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METHODS OF SUSTENANCE AND RESERVATION OF ECOSYSTEMS AND THEIR COMPONENTS

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INTEGRATED METHODOLOGY AND ITS APPLICATION FOR ASSESSING THE PROTECTION OF GROUND AND CONFINED SUBTERRANEAN WATERS FROM VARIOUS POLLUTANTS AND THEIR VULNERABILITY TO POLLUTION IN THE KALUGA REGION IN THE RADIOACTIVE TRACE FROM THE ACCIDENT AT THE CHERNOBYL NPP

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The object of our research is groundwater and confined subterranean waters in the territory of the Kaluga Region, most affected by the accident at the Chernobyl Nuclear Power Plant. Our aim was to develop a complex methodology to assess the level of protection and vulnerability of groundwater and confined subterranean water against various pollutants, including radionuclides.

The methodology was tested in the territory of the Kaluga Region, in its zone of the radioactive contamination zone from the Chernobyl Accident.

Our earlier studies that assessed protection and vulnerability of subterranean waters began almost immediately after the accident and were carried out according to the original methodology, developed by the authors of this article. They were fully focused on groundwater only or, more specifically, on the first aquifer under the ground surface. However, this research studies both groundwater and confined subterranean water, located below the groundwater aquifer.

Depending on the location of pollution source, two approaches are considered to solve our main aim. The first option involves a pollution source placed on the ground surface, the way it was observed right after the Chernobyl Accident. The second option involves a pollution source located directly in the groundwater or spreading over a large area, in which case the number of study objects decreases, and it becomes a specific case of the first option.

The results of our research and the methodology we offer for the further use can be applied for assessment of the ecological state of subterranean waters in different country territories, at different scales; for design and construction of fresh subterranean water intakes for drinking purposes; for design and organization of subterranean water monitoring in the areas affected by the Chernobyl Accident. The results of our research are new and significant for further studies.

Keywords: groundwater, subterranean confined water, pollutant, subterranean water protection from pollution, subterranean water vulnerability to pollution, radionuclides, sorption, migration period.

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The accident at the Chernobyl Nuclear Power Plant happened more than 30 years ago, but the aftermath of environmental pollution caused by radionuclides will affect us for much longer. It is known that the fallout activity comes to a halt after 10 half-lives of radionuclides. The most affected is the first layer of aquifers or groundwater, located under the ground surface, while the confined waters in the depth are less polluted. Therefore, it is important to study and assess protection of subterranean waters from pollution and their vulnerability to it in the radioactive trace in the Kaluga Region.

On the basis of our research, we developed a methodology for a comprehensive assessment of protection of groundwater and confined subterranean waters to pollution and their vulnerability to various substances, which then was tested in Kaluga region, where the radioactive trace from the

Chernobyl Accident is located.

Our previous studies on the subject began almost immediately after the accident and carried out according to the original methodology, developed by the authors (Belousova, 2001, 2003, 2005, 2012, 2019; Belousova et al., 2006, 2019). However, they were focused on groundwater only, i.e. the first aquifer under the ground surface. The current study presented in this article covers this problem fully, both for groundwater and confined subterranean waters that are located below the aquifer.

Assessment of groundwater protection and its vulnerability to pollution

To study the migration processes of various pollutants (from poorly to highly sorbed), including radionuclides, through the groundwater and confined subterranean waters we used mathematical modeling and a MT3D mathematical model (Belousova, Rudenko, 2021). It studied an aquiclude with a consistent lithological structure, located between groundwater and confined waters. However, such structure is quite unusual, because natural aquicludes may contain lenses, layers of more permeable sediments and industrial elements, such as drill wells and other deep structures, all of which can significantly disrupt the aquiclude and accelerate pollution of subterranean waters. This indicates that aquicludes cannot fully protect the confined waters from pollution. However, they have a complex permeability, which makes it possible for lenses of pollution to form in the confined waters (the concentration of pollutants would be insignificant in that case).

The aforesaid information confirms that it is necessary to assess the protection of subterranean confined water from pollution by various substances using other methods, including the model-cartographic one, the methodology of which we developed while assessing the protection of groundwater from pollution and which will be applied to confined waters together with groundwater.

We developed a structure of a complex methodology for assessing the protection degree of ground and confined subterranean waters and their vulnerability to pollutions, and then tested it out in the area of the radioactive trace from the Chernobyl Accident in the territory of the Kaluga Region.

Depending on the location of the subterranean waters pollution source, we consider two approaches to solve the stated problem.

The first approach is used when the source of pollution is located on the ground, the same way it was after the accident. The study objects are as following: 1) protective zone, 2) groundwater, 3) separate protective layer, i.e. aquiclude, 4) confined waters.

The second approach is used when the pollution source is located in the groundwater or when the pollution is spread over a large area. In this case, the study is one step shorter and includes the following objects: 1) groundwater, 2) aquiclude, 3) confined waters. This approach is considered a special case of the first one.

Further below we will discuss the first approach for assessing the subterranean waters (including groundwater and confined waters) protection and their vulnerability to pollution.

A protective zone to shield the groundwater from pollution. This is a two-level zone that consists of soil and rock of the aeration zone and separates subterranean waters from surface pollution. *Protection* is its ability to prevent penetration of pollutants into subterranean waters for a certain period of time. *Vulnerability* to pollution is the ratio between the real industrial load of the study area and the natural protection of subterranean waters. *Natural protective potential* is the ability of the geological environment, such as soils and rocks of the aeration zone, to keep pollution in the protective zone; it depends on the lithological, filtration and sorption properties of soils and rocks (Belousova, 2001, 2003, 2005, 2012, 2019; Belousova et al., 2006, 2019; Belousova, Rudenko, 2020; Rudenko, Belousova, 2020).

