/year. The adequacy of these estimates was confirmed through calibration of the regional groundwater flow model. The obtained recharge estimates were used to evaluate the barrier properties of the vadose zone soils with respect to the migration of Chornobyl-derived radionuclides and radionuclides present in the waste streams of NNEGC “Energoatom”. The calculations were performed using migration models that take into account for advection, dispersion, sorption, and radioactive decay. A screening analysis showed that the main groundwater contamination risks are associated with ^{90}Sr, ^{3}H, and ^{14}C. For these radionuclides, the migration time through the vadose zone and the concentration attenuation factors in groundwater were assessed, taking into account the above-mentioned geo-migration mechanisms included in the model. The calculated parameters can be used in integrated geo-migration models that consider the barrier properties of the geological environment in both near-field and far-field zones of the RWDF, in combination with dose models for determining the waste acceptance criteria for disposal.

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1. Introduction

The "Vector" Industrial Complex (IC) and the near-surface trench-type radioactive waste disposal facility (RWDF) "Buryakivka" are key radioactive waste (RAW) management facilities within the Chornobyl Exclusion Zone (ChEZ). These facilities are located 15 km southwest of the Chornobyl Nuclear Power Plant (ChNPP) in a forested watershed area between the Pripyat and Uzh rivers, within the Chystogalivska moraine ridge (Fig. 1).

The "Buryakivka" RWDF site contains 31 trenches, with a total capacity of 687,000 m^3 of RAW with a total activity of 2.54 × 10^{15} Bq. It received clean-up waste generated during the remedial activities following the ChNPP accident within the Exclusion Zone. The site also stores waste from the ongoing operations of the ChNPP, the "Shelter" Object, and other ChEZ enterprises. This includes contaminated soil, construction rubble, and other materials (Antropov et al., 2001). Further expansion of this RWDF is planned through the construction of new trenches for the disposal of low-level waste. The "Vector" IC comprises a number of existing and planned facilities for the near-surface disposal of short-lived waste, the storage of long-lived and high-level waste, spent sealed radioactive sources, as well as facilities for RAW processing (e.g., segregation, conditioning). The "Vector" IC is planned to serve as a national center of Ukraine for RAW disposal and storage, encompassing RAW from: sites of the State Specialized Enterprise "Radon Association", operational waste from nuclear power plants, wastes from the decommissioning of the ChNPP, and decontamination wastes from the Exclusion Zone (Lisichenko et al., 2017).

Understanding the patterns and conditions of groundwater recharge, groundwater flow, and radionuclide migration in the vicinity of these facilities is crucial for conducting safety assessments for RAW disposal and storage. This is especially important for predicting long-term potential impacts on groundwater and the river network due to radionuclide migration (Bugai et al., 2017). Vadose zone soils play a key role as a natural geological barrier in near-surface RAW disposal (IAEA, 2002, 2011). They provide retardation and attenuation of radionuclide migration through sorption, dispersion, and radioactive decay, thereby reducing the risk of their release into groundwater and surface water (McLin et al., 2005; Zachara et al., 2007; De Salve et al., 2014). Through these mechanisms, vadose zone soils provide the natural attenuation of contaminant migration fluxes and retain radionuclides in the solid phase, constituting a vital element of the multi-barrier protection system for the environment in RAW disposal.

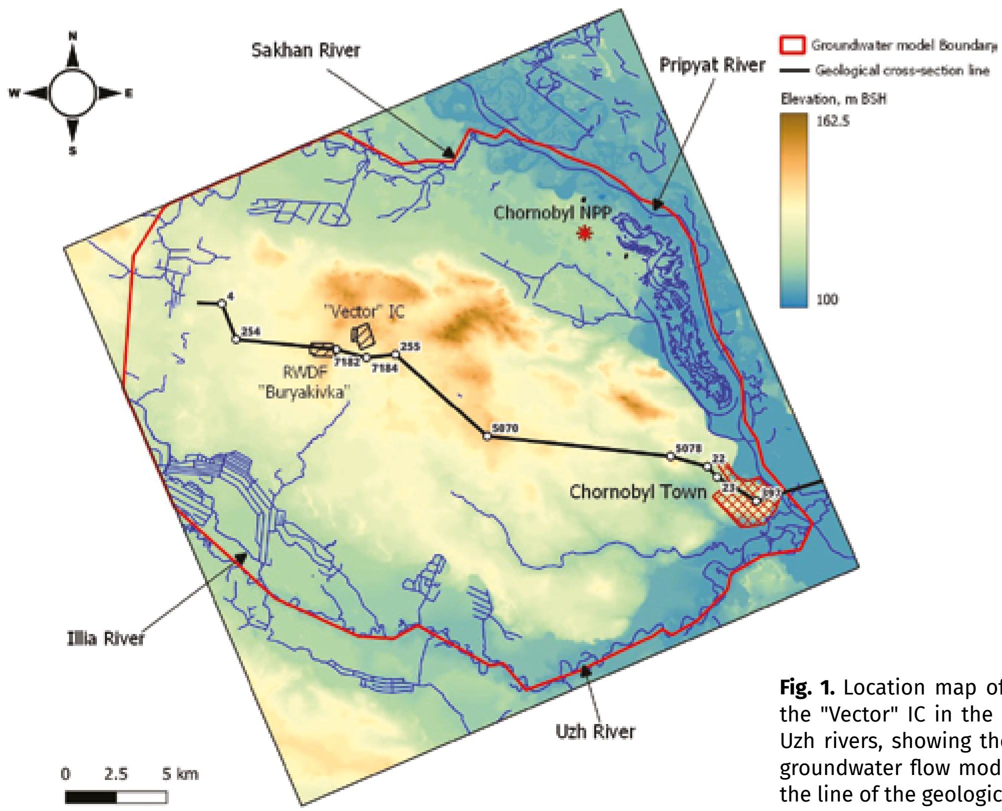


Fig. 1. Location map of the "Buryakivka" RWDF and the "Vector" IC in the interfluve of the Pripyat and Uzh rivers, showing the boundaries of the regional groundwater flow model of the Exclusion Zone and the line of the geological cross-section

Groundwater recharge rate is one of the key parameters for predictive hydrogeological modeling of geo-migration processes in the vadose zone and groundwater. As groundwater recharge rate is typically determined only by indirect methods, cross-validation of this parameter using different approaches is important (Gumuła-Kawęcka et al., 2022). This work presents estimates of groundwater recharge rate for the study area based on the following methods: chloride-ion balance in groundwater and atmospheric precipitation; analysis of groundwater level fluctuations; calibration of a regional groundwater flow model of the ChEZ.

The obtained groundwater recharge rate estimates were used to assess the barrier properties of the vadose zone soils with respect to the migration of Chornobyl-origin radionuclides and radionuclides present in the waste streams of NNEGC "Energoatom". The calculations were performed using migration models that account for advection, dispersion, sorption, and radioactive decay (see section 2.6 for more detail). The calculated parameters (radionuclide migration times through the vadose zone and the concentration reduction factors in groundwater due to the listed geo-migration mechanisms) can be used for calculating waste acceptance criteria (WAC) for disposal.

2. Materials and methods

2.1 Environmental Conditions

The "Buryakivka" RWDF and the "Vector" IC sites are located in the watershed area between the Pripyat and Uzh rivers, 15 km from the ChNPP (see Fig. 1). The ground surface elevations for these sites range from 137 to 141 meters BSH (Baltic system of heights). The topography at the waste-storage sites is relatively flat, reflecting grading and levelling performed during construction.

The Exclusion Zone is characterized by a temperate continental climate with distinct seasonal variations in temperature and precipitation. Average monthly temperatures and precipitation values are shown in Fig. 2. The mean annual air temperature is approximately +8.2 ± 0.8 °C (for the period 1990–2021). Average annual precipitation over the same period is 620 ± 60 mm (Matsala et al., 2021). Evapotranspiration is strongly controlled by air temperature, with potential evapotranspiration (PET) values ranging from 1–3 mm/day in early spring and late autumn to 6–7 mm/day during the summer months (Likhovid, 2020).

2.2 Hydrogeological Conditions

Within the Exclusion Zone, the "zone of active water exchange" between atmospheric water, ground-

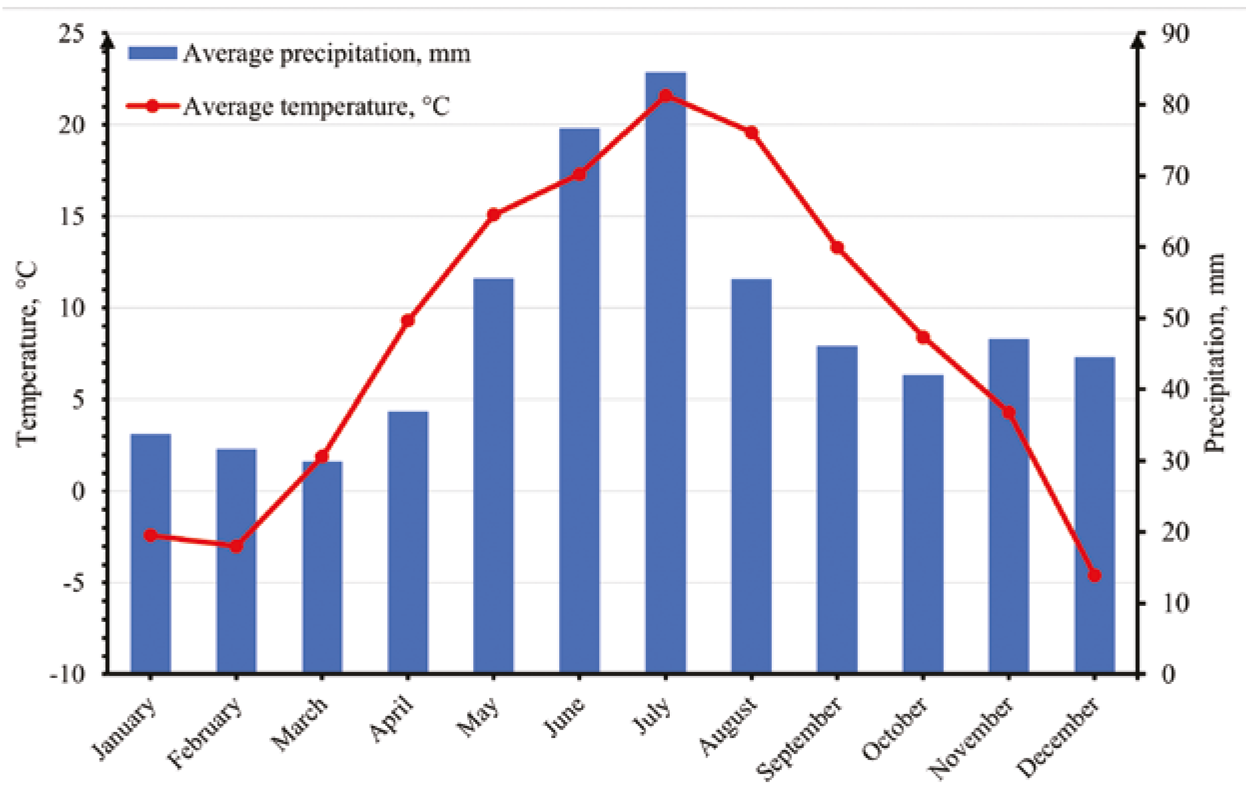


Fig. 2. Average monthly temperatures and precipitation in the Exclusion Zone (data of Chornobyl weather station)

