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## Radioactive Contamination of Groundwater in the Chernobyl Exclusion Zone: Current Status, Long-Term Trends, and Challenges in Monitoring System Modernization

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**Радіоактивне забруднення підземних вод у Чорнобильській зоні відчуження: сучасний стан, довгострокові тенденції та актуальні питання модернізації системи моніторингу**

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**Keywords:** Chernobyl Exclusion Zone, groundwater contamination, strontium-90, radionuclide migration, monitored natural attenuation, groundwater monitoring, radioactive waste disposal sites.

**Ключові слова:** Чорнобильська зона відчуження, забруднення підземних вод, стронцій-90, міграція радіонуклідів, моніторинг природного самоочищення, моніторинг підземних вод, пункти захоронення РАВ.

Groundwater contamination by radionuclides in the Chernobyl Exclusion Zone (CEZ) has been recognized since the early post-accident period (i.e., May – June 1986), when large-scale protective measures were implemented, as a potential pathway for the transport of radioactivity to the river network of the Pripyat–Dnipro basin. This study reviews long-term monitoring data and research results on radioactive contamination of groundwater in the CEZ, with particular attention to spatial patterns, temporal trends, and implications for monitoring and management strategies. Analysis of monitoring datasets for the period 1989–2024 shows that  $^{90}\text{Sr}$  remains the primary contaminant of concern in groundwater, with concentrations locally reaching  $10^5$ – $10^6$  Bq  $\text{m}^{-3}$  in areas influenced by radioactive waste burial sites and contaminated water bodies. In contrast,  $^{137}\text{Cs}$  concentrations in groundwater are generally low, typically below 100 Bq  $\text{m}^{-3}$  and well below the drinking water standard. Long-term trends indicate an overall stabilization and gradual decline of  $^{90}\text{Sr}$  concentrations in the majority of monitoring wells over the last decade, reflecting depletion of the source term and natural attenuation processes in the vadose zone and aquifer.

These observations, together with the results of modelling analyses reviewed in this paper, support the strategy of monitored natural attenuation (MNA) as an appropriate approach for managing contaminated groundwater in the CEZ, provided that reliable monitoring demonstrates plume stability and acceptable risk levels for potential receptors, including the Pripyat River. At the same time, the existing groundwater monitoring system has several limitations related to monitoring well design, spatial coverage, and sampling methodologies. Results from detailed polygon field studies show that higher radionuclide concentrations may occur in specific hydro-geological zones that are not adequately captured by the current monitoring network.

The paper discusses priorities for modernization of the groundwater monitoring system in the CEZ, including optimization of monitoring objectives, improvement of monitoring well design and sampling methods, integration of geochemical and radiological observations, and development of updated methodological guidance. Modernization of the monitoring system will enable more reliable assessment of contaminant migration and provide a stronger scientific basis for long-term management of radioactive groundwater contamination in the CEZ.

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## 1. Introduction

Radioactive contamination of groundwater in the Chernobyl Exclusion Zone (CEZ) has been considered, since the first days following the Chernobyl accident, as a potentially significant pathway for the off-site transport of radionuclides to the river network and to downstream territories within the Dnipro River basin (IAEA, 1999, 2006a; Sobotovich, Olshtinsky, 1992). Sources of radioactivity within the CEZ include the Chernobyl NPP industrial site with the Shelter Object (SO), currently covered by the New Safe Confinement (NSC), engineered radioactive waste disposal facilities (RWDF), trench-type near-surface radioactive waste burial sites (such as the Red Forest site), areas with surface contamination of topsoil by radioactive fallout, and contaminated water bodies such as the ChNPP cooling pond (Antropov et al., 2001; IAEA, 2006a).

The hydrogeological conditions of the CEZ, which is characterized by a moderately humid continental climate (precipitation about 600 mm/y), relatively flat topography, sandy and permeable surficial Quaternary deposits, and a shallow groundwater table (e.g., often only 1–2 m deep in river floodplain and terrace areas), generally promote radionuclide migration into the groundwater system (Bugai et al., 1996a, 2022). Trends toward warmer conditions, increased evapotranspiration, and higher hydroclimatic variability have become increasingly evident in recent decades (Matsala et al., 2021; Boychenko et al., 2025). However, these changes have not yet resulted in significant (e.g., 1 m or more) shifts in mean multi-annual groundwater levels. A detailed description of the site geology and hydrogeology can be found in Dzhepo and Skalskyy (Dzhepo, Skalskyy, 2002) and Matoshko (Matoshko, 1995, 1996; Matoshko et al., 2004).

To protect the Pripjat River from radioactively contaminated groundwater, large-scale protective measures were implemented in May–June 1986. These included drainage barriers consisting of hundreds of interception wells and the construction of a clay cut-off wall (slurry wall) around the Chernobyl Nuclear Power Plant. Later, these measures were recognized as excessive: the drainage barriers were never put into operation and were subsequently dismantled (IAEA, 1999; Voitsekho-vych et al., 2007).

Modelling studies conducted during the first decade after the accident indicated relatively low releases of radioactivity from contaminated catchments within the Exclusion Zone to the Dnipro River

system, suggesting that large-scale and costly water-protection measures were not justified (Bugai et al., 1996a). At the same time, particular attention was focused on the ChNPP cooling pond, as seepage from this reservoir represented one of the main sources of  $^{90}\text{Sr}$  contamination of the Pripjat River (IAEA, 2019). In addition, intensive migration of radionuclides to groundwater was identified at the so-called radioactive waste temporary storage sites (RWTSS)—trench-type radioactive waste burial sites created during the emergency response and cleanup operations in the near zone of the ChNPP (Il'ichev, Akhunov, 1992; Dzhepo, Skalskyy, 2002). Concerns were also raised regarding the potential migration of radionuclides into groundwater from highly contaminated soils at the ChNPP industrial site and from the Shelter Object (Panasiuk et al., 1999; Shestopalov et al., 2002).

In recent decades, several measures have been implemented that have improved the protection of groundwater from radioactive contamination in the near zone of the ChNPP. In particular, the drainage of the cooling pond in 2014 resulted in a decline in groundwater levels at the ChNPP industrial site and at the locations of the RWTSS (IAEA, 2019). In addition, the construction of the New Safe Confinement in 2016 over the destroyed Unit 4 significantly reduced the infiltration of atmospheric precipitation into the Shelter Object, thereby decreasing the potential for radionuclide leaching. A recent statistical analysis of groundwater monitoring data from a set of representative monitoring wells revealed a prevailing trend toward stabilization and decline of radioactive contamination levels in groundwater at most facilities within the Exclusion Zone (Bugai et al., 2022).

At the same time, groundwater monitoring in the CEZ remains an important task for ensuring compliance with licensing requirements for radioactive waste storage and disposal facilities, such as the Buryakivka RWDF and the Vector complex, as well as for providing information needed to support strategies for the management of contaminated groundwater based on monitoring of natural attenuation processes (MNA). Groundwater monitoring is also of significant scientific interest, as the Chernobyl Exclusion Zone represents a unique “open-air laboratory” for investigating the processes controlling the long-term migration and fate of radionuclides in soils and groundwater systems (Smith, Beresford, 2005; IAEA, 2006a; Bondarkov et al., 2011; Beresford et al., 2016).

The aim of this article is to review and analyse available data on radioactive contamination of groundwater in the Chernobyl Exclusion Zone, including an extended analysis of long-term trends in radionuclide concentrations. The paper also evaluates the objectives of groundwater monitoring, identifies key limitations and gaps in the existing monitoring system, and discusses priorities for its further development and improvement.

## 2. Data sources

### 2.1 Groundwater monitoring programmes

The principal source of information on radioactive contamination of groundwater in the CEZ is provided by groundwater monitoring programmes implemented by the State Specialized Enterprises (SSE) “Ecocenter” and “ChNPP”.

The main groundwater monitoring programme in the CEZ is implemented by Ecocenter and includes approximately 150 monitoring wells (Fig. 1). The monitoring network covers major potential sources of groundwater contamination, including RWTSS, the RWDF Pidlisnyi and “3rd Stage ChNPP”, the ChNPP cooling pond and Lake Azbuchyn, the Pripyat town area (within the floodplain and the first terrace of the Pripyat River), the Buryakivka RWDF, and the surroundings of former villages of Kopachi and Chystohalivka located within the fluvioglacial Chystohalivsky moraine ridge. The sampling frequency of monitoring wells varies from monthly to once every six months. Radiological analyses are carried out on unfiltered samples (Kireev et al., 2013; Bugai et al., 2022).

