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B. Yu. Zanoz[1,*], D. O. Bugai[1], D. O. Koliabina[2], R. Avila[3]

[1] *Institute of Geological Sciences, National Academy of Sciences of Ukraine, Kyiv, Ukraine*
[2] *AFRY UKRAINE LLC, Kyiv, Ukraine*
[3] *ÅF-Consult, Stockholm, Sweden*

*Corresponding author: bzanoz@gmail.com

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

Radioactive and chemical contamination of groundwater and surface water (Konoplyanka and Dnipro Rivers) in the zone of influence of the soviet era uranium production legacy site – Prydniprovsky Chemical Plant (PChP, Kamianske) is a source of radiological and toxicological risks for the population. Modeled water use scenarios included drinking water consumption, crop irrigation, fishing, and usage of the river beaches for recreation. According to the assessment results, the radiological risks of water usage in current conditions are low. At the same time, a conservative assessment indicates potential future toxicological risks from uranium (use of groundwater for drinking) and from manganese (due to accumulation in river fish). In the long term, risks from groundwater may increase significantly due to the dispersion of contaminated groundwater plumes outside the industrial site, or due to unrestricted access of the population to the territory of the PChP. To reduce uncertainty in the risk assessment results, it is important to improve the groundwater monitoring network downstream from the PChP site and to collect site-specific data on manganese transfer coefficients to fish.

Keywords: Prydniprovsky Chemical Plant, uranium legacy site, groundwater, radiological risks, toxicological risks.

1. Introduction

Uranium ore mining and processing facilities created at the beginning of the era of nuclear energy development in the 50s - 60s of the XX century, in particular uranium mill tailings, in many cases pose serious risks of radioactive and chemical contamination of the surrounding hydrogeological environment and hydrosphere [1, 2]. Radioactive contamination is caused by the residual content in tailings of uranium isotopes (^{238}U, ^{234}U) and other radionuclides of the uranium decay series (^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po) after selective extraction of uranium from the ore. Chemical contamination of groundwater at uranium facilities is caused by reagents used in the technological process of uranium leaching, related elements present in uranium ore, as well as waste from related chemical industries. Therefore, remedial activities aimed at bringing uranium facilities to an environmentally safe condition should consider not only radiological but also other toxicological risks [2, 3].

This study considers the soviet uranium production legacy site – Prydniprovsky Chemical Plant (PChP) located in the industrial suburb of the city of Kamianske (formerly Dniprodzerzhynsk) in the Dnipropetrovsk region of Ukraine, where uranium was produced for the soviet nuclear program in the period from 1949 to 1991 (Fig. 1).

The industrial site of the PChP has not been properly decommissioned, and it contains significant residual radioactive and chemical contamination, which is localized in uranium mill tailings, numerous technological buildings (plant workshops), sludge ponds, etc. (see Fig. 1) [4, 5]. Groundwater and surface water monitoring of the PChP site, conducted in 2005 - 2021 has revealed serious contamination of groundwater below and downstream from the uranium mill tailings by radionuclides of ^{238}U decay series, major ions, and toxic metals. The main sources of groundwater contamination are uranium mill tailings “Zahidne” and “Dniprovske” [6 - 8]. Contaminated groundwater from the sources of contamination located at the PChP site and from the “Dniprovske” uranium mill tailings located in the river floodplain discharges into the Konoplyanka River, which flows into the Dnipro River (see Fig. 1).

Previous risk assessment analyses of the PChP site considered mainly radiological aspects of the problem, and the exposure pathways to the population caused by atmospheric dispersion of radon from tailings and due to surface contamination of soils and technological buildings at the PChP site [5], as well as due to contamination of agricultural land due to atmospheric dispersion of radionuclides from uranium mill tailings [4]. In this article, we focus on assessments of radiological and other toxicological risks to the population living in the vicinity of the PChP site caused by radioactive and chemical contamination by toxic metals of groundwater and surface waters (Konoplyanka River, Dnipro River) as a result of leakages of contaminants from uranium mill tailings and other contaminated objects located at the PChP industrial site.