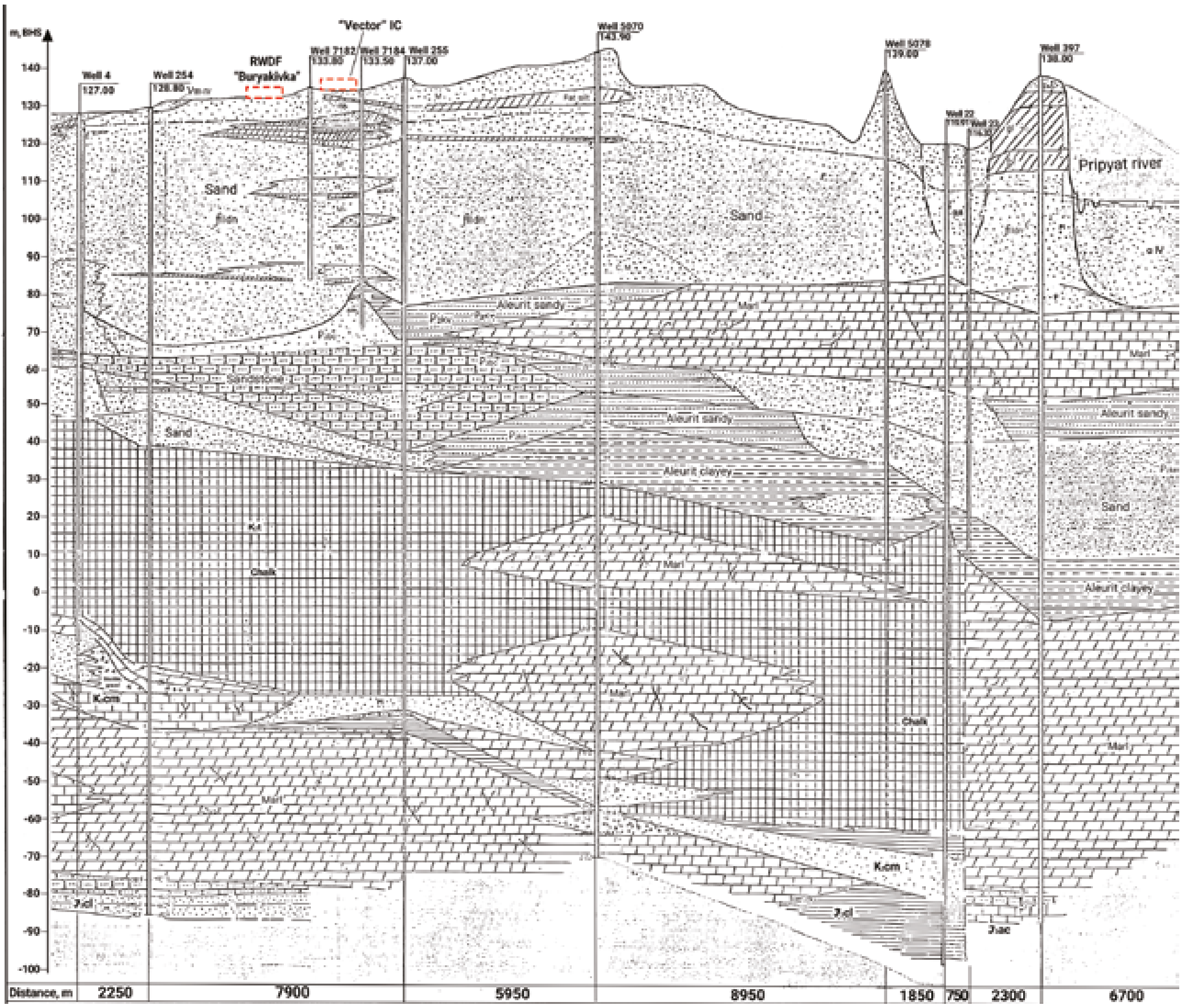


Fig. 3. Regional geological cross-section of the Exclusion Zone (adapted from TACIS (1995))

water, and surface water comprises the following main aquifers (from top to bottom): (1) the first from the surface unconfined aquifer in Quaternary and Neogene sandy deposits, and (2) a confined aquifer in Eocene sandy deposits (Dzhepo, Skalskyy, 2002). These aquifers are separated from each other by a layer of low-permeability clays and marls of the Eocene Kyiv Formation.

The regional cross-section of the Exclusion Zone is shown in Fig. 3. The geological structure and hydrogeological conditions within the study site are discussed in more detail below.

The upper part of the geological sequence at the "Buryakivka" RWDF and "Vector" IC sites, which contains the unconfined aquifer, consists of fluvioglacial sandy deposits of Quaternary age with interlayers of loams and sandy loams of varying thickness. Typical geological logs of selected wells within the study site are shown in Fig. 4, *b*.

The depth to the groundwater table in the Quaternary deposits within the "Buryakivka" RWDF and the "Vector" Complex in 2024–2025 varied between 14–19 m (122–125 m BSH). The unconfined aquifer is recharged by atmospheric precipitation.

The second aquifer from the surface is a confined aquifer that occurs within the sandy deposits of the Eocene Buchach and Kaniv Formations. The total thickness of the water-bearing rocks is about 40 m. The unconfined and confined aquifers are separated by a regional aquitard composed of marl clays of the Middle Paleogene Kyiv Formation. The thickness of the marl aquitard reaches its maximum (15–25 m) in the northeast and northwest sectors of the ChEZ. In the area of the "Buryakivka" RWDF and the "Vector" IC the marl layer is completely eroded, and as a result the Quaternary, Neogene, and Eocene sandy deposits form a single unconfined aquifer. Beneath the Eocene sediments the deposits of Cretaceous

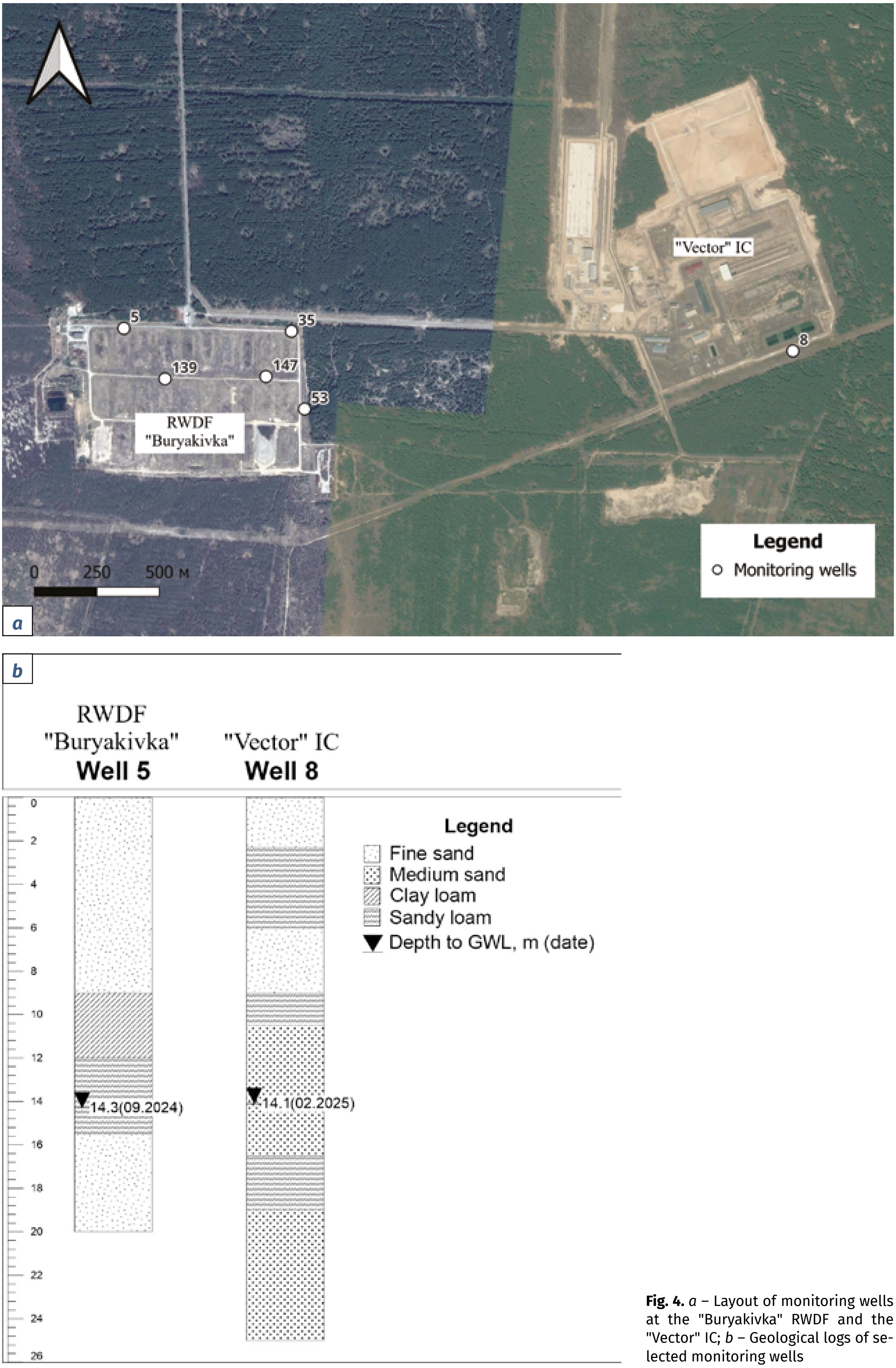


Fig. 4. *a* – Layout of monitoring wells at the "Buryakivka" RWDF and the "Vector" IC; *b* – Geological logs of selected monitoring wells

system lie, represented by low permeable chalk and marly chalk (marl), sands, sandstones, and siltstones (see Fig. 3).