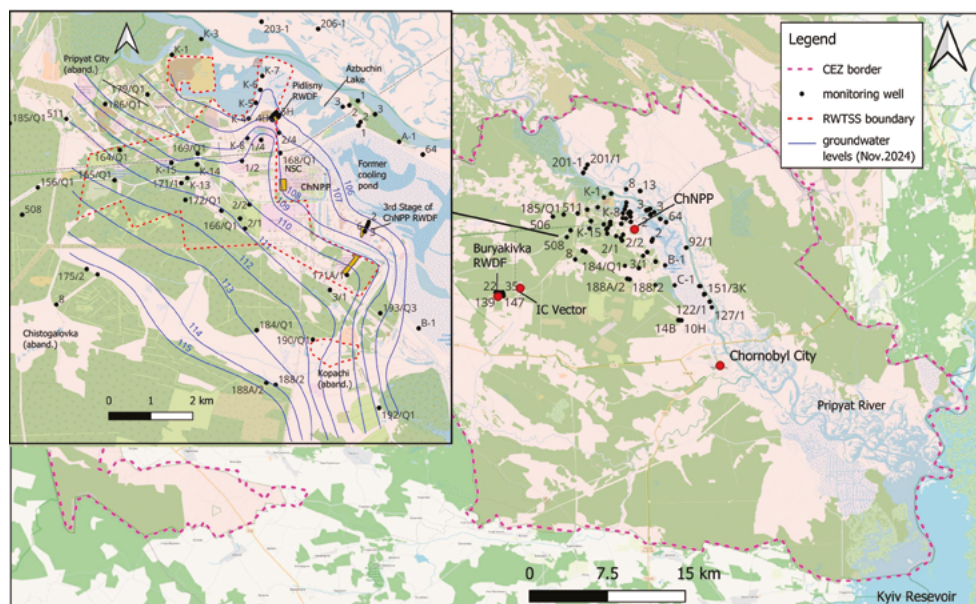
The main groundwater monitoring network of Ecocenter in the ChNPP near zone was constructed in 1989–1991. These include wells numbered 1/1, 1/1-D, 2/2, etc., as well as K-1, K-2, etc. (see Fig. 1). In 1995–1997, the observation well network in the ChNPP near zone was expanded using wells of a more modern design with PVC casing columns and shorter (2–3 m) screens (wells of series 160, 170, 180, and 190). These wells allowed a partial expansion of monitoring observations to peripheral areas of the RWTSS, the city of Pripyat, and the village of Kopachi.

Importantly, the 1989–1991 wells, which still constitute the core of the monitoring network of the Ecocenter, have several design flaws that do not meet modern standards, including:

- use of casing made from corrodible material (iron);
- long 12 m screens, which promote vertical mixing and crossflows;
- lack of proper sealing of the wellhead and screened interval.

The ChNPP monitoring programme includes approximately 120 wells located within the Chernobyl NPP industrial site and the New Safe Confinement – Shelter Object (NSC–SO) complex, where sampling is conducted once per month.

The groundwater monitoring system at ChNPP industrial site was installed in 1989 and was initially based on wells with iron casing with 12 m long screens. However, this system has undergone several modernizations, and as of 2024, the wells of outdated design were replaced with individual wells or multi-level well clusters with PVC casing and 2–3 m long screens.



**Fig. 1.** Overview maps of the groundwater monitoring network of the SSE Ecocenter in the Chernobyl Exclusion Zone

For both monitoring programmes, the main monitored parameters are groundwater levels and concentrations of  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  in groundwater.

Over the last decade, the EcoCenter monitoring programme has effectively become the only continuous source of data on the dynamics of radioactive groundwater contamination in the CEZ at the site-scale, and these data form the main basis for the analysis presented in this paper.

## 2.2 Experimental field studies and site investigations

Additional information on groundwater contamination processes has been obtained from experimental field studies (“polygon studies”) conducted primarily by the Institute of Geological Sciences (IGS) during 1995–2015. In 1995–1998, IGS established a network of small-diameter wells (1–2 inches) screened in the upper part of the unconfined Quaternary aquifer in the near zone of the Chornobyl NPP, comprising more than 100 observation points. These investigations enabled the development of a detailed map of  $^{90}\text{Sr}$  contamination in groundwater (Dzhepo, Skalsky, 2002). However, monitoring within this network was subsequently discontinued.

In 1999–2001, IGS together with the University of British Columbia (Canada) conducted investigations in the experimental catchment of the Borshchi stream located in the near zone of the ChNPP, with particular attention to groundwater contamination processes (Freed et al., 2004).

Later, during 2000–2015, IGS in cooperation with the French Institute for Radiological Protection and Nuclear Safety (IRSN) and the Ukrainian Institute of Agricultural Radiology carried out detailed monitoring studies at the experimental site near trench No. 22 of the “Red Forest” RWTSS (Van Meir et al., 2009; Bugai et al., 2012a). These studies provided detailed information on hydrogeological parameters, including infiltration recharge and groundwater flow velocities, as well as geochemical parameters, such as radionuclide ( $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$ ) sorption coefficients (Kd). The investigations also resulted in the development of conceptual and numerical models of radionuclide migration processes (Bugai et al., 2012a; Le Coz et al., 2023).

In addition, one-time groundwater surveys were conducted by various organizations during the characterization of radioactive waste trenches within RWTSS sectors (Il'ichev, Akhunov, 1992; Ledenev et al., 1995; Bugai et al., 2020).

In 1996–2017, extensive groundwater investigations at the Shelter Object area were carried out by the Institute for Safety Problems of Nuclear Power Plants (ISPNNP) (Litvin et al., 2016; Panasiuk et al., 2018, 2019).

However, experimental polygon-type investigations in the near zone of the ChNPP have largely ceased during the past decade. The only recent example is a small research project on  $^{137}\text{Cs}$  in groundwater initiated by Kyoto University (Fujikawa et al., 2024).

Comparison of the results of these experimental studies with the EcoCenter monitoring data presented below indicates that the current monitoring system has several limitations, highlighting the need for further improvement and modernization of groundwater monitoring in the CEZ.

## 3. Overview of groundwater monitoring data and modelling studies

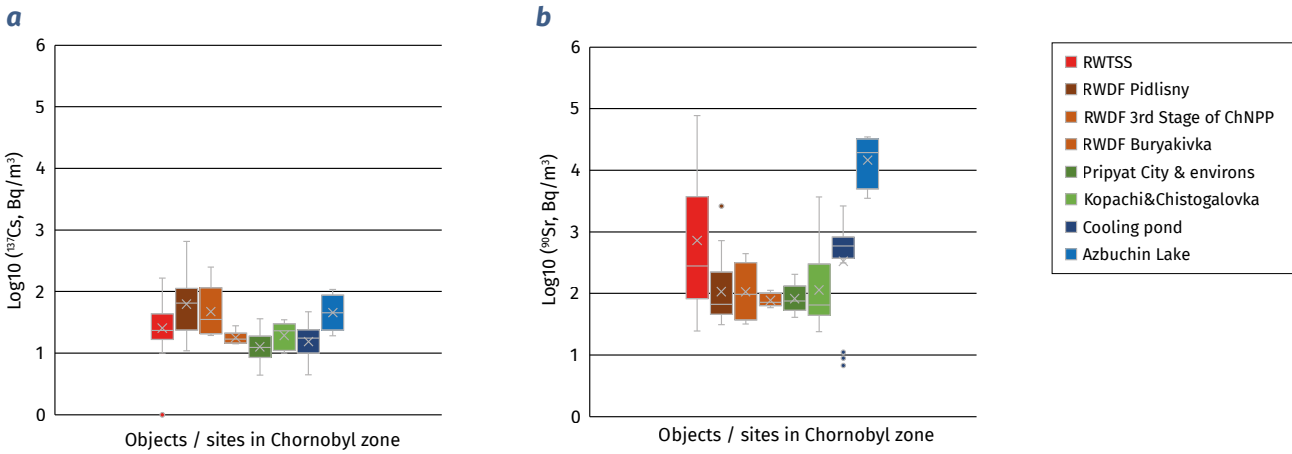
### 3.1 Radioactive contaminants of concern

Data on groundwater monitoring in the CEZ during the post-accident period are summarized in Bugai et al. (Bugai et al., 1996a, 2022), Dzhepo and Skalsky (Dzhepo, Skalsky, 2002), Kireev (Kireev et al., 2013, 2024), Panasiuk (Panasiuk et al., 2019), and Sato (Sato et al., 2023). A review of these sources, combined with the analysis of monitoring databases of SSE EcoCenter presented below, indicates that the main groundwater contaminant of concern in the CEZ is  $^{90}\text{Sr}$ . Its concentrations in groundwater at certain locations as of 2024 reached  $10^5$ – $10^6$  Bq/m<sup>3</sup>. For comparison, the permissible concentration of  $^{90}\text{Sr}$  in drinking water according to the Ukrainian regulatory standard GN 6.6.1.1-130-2006 (DR-2006) is 2000 Bq/m<sup>3</sup> (see Fig. 2a).