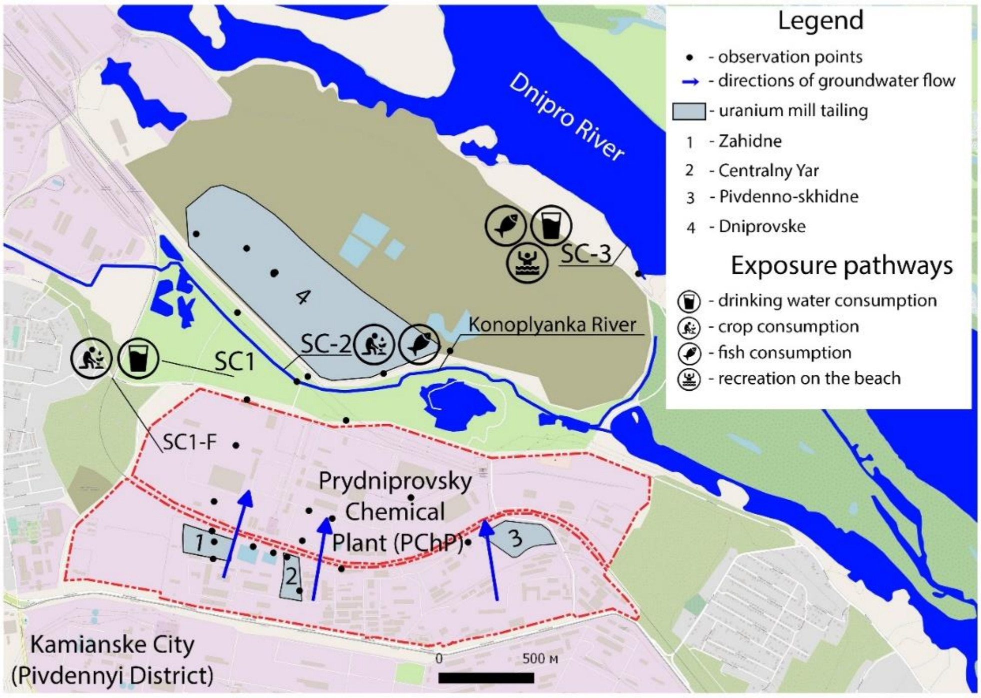


Fig. 1. Map of the territory of the PChP site with groundwater and surface water sampling points, and icons depicting water usage. (See color Figure on the journal website.)

2. Materials and methods

2.1. Groundwater and surface water monitoring data

The data on levels of groundwater and surface water contamination in the zone of influence of the PChP site used in the risk assessments are presented in Table 1 and are based on monitoring studies conducted in 2020 - 2021 [7]. Groundwater monitoring data listed in Table 1 correspond to wells with the highest contamination levels of radionuclides and toxic chemicals. It was checked that the monitoring data used are representative of multi-annual statistical trends in respective monitoring locations (statistical outliers were not taken into account). The location of groundwater and surface water sampling points is shown in Fig. 1. It should be noted that the monitoring network outside the PChP site at its northern periphery was rather limited, and as of 2021 consisted of only two observation wells. Hydrogeological and hydrological conditions of the PChP site are described in detail in [6, 8].

Table 1. **Data on contamination levels of water objects in the vicinity of the PChP used in risk assessments (2021 data) [7, 8]**

Element	Groundwater downstream of the PChP industrial site (current conditions, scenario SC-1)	Groundwater within the PChP industrial site (future conditions, scenario SC-1F)	Konoplyanka River (scenario SC-2)	Dnipro River (scenario SC-3)
Radionuclides, Bq/m^3*				
^{238}U	2560	46100	165	11
^{234}U	2740	43000	165	20
^{226}Ra	70	90	45	10
^{210}Pb	75	45	35	25
^{210}Po	35	15	5	5
Toxic metals, mg/m^3**				
Uranium	206	58858	13.3	0.9
Manganese	1444	2250	18	69
Nickel	10	36	3	5
Chromium	8.9	50,8	2.9	6.8
Lead	2.7	5.3	1.3	5.8

N o t e.
Analytical measurement error: * $^{238/234}$U – 15 - 20 %, ^{226}Ra, ^{210}Pb, ^{210}Po – 20 - 25 %.
** Manganese – 10 %, Nickel, Chromium – 20 %, Lead – 30 %.

2.2. The water usage scenarios

The IAEA International Safety Assessment Methodology was used to assess the hazardous impacts of radioactive and chemical contamination on the population [9]. Several scenarios of possible usage of contaminated water resources in the zone of the PChP by hypothetical “representative persons” from the local population were formulated, mathematical dose assessment models were developed, and the consequences of water usage scenarios were assessed. By definition, a representative person is an individual who receives a dose (or is exposed to toxicological impact) that is representative of the *most highly exposed individuals* in the respective population [10]. The risk assessments take into account several scenarios involving the use of contaminated groundwater from the near-surface unconfined aquifer in alluvial sediments or river water (Konoplyanka River and Dnipro River). Based on observations during field works at the PChP in 2005 - 2021, the terrace of the Konoplyanka River, which is adjacent to the PChP site from the northern side, was used by the local population for agricultural activities (irrigation of vegetables in gardens). The Konoplyanka and Dnipro Rivers are commonly used for fishing (Fig. 2). The Dnipro River shorelines are also used by the local population for recreational purposes (camping, picnics, etc.). The evaluated water use scenarios are described in Table 2.

a

b

Fig. 2. *a* – Private garden near the Konoplyanka River; *b* – “window” in the reeds for fishing on the Konoplyanka River (photos taken in September 2013). (See color Figure on the journal website.)