2.3 Estimation of groundwater recharge rate based on Chloride-ion Balance Method

The Chloride Balance Method (CBM) for estimating groundwater recharge is based on the assumption that chloride ions from atmospheric precipitation are not retained by the soil matrix, do not participate in chemical reactions, and have no internal sources or sinks within the system. Their concentration in groundwater is thus determined solely by evapotranspiration processes (Alison and Hughes, 1978). The mean annual recharge rate is calculated using the formula:

$$q = P \times \frac{Cl_p}{Cl_w} ,$$

where: q – groundwater recharge rate, mm/year; P – mean annual atmospheric precipitation, mm/year; Cl_p – chloride-ion concentration in precipitation, mg/L; Cl_w – average chloride-ion concentration in groundwater, mg/L.

2.4 Estimation of groundwater recharge based on Water Table Fluctuation analysis

The Water Table Fluctuation (WTF) method is used to determine groundwater recharge by analyzing temporal changes in the groundwater level in observation wells. The method is based on the assumption that a rise in the water table is caused by the infiltration of atmospheric precipitation to the groundwater surface (Healy, Cook, 2002).

For each water table rise period identified on the well hydrograph, the calculated water level increase due to water infiltration (ΔH_{inf}) is determined as the sum of the actual water table rise (ΔH_{real}) and the expected water table decline (ΔH_{exp}), that would have occurred in the absence of infiltration input (see Fig. 4):

$$\Delta H_{inf\ i} = \Delta H_{real\ i} + \Delta H_{exp\ i} ,$$
$$\Delta H_{exp\ i} = r_{avg} \times \Delta t_i ,$$

where: $\Delta H_{real\ i}$ – rise in the water table during an individual calculation period "i", m; $\Delta H_{exp\ i}$ – expected decrease in the water table during the calculation period assuming no groundwater recharge, m; r_{avg} – recession rate (rate of water table decrease), calculated based on periods on the well hydrograph when the water table decreases in the absence of groundwater recharge (e.g., periods without rainfall), m/day.

The recession rate is estimated according to the equation:

$$r_{avg} = \frac{\Delta H_{red}}{\Delta t_j} ,$$

where: ΔH_{red} – decrease in the water table over a period Δt_j when groundwater replenishment is absent, m; $\Delta t_{i(j)}$ – number of days during which the water table rise (or decrease) occurred in the respective period, days.

The annual groundwater recharge (q, m/year) is calculated using the equation:

$$q = \Sigma \Delta H_{inf\ i} \times \frac{S_y}{dT} ,$$

where: S_y – specific yield, dimensionless; dT – observation period over which the water table increments are summed, years; $\Sigma \Delta H_{inf\ i}$ – total sum of water table rise increments due to groundwater recharge over the calculation period, m.

2.5 Estimation of groundwater recharge rate based on calibration of the regional groundwater flow model of the Exclusion zone

A regional groundwater flow model of the ChEZ was developed by the Institute of Geological Sciences of the NAS of Ukraine in 1997 (IGS, 1998). The Visual Modflow software was used for its implementation (https://www.waterloohydrogeologic.com/product/visual-modflow-flex/).

This flow model of the ChEZ covers an area of approximately 30 × 30 km (see Fig. 1). Vertically, the model encompasses the zone of active water exchange, which consists of two aquifers – an unconfined aquifer in Quaternary-Neogene deposits and a confined aquifer in Eocene deposits, separated by a layer of low-permeability Kyiv marls. The groundwater flow model of the ChEZ is described in detail in (IGS, 1998; Skalskyy, Kubko, 2001; Bugai, Deviere, 2004).

In this study, the model was refined by incorporating additional data obtained in recent years. This includes data on the geological structure from deep monitoring wells drilled at the cooling pond site under the Japanese-Ukrainian SATREPS project, as well as data from monitoring wells drilled at the sites of the Interim Spent Nuclear Fuel Storage Facility (ISF-2) and the Centralized Spent Nuclear Fuel Storage Facility (CSFSF) near the "Vector" site.

Based on the generalization of data from hydrogeological works in the ChEZ and previous groundwater flow modeling experience, the following average hydraulic conductivity (K) values were adopted in the model for the unconfined aquifer: *K* = 15 m/day for floodplain areas, 10 m/day for the first river terrace, and 7 m/day for the Chystohaliv moraine fluvioglacial plateau. For the confined aquifer in Eocene deposits, the average *K* value in the model is 5 m/day. The *K* value for the aquitard layer was set at 0.003 m/day, and for the "hydrogeological window" in the marl aquitard layer, it was set at 2.5 m/day (Skalskyy, Kubko, 2001; Bugai, Deviere, 2004; IAEA, 2019).

The model was calibrated by comparing modeling results with data on the averaged groundwater levels in the unconfined aquifer for the period 2019–2024, according to monitoring data from the SSE "Ecocentr" from 27 observation wells located in different geomorphological areas of the Exclusion Zone. The primary calibration criterion was the minimization of the root mean square error between the simulated and measured groundwater levels of the unconfined aquifer in the control wells.

2.6 Methodology for assessing the barrier properties of Vadose Zone

Barrier properties were assessed for a list of radionuclides of Chornobyl origin and those present in RAW from NNEGC "Energoatom" enterprises, which are planned for disposal at the "Buryakivka" RWDF (Table 1) (SAEZM, 2024).

The assessment of the barrier properties of the vadose zone soils was conducted in two stages.

1. First, calculation of radionuclide migration in the vadose zone soils was performed using a simplified approach accounting for advective transport and sorption. Based on this, a preliminary conclusion was made regarding the potential risk of groundwater contamination by a specific radionuclide.
2. For those radionuclides for which the risk of reaching groundwater was determined as potentially significant, a more detailed analysis was performed using the advection-dispersion equation, accounting for sorption and radioactive decay.

2.6.1 Screening assessments of radionuclide migration time in the Vadose Zone

Radionuclide migration in humid climatic conditions within relatively permeable vadose zone soils occurs primarily via the mechanism of advective transport (vertical movement of moisture in the soil pore space under the influence of gravitational and capillary forces), being Influenced and retarded by absorption interactions between radionuclides dissolved in the water and the soil matrix. To describe the sorption of radionuclides from the solution by the soil matrix, the model of fast, reversible sorption with a linear isotherm (the so-called K_d model) is used below.

Table 1. List of radionuclides and their sorption distribution coefficients

Radionuclide	Half-life, years	Distribution Coefficient, K_d, m^3/kg (Fine-grained sand)	References
^{3}H	12.33	0	IAEA, 2010
^{14}C	5729.32	0	IAEA, 2010
^{60}Co	5.27	0.48	IAEA, 2010
^{63}Ni	100.10	0.14	IAEA, 2010
^{90}Sr	28.79	0.001	Bugai et al., 2020
^{94}Nb	20299.81	0.17	IAEA, 2010
^{134}Cs	2.06	0.09	Bugai et al., 2020
^{137}Cs	30.07	0.09	Bugai et al., 2020
^{226}Ra	1599.96	1.9	IAEA, 2010
^{238}Pu	87.71	0.05	Bugai et al., 2020
^{239}Pu	24111.96	0.05	Bugai et al., 2020
^{240}Pu	6562.74	0.05	Bugai et al., 2020
^{241}Pu	14.35	0.05	Bugai et al., 2020
^{241}Am	432.23	1	IAEA, 2010

Under these assumptions, the sorption retardation factor (*R*, dimensionless) can be used to calculate the migration velocity of a radionuclide in the geological environment (Freeze, Cherry, 1979; IAEA, 2001, 2003, 2004a, b):

$$R = 1 + \frac{\rho_b \times K_d}{\theta},$$

where: K_d – sorption distribution coefficient for the radionuclide in the water-rock system for vadose zone soils (m³/kg); ρ_b – bulk density of the soil (kg/m³); θ – volumetric water content of the soil (dimensionless).

The velocity of contaminant transport via advective moisture flow ϑ_r (m/year) is determined by the following equation:

$$\vartheta_r = \frac{\vartheta}{R} = \frac{q}{\theta \times R},$$

where: $\vartheta = \frac{q}{\theta}$ – pore water velocity (m/year); *q* – groundwater recharge rate (m/year).

The time (t_{RnUZ}, years) for a radioactive contaminant to migrate through a vadose zone of thickness *L* (m) is calculated as:

$$t_{RnUZ} = \frac{L}{\vartheta_e} = \frac{L \times R}{\vartheta} = \frac{L \times (\theta + \rho_b \times K_d)}{q}.$$

Based on this, the "concentration reduction factor" for the radionuclide in solution due to radioactive decay ($CRF_{Rn\ UZ}$ – dimensionless) during transport through the vadose zone can be calculated:

$$CRF_{Rn\ UZ} = e^{(-\lambda_{decay} \times t_{RnUZ})},$$

where: $\lambda_{decay} = \frac{ln2}{T_{1/2}}$, $T_{1/2}$ – radionuclide half-life (years).

An important consideration is the choice of the "time horizon" (i.e., the safety assessment interval) for near-surface RAW disposal facilities. According to existing recommendations from reputable international organizations and the practice of conducting such assessments, this interval typically does not exceed 300–500 years (IAEA, 2002, 2003, 2011, 2012). In some studies, if the facility contains long-lived radionuclides, the calculation period may be extended to 1000 years to demonstrate facility safety with a "margin of protective assurance" (IAEA, 2002; NRC, 2024), and for illustrative purposes – up to 10,000 years.