Concentrations of  $^{137}\text{Cs}$  in groundwater in the CEZ at most monitoring sites of SSE EcoCenter, as of 2024, did not exceed 100 Bq/m<sup>3</sup>, which is about an order of magnitude lower than the regulatory standard GN 6.6.1.1-130-2006 (2000 Bq/m<sup>3</sup> for this radionuclide) (see Fig. 2b). Concentrations of plutonium isotopes and  $^{241}\text{Am}$  in groundwater in the CEZ are relatively low, typically below 1 Bq/m<sup>3</sup>, and therefore do not pose significant radiological risks.

Considering these observations, groundwater monitoring programmes in the CEZ have been primarily focused on measuring concentrations of  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$ .

The relatively high mobility of  $^{90}\text{Sr}$  in groundwater, compared with  $^{137}\text{Cs}$  and plutonium isotopes, has also been reported at other nuclear legacy sites, including the Sellafield site in the UK (Sellafield Ltd., 2017) and Chalk River Nuclear Laboratories in Canada (IAEA, 2004).



**Fig. 2.** Whisker plot of log-transformed radionuclide concentrations in groundwater in monitoring wells at different objects / sites in Chernobyl zone in 2024 (based on data of the SSE EcoCenter): a) <sup>137</sup>Cs activity in monitoring wells; b) <sup>90</sup>Sr activity in monitoring wells

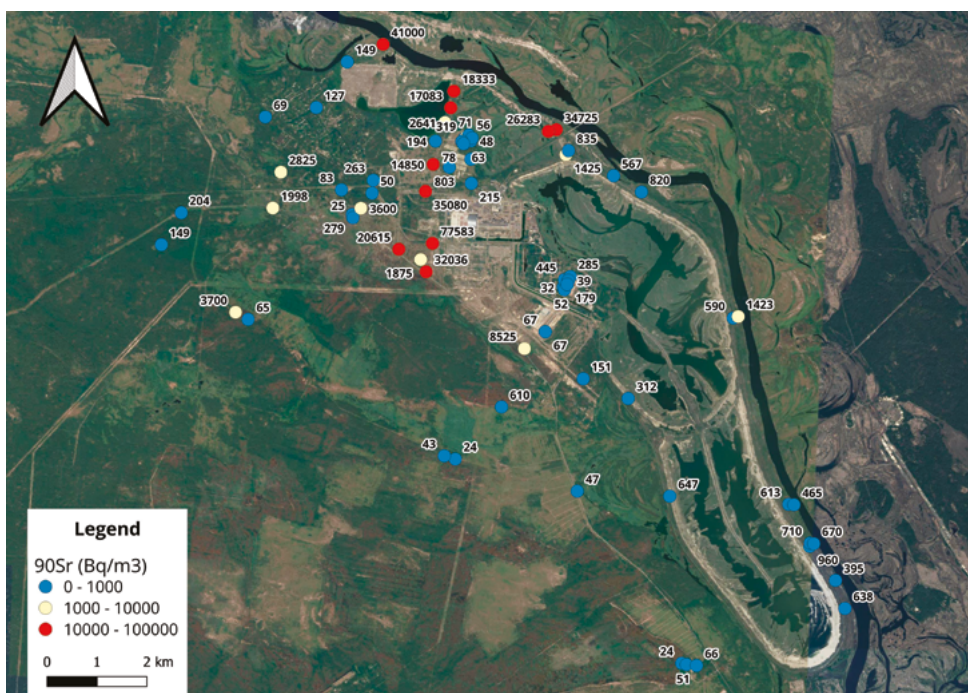
### 3.2 Spatial groundwater contamination patterns and hotspots

Groundwater concentrations of <sup>90</sup>Sr in monitoring wells of the SSE EcoCenter within the 10-km zone of the ChNPP showed high variability in 2024, ranging from 10<sup>2</sup> to 10<sup>5</sup> Bq/m<sup>3</sup> (see Fig. 3). In many wells, these concentrations exceeded the DR-2006 drinking water standard.

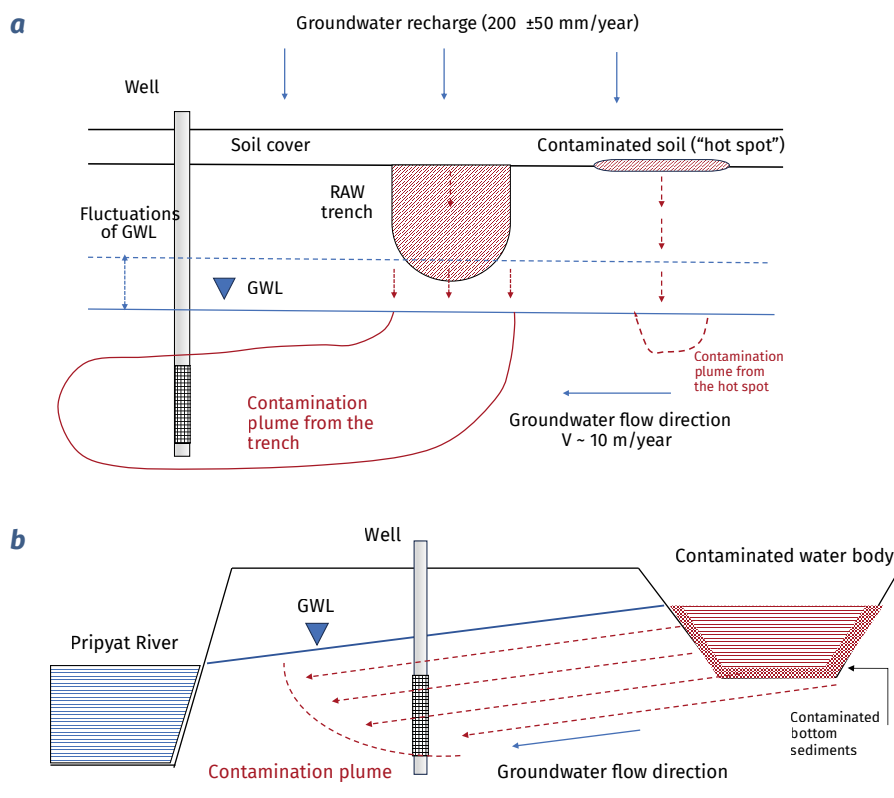
The variability of groundwater contamination by <sup>90</sup>Sr is evidently caused by differences in the types of radioactive sources influencing individual monitoring wells and by variations in hydrogeological conditions across the site. The following main types of contaminant sources can be distinguished:

radioactive waste trench storage sites (RWTS), contaminated surface water bodies, and contaminated soils. The highest levels of groundwater contamination by <sup>90</sup>Sr are observed in monitoring wells located within RWTS areas and in those influenced by seepage from contaminated water bodies (such as the former cooling pond and Lake Azbuchyn) (see Fig. 2b).

The conceptual model of radionuclide migration from trenches containing radioactive waste at RWTS sites is shown in Fig. 4a. During decontamination of the near zone of the ChNPP, trench areas were covered with a “clean” soil (sand) cap 0.5–1 m thick. In addition to the trenches themselves, residual “hot spots” of contaminated soil that were not completely



**Fig. 3.** Distribution of <sup>90</sup>Sr in groundwater in the ChNPP near zone in 2024 (yearly average values in wells; data of the SSE EcoCenter)



**Fig. 4.** Conceptual model of radionuclide migration to groundwater from trenches in RWTSS (a) and from contaminated water bodies into the Pripyat River (b)

removed during decontamination works (see Fig. 4a) may serve as additional sources of groundwater contamination in RWTSS sectors. Radionuclides are leached from the trenches and residual "hot spots" by precipitation and subsequently enter groundwater after migrating through soils of the vadose zone. Furthermore, some trenches may undergo temporary flooding by groundwater during wet seasons due to seasonal groundwater level fluctuations (Antropov et al., 2001). These mechanisms may create a complex "patchy" structure of groundwater contamination both laterally and vertically within the aquifer.