Table 2. **Description of scenarios of contaminated groundwater and surface water usage in the vicinity of the PChP site**

Scenario (source of water)	Exposure pathway (% of yearly consumed local products, or duration of exposure)			
	Drinking water	Crop irrigation	Fish consumption	Beach recreation
SC-1 (groundwater)				
Realistic	10 %	100 % (potatoes)	–	–
Conservative	25 %	100 % (potatoes), 50 % (vegetables)	–	–
SC-2 (Konoplyanka River)		100 % (potatoes)	100 %	–
Realistic	–	100 % (potatoes), 50 % (vegetables)	100 %	–
Conservative	–			
SC-3 (Dnipro River)				
Realistic	7 %	–	50 %	24 days/year (4 h/day)
Conservative	14 %	–	100 %	40 days/year (8 h/day)

Scenario SC-1 assumes the use of contaminated groundwater from the unconfined aquifer from a well located in the zone of influence of the contamination source outside the PChP fence as irrigation water for growing potatoes and vegetables (e.g., tomatoes, cucumbers, etc.) in the garden. It is also assumed that groundwater is occasionally used for drinking (e.g., during the garden works throughout the year). This results in internal exposure of the respective individual due to the consumption of contaminated agricultural products and water. Calculations for scenario SC-1 are performed for two input parameter data sets. The dataset corresponding to “current conditions” uses monitoring data from wells located outside the PChP territory (between the PChP fence and the Konoplyanka River) with free access to the population. The calculation for “future conditions” (SC-1F) uses monitoring data from wells located at the PChP industrial site. In this scenario, it is assumed that in the future groundwater will migrate outside the territory of the PChP, or access restrictions may be lifted on the territory of the PChP site in the long term, and this territory will be accessed by the local population.

Scenario SC-2 considers the use of contaminated water from the Konoplyanka River for irrigation of the garden as for scenario SC-1 and also the consumption of fish from the river. Usage of water from Konoplyanaka River for drinking purposes is not considered, because this river flows through a wetland area, and also it receives inflows from several drainage and stormwater collectors from the adjacent urban and industrial areas.

Scenario SC-3 considers the use of the Dnipro River near the PChP site downstream of the confluence of the Konoplyanka River by the local population for recreational purposes: spending time on the shoreline (beach), occasional drinking water and fish consumption from the river. It is assumed that relevant persons visit the Dnipro River shoreline during three summer months, spending all available weekends and vacations near the river. The pathways of exposure include the consumption of contaminated fish and water. In addition, vacationers are exposed to radiation on the river shoreline (see Section 2.3.4).

It should be noted that available monitoring data does not suggest a significant impact of the PChP site on the radioactivity of water in the Dnipro River [6]. This is explained by the large dilution of the river flow from the Konoplyanka River (average water flow rate of 0.5 - 1.5 m^3/s) by the Dnipro River (average flow rate of 1700 m^3/s). Nevertheless, this scenario is considered below for a better understanding of the “big picture” of radiological and other toxicological risks caused by the usage of different groundwater and surface water sources in the vicinity of the PChP site. An overview of sources of contamination of the Dnipro River by radionuclides of uranium series is provided in [11].

All the above scenarios consider two age groups of representative persons: (1) an adult; and (2) a 10-year-old child.

2.3. Methodology for assessment of radiological and toxicological impacts on humans

2.3.1. General approach to the calculation of doses

The described above scenarios were modeled using the IAEA NORMALYSA software tool [12]. NORMALYSA uses IAEA-recommended screening-level models for the migration and transfers of radionuclides and the calculation of the resulting dose impacts on the population [13, 14]. The standard library of NORMALYSA modules was supplemented in this study with a model of contaminant accumulation in irrigated crops described in [14, p. 41]. This model takes into account the interception of irrigated water by above-surface parts of plants, as well as root uptake of contaminants. The Ecolego 8.0 software (https://www.ecolego.se/) was used for programming and tuning the models.

2.3.2. Modelling of radiological impacts

The endpoint for radiological dose calculations is the annual effective dose via all relevant pathways to an exposed representative person. Doses were assessed for the following ^{238}U decay series radionuclides: ^{238}U, ^{234}U, ^{226}Ra, ^{210}Pb, and ^{210}Po. Dose coefficients recommended in [15] were used for calculations of internal exposure (oral ingestion, inhalation pathways). As a radiation safety criterion, it was assumed that the annual effective dose for representative persons should not exceed 1 mSv/year. This criterion corresponds to the lower bound of reference levels for the “existing exposure situations” [10, 15].

2.3.3. Modelling of other toxicological impacts

Toxicological risks to human health are assessed using the methodology developed by the US Environmental Protection Agency for the assessment of exposure to non-carcinogenic substances [16]. The impact assessment is carried out by comparing the calculated accumulation of toxic substances in the body by the oral pathway with the corresponding reference dose criterion (RfD) of the toxic element [17]. According to the definition, the RfD represents the estimated chronic chemical exposure (intake) value to humans (including sensitive subgroups) that is likely to be below the level at which an appreciable risk of deleterious effects would be observed during a lifetime. RfD values are available from the Integrated Risk Information System database (https://www.epa.gov/iris). The endpoint in the toxicological assessment is the daily intake of a toxic element per kilogram of body weight. The calculated intake by the representative person of a chemical 'i' ($Dose_i$) is further used to calculate the 'Hazard index' (HI):

$$HI = Dose_i/RfD_i.$$

If the calculated intake of a chemical exceeds the RfD value (HI > 1), this means that exposure to the chemical results in a risk to human health.