Considering the above discussion, we proceeded from the premise that if, according to the forecast under conservative assumptions: 1) t_{RnUZ} > 10,000 years, or 2) $CRF_{Rn\ UZ} < 10^{-15}$, then the migration of this radionuclide from the RAW disposal facility into groundwater is not a significant risk factor for human and environmental impact. (This threshold $CRF_{Rn\ UZ}$ value ensures a reduction in the radionuclide's specific activity below clearance levels). For such radionuclides, safety aspects and maximum permissible activities for disposal in a near-surface facility will likely be determined not by groundwater migration, but by other scenarios and exposure pathways. These could include scenarios of human intrusion into the RAW facility after the period of institutional control (which usually does not exceed 100–300 years) has ended, or by dose limits for facility personnel handling RAW prior to disposal (IAEA, 2002, 2003, 2011, 2012).

2.6.2 Calculation of the $CRF_{Rn\ UZ}$ factor accounting for radioactive decay and hydrodynamic dispersion

For those radionuclides identified during the screening stage as posing a potentially significant risk of reaching groundwater, a more detailed assessment was performed. This modeling assessment utilized the advection-dispersion equation, accounting for sorption and radioactive decay.

To quantitatively assess the barrier properties of the vadose zone soils, a model scenario was considered involving the leaching of a radionuclide by an infiltrating moisture flux from a source representing a near-surface, trench-type RAW disposal facility (Fig. 5). The facility's geometry is analogous to the trenches of the "Buryakivka" RWDF.

In this case, the $CRF_{Rn\ UZ}$ factor was defined as the ratio of the maximum radionuclide concentrations in the solution entering from the source to the vadose zone and the maximum concentration at the output from the vadose zone (see Fig. 5):

$$CRF_{Rn\ UZ} = \frac{CRF_{Rn\ UZ\ in}}{CRF_{Rn\ UZ\ out}}.$$

For the modeling, we used the IAEA's NORMALYSA v2.3 software system (http://project.facilia.se/normalysa/software.html). The "Tailing without cover" module was used to model the source, which implements the mathematical model for leaching radionuclides from the trench body as described in (Baes. Sharp, 1983). To predict migration in the unsaturated soil zone, the "Unsaturated Zone" module was used; it implements the advection-dispersion equation for contaminants, accounting for sorption and radioactive decay. A detailed description of the corresponding mathematical models is provided in (IAEA, 2023).

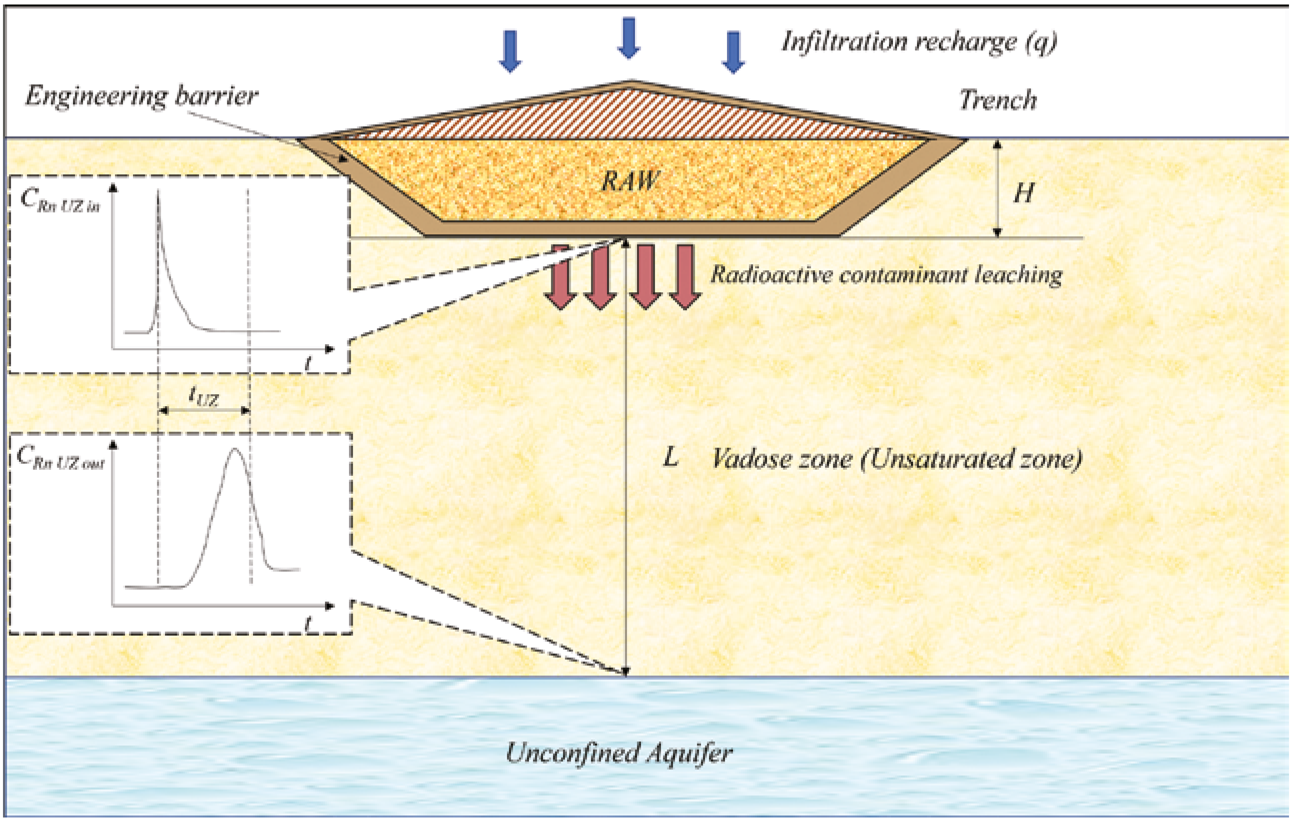


Fig. 5. Schematic diagram of radionuclide leaching from a trench and subsequent migration in the vadose zone soils

3. Results and Discussion

3.1 Estimates of groundwater recharge rate using the Chloride-ion Balance Method

Data on chloride-ion concentrations in groundwater from reports by the "Energoproekt" Institute (Energoproject, 1996; SAR-302, 2007), as well as regional data on long-term average precipitation amounts and chloride-ion concentrations in precipitation (Khilchevskyi et al., 2019; Karamushka et al., 2023), were used for the groundwater recharge calculations (Table 2).

Using input data presented in Table 2, groundwater recharge for the "Vector" IC area is estimated at 66 ± 16 mm/year, and for the "Buryakivka" RWDF area at 54 ± 16 mm/year.

3.2 Groundwater recharge rate estimates based on Water Table Fluctuation analysis

Data from SSE "Ecocentr" on water table levels in 5 wells (Wells 5, 53, 35, 139, 147) located at the "Buryakivka" RWDF site for the period 1993–2024 were used to calculate groundwater recharge (Fig. 6). We assume no external influences on the groundwater-level regime at the site other than infiltration of atmospheric precipitation.

An example of the groundwater recharge rate calculation for Well 35 is illustrated in Fig. 7 and Table 3.

The average daily recession rate (r_{avg}) for well 35 is 0.78 mm/day, ΔH_{real} = 3.45 m, ΔH_{exp}= 5.11 m.

Table 2. Input data for estimating groundwater recharge rate based on the chloride-ion balance in atmospheric precipitation and groundwater for the "Buryakivka" RWDF and "Vector" IC sites

Parameter	Value	Units	References
Long-term average precipitation data for Polissya (1991–2020)	620	mm/year	Karamushka et al., 2023
Chloride-ion value in atmospheric precipitation for the Kyiv meteorological station (1963–2011)	1.4	mg/L	Khilchevskyi et al., 2019
Average chloride-ion concentration in groundwater at the "Vector" IC site (Wells 8193, 8198, 8195, 2002 data)	13±3	mg/L	SAR-302, 2007
Average chloride-ion concentration in groundwater in the Chystohalivka-Lelev-Buryakivka area (Wells 7891, 7892, 7893, 7894, 1996 data)	16±4	mg/L	Energoproject, 1996

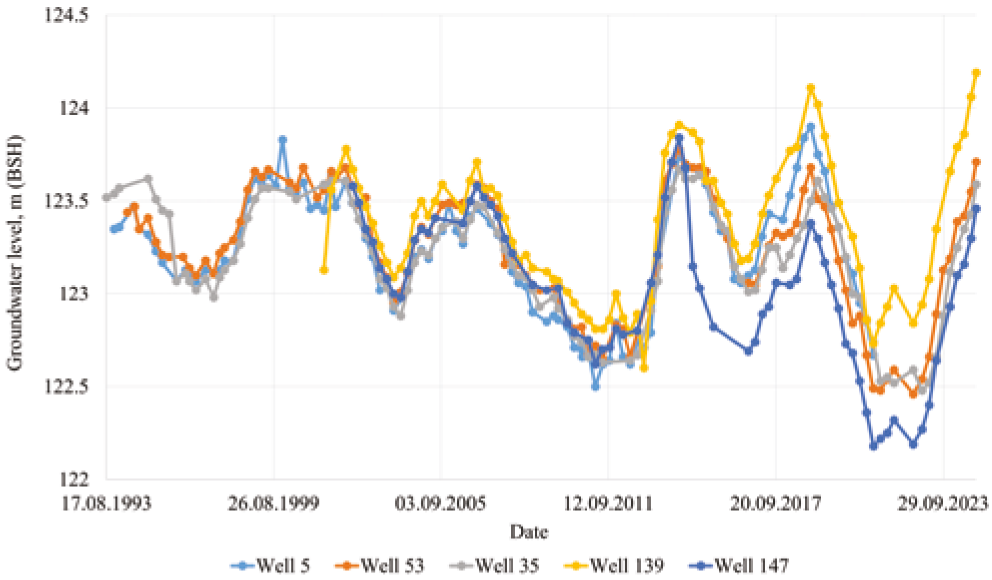


Fig. 6. Hydrographs of observation wells located at the "Buryakivka" RWDF for the period 1993–2024 (Data from SSE "Ecocentr", Chornobyl)