Water bodies located near the ChNPP – namely the cooling pond, river inlets, and floodplain lakes – experienced significant radioactive contamination during the accident. Over time, most radionuclide inventories in these water bodies have been redistributed from the water column to bottom sediments due to sorption and sedimentation processes.

The most contaminated water bodies in the near zone of the ChNPP include residual ponds within the former cooling pond basin and Lake Azbuchyn (see Fig. 1). Water levels in these water bodies are higher than the low-flow level of the Pripyat River, resulting in continuous head-driven seepage of contaminated water toward the river throughout the year.

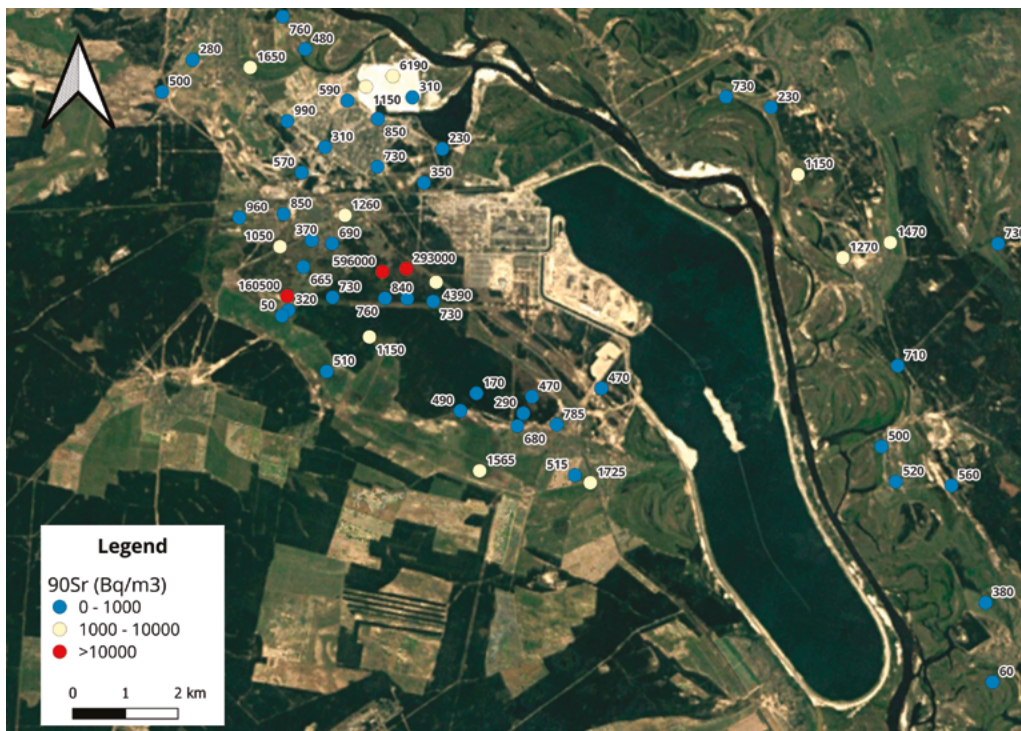
The conceptual model of radionuclide migration via groundwater pathways from contaminated water bodies into the Pripyat River is shown in Fig. 4b.

Due to water level differences of approximately 1–2 m between these floodplain water bodies and the Pripyat River, these areas are characterized by relatively high hydraulic gradients of groundwater flow. The floodplain sediments consist of highly permeable channel-facies quartz sands (hydraulic conductivity  $K = 12\text{--}15$  m/day) with low sorption capacity.  $^{90}\text{Sr}$  concentrations in seepage waters may increase when water passes through bottom sediments contaminated with fuel particles. A similar groundwater contamination mechanism was studied for the ChNPP cooling pond during its operation (IAEA, 2019).

These factors promote intensive migration of  $^{90}\text{Sr}$  in groundwater from contaminated water bodies, as confirmed by monitoring data from the SSE Ecocentre (see Fig. 2b, Fig. 3). These areas are characterized by the highest levels of groundwater contamination and therefore require particular attention in monitoring programs.

When the radionuclide source to groundwater is represented by contaminated surface soils, the unsaturated zone (vadose zone) acts as a protective barrier. Groundwater recharge within the Pripyat River terrace in the ChNPP near zone is estimated at  $200 \pm 50$  mm/year (Dzhepo, Skalsky, 2002; Bugai et al., 2012a).

Modeling of  $^{90}\text{Sr}$  migration through vadose-zone soils, accounting for retardation due to sorption, shows that even under minimal  $K_d$  values, a sandy vadose zone 4–5 m thick provides reliable



**Fig. 5.** Distribution of  $^{90}\text{Sr}$  in groundwater in the ChNPP near zone based on monitoring network of IGS (data for 1997) (IGS, 1998)

protection of groundwater against radioactive contamination throughout the period since the ChNPP accident. The presence of clay interlayers in the vadose zone further enhances groundwater protection. This conclusion is supported by monitoring observations at surface-contaminated sites, which show low levels of groundwater contamination (see Fig. 2b).

Thus, radioactive contamination of groundwater via radionuclide migration from surface soils may represent a risk primarily in areas with a shallow groundwater table and in zones of potential focused infiltration of precipitation or technogenic water discharges.

Concentrations of  $^{137}\text{Cs}$  in groundwater in the vast majority of observation wells do not exceed  $100 \text{ Bq/m}^3$ , which is close to the analytical detection limit for this radionuclide in water samples (Fig. 2a). These concentrations are an order of magnitude lower than the DR-2006 drinking water standard. The mechanisms responsible for the presence of low levels of  $^{137}\text{Cs}$  in monitoring wells will be discussed in more detail in the next section.

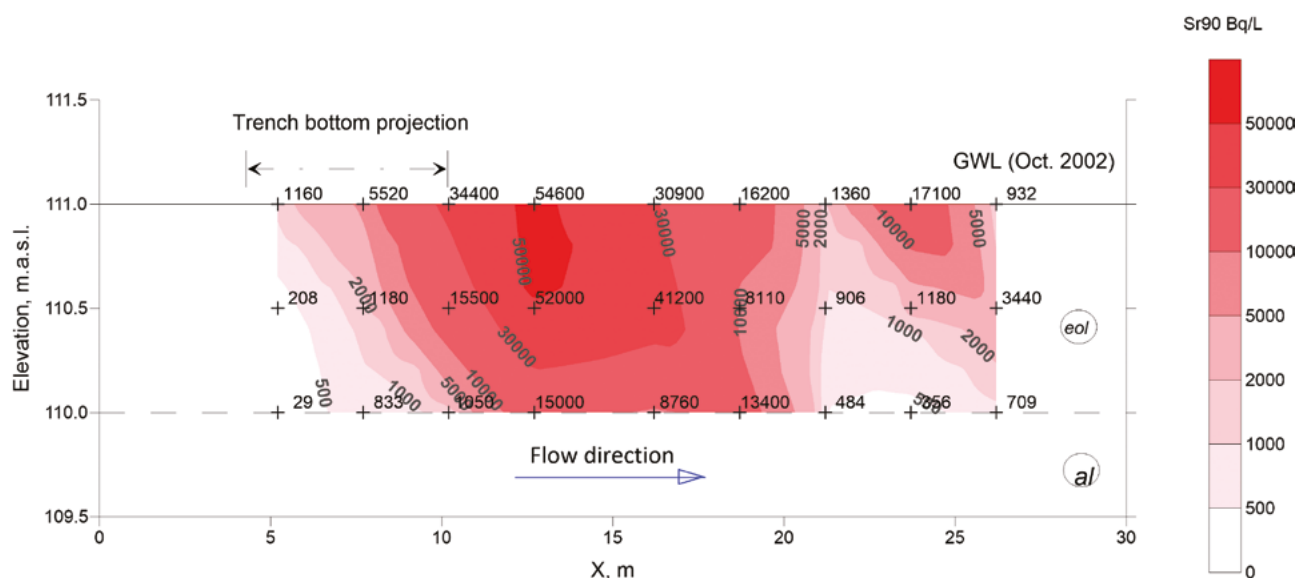
It should be noted that polygon field studies and groundwater surveys using small-diameter (1–2 inch) wells with short screens (0.5–1 m), as well as drill-auger sampling, often reported significantly higher  $^{90}\text{Sr}$  concentrations in groundwater compared with the data obtained from the monitoring network of the SSE EcoCenter. Reported

concentrations reached up to  $10^6$ – $10^7 \text{ Bq/m}^3$  (Antropov et al., 2001; Van Meir et al., 2009; Bugai et al., 2012a, 2020).