The toxicological impact of the following elements was analyzed: uranium (U, RfD = 0.003 mg/(kg·day)), manganese (Mn, RfD = 0.14 mg/(kg·day)), nickel (Ni, RfD = 0.02 mg/(kg·day)), chromium (Cr, RfD = = 0.003 mg/(kg·day)), and lead (Pb, RfD = = 0.004 mg/(kg·day)). These elements have been identified as potentially important chemical toxic pollutants based on previous studies and due to their presence in the water samples studied [6 - 8].

2.3.4. Parameterization of dose models

Parameters of radioecological and dose models were selected according to the IAEA recommendations [12 - 14, 18]. Radioecological parameters are shown in Table 3. It was assumed that irrigation occurs with a water application rate of 10 L/m^2 during 4 months a year (spring - summer period) at weekly intervals, which results in an irrigation rate of 160 mm/year [13]. Physiological parameters and food consumption rates (vegetables and fish) were based on [19, 20].

Table 3. **Radioecological parameters of dose models**

Element	Concentration ratio for crops (Dimensionless quantity) and fish, m^3/kg*						Kd, m^3/kg**	
	Tubers		Vegetables		Fish		For the suspended particulate matter in river	For agricultural soil
	Realistic	Conservative	Realistic	Conservative	Realistic	Conservative		
U	$2.8\cdot10^{-2}$	$8.0\cdot10^{-2}$	$2.3\cdot10^{-2}$	$4.7\cdot10^{-2}$	$9.6\cdot10^{-4}$	$2.0\cdot10^{-2}$	$5.0\cdot10^{-2}$	$2.0\cdot10^{-1}$
Ra	$1.2\cdot10^{-2}$	$6.2\cdot10^{-1}$	$4.8\cdot10^{-2}$	$3.4\cdot10^{-1}$	$4.0\cdot10^{-3}$	$1.5\cdot10^{-1}$	7.4	2.5
Pb	$5.2\cdot10^{-4}$	$2.3\cdot10^{-3}$	$1.5\cdot10^{-2}$	3.9	$2.5\cdot10^{-2}$	$2.7\cdot10^{-1}$	$5.4\cdot10^{2}$	2.0
Po	$2.7\cdot10^{-3}$	$3.4\cdot10^{-2}$	$1.9\cdot10^{-4}$	$3.7\cdot10^{-4}$	$3.6\cdot10^{-2}$	$1.7\cdot10^{-1}$	$3.5\cdot10^{2}$	$2.1\cdot10^{-1}$
Mn	$3.6\cdot10^{-2}$	$7.6\cdot10^{-2}$	$3.1\cdot10^{-1}$	1.5	$2.4\cdot10^{-1}$	$1.4\cdot10^{2}$	$1.3\cdot10^{2}$	1.2
Ni	$4.0\cdot10^{-2}$	$4.0\cdot10^{-1}$	$2.0\cdot10^{-2}$	$2.0\cdot10^{-1}$	$2.1\cdot10^{-2}$	$4.4\cdot10^{-2}$	$2.8\cdot10^{1}$	$2.8\cdot10^{-1}$
Cr	$5.0\cdot10^{-4}$		$1.0\cdot10^{-3}$		$4.0\cdot10^{-2}$	$1.2\cdot10^{-1}$	$1.0\cdot10^{1}$	$4.0\cdot10^{-2}$

* Based on [18, 22].
** Based on [12, 18, 23].

For calculations of doses from recreation on the river shoreline, a model was used described in [12, p. 57]. The dose calculations took into account external exposure from contaminated beach soil, inhalation of dust, unintentional ingestion of small fragments of soil; drinking water consumption from the river; and fish consumption. For calculating the equivalent dose rate on the beach, the geometry dose factor of 0.2 is used [21].

Impacts were calculated for “realistic” and “conservative” sets of input parameters. The “realistic” data set uses average values of contaminant concentration ratios (CR-s) in agricultural products and fish (see Table 3). The “conservative” (pessimistic) scenario uses the maximum values of the CR-s (see Table 3), as well as assumptions on higher consumption rates of contaminated products and/or time spent in the contaminated area (see Table 2). Thus, the conservative set of parameters provides an upper bound for the assessment of potential dose impacts.