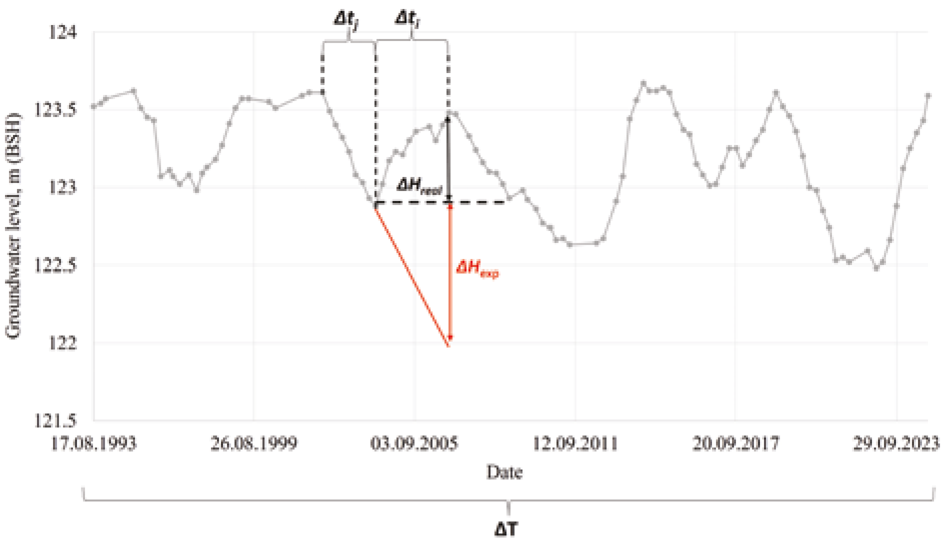


Fig. 7. Example of hydrograph analysis for Well 35 at the "Buryakivka" RWDF for calculating groundwater recharge using the WTF method for an individual water table rise event

Table 3. Data from hydrograph analysis for calculating groundwater recharge rate for Well 35 at the "Buryakivka" RWDF

Period	ΔH_{real}, m	ΔH_{exp}, m	$\Delta H_{inf} = \Delta H_{real} + \Delta H_{exp}$, m
18.08.1993–01.02.1994	0.05	0.51	0.56
25.06.1996–22.09.2001	0.5	1.97	2.47
20.06.2004–21.09.2006	0.38	0.85	1.23
25.06.2012–24.12.2014	1	0.93	1.93
20.12.2016–22.12.2018	0.48	0.77	1.25
22.09.2021–02.02.2024	1.04	1.09	2.13
Total			**9.57**

Table 4. Estimates of groundwater recharge for the "Buryakivka" RWDF based on the analysis of water table fluctuations in observation wells

No. well	Observation Period	Average Recession Rate, mm/day	Infiltration Recharge rate, mm/year
5	17.08.1993–02.12.2024	0.76	54
53	22.08.1994–02.12.2024	0.87	57
35	18.08.1993–02.12.2024	0.78	55
139	18.06.2001–02.12.2024	0.88	66
147	30.06.2002–02.12.2024	0.92	60
Average			**58 ± 5**

The observation period for water table fluctuations was 31.3 years. For the fine-grained sands composing the geological section where the water table fluctuations occur, a specific yield (S_y) value of 0.2 was adopted in the calculation (Healy, Cook, 2002; Gumuła-Kawęcka et al., 2022). Using these data, the calculated groundwater recharge rate (q) for Well 35 is 55 mm/year.

A summary of the groundwater recharge rate calculations using data from different wells is provided in Table 4. The resulting average groundwater recharge rate value is 58 ± 5 mm/year.

3.3 Estimates of groundwater recharge by calibrating the regional groundwater flow model of the ChEZ

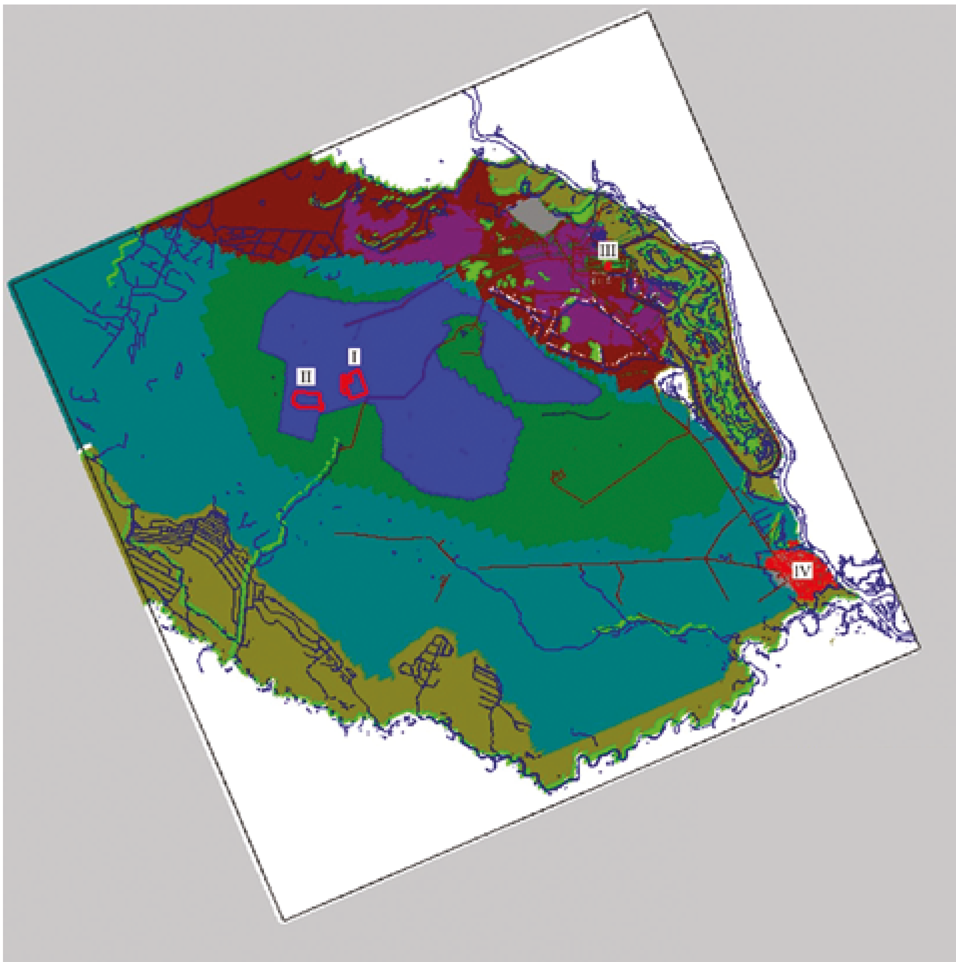
During the calibration of the regional groundwater flow model of the ChEZ, we adjusted the distribution of groundwater recharge rate across the watershed area of the Chystogalivska Moraine ridge and the boundary conditions (surface water levels) for specific residual water bodies within the bed of the former ChNPP cooling pond.

The following groundwater recharge rate values were assigned in the model for different geomorphological areas of the Exclusion Zone (Fig. 8):

- within floodplain areas – 200 mm/year;
- within the 1st terrace of the Pripyat River 150–170 mm/year;
- within the forested fluvioglacial plateau (Chystogalivska moraine-outwash plain) – 60–70 mm/year;
- on the slopes of the Chystogalivska Moraine ridge – 100 mm/year.

At the hydraulic engineering facility "ChNPP filtration fields" (wastewater biological treatment ponds), the groundwater recharge rate was assigned values of 3600 mm/year (82,800 m^3/year) (based on information received from the ChNPP).

The groundwater recharge rate values specified above for the different geomorphological elements of the ChEZ incorporate data from hydro-physical and geochemical studies (Bugai et al., 2012), isotopic dating of groundwater (Bugai et al., 2010), as well as the experiences from calibration of previous versions of the regional ChEZ groundwater flow model (Skalskyy, Kubko, 2001; Bugai, Deviere, 2004; IAEA, 2019).



Zone	Color	Recharge rate (mm/year)
1		100
2		70
3		100
4		150
5		170
6		200
7		28000
8		110
9		60
10		0

Fig. 8. Distribution of groundwater recharge rate within the domain of the regional groundwater flow model of the ChEZ. Legend for sites: I – "Vector" IC, II – "Buryakivka" RWDF, III – ChNPP, IV – Chornobyl town