Data on the distribution of  $^{90}\text{Sr}$  in the unconfined aquifer based on the monitoring network installed by the Institute of Geological Sciences (IGS), which sampled the upper part of the unconfined aquifer in Quaternary deposits in 1997, are shown in Fig. 5. The observed groundwater contamination levels within the RWTSS sectors and in areas affected by topsoil contamination are an order of magnitude higher than those reported by the EcoCenter monitoring network and presented in Fig. 3.

Example of the distribution of  $^{90}\text{Sr}$  in groundwater downstream of trench No. 22 at the Red Forest site, based on sampling using the Waterloo Profiler push-drill system, is shown in Fig. 6. It reveals a high-activity  $^{90}\text{Sr}$  plume, with concentrations of up to  $5 \times 10^7 \text{ Bq/m}^3$ , that has migrated approximately 10 m downgradient from the trench.

The lower  $^{90}\text{Sr}$  groundwater contamination levels reported from EcoCenter monitoring wells can be explained by several factors. The long 12 m well screens and the absence of proper sealing promote vertical cross-flow along the casing between the upper, more contaminated, and lower parts of the unconfined aquifer. As a result, water samples collected from such wells represent depth-averaged groundwater over a broad screened interval.



**Fig. 6.**  $^{90}\text{Sr}$  distribution in groundwater downstream from trench no.22 at Red Forest RWTSS characterized using the Waterloo Profiler push-drill sampler in October 2002 (data of the IGS)

Another problem is that the placement of monitoring wells within the RWTSS sectors is not aligned with the actual locations of contamination sources. This is because, at the time of well construction, the exact positions of individual RAW trenches were not known. Detailed surveys of the RWTSS sectors and field mapping of the trenches were carried out later. At the same time,  $^{90}\text{Sr}$  plumes are confined to the immediate vicinity of the trenches (see Fig. 6).

### 3.3 Time trends of radioactive contaminants in groundwater

Cumulative time series of  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  concentrations in groundwater for the period 1989–2024, compiled for groups of monitoring wells influenced by different source types (RWTSS, water bodies, and topsoil contamination), are shown in Fig. 7.

The  $^{137}\text{Cs}$  concentrations exhibit declining trends over the observation period for all subsets of monitoring wells. The measured values, except for few outliers, remain below the DR-2006 drinking water standard.

The  $^{90}\text{Sr}$  concentrations show an initially increasing trend during 1989–1995, followed by a period of relatively stable concentrations in 1995–2015, and then gradually decreasing trend over the last decade. In many wells  $^{90}\text{Sr}$  concentrations still remain orders of magnitude above the DR-2006 drinking water standard.

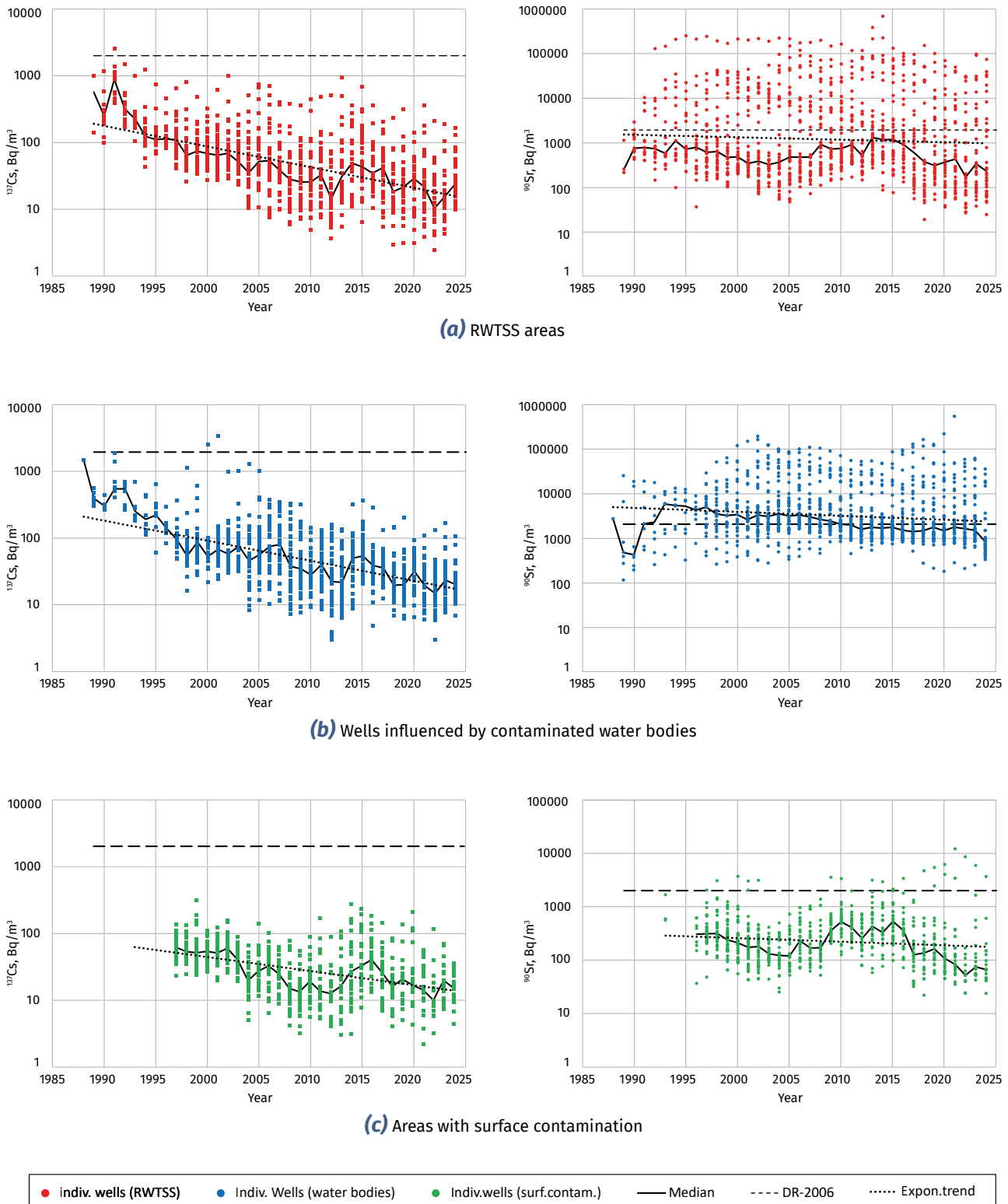
These long-term  $^{90}\text{Sr}$  trends are generally consistent with the conceptual model assuming release of  $^{90}\text{Sr}$  from the radioactive source-term, namely

micron-sized nuclear fuel particles, followed by migration through the vadose zone towards groundwater system (Kashparov et al., 2019).

The decreasing trends of  $^{137}\text{Cs}$  can be explained by contamination of monitoring wells with radioactive topsoil material introduced during drilling. This hypothesis is supported by the fact that  $^{137}\text{Cs}$  concentrations in groundwater do not show substantial variation among different source types (Fig. 8a) or between the upper and lower parts of the unconfined aquifer (Fig. 8b).

This interpretation is further supported by data of Dzhepo (Dzhepo et al., 1997), who reported the presence of low-mobility refractory radionuclides such as  $^{95}\text{Zr}$  and  $^{144}\text{Ce}$ , associated with nuclear fuel matrix, in groundwater samples collected in 1987 from monitoring wells installed at the cooling pond site. This observation indicates contamination introduced from the topsoil rather than true dissolved-phase transport in groundwater.