3. Results

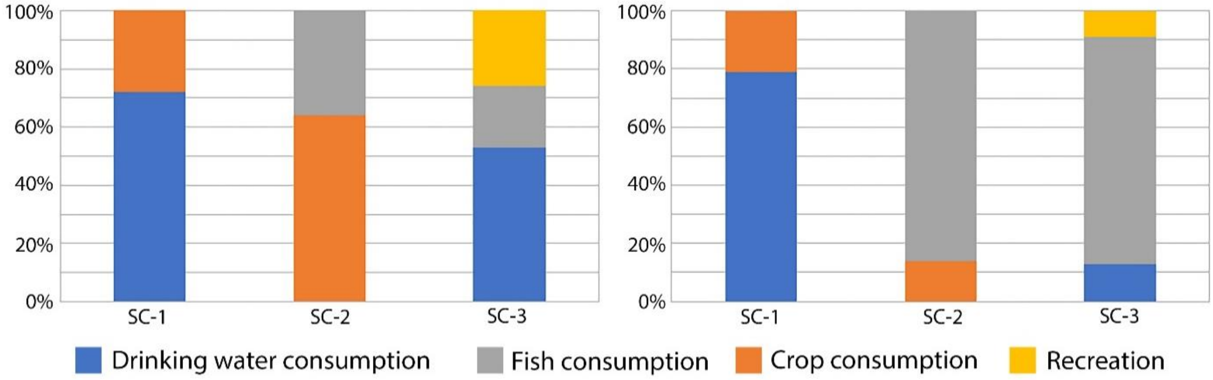
3.1. Radiological impacts

The dose calculations show (Table 4) that in current conditions usage of groundwater and surface water in the zone of influence of the PChP does not pose unacceptable radiological risks to the population. The values of the annual effective dose are significantly lower than the reference level of 1 mSv/year for both “realistic” and “conservative” data sets.

For the hypothetical future exposures, corresponding to the use of highly contaminated groundwater within the PChP site (scenario SC-1F, see Table 1), the exposure doses significantly exceed the reference level of 1 mSv/year (see Table 4). The main exposure pathway for this scenario is drinking water consumption (Fig. 3), the main dose-forming radionuclides are ^{238}U and ^{234}U (see Table 4).

Table 4. **Radiological impacts due to ground and surface water usage in the vicinity of the PChP, doses, mSv/year**

Radionuclide	SC-1 (using groundwater in current conditions)		SC-1F (using groundwater in predictive conditions)		SC2 (Konoplyanka River)		SC3 (Dnipro River)	
	Adult	Child	Adult	Child	Adult	Child	Adult	Child
Realistic data set								
^{238}U	$1.5\cdot10^{-2}$	$1.5\cdot10^{-2}$	4.4	4.3	$2.9\cdot10^{-4}$	$3.0\cdot10^{-4}$	$2.8\cdot10^{-5}$	$2.7\cdot10^{-5}$
^{234}U	$1.8\cdot10^{-2}$	$1.7\cdot10^{-2}$	4.4	4.3	$3.1\cdot10^{-4}$	$3.3\cdot10^{-4}$	$5.6\cdot10^{-5}$	$5.3\cdot10^{-5}$
^{226}Ra	$2.6\cdot10^{-3}$	$4.8\cdot10^{-3}$	$3.3\cdot10^{-3}$	$6.1\cdot10^{-3}$	$5.4\cdot10^{-4}$	$1.1\cdot10^{-3}$	$2.2\cdot10^{-4}$	$3.7\cdot10^{-4}$
^{210}Pb	$6.9\cdot10^{-3}$	$1.2\cdot10^{-2}$	$2.8\cdot10^{-1}$	$5.1\cdot10^{-1}$	$1.7\cdot10^{-3}$	$3.3\cdot10^{-3}$	$2.0\cdot10^{-3}$	$4.7\cdot10^{-3}$
^{210}Po	$5.6\cdot10^{-3}$	$7.8\cdot10^{-3}$	$2.0\cdot10^{-1}$	$2.8\cdot10^{-1}$	$5.2\cdot10^{-4}$	$7.8\cdot10^{-4}$	$6.7\cdot10^{-4}$	$1.1\cdot10^{-3}$
Total	$\mathbf{4.8\cdot10^{-2}}$	$\mathbf{5.7\cdot10^{-2}}$	**9.3**	**9.4**	$\mathbf{3.4\cdot10^{-3}}$	$\mathbf{5.8\cdot10^{-3}}$	$\mathbf{3.0\cdot10^{-3}}$	$\mathbf{6.2\cdot10^{-3}}$
Conservative data set								
^{238}U	$2.9\cdot10^{-2}$	$2.8\cdot10^{-2}$	8.2	7.9	$8.6\cdot10^{-4}$	$9.1\cdot10^{-4}$	$7.1\cdot10^{-5}$	$7.0\cdot10^{-5}$
^{234}U	$3.3\cdot10^{-2}$	$3.2\cdot10^{-2}$	8.3	8.0	$9.3\cdot10^{-4}$	$9.9\cdot10^{-4}$	$1.4\cdot10^{-4}$	$1.4\cdot10^{-4}$
^{226}Ra	$5.0\cdot10^{-3}$	$9.2\cdot10^{-3}$	$6.3\cdot10^{-3}$	$1.2\cdot10^{-2}$	$6.0\cdot10^{-3}$	$1.2\cdot10^{-2}$	$1.6\cdot10^{-3}$	$2.9\cdot10^{-3}$
^{210}Pb	$1.4\cdot10^{-2}$	$2.4\cdot10^{-2}$	$5.6\cdot10^{-1}$	1.0	$2.0\cdot10^{-2}$	$3.8\cdot10^{-2}$	$1.7\cdot10^{-2}$	$3.5\cdot10^{-2}$
^{210}Po	$1.0\cdot10^{-2}$	$1.4\cdot10^{-2}$	$3.7\cdot10^{-1}$	$5.2\cdot10^{-1}$	$3.1\cdot10^{-3}$	$4.8\cdot10^{-3}$	$3.5\cdot10^{-3}$	$5.5\cdot10^{-3}$
Total	$\mathbf{9.1\cdot10^{-2}}$	$\mathbf{1.1\cdot10^{-1}}$	$\mathbf{1.7\cdot10^{1}}$	$\mathbf{1.7\cdot10^{1}}$	$\mathbf{3.1\cdot10^{-2}}$	$\mathbf{5.7\cdot10^{-2}}$	$\mathbf{2.2\cdot10^{-2}}$	$\mathbf{4.3\cdot10^{-2}}$