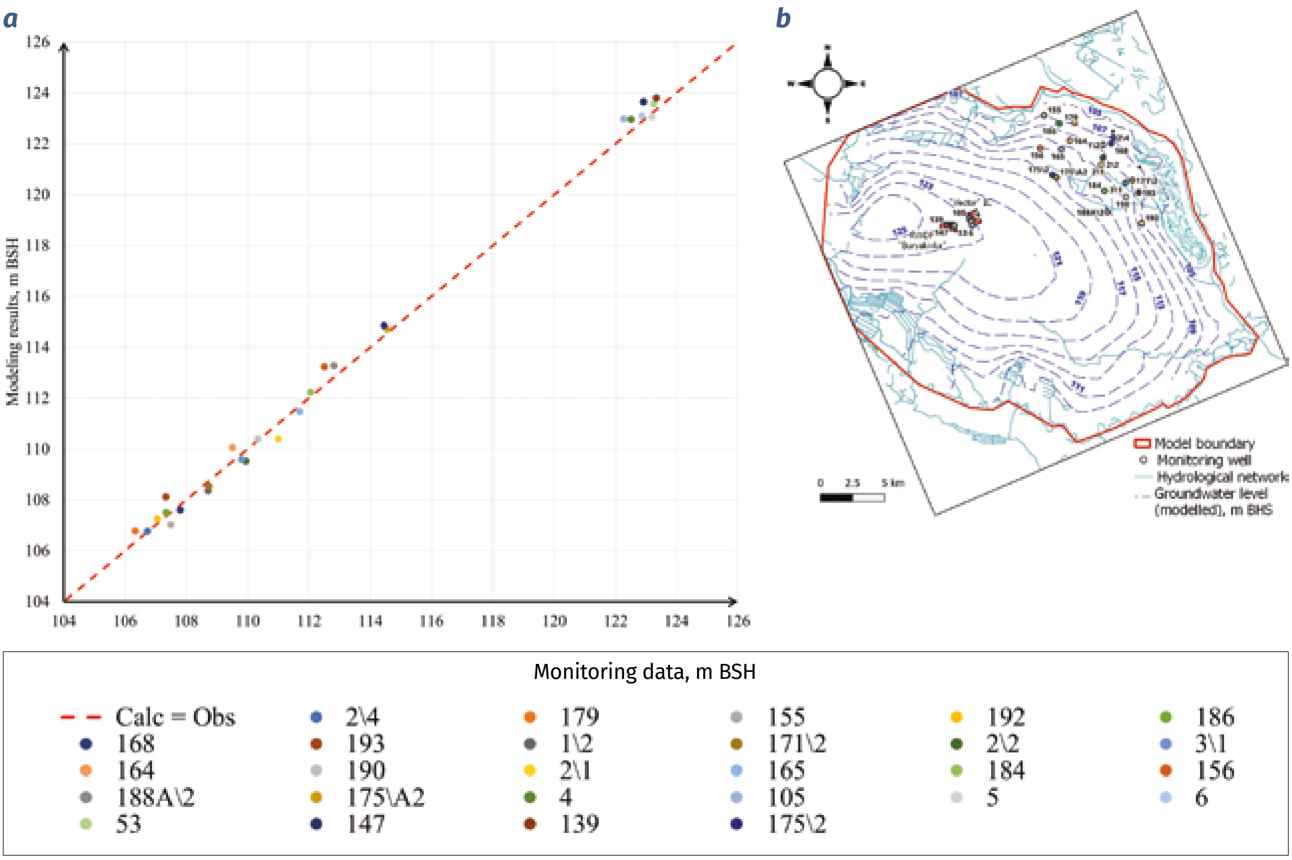


Fig. 9. Calibration results of the regional groundwater flow model of the ChEZ: *a* – Modelled vs. observed groundwater levels in the unconfined aquifer; *b* – Simulated hydraulic heads in the unconfined aquifer

The results of the flow model calibration are presented in Fig. 9. The average calibration error for the water table levels across 27 wells is 0.37 m, and the maximum error is 0.78 m. This level of agreement between the modeled and field data can, in our opinion, be considered acceptable, given that the seasonal water table fluctuations in the observation wells typically range from 1 to 1.5 m.

Thus, the value of groundwater recharge rate used in the modeling for the location of the "Buryakivka" RWDF and the "Vector" IC – 60 mm/year, which is close to the estimates obtained above using the chloride-ion balance and water table fluctuation methods, provided satisfactory calibration results for the regional groundwater flow model of the Exclusion Zone.

3.4 Screening assessments of radionuclide migration in vadose zone soils

The calculations were based on the conservative assumption that the vadose zone consists of homogeneous fine-grained sands. Possible interlayers of loamy sand and clayey soils with higher sorption properties were not considered. Input data for the screening assessment are provided in Table 5. The minimum value for the vadose zone thickness was selected (L = 10 m), corresponding to the conditions at the "Buryakivka" RWDF, considering the depth of the RAW trench (H = 4 m). The value for groundwater recharge rate was set at q = 80 mm/year, corresponding to the upper bound of the estimates in Sections 3.1–3.2. The soil moisture content (θ) was assumed to be 0.1, consistent with sandy and loamy sand materials with low organic matter content (Saxton and Rawls, 2006). Sorption parameters for the radionuclides are listed in Table 1. For Cs, Sr, and Pu isotopes, the K_d values were adopted based on experimental studies within the Exclusion Zone (Bugai et al., 2020). For the remaining radionuclides, K_d values for sands recommended by the IAEA (IAEA, 2010) were used. The calculation results are presented in Table 6.

Analysis of the screening assessment results, considering the criteria described in Section 2.6.1, indicates that, given the hydrogeological conditions of the study site, only a few radionuclides from the list in Tables 1 and 6 pose a potential risk of radioactive contamination to groundwater, namely ^{3}H, ^{14}C and ^{90}Sr. This shortlist is consistent with the practical experience of monitoring the environmental radiological impacts of RAW disposal facilities (Bugai, Avila, 2020). For the other radionuclides, the migration time through the vadose zone exceeds the 10,000-year time horizon. Additionally, for the isotopes ^{60}Co, ^{63}Ni, ^{134}Cs, ^{137}Cs, ^{226}Ra, ^{238}Pu, ^{241}Pu і ^{241}Am the following condition holds – $CRF_{Rn\ UZ} < 10^{-15}$, meaning they decay to very low levels during transit through the vadose zone.

Table 5. Input parameters for the screening assessment of radionuclide migration in the vadose zone soils

Parameter	Symbol	Value
Vadose zone thickness, m	L	10
Moisture content in vadose zone soils, dimensionless	θ	0.1
Bulk density of soil, kg/m³	ρ_b	1600
Groundwater recharge rate, mm/year	q	80
Sorption distribution coefficient of radionuclides in vadose zone soils, m³/kg	K_d	According to Table 1

Table 6. Screening assessment of radionuclide migration through the vadose zone

Radionuclide	Migration Time through Vadose Zone, years	$CRF_{Rn\ UZ}$
^{3}H	**12.5**	**4.95E-01**
^{14}C	**12.5**	**9.98E-01**
^{60}Co	96,012	<1E-15
^{63}Ni	28,012	<1E-15
^{90}Sr	**212.5**	**6.00E-03**
^{94}Nb	34,012	3.13E-01
^{134}Cs	18,012	<1E-15
^{137}Cs	18,012	<1E-15
^{226}Ra	380,013	<1E-15
^{238}Pu	10,012	<1E-15
^{239}Pu	10,012	7.50E-01
^{240}Pu	10,012	3.47E-01
^{241}Pu	10,012	<1E-15
^{241}Am	200,013	<1E-15

3.5 Detailed radionuclide migration assessment based on the Advection-Dispersion Equation

An important parameter in calculations of advective-dispersive contaminant transport in the subsurface is the dispersivity (α_L, m), which determines the value of the hydrodynamic dispersion coefficient (D, m²/year):

$$D = \alpha_L \times \vartheta_e .$$

According to the review (Vanderborght, Vereecken, 2007), for a vadose zone composed of sandy deposits at a depth of about 10 m, the longitudinal dispersivity (α_L) is typically 0.1–1 m. In the subsequent forecasts, values of α_L = 0.1 m and α_L = 1 m were used, representing the lower and upper bounds of typical values, respectively. All other vadose zone parameters are described in detail in the previous section.

The contamination source is a trench with a RAW layer thickness of H = 4 m (see Fig. 4). The RAW is assumed to consist of loose materials (e.g., contaminated soil), with their sorption properties corresponding to the values given in Table 1. This assumption is conservative. The moisture content in the waste matrix is assumed to be 0.15, corresponding to the default value in the NORMALYSA software (IAEA, 2023). The modeling is aimed at assessing the barrier properties of the geological environment and does not account for the isolating functions of engineered barriers. The concentration of all radionuclides in the RAW ($C_{Rn\ source}$) is assumed to be 1 Bq/kg.

The predicted breakthrough curves of radionuclide concentrations at the output (lower) boundary of the vadose zone are presented in Fig. 10, *a*–*c*. The results of the calculations are summarized in Table 7. In particular, the last column of Table 7 contains the Concentration Conversion Factor ($CCF_{Rn\ Source}$), which represents the ratio of the maximum radionuclide activity in groundwater at the output boundary of the vadose zone to the initial radionuclide activity in the source:

$$CCF_{Rn\ Source} = \frac{MAX(C_{Rn\ UZ\ out})}{C_{Rn\ source}} .$$

The calculated values of the $CCF_{Rn\ Source}$ coefficient allow for the estimation of radionuclide concentrations in groundwater by scaling with any given concentration in the migration source.

The calculation results show that for radionuclides ^{14}C and ^{3}H, which are practically non-sorbing in soils, dispersion is an important mechanism that reduces contaminant concentrations in groundwater. For these radionuclides, the $CRF_{Rn\ UZ}$ predictably decreases with increasing dispersivity parameter.

For ^{90}Sr a paradoxical pattern is observed: as α_L increases, the maximum radionuclide concentrations at the vadose zone output boundary (groundwater table) increase (whereas for non-decaying contaminants the opposite trend is typically expected), while the time to reach these maximum *a*