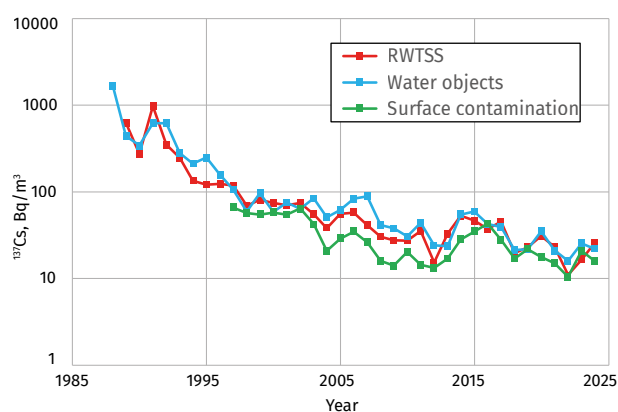
To examine radionuclide behaviour in individual monitoring wells of the SSE Ecocenter, trend analysis was carried out using the Mann–Kendall (MK) method (Aziz et al., 2003). The MK test assumes independence of observations and a monotonic trend. In this study, groundwater monitoring data were aggregated to annual values to reduce short-term variability and potential serial correlation. Given the slow response of the groundwater system and the long-term nature of the observed trends, these assumptions are considered acceptable for the purposes of the analysis. Prior to averaging, outliers were filtered from



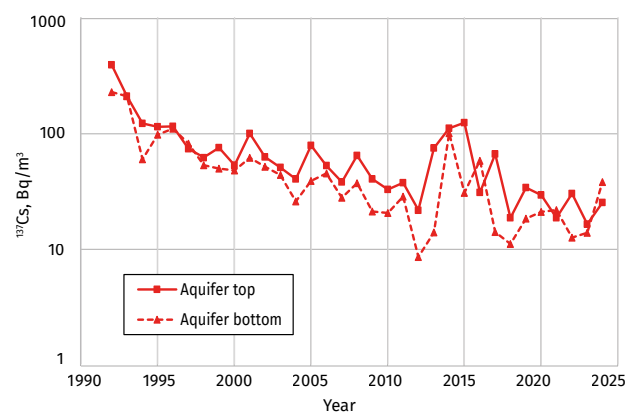
**Fig. 6.**  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$  concentrations in monitoring wells influenced by various types of sources of radioactivity (data of the SSE Ecocenter)

the observation series using the z-score method ( $2\sigma$  criterion). The analysis covered the last 10 years (2015–2024). The analyses were performed using the pyMannKendall Python library (<https://pypi.org/project/pymannkendall/>). Data from all 154 monitoring wells operated by the SSE

Ecocenter in the near zone of the ChNPP were analysed. The results of the analyses are presented in Table. Earlier, similar analyses had been carried out for a smaller subset of representative wells (74 wells) covering the period 2010–2019 (Bugai et al., 2022).



(a) Median  $^{137}\text{Cs}$  concentration in monitoring wells influenced by different source-terms of radioactivity



(b) Median  $^{137}\text{Cs}$  concentrations in wells sampling the top and the bottom parts of the unconfined aquifer in RWTSS

**Fig. 8.** Comparison of  $^{137}\text{Cs}$  concentrations in monitoring wells across contamination sources and aquifer depths (upper vs. lower unconfined aquifer)

**Table.** Summary results of Mann-Kendall trend analysis of radionuclide concentrations in groundwater monitoring wells in Chernobyl zone (2015–2024)

Site	$^{137}\text{Cs}$			$^{90}\text{Sr}$		
	No trend	Increase	Decrease	No trend	Increase	Decrease
RWTSS areas	31	–	8	21	1	17
RWDS Pidlisnyi	9	1	3	9	–	4
RWDS 3rd Stage of ChNPP	5	–	1	2	–	4
RWDS Buryakivka	8	–	1	9	–	–
Pripyat City and its environs (area with surface contamination)	10	–	5	8	–	7
Kopachi and Chistogalivka (area with surface contamination)	7	–	3	6	–	4
Cooling pond	43	–	5	38	1	9
Azbuchyn Lake	5	1	–	6	–	–
Left bank of Pripyat River	4	–	4	4	–	4
<b>TOTAL</b>	<b>122</b>	<b>2</b>	<b>30</b>	<b>103</b>	<b>2</b>	<b>49</b>

Only two wells for  $^{137}\text{Cs}$  and two wells for  $^{90}\text{Sr}$  out of 154 (<2%) show statistically significant increasing concentration trends. For  $^{137}\text{Cs}$ , 30 wells (20%) show decreasing concentrations, while 122 wells do not show a clear trend (e.g., concentrations fluctuate around a stable level and/or measurement uncertainty is large).

For  $^{90}\text{Sr}$ , 49 wells (32%) show decreasing trends, while for 103 wells no clear trend is observed.

Compared with the results for 2010–2019, the proportion of wells with increasing trends during the last decade has decreased: for  $^{137}\text{Cs}$  from 10% to 2%,

and for  $^{90}\text{Sr}$  from 7% to 2%. Overall, decreasing or relatively stable radionuclide concentrations dominate.

### 3.4 Overview of groundwater modelling studies

Considering the status of the CEZ, post-accident studies on forecasting the migration of radioactive contaminants in groundwater were mainly aimed at assessing the risks of radionuclide transport by groundwater to the Prypiat River, as well as the risks of contamination of the second-from-surface

confined aquifer within Eocene deposits, which is used for water supply at the ChNPP.

Screening assessments of  $^{90}\text{Sr}$  migration from contaminated soils in Exclusion Zone catchments were carried out in (Bugai et al., 1996a). Modeling studies of radionuclide migration from RWTSS facilities are presented in (Il'ichev, Akhunov, 1992; Consortium..., 1995; Mishunina et al., 1995; Bugai et al., 1996a, 2012a; Molitor et al., 2017). These studies demonstrated that groundwater migration of  $^{90}\text{Sr}$  and other radionuclides from Chernobyl fallout does not have the potential to cause unacceptable contamination levels in the Prypiat River that could pose risks to populations outside the CEZ. Similar conclusions were drawn from modelling radionuclide migration in groundwater from the Shelter Object (Kiva et al., 1996; Shestopalov et al., 2002).

Numerical modelling of  $^{90}\text{Sr}$  groundwater transport toward the Yaniv well field, which exploits the confined aquifer in Eocene deposits (Bugai et al., 1996b; Smith, Gaganis, 1998), showed that this aquifer is well protected from surface contamination sources by geological barriers, and that the risks of exceeding drinking-water standards are very low.

A key factor ensuring low risks of radionuclide transport in groundwater beyond the CEZ is radioactive decay during the retarded migration of radionuclides caused by sorption on geological deposits, which delays their movement from contamination sources to receptors. Radionuclide concentrations in groundwater are further reduced due to dilution (mixing) in discharge zones (e.g., abstraction wells or rivers), where only a relatively small fraction of inflow is represented by relatively “young” waters that may contain radionuclides. An additional dilution effect in surface waters occurs through mixing of groundwater discharge with “clean” river waters from uncontaminated parts of the catchment upstream (Bugai et al., 2022).

### 3.5 Strategy for managing contaminated groundwater

The radionuclide transport forecasts discussed above, together with the declining trends of  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  in surface water and groundwater of the CEZ, support the strategy of Monitored Natural Attenuation (MNA) for managing contaminated groundwater (Bugai et al., 2022).

MNA is a remediation strategy in which naturally occurring physical, chemical, and biological processes are relied upon to reduce the concentration, mobility, or volume of contaminants in

groundwater to acceptable levels while the site is carefully monitored. Under the MNA approach, no active engineered remediation measures are implemented; instead, a monitoring program is established to demonstrate that attenuation processes are occurring and that contaminant plumes remain stable or are shrinking, ensuring that risks to receptors (such as drinking water sources or surface waters) remain within acceptable limits (Azadpour-Keeley et al., 2001; IAEA, 2006b; US EPA, 2007; Devlin et al., 2025).

The natural attenuation processes responsible for declining groundwater concentrations of  $^{90}\text{Sr}$  in the CEZ include (Bugai et al., 2012a, b):

- gradual depletion of the  $^{90}\text{Sr}$  source in the form of fuel particles in soils due to dissolution of uranium oxide matrix and subsequent leaching;
- geochemical evolution of groundwater downstream of waste trenches in RWTSS caused by maturation of buried organic materials, leading to decreased concentrations of cations competing with  $^{90}\text{Sr}$  for sorption sites on soil;
- retardation of radionuclides in near-surface soil due to sorption process; and
- involvement of  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  (biochemical analogues of Ca and K) in the biological cycle within vegetation.

Recent safety assessment analyses by Molitor (Molitor et al., 2017) indicate that source control measures in the CEZ, such as excavation and re-disposal of radioactive waste trench sites (RWTSS) – which represent major sources of groundwater contamination – are not justified. This is due to their high cost, the very large volumes of secondary waste generated requiring management, and the negligible (or absent) radiological benefit.

This conclusion is consistent with recent analyses of the challenges associated with large-scale remedial activities in areas of Japan affected by the Fukushima accident, where the management of enormous volumes of remediation waste became a major environmental, technical, and social issue (IAEA, 2023).