a *b*

Fig. 3. Contribution from different exposure pathways to annual effective dose for water usage scenarios (for an adult): *a* – realistic data set; *b* – conservative data set. (See color Figure on the journal website.)

For scenarios SC-2 and SC-3 the main dose-forming radionuclides are ^{210}Pb and ^{210}Po (see Table 4) due to the relatively high transfer coefficients of these elements to fish.

3.2. Impacts from toxic metals

The results of the calculations of toxicological impacts are summarized in Table 5.

Table 5. **Toxicological impacts due to groundwater and surface water usage in the vicinity of the PChP (HI values)**

Toxic element	SC-1 (using groundwater in current conditions)		SC-1F (using groundwater in predictive conditions)		SC2 (Konoplyanka River)		SC3 (Dnipro River)	
	Adult	Child	Adult	Child	Adult	Child	Adult	Child
Realistic data set								
U	$3.6\cdot10^{-1}$	$5.1\cdot10^{-1}$	$1.0\cdot10^{2}$	$1.4\cdot10^{2}$	$6.7\cdot10^{-3}$	$1.0\cdot10^{-2}$	$6.6\cdot10^{-4}$	$9.0\cdot10^{-4}$
Mn	$5.4\cdot10^{-2}$	$7.6\cdot10^{-2}$	$8.4\cdot10^{-2}$	$1.2\cdot10^{-1}$	$1.8\cdot10^{-3}$	$2.8\cdot10^{-3}$	$7.5\cdot10^{-3}$	$1.2\cdot10^{-2}$
Ni	$2.6\cdot10^{-3}$	$3.7\cdot10^{-3}$	$9.4\cdot10^{-3}$	$1.3\cdot10^{-2}$	$3.9\cdot10^{-4}$	$6.0\cdot10^{-4}$	$8.4\cdot10^{-4}$	$1.2\cdot10^{-3}$
Cr	$1.5\cdot10^{-2}$	$2.2\cdot10^{-2}$	$8.8\cdot10^{-2}$	$1.2\cdot10^{-1}$	$3.5\cdot10^{-3}$	$5.3\cdot10^{-3}$	$9.9\cdot10^{-3}$	$1.4\cdot10^{-2}$
Pb	$4.0\cdot10^{-3}$	$5.7\cdot10^{-3}$	$7.9\cdot10^{-3}$	$1.1\cdot10^{-2}$	$1.0\cdot10^{-3}$	$1.6\cdot10^{-3}$	$7.5\cdot10^{-3}$	$1.6\cdot10^{-2}$
Conservative data set								
U	$6.7\cdot10^{-1}$	$9.4\cdot10^{-1}$	$1.9\cdot10^{2}$	$2.7\cdot10^{2}$	$2.0\cdot10^{-2}$	$3.1\cdot10^{-2}$	$1.6\cdot10^{-3}$	$2.3\cdot10^{-3}$
Mn	$1.0\cdot10^{-1}$	$1.4\cdot10^{-1}$	$1.6\cdot10^{-1}$	$2.2\cdot10^{-1}$	1.9	3.0	7.4	$1.1\cdot10^{1}$
Ni	$5.0\cdot10^{-3}$	$7.0\cdot10^{-3}$	$1.8\cdot10^{-2}$	$2.5\cdot10^{-2}$	$1.1\cdot10^{-3}$	$1.7\cdot10^{-3}$	$2.0\cdot10^{-3}$	$3.0\cdot10^{-3}$
Cr	$2.9\cdot10^{-2}$	$4.0\cdot10^{-2}$	$1.6\cdot10^{-1}$	$2.3\cdot10^{-1}$	$1.5\cdot10^{-2}$	$2.2\cdot10^{-2}$	$3.7\cdot10^{-2}$	$5.5\cdot10^{-2}$
Pb	$7.9\cdot10^{-3}$	$1.1\cdot10^{-2}$	$1.6\cdot10^{-2}$	$2.2\cdot10^{-2}$	$1.2\cdot10^{-2}$	$1.8\cdot10^{-2}$	$5.3\cdot10^{-2}$	$8.1\cdot10^{-2}$

For the current water usage conditions for the "realistic" input data set, all water usage scenarios do not pose unacceptable toxicological risks for all analyzed elements.

Calculations of the impacts of using water in current conditions for the "conservative" input data set show that the uranium hazard index is close to 1 for scenario SC-1 (see Table 5). The main toxicological impact is caused by groundwater use for drinking. In case we assume that the drinking water consumption in this scenario exceeds 25 % of the annual rate, the uranium HI may exceed 1.