b

c

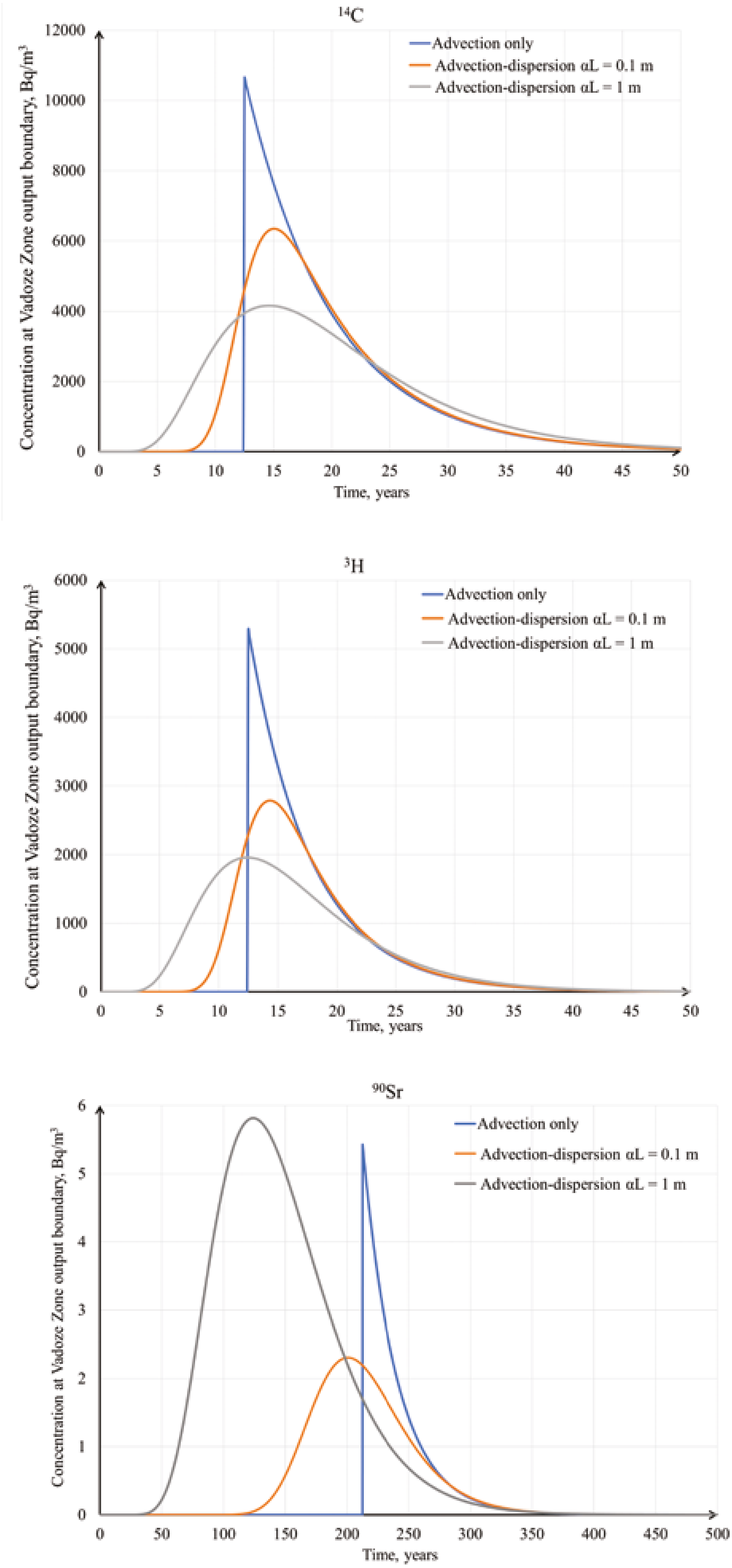


Fig. 10. Predicted concentrations of radionuclides: *a* – ^{14}C; *b* – ^{3}H; *c* – ^{90}Sr in groundwater at the output boundary of the vadose zone for the model scenario, considering different transport mechanisms and mass-transfer parameters

Table 7. Results of assessment of radionuclide concentrations in groundwater at the outlet of the vadose zone (groundwater level) using advection-dispersion model

Radio-nuclide	Contaminant Transport Model	$CRF_{Rn\ UZ}$	Time to Reach Max. Concentration at Vadose Zone output boundary, years	$CCF_{Rn\ Source}$, (Bq/m³)/(Bq/kg)
^{14}C	Advection only	9.98E-01	12.5	10650.55
	Advection-dispersion, α_L = 0.1 m	5.95E-01	15	6348.43
	Advection-dispersion, α_L = 1 m	3.90E-01	14.6	4157.76
^{3}H	Advection only	4.95E-01	12.5	5282.63
	Advection-dispersion, α_L = 0.1 m	2.61E-01	14.3	2789.7
	Advection-dispersion, α_L = 1 m	1.84E-01	12.4	1957.68
^{90}Sr	Advection only	6.00E-03	212.5	5.48
	Advection-dispersion, α_L = 0.1 m	2.52E-03	200.7	2.3
	Advection-dispersion, α_L = 1 m	6.36E-03	124	5.82

concentrations decreases. This is due to the combined effect of hydrodynamic dispersion and radioactive decay: the dispersion front of radiostrontium reaches the vadose zone output boundary earlier, and thus the radiostrontium undergoes less radioactive decay compared to transport solely by the advective mechanism.

The coefficients we calculated can be used to assess dose impacts from trench-type RAW disposal facilities of corresponding geometry within the study site, using integrated geo-migration models. These models account for the barrier properties of the geological environment in both the near and far fields of the RAW facility, combined with dose models. The general formula is as follows:

$$Dose_{Rn\ GW} = C_{Rn\ Source} \times CRF_{Rn\ Eng} \times CCF_{Rn\ Source} \times CRF_{Rn\ Aq} \times DCF_{Rn\ GW},$$

where: $Dose_{Rn\ GW}$ – dose to a representative person from the radionuclide due to consumption of groundwater from a well in the zone influenced by the RAW facility (Sv/year); $CRF_{Rn\ Eng}$ – coefficient describing the reduction in radionuclide concentration within the disposal facility due to decay during the period when engineering barriers remain intact and prevent infiltration of atmospheric water into the RAW (dimensionless); $CRF_{Rn\ Aq}$ – coefficient accounting for the reduction in radionuclide concentration in the aquifer during migration from the facility to the well used as a water supply source (dimensionless), $DCF_{Rn\ GW}$ – dose coefficient describing the radiation dose to a representative person from consuming water from a well with a radionuclide concentration of 1 Bq/m³ ((Sv/year)/(Bq/m³)).

The coefficients $CRF_{Rn\ Aq}$ can be calculated using the regional groundwater flow model of the Exclusion Zone, following a methodology analogous to that used for constructing the $CRF_{Rn\ UZ}$. Examples of calculating the dose coefficients $DCF_{Rn\ GW}$ are provided in (IAEA, 2005; Zanoz et al., 2022).

4. Conclusions

The set of methods we applied based on the analysis of groundwater level dynamics and the calculation of chloride-ion balance in groundwater and atmospheric precipitation, yielded consistent values for the key hydrogeological safety assessment parameter – groundwater recharge rate – at the sites of the "Buryakivka" RWDF and "Vector" IC in the Chornobyl Exclusion Zone, in the range of (55–65) ± 15 mm/year. The consistency of these estimates was confirmed by calibrating the regional groundwater flow model of the Exclusion Zone. The obtained groundwater recharge rate estimates allowed for the assessment of the barrier properties of the vadose zone soils concerning the migration of Chornobyl-origin radionuclides and those present in NNEGC "Energoatom" RAW streams planned for disposal within the study site. The screening analysis showed that the primary risks of groundwater contamination are associated with ^{90}Sr, ^{3}H and ^{14}C. For these radionuclides, the migration time through the vadose zone and the concentration reduction factors in groundwater were estimated using a subsurface transport model that accounts for advection, dispersion, sorption, and radioactive decay. It was demonstrated that for ^{90}Sr, an effect of increasing predicted concentrations in groundwater at the vadose zone outflow boundary is observed with an increase in the dispersivity parameter. This effect needs to be considered when selecting conservative geochemical migration parameter values for this radionuclide in RAW disposal safety assessments. The calculated coefficients ($CRF_{Rn\ UZ}$, $CCF_{Rn\ Source}$) can be used in integrated geo-migration models that consider the barrier properties of the geological environment in the near and far field of a RAW disposal facility, in conjunction with dose models, for calculating waste acceptance criteria for disposal.

The presented research was conducted within the framework of the research theme of Institute of Geological Sciences of the National Academy of Sciences of Ukraine III-11–24 "Combined approaches based on machine learning methods and physics-based models for the analysis of monitoring data and predicting geo-migration processes".

У роботі наведено оцінки інфільтраційного живлення підземних вод за рахунок атмосферних опадів і проаналізовано захисні властивості зони аерації щодо затримки й ослаблення міграції радіонуклідів у районі пункту захоронення радіоактивних відходів (ПЗРВ) «Буряківка» та комплексу виробництв (КВ) «Вектор» у Чорнобильській зоні відчуження. Розуміння закономірностей інфільтраційного живлення, фільтрації підземних вод і міграції радіонуклідів поблизу цих об'єктів є критично важливим для проведення оцінок безпеки захоронення та зберігання відходів. Територія дослідження розміщена у межах Чистогалівської моренної гряди та характеризується наявністю безнапірного водоносного горизонту у четвертинних відкладах, який живиться переважно атмосферними опадами. Для оцінки інфільтраційного живлення підземних вод застосовано комплекс методів. У результаті аналізу динаміки рівнів ґрунтових вод і балансу хлор-іону у підземних водах та атмосферних опадах отримано узгоджені значення інфільтраційного живлення в діапазоні (55–65) ± 15 мм/рік. Коректність наведених оцінок підтверджено калібруванням регіональної фільтраційної моделі. Одержані оцінки інфільтраційного живлення застосовано для оцінки бар'єрних властивостей ґрунтів зони аерації щодо міграції чорнобильських і присутніх у потоках радіоактивних відходів (РАВ) НАЕК «Енергоатом» радіонуклідів. Розрахунки виконано з використанням міграційних моделей, що враховують адвекцію, дисперсію, сорбцію та радіоактивний розпад. Скринінговий аналіз показав, що основні ризики забруднення підземних вод обумовлені ^{90}Sr, ^{3}H та ^{14}C. Для зазначених радіонуклідів оцінено час міграції в ґрунтах зони аерації та коефіцієнти зниження концентрації в підземних водах за рахунок перелічених вище врахованих у моделі геоміграційних механізмів. Отримані розрахункові параметри можуть бути використані в інтегрованих геоміграційних моделях, що враховують бар'єрні властивості геологічного середовища в ближній та дальній зонах сховища РАВ у комплексі з дозовими моделями для розрахунку критеріїв приймання РАВ на захоронення.