The conceptual framework adopted by the SSE EcoCenter for managing contaminated water resources in the CEZ considers MNA to be an appropriate approach for contaminated groundwater in the CEZ (SSE..., 2019).

An essential condition for implementing the MNA strategy is reliable groundwater monitoring aimed at controlling radionuclide migration processes, refining models, and ensuring an adaptive response to potential changes in the situation (US EPA, 2007).

In view of the shortcomings of the monitoring network of the SSE Ecocenter discussed above, modernization and improvement of groundwater monitoring in the CEZ are of vital importance.

#### 4. Priorities for modernizing groundwater monitoring in the Chernobyl zone

To define priorities for improving the groundwater monitoring program in the CEZ, it is important to identify the objectives of this program in a comprehensive way.

##### 4.1 Objectives of monitoring program

The monitoring objectives are defined by the Statute and activities of SSE Ecocentre (SSE..., 2021). The radiation monitoring system should provide information on the following key groundwater indicators:

- contamination of groundwater in the CEZ by Chernobyl-derived radionuclides and radioactive pollutants that may originate from radioactive waste storage sites of the Vector complex;
- groundwater level regime in aquifers, which makes it possible to assess conditions for potential flooding of radiation-hazardous sites, as well as the directions and velocities of contaminant transport via groundwater toward potential receptors.

Groundwater radiation monitoring data in the CEZ should serve the following main purposes:

- ensuring compliance with regulatory licensing requirements for the monitoring of radioactive waste storage and disposal sites;
- planning and implementing measures to protect the Pripyat River and its tributaries from radioactive contamination;
- providing data for predicting and assessing radiological impacts of contaminated water resources on human health and the environment;
- assessing the dynamics of natural attenuation processes in groundwater and surface water.

For licensed radioactive waste disposal sites in the CEZ, such as the RWDS Buryakivka and the Vector complex, the groundwater monitoring program is a key element in verifying that the facility complies with established operational and safety requirements, particularly with regard to impacts on the environment and the public (IAEA, 2014). The General Safety Provisions for Radioactive Waste Disposal (SNRIU Order No. 331 of 13 August 2018) re-

quire the development and implementation of an environmental monitoring program, which must include groundwater monitoring in accordance with a program approved by the regulator and justified in the Safety Analysis Report (SAR). The requirements for the structure and content of the SAR for surface and near-surface radioactive waste disposal facilities (SNRIU Order No. 520 of 2 December 2019) explicitly state that the SAR must include a description of the site's hydrogeological conditions, predictions of radionuclide transport in aquifers, and the groundwater monitoring program, including the well network, monitored parameters, sampling frequency, and measurement methods.

With regard to supporting the MNA strategy for nuclear legacy facilities, the monitoring system should serve the following purposes (US DOE, 2012):

- Demonstrate that natural attenuation processes in groundwater occur as predicted.
- Detect changes in hydrogeological or geochemical conditions that could reduce attenuation effectiveness.
- Confirm that contamination plumes remain stable and do not expand downgradient, laterally, or vertically.
- Verify that no unacceptable impacts occur at potential receptors, such as surface water bodies or deeper aquifers, and identify possible new contamination sources.

##### 4.2 Directions for modernization of groundwater monitoring system

The analysis presented above has revealed several critical problems and shortcomings of the current groundwater monitoring network in the CEZ. These include the outdated design of monitoring wells, inappropriate placement of wells with respect to contamination sources, and an insufficient or even absent monitoring network at some key locations, for example in the vicinity of the Buriakivka RWDF and the Vector Complex. As discussed earlier, monitoring data also indicate a high probability of well contamination during drilling in the 1990s, which distorts monitoring results; this issue is particularly evident for the relatively immobile radionuclide <sup>137</sup>Cs detected in some wells.

The conceptual approach to the improvement and modernization of groundwater monitoring in the CEZ was recently addressed in the technical assistance project to Ukraine implemented under the European Union Instrument for Nuclear Safety Cooperation (INSC) programme, "Design of a Comprehensive Water

Monitoring System for the Chernobyl Exclusion Zone” (Bugai, Hrygorenko, 2025). The main directions for modernization of the monitoring system are largely based on earlier studies and recommendations of the IGS (Dzhepo et al., 1997; Dzhepo, Skalsky, 2002) and are briefly outlined below.

The proposed approach is based on the following key provisions:

- Extension and optimization of the groundwater monitoring network through the introduction of modern designs of observation wells.
- Introduction of modern and reliable groundwater sampling methods.
- Optimization of the monitoring program (sampling frequency, types of analyses) and expansion of the list of measured parameters, including basic geochemical indicator parameters (pH, *Eh*, electrical conductivity, and major-ion composition).
- Implementation of automated monitoring equipment (in particular, water-level sensors with data loggers).
- Development of an effective information system (database) for storing and analysing monitoring data.
- Strict adherence to field and laboratory QA/QC procedures.

The key provisions of the above list are briefly described below.

#### 4.2.1 Monitoring well design

It is essential to replace outdated wells constructed in 1989–1991 with iron casings and long 12 m screens lacking proper annular seals, with wells or multi-level well clusters designed according to modern standards (PVC casing, 2–3 m screens, proper sealing of the screened interval and wellhead) (ISO, 2009; Brown et al., 2014; ASTM..., 2024). Appropriate precautions should also be taken during installation, such as careful removal of contaminated topsoil before drilling, to prevent radioactive contamination of the borehole.

#### 4.2.2 Monitoring network extension and optimization

The proposed approach to improving the groundwater monitoring system provides for the integration of monitoring networks at different spatial levels (scales) – from the object/site level (e.g., a specific RWDF or RWTSS sector) to the regional level.

A typical object-level monitoring network includes:

- an upstream well to characterize background aquifer conditions;
- wells located in “target zones” within the aquifer affected (or potentially affected) by contaminant transport from a radiation-hazardous site.

In RWTSS sectors, wells that allow tracking the impact on groundwater from selected individual waste burials (representative and/or higher-risk ones) should also be installed.

The CEZ is characterized by a large number of radiation-hazardous sites. Therefore, a graded (risk-based) approach (IAEA, 2014) should be applied when defining priorities for the development and modernization of the CEZ groundwater monitoring system. This prioritization should consider:

- presence of aquifer contamination;
- inventory of radionuclide activity at the transport source and radionuclide mobility;
- availability and condition of engineered barriers;
- unfavourable hydrogeological and/or geochemical conditions (e.g., shallow groundwater depth, potential flooding, proximity to surface water bodies).

An important aspect is the improvement of the monitoring network in the area of the Buryakivka RWDS and the Vector complex (see Fig. 1) to allow reliable determination of regional groundwater flow directions toward discharge zones (surface watercourses).

For sites where a detailed network of observation wells is currently absent and the spatial distribution of the contamination plume is undefined (e.g., certain RWTSS sectors), an adaptive monitoring approach should be followed. At the initial screening stage, the proposed minimum network includes one upstream (background) well and one downstream well from the contamination source within the expected target zone, assuming that the groundwater flow direction is known or can be estimated from a groundwater flow model.

#### 4.2.3 Sampling methods and QA/QC

Alongside well construction, the methodology of groundwater sampling using appropriate specialized equipment is a critical component of groundwater monitoring.

It is recommended to introduce into monitoring practice in the CEZ standardized sampling protocols that comply with modern international standards (ASTM..., 2019a, 2023; ISO, 2009, 2021). The application of such protocols enables repeated measurements while maintaining the accuracy and reproducibility of results, which is essential both for long-term trend analysis and for the comparability of monitoring data obtained by different institutions.

An important requirement for obtaining representative groundwater samples is well purging prior to sampling in order to remove stagnant water from the well. The renewal of groundwater during purging should be controlled through online monitoring of indicator parameters, such as groundwater pH, electrical conductivity, and temperature. It is also recommended that groundwater samples be filtered at the time of collection through a 0.45 µm filter to remove suspended material. Suspended particles can contain a significant fraction of radionuclides, particularly  $^{137}\text{Cs}$ , and may therefore bias the interpretation of dissolved radionuclide concentrations in groundwater in samples (Fujikawa et al., 2025).

A critically important aspect is the improvement of QA/QC procedures at all stages of monitoring activities in the CEZ, in accordance with the requirements of relevant national and international standards (DSTU..., 2007; ISO, 2014; ASTM..., 2018, 2019b). These procedures should cover:

- Field operations related to well purging and groundwater sample collection.
- Sample filtration and preservation (stabilization).
- Documentation of sampling conditions.
- Transfer and handling of samples during transportation to the laboratory.
- Analytical measurements in the laboratory.
- Entry of analytical results into the monitoring database.