Table 5 shows also unacceptable risks from manganese for scenarios considering toxicological impacts from contamination of surface waters of the Konoplyanka and Dnipro Rivers for "conservative" data sets. The main toxicological impact is caused by the consumption of fish from the river. This is because the calculations for the conservative scenario use transfer factor (TF) values to fish, which is almost 600 times higher than the corresponding coefficient for the "realistic" data set (see Table 3). Thus, calculations of toxicological impacts from manganese are subject to significant uncertainty. It should also be noted that the area of the PChP is characterized by high manganese content in the environment due to regional emissions from the metallurgical industry [24].

For the hypothetical future exposures, corresponding to the conditions of use of highly contaminated groundwater within the PChP site (scenario SC-1F, see Table 1), the hazard index values for uranium reach 100 and more, indicating unacceptable toxicological risk due to groundwater contamination by this element (see Table 5).

According to the results of calculations, chromium, nickel, and lead in natural waters in the vicinity of the PChP site even for conservative assumptions do not pose unacceptable toxicological risks to the population (for the analyzed scenarios).

It should be noted that this article is limited to analysis of health impacts from radionuclides and toxic metals in natural waters in the vicinity of the PChP site, and it does not consider possible impacts or restrictions caused by groundwater and surface water contamination by major ions (e.g., nitrate, sulfate, etc.). Adverse effects from major ions in natural waters deserve a separate focused investigation.

4. Conclusions

The dose assessment carried out using the IAEA-recommended screening models shows that in current conditions usage of groundwater and surface water in the zone of influence of PChP at the site does not pose unacceptable radiological risks to the population.

At the same time, according to conservative assessments, groundwater contamination by uranium, as well as surface water contamination by manganese in the current conditions can be a potential source of unacceptable toxicological risks to the population.

Uranium may pose risks primarily due to the consumption of groundwater for drinking. Manganese poses a potential risk to the population due to accumulation in fish (provided that the maximum literature values of TFs of this element are used in the calculations). According to the available literature [18], manganese is characterized by a wide range of TF to fish. In order to reduce uncertainty in the results of toxicological assessment for manganese, it is expedient to determine site-specific TF values of this element for water bodies in the vicinity of the PChP site.

Toxicological risks from chromium, nickel, and lead in groundwater and surface water in current conditions are low.

The usage of groundwater within the PChP industrial site poses risks both in terms of radiological and toxicological impacts (in particular due to high uranium content). Therefore, it is important to monitor the subsurface dispersion of contaminated groundwater plumes from the sources of contamination at the PChP site beyond its boundaries in the direction of the Konoplyanka River and to develop an adequate groundwater monitoring network downstream from the PChP site.

Some PChP site remediation plans envisage decontamination of the northern sector of the PChP industrial site and the release of this territory from regulatory control. Our calculations show that even with the decontamination of surface soils, risks from contaminated groundwater would remain at the PChP industrial site. Accordingly, long-term restrictions on groundwater use in this area would be necessary.

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REFERENCES

1. Q.H. Hu, J.Q. Weng, J.S. Wang. Sources of anthropogenic radionuclides in the environment: a review. Journal of Environmental Radioactivity 101 (2020) 426.

2. Managing Environmental and Health Impacts of Uranium Mining. Nuclear Energy Agency No. 7062 (Organisation for Economic Co-Operation and Development, 2014) 144 p.