References

Allison G.B., and Hughes M.W. 1978. The Use of Environmental Chloride and Tritium to Estimate Total Recharge to an Unconfined Aquifer. *Australian Journal of Soil Research,* 16, 181–195. http://dx.doi.org/10.1071/SR9780181

Antropov V.M., Bugai D.A., Dutton L.M.C., Gerchikov M.Y., Kennett E.J., Ledenev A.I., Novikov A.A., Rudko V., Ziegenhagen J. 2001. Review and analysis of solid long-lived and high-level radioactive waste arising at the Chernobyl Nuclear Power Plant and the Exclusion Zone. EUR 198197 EN. NNC Ltd, Manchester. https://doi.org/10.13140/RG.2.2.31635.17442/1

Baes C.F., and Sharp R.D. 1983. A Proposal for Estimation of Soil Leaching and Leaching Constants for Use in Assessment Models. *Journal of Environmental Quality,* 12 (1), 17–28. https://doi.org/10.2134/jeq1983.00472425001200010003x

Bugai D., Avila R. 2020. Scenarios and Pathways of Radionuclide Releases from Near-Surface Waste Disposal Facilities: A Brief Overview of Historical Evidence. *Nuclear and Radiation Safety,* 3 (87), 21–27. https://doi.org/10.32918/nrs.2020.3(87).03

Bugai D., Dewiere L. 2004. Geological structure and hydrogeological conditions of the Chernobyl Pilot Site. Rapport DEI/SARG n° 04-16., Institute for Radioprotection and Nuclear Safety, Fontenay-aux-Roses, France. https://doi.org/10.13140/RG.2.1.4992.1048

Bugai D., Skalskyy A., Dzhepo S., Kubko Yu., Kashparov V., Van Meir N., Stammose D., Simonucci C., Martin-Garin A. 2012. Radionuclide migration at experimental polygon at Red Forest waste site in Chernobyl zone. Part 2: Hydrogeological characterization and groundwater transport modeling. *Applied Geochemistry,* 27 (7), 1359–1374. https://doi.org/10.1016/j.apgeochem.2011.09.028

Bugai D., Skalskyy A., Haneke K., Thierfeldt S., Nitzsche O., Tretyak A., Kubko Yu. 2017. Groundwater monitoring and modelling of the Vector site for near-surface radioactive waste disposal in the Chernobyl Exclusion Zone. *Nuclear Physics and Atomic Energy,* 18 (4), 382–389. https://doi.org/10.15407/jnpae2017.04.382

Bugai D., Smith J., Hoque M. 2020. Solid-liquid distribution coefficients (Kd-s) of geological deposits at the Chernobyl Nuclear Power Plant site with respect to Sr, Cs and Pu radionuclides: A short review. *Chemosphere,* 242, 125175, ISSN 0045-6535. https://doi.org/10.1016/j.chemosphere.2019.125175

Bugai D.A., Fourre E., Jean-Baptiste P., Dapoigny A., Baumier D., C. Le Gal La Salle, Lancelot J., Skalskyy A.S., Van Meir N. 2010. Estimation of groundwater exchange at Chernobyl site using the data of the isotope dating and hydrogeological modeling. *Geologičnij žurnal,* 4 (333), 119–124 (in Ukrainian).

De Salve M., Testoni R., Levizzari R. 2014. Radionuclides Transport Phenomena in Vadose Zone. *International Journal of Physical, Nuclear Science and Engineering,* 8 (3), 31–37.

Dzhepo S., Skalskyy A. 2002. Radioactive contamination of groundwater within the Chernobyl Exclusion Zone. In: Shestopalov V. (Ed.), *Chernobyl disaster and groundwater.* A.A. Balkema Publishers, pp. 25–70.

Energoproject. 1996. Report on engineering and hydrogeological investigations in the area of the villages Lelev, Chistogalovka, and Buryakivka (for the adjustment of the working design of the monitoring network for radiological monitoring of the right-bank area) (in Russian).

Freeze R.A., Cherry J.A. 1979. Groundwater. Prentice-Hall, Englewood Cliffs, New Jersey. 604 p.

Gumuła-Kawęcka A., Jaworska-Szulc B., Szymkiewicz A., Gorczewska-Langner W., Pruszkowska-Caceres M., Angulo-Jaramillo R., Šimůnek J. 2022. Estimation of groundwater recharge in a shallow sandy aquifer using unsaturated zone modeling and water table fluctuation method. *Journal of Hydrology,* 605, 127283. https://doi.org/10.1016/j.jhydrol.2021.127283

Healy R.W., Cook P.G. 2002. Using groundwater levels to estimate recharge. *Hydrogeology Journal,* 10, 91–109. https://doi.org/10.1007/s10040-001-0178-0

IAEA. 2001. Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment. Safety Reports Series No. SRS-19. International Atomic Energy Agency, Vienna.

IAEA. 2002. Scientific and Technical Basis for the Near Surface Disposal of Low and Intermediate Level Waste. Technical Reports Series No. TRS-412. International Atomic Energy Agency, Vienna.

IAEA. 2003. Derivation of Activity Limits for the Disposal of Radioactive Waste in Near Surface Disposal Facilities. IAEA-TECDOC-1380. International Atomic Energy Agency, Vienna.

IAEA. 2004a. Safety Assessment Methodologies for Near Surface Disposal Facilities. Results of a co-ordinated research project. 1. Review and enhancement of safety assessment approaches and tools. International Atomic Energy Agency, Vienna.

IAEA. 2004b. Safety Assessment Methodologies for Near Surface Disposal Facilities. Results of a co-ordinated research project. 2. Test cases. International Atomic Energy Agency, Vienna.

IAEA. 2005. Derivation of Activity Concentration Values for Exclusion, Exemption and Clearance. Safety Report Series No. SRS-44. International Atomic Energy Agency, Vienna.

IAEA. 2010. Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments. Technical Reports Series No. TRS-472. International Atomic Energy Agency, Vienna.

IAEA. 2011. Disposal of Radioactive Waste. Safety Standards Series No. SSR-5. International Atomic Energy Agency, Vienna.

IAEA. 2012. The Safety Case and Safety Assessment for The Disposal of Radioactive Waste. Safety Standards Series No. SSG-23. International Atomic Energy Agency, Vienna.

IAEA. 2019. Environmental Impact Assessment of the Drawdown of the Chernobyl NPP Cooling Pond as a Basis for Its Decommissioning and Remediation. IAEA-TECDOC-1886, International Atomic Energy Agency, Vienna.

IAEA. 2023. User Manual for Normalysa V.2.3. Description Of Program Module Libraries, Mathematical Models and Parameters. Modelling And Data for Radiological Impact Assessments (Modaria) Programme. IAEA-TECDOC-2037. International Atomic Energy Agency, Vienna.

IGS. 1998. Operational and forecast assessments of the radio-hydrogeological conditions of the Exclusion Zone and development of recommendations for improving groundwater monitoring. Institute of Geological Sciences, NAS of Ukraine, Kyiv: Institute of Geological Sciences of the NAS of Ukraine. 247 p. (in Ukrainian).

Karamushka, V., Kuchma, T., Boychenko, S., Nazarova, O. 2023. Climate change and fires in the Ukrainian Polissia region. 17th International Conference "Monitoring of Geological Processes and Ecological Condition of the Environment", European Association of Geoscientists & Engineers, Kyiv, Ukraine, Nov. 2023, pp. 1–5. https://doi.org/10.3997/2214-4609.2023520235

Khilchevskyi V.K., Kurylo S.M., Sherstyuk N.P., Zabokrytska M.R. 2019. The chemical composition of precipitation in Ukraine and its potential impact on the environment and water bodies. *Journal of Geology, Geography and Geoecology,* 28 (1), 79–86. https://doi.org/10.15421/111909

Lisichenko G., Shteinberg M., Chumak D., Prokip A., Shutyak S., Maskalevich I., Vasilkivskiy B. 2017. The Ukrainian Nuclear Industry: Expert review. Bellona, Oslo, Norway. 118 p.

Lykhovyd P. 2020. Reference Evapotranspiration Calculation in the Zone of Ukrainian Polisia Using Air Temperature. *Biosc. Biotech. Res. Comm.,* 13 (4), 1834–1836. http://dx.doi.org/10.21786/bbrc/13.4/29

Matoshko A., Bugai D., Dewiere L., Skalskyy A. 2004. Sedimentological study of the Chernobyl NPP site to schematize radionuclide migration conditions. *Environmental Geology,* 46, 820–830. https://doi.org/10.1007/s00254-004-1067-3

Matsala M., Bilous A., Myroniuk V., Holiaka D., Schepaschenko D., See L., Kraxner F. 2021. The Return of Nature to the Chernobyl Exclusion Zone: Increases in Forest Cover of 1.5 Times Since the 1986 Disaster. Forests, 12, 1024. https://doi.org/10.3390/f12081024

McLin S.G., Newman B.D., Broxton D.E. 2005. Vadose Zone Characterization and Monitoring Beneath Waste Disposal Pits Using Horizontal Boreholes. *Vadose Zone Journal,* 4 (3), 774–788. https://doi.org/10.2136/vzj2004.0106

NRC. 2024. Licensing Requirements for Land Disposal of Radioactive Waste. Title 10, Code of Federal Regulations, Part 61 (10 CFR Part 61). Washington, D.C.: U.S. Nuclear Regulatory Commission.

SAEZM. 2024. Safety Analysis Report for the Design Stage of Storage Facility No. 11A at the "Buryakivka" Radioactive Waste Disposal Point in the Kyiv Oblast Exclusion Zone. Report No. 3B-III.6-05.0.142-2024. Chornobyl: State Agency of Ukraine on Exclusion Zone Management (in Ukrainian).

SAR-302. 2007. Safety Analysis Report for ENSDF. Chapter 2. Site Characterization of the Storage Facility. Nuclear Power Plant Operation Support Institute. Kyiv, 2007. 66 p. (in Russian).

Saxton K.E., Rawls W.J. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal,* 70 (5), 1569–1578. https://doi.org/10.2136/sssaj2005.0117

Skalskyy A.S., Kubko Yu.I. 2001. Filtration models of the ChNPP area. In: *Water exchange in hydrogeological structures and the Chernobyl disaster. Part 2: Modelling of water exchange and radionuclide migration in hydrogeological structures.* Kyiv: IGS of the NAS of Ukraine, pp. 462–494 (in Russian).

TACIS. 1995. Siting of Storage and Disposal Facilities. Report on Project "Management of Radioactive Waste in Dumps in Chernobyl Exclusion Area". TACIS Project UR/029, Document No. 3100/BK/03.0001/01.

Vanderborght J., Vereecken H. 2007. Review of dispersivities for transport modeling in soils. *Vadose Zone Journal,* 6 (1), 29–52. https://doi.org/10.2136/vzj2006.0096

Zachara J.M., Serne J., Freshley M., Mann F., Anderson F., Wood M., Jones T., Myers D. 2007. Geochemical Processes Controlling Migration of Tank Wastes in Hanford's Vadose Zone. *Vadose Zone Journal,* 6 (4), 985–1003. https://doi.org/10.2136/vzj2006.0180

Zanoz B.Yu., Bugai D.O., Koliabina D.O., Avila R. 2022. Assessments of radiological and toxicological risks from the use of groundwater and surface water in the zone of influence of the uranium production legacy site. *Nuclear Physics and Atomic Energy,* 23 (4), 271–279. https://doi.org/10.15407/jnpae2022.04.271