#### 4.2.4 Optimization of monitoring program (sampling frequency and analytical scope)

The observation frequency of once per month for groundwater radiological parameters, which is currently applied to some monitoring wells in the CEZ, is in most cases not justified. Groundwater represents a relatively conservative environment, where changes in hydrochemical conditions generally occur slowly. Exceptions may occur in specific situations, such as areas with shallow groundwater tables or aquifers hydraulically connected to surface water bodies, where rapid fluctuations in surface-water levels may influence groundwater conditions.

Moreover, radionuclides typically exhibit very slow migration rates in geological media due to sorption onto the soil and sediment matrix. In addition, frequent purging of wells during sampling may disturb natural hydrogeological conditions in the aquifer.

Based on international experience (European...2009) and the analysis of long-term trends in radioactive contamination of groundwater in the CEZ presented earlier, the following indicative monitoring frequencies for radiological parameters are recommended:

- Wells exhibiting increasing trends of radioactive contamination – once per quarter.
- Wells with stable or decreasing trends but with concentrations exceeding drinking water standards for  $^{90}\text{Sr}$  and/or  $^{137}\text{Cs}$  – twice per year.
- Wells with consistently low concentrations of  $^{90}\text{Sr}$  and/or  $^{137}\text{Cs}$  and non-increasing trends (not exceeding the DR-2006 standard) – once per year.
- Newly constructed wells at priority (high risk) sites – once per quarter during the first year of monitoring; at other sites – twice per year, in order to establish initial trends in groundwater contamination.

In addition to monitoring radioactive constituents, it is advisable during the modernization stage to include key hydrochemical parameters in the monitoring program. These parameters help characterize hydrogeological conditions and influence radionuclide transport processes in groundwater. Such parameters may include pH, redox conditions ( $E_h$ ), electrical conductivity, and major-ion composition.

#### 4.2.5 Update and revision of national standards

In Ukraine, methodological aspects of groundwater monitoring are regulated by the normative documents DSTU ISO 5667-18:2007 (DSTU..., 2007) and SOU-N MEV 40.1-00013741-79:2012 (SOU-N..., 2012). These regulatory documents are partly outdated (for example, with regard to requirements for the design of monitoring wells and other aspects), do not take into account modern technologies, and contain significant gaps concerning important aspects of groundwater monitoring discussed above.

Accordingly, there is a need to develop a national methodological guidance document (guideline/standard) covering key aspects of monitoring radioactive contamination of groundwater at the most important nuclear-legacy facilities, in particular in the Chernobyl Exclusion Zone. Such a regulatory document would also be useful for the development of groundwater monitoring systems at other radiologically hazardous sites in Ukraine, including the Prydniprovskiy Chemical Plant uranium legacy site, nuclear power plant sites, and regional specialized radioactive waste storage facilities of the State Corporation "Radon".

## 5. Conclusions

The analysis of groundwater monitoring data and modelling studies shows that  $^{90}\text{Sr}$  remains the principal radionuclide of concern in groundwater in the Chernobyl Exclusion Zone, whereas concentrations of  $^{137}\text{Cs}$  and transuranic radionuclides are generally low. Long-term monitoring records covering more than three decades indicate that radionuclide concentrations in groundwater are predominantly stable or declining, particularly during the last decade. These trends suggest a gradual reduction of radionuclide inputs to groundwater and support the conceptual understanding of radionuclide migration processes in the CEZ.

The observed behaviour of radionuclides is consistent with the combined effects of source depletion, sorption-driven retardation in geological media, radioactive decay, and dilution in groundwater discharge zones. Together with earlier modelling studies, these findings indicate that large-scale migration of radionuclides via groundwater pathways beyond the CEZ poses relatively low risks to external receptors, including the Pripjat River system.

Under these conditions, Monitored Natural Attenuation appears to be an appropriate strategy for managing contaminated groundwater in the CEZ. However, the successful implementation of this approach requires a reliable and scientifically justified groundwater monitoring system capable of confirming the stability or decline of contaminant plumes and detecting possible changes in hydrogeological conditions.

The present analysis highlights several limitations of the existing groundwater monitoring network, including outdated well designs, insufficient spatial coverage in some areas, and methodological issues related to sampling and QA/QC procedures. Modernization of the monitoring system is therefore necessary and should include improved well design, optimization of monitoring networks, standardized sampling protocols, enhanced QA/QC procedures, and improved data management systems.

An important contribution to the understanding of groundwater contamination processes in the CEZ has been provided by experimental

polygon-type field studies, which revealed detailed plume structures and radionuclide concentrations that are not fully captured by the routine monitoring network. The continuation of such targeted research investigations is essential for improving conceptual models and validating predictions of radionuclide migration.

Following the modernization of the groundwater monitoring system and the accumulation of improved monitoring data, it will be necessary to re-evaluate the current MNA-based management strategy and refine predictive models of radionuclide transport. Such an adaptive approach will ensure that groundwater management in the CEZ remains scientifically justified and responsive to new monitoring information.

It should be noted that the analyses presented in this study constitute an initial stage of interpretation of the extensive groundwater monitoring dataset accumulated in the CEZ. While the current work is based on relatively simple and robust statistical approaches, the dataset itself is well suited for the application of more advanced methods, such as generalized additive models, change-point detection, spatio-temporal statistical modelling, and machine learning techniques. The implementation of such approaches is expected to yield additional insights into the dynamics and controlling factors of radionuclide migration and will be pursued in future studies.

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Радіоактивне забруднення підземних вод у Чорнобильській зоні відчуження (ЧЗВ) з перших місяців після аварії на ЧАЕС (травень – квітень 1986 р.), коли були реалізовані масштабні водозахисні заходи, розглядається як важливий шлях перенесення радіоактивності до річкової мережі басейну Прип'яті–Дніпра. У даній роботі узагальнено результати довгострокового моніторингу та наукових досліджень радіоактивного забруднення підземних вод у ЧЗВ з особливою увагою до просторових закономірностей, часових тенденцій та їх значення для вдосконалення системи моніторингу та стратегій поводження із забрудненими підземними водами.

Аналіз даних моніторингу за період 1989–2024 рр. разом з даними моделювання, огляд яких наведений у статті, показує, що  $^{90}\text{Sr}$  є основним радіонуклідом, який визначає радіологічні ризики від забруднення підземних вод, причому його концентрації локально досягають  $10^5$ – $10^6$  Бк  $\text{м}^{-3}$  у районах впливу пунктів захоронення радіоактивних відходів (РАВ) і забруднених водоєм. Натомість концентрації  $^{137}\text{Cs}$  у підземних водах, як правило, є зазвичай нижчими за 100 Бк  $\text{м}^{-3}$  і значно меншими за норматив для питної води. Довгострокові тенденції свідчать про загальну стабілізацію та поступове зниження концентрацій  $^{90}\text{Sr}$  у більшості спостережних свердловин протягом останнього десятиліття, що відображає виснаження джерела забруднення та прояв процесів природного самоочищення у підземних водах.

Отримані результати підтверджують доцільність застосування стратегії моніторингу процесів природного самоочищення (Monitored Natural Attenuation – MNA) для поводження із забрудненими підземними водами за умови, що система моніторингу забезпечує надійне підтвердження стабільності ореолів забруднених підземних вод і низьких ризиків для потенційних рецепторів, включаючи р. Прип'ять. Водночас існуюча система моніторингу підземних вод у ЧЗВ має низку обмежень, пов'язаних із конструкцією спостережних свердловин, просторовим покриттям мережі та методами відбору проб. Результати детальних полігонних досліджень свідчать, що на певних гідрогеологічних ділянках можуть формуватися значно вищі концентрації радіонуклідів, які не завжди належним чином фіксуються існуючою мережею моніторингу.

Розглянуто пріоритети модернізації системи моніторингу підземних вод у ЧЗВ, зокрема щодо системного визначення цілей моніторингу, удосконалення конструкції спостережних свердловин і методів відбору проб, інтеграції геохімічних і радіологічних спостережень, а також розроблення оновлених методичних рекомендацій. Модернізація системи моніторингу дозволить забезпечити більш надійну оцінку міграції забруднювачів і створить науково обґрунтовану основу для довгострокового управління радіоактивним забрудненням підземних вод у ЧЗВ.

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