3. Current Practices for the Management and Confinement of Uranium Mill Tailing. Technical Reports Series No. 335 (Vienna, IAEA, 1992) 119 p.
4. V.K. Kyrychenko, V.O. Kashparov. Assessment of the radiological safety of Pridneprovsky Chemical Plant's tailings. Yaderna Fizyka ta Energetyka (Nucl. Phys. At. Energy) 13(3) (2012) 297. (Ukr)
5. T. Lavrova, O. Voitsekhovych. Radioecological assessment and remediation planning at the former uranium milling facilities at the Pridnieprovsky Chemical Plant in Ukraine. Journal of Environmental Radioactivity 115 (2013) 118.
6. E.Yu. Tkachenko et al. Monitoring of technogenic contamination of groundwater and surface water in the zone of influence of uranium tailings of the Pridneprovsky Chemical Plant (Kamyanske). Heolohichnyy Zhurnal 3 (2020) 17. (Ukr)
7. D.O. Bugai et al. Development of the groundwater monitoring system in the zone of influence of uranium production legacy facilities of the Prydniprovsky Chemical Plant. Heolohichnyy Zhurnal 4 (2021) 56. (Ukr)
8. T.V. Lavrova et al. Statistical assessment of data on hydrochemical composition and radioactive contamination of surface waters in area adjacent to former uranium production site. In: *Problems of Hydrology, Hydrochemistry, Hydroecology* (Kyiv: Nika Center, 2019) p. 261. (Rus)
9. Safety Assessment Methodologies for Near Surface Disposal Facilities. Results of a Co-ordinated Research Project. Vol. 1. Review and Enhancement of Safety Assessment Approaches and Tools. Non-serial Publications (Vienna: IAEA, 2004) 408 p.
10. Remediation Strategy and Process for Areas Affected by Past Activities or Event. IAEA Safety Standards Series No. GSG-15 (Vienna, IAEA, 2022) 226 p.
11. Radiological conditions in the Dnieper River basin. (Vienna, IAEA, 2006) 185 p.
12. R. Avila et al. *User's manual for NORMALYSA v.2.1 Description of Program Module Libraries, Mathematical Models and Parameters* (Stockholm: Facilia AB, 2018) 190 p.
13. Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment. Safety Reports Series No. 19 (Vienna, IAEA, 2001) 229 p.
14. Derivation of Activity Concentration Values for Exclusion, Exemption and Clearance. Safety Reports Series No. 44 (Vienna, IAEA, 2005) 141 p.
15. Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards. IAEA Safety Standards Series No. GSR Part 3 (Vienna, IAEA, 2014) 471 p.
16. Technical Report: *Risk-Assessment Guidance for Superfund*. Vol. I. Human Health Evaluation Manual (Part A). Interim report (Final) (Washington: U.S. Department of Energy, Office of Scientific and Technical Information, 1989) 291 p.
17. X. Wang et al. Health risks of heavy metals to the general public in Tianjin, China via consumption of vegetables and fish. Science of The Total Environment 350 (2005) 28.
18. Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater, IAEA Technical Reports Series No. 472 (Vienna, IAEA, 2010) 194 p.
19. Radiation Safety Standards of Ukraine; Additions: Radiation Protection from Potential Radiation Sources (RSSU-97 / D-2000), State Hygiene Standards 6.6.1-6.5.061-2000. Approved by the Resolution of the Chief State Sanitary Physician of Ukraine dated 12.07.2000 No. 116. (Ukr)
20. *Balances and Consumption of the Main Food Products by Population of Ukraine* (Kyiv: State Statistics Service of Ukraine, 2021) 59 p. (Ukr)
21. M.B. Bellamy et al. *External Exposure to Radionuclides in Air, Water and Soil*. External Dose Rate Coefficients for General Application. Federal Guidance Report No. 15. EPA 402-R-19-002 (Oak Ridge, Tennessee, Oak Ridge National Laboratory, 2019) 346 p.
22. U. Bergström, S. Nordlinder, I. Aggeryd. *Models for Dose Assessments. Modules for Various Biosphere Types*. Technical Report TR-99-14 (Stockholm: Swedish Nuclear Fuel and Waste Management Co., 1999) 143 p.
23. M. Tröjbom et al. *K_d and CR Used for Transport Calculations in the Biosphere in SR-PSU*. R-13-01 (Stockholm: Swedish Nuclear Fuel and Waste Management Co., 2013) 365 p.
24. N.N. Tsvetkova, A.A. Dubina. Manganese level in soils of urban systems of industrial cities of steppe Dnieper River region. Visnyk of Dnipropetrovsk University. Biology. Ecology 16(1) (2008) 204. (Rus)

Б. Ю. Заноз[1,*], Д. О. Бугай[1], Д. О. Колябіна[2], Р. Авіла[3]

[1] *Інститут геологічних наук НАН України, Київ, Україна*
[2] *ТОВ «АФРІ УКРАЇНА», Київ, Україна*
[3] *ÅF-Consult, Стокгольм, Швеція*

*Відповідальний автор: bzanoz@gmail.com

ОЦІНКИ РАДІОЛОГІЧНИХ І ТОКСИКОЛОГІЧНИХ РИЗИКІВ ВІД ВИКОРИСТАННЯ ПІДЗЕМНИХ І ПОВЕРХНЕВИХ ВОД У ЗОНІ ВПЛИВУ УРАНОВОГО ОБ'ЄКТА ЯДЕРНОГО СПАДКУ

Радіоактивне і хімічне забруднення підземних та поверхневих вод (р. Коноплянка і Дніпро) в зоні впливу об'єкта ядерного спадку СРСР – Придніпровського хімічного заводу (ПХЗ, м. Кам'янське) є потенційним джерелом радіологічних та токсикологічних ризиків для населення. Змодельовані сценарії водокористування включали споживання питної води, зрошення сільськогосподарських культур, рибальство та використання річкового пляжу для відпочинку. Згідно з розрахунками в сучасних умовах радіаційні ризики водокористування є незначними. У той же час, консервативні оцінки вказують на потенційні токсикологічні ризики від урану (питне використання підземних вод) і марганцю (накопичення в рибі). У довгостроковій перспективі ризики від підземних вод можуть суттєво зрости за рахунок дисперсії ореолів забруднених підземних вод за межі промислового майданчику, або внаслідок доступу населення на територію ПХЗ. Для уточнення оцінок ризику актуальним є вдосконалення мережі моніторингу підземних вод за межами проммайданчика ПХЗ, і уточнення даних про коефіцієнти накопичення марганцю в рибі.

Ключові слова: Придніпровський хімічний завод, урановий об’єкт ядерного спадку, підземні води, радіологічні ризики, токсикологічні ризики.

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