A substance is considered a pollutant if its concentration exceeds the background values. Therefore, when assessing protection, we take into account the structural features of the protective zone that separates groundwater from surface pollution, and the processes caused by pollution in the said zone.

The assessment of groundwater protection is performed for extreme conditions, when it is assumed that pollution has spread over the entire study area, regardless of its intensity.

If radionuclides contaminate the ground surface, then the soils that can bind a large amount of radionuclides act as a protective zone or a buffer. The zone that protects subterranean waters from radioactive contamination has a two-level structure: the first level is soils; the second level is rocks of the aeration zone.

When *a map of the protective zone* is compiled (Belousova, 2001, 2003, 2005, 2012, 2019; Belousova et al., 2006, 2019; Belousova, Rudenko, 2020; Rudenko, Belousova, 2021a), the first level is reflected on the soil map (State Soil Map of the USSR, 1953), showing the soils type and their mechanical composition. The structure of the second level is shown on a map of the groundwater depth (Hydrogeological map of the USSR, 1972-1976) and a map of the lithological structure of the aeration zone. To characterize the second level the maps of Quaternary deposits (Geological map of the USSR …, 1976-1980) were used, because they summarize the data on lithology, water-physical and filtration properties of rocks of the aeration zone for all lithological-genetic complexes. The lithological structure of the protective zone can be of 3 different types: one-layered, two-layered and three-layered.

The next step in the mapping is to establish the categories, used to characterize the natural potential of the zone and its ability to shield groundwater from pollution of any type (radionuclides, heavy metals, nitrates, etc.). At a qualitative level, taking into account the ratio of the lithological structure of both levels, as well as the groundwater depth, the following categories of the protective potential were established: extremely low, low, average and high. The lithological structure of the aeration zone can be of 3 different types: one-layered, two-layered and three-layered (Table 1).

A map of the protective zone (Fig. 1) is created by combining a soil map, displaying the structure of its first level, and maps that characterize the structure of its second level (such as groundwater depth and lithological structure of the aeration zone). Then the model sites with a specific structure of the first and second levels and with the groundwater depth are mapped on it. These sites are described in the legend to the map in Table 1. Due to the complex lithological structure of the protective zone (which can consist even of four layers) and in order to determine its protective potential, we used the “weight” method for assessing all its components. We assigned each of them a weight value, starting from the smallest (sandy soils, sands of the aeration zone, shallow groundwater depths) to characterize the weak protective properties, to the highest (soils with a high humus content, clay, high groundwater depths), then summed up the weights (of soil structure, layered structure of the aeration zone, groundwater depth) for every model site (Table 1). The protective potential is given according to the following weight intervals: low – 4-8, medium – 9-13, high – 14-17 (Belousova, Rudenko, 2020).

The map of the protective zone (Fig. 1) shows that the areas with a low protective potential are located in the river valleys within the radioactive trace in the Kaluga Region. The water catchment areas have a medium potential, while the local areas in the southwest, west and northwest have a strong potential.

The map of the protective zone works as the basis for compiling maps of the groundwaters protection and their vulnerability to any pollutants.

Groundwater as a pollution receiver

The main fallout radionuclides in the radioactive trace in the Kaluga Region are ^{137}Cs and ^{90}Sr.

Table 1. Explication to the map of the protective zone.

Soil type and their lithological structure (weight)					**Groundwater depth, m (weight)**
Alluvial, layered sands, sandy loams and loams (1)	**Podzolic**			**Forest loamy (5)**	
	Sandy (2)	**Sandy loam (3)**	**Loamy (4)**		
1-2-4			47-4-8		0-1 (1)
2-2/4-8					
3-4/2-8					
4-4-6					
	5-2-6	35-2/4-11	57-2-8	73-2-9	1-3 (2)
	6-2-6	36-2/4-11	60-2/3-11	74-3-10	
	7-2-7	32-2/4-12	58-2-9	75-3-11	3-5 (3)
	8-2-7	37-2/4-12	59-2-9	76-3-11	
	9-2-8	33-2-9	62-2/3-13		5-10 (4)
	10-2-8				
	11-2/3-9	48-4-9	63-2/4-12	77-4-11	1-3 (2)
	12-2/4-10	49-4-9	64-2/4/1-12	77a-4-10	
	13-2/4-11	38-2/4-12	31-2/3-12	78-4-11	3-5 (3)
	14-2/4-13	45-2/5-13	66-3-10	79-4-12	
	15-2/5-11	39-2/4/2-13**	67-4/2-12		1-3 (2)
	16-2/5-12	40-2/4/2-14		80-4-12	3-5 (3)
	17-4/2-10	41-2/4/2/1-14			1-3 (2)
	18-4/2-11	46-4/3-13	68-4-11	81-1-10	3-5 (3)
	19-4/2-11	50-4-10			
	20-4/3-13	51-4-11	69-4-12		5-10 (4)
	21-4-8*	42-2/1/2-10			1-3 (2)
	22-4-9	54-1-7			3-5 (3)
	23-4-10		70-4-12		5-10 (4)
	24-4-11				10-25 (6)
	25-1-5	43-2/5-12			1-3 (2)
	26-1-6	56-5-11			3-5 (3)
	27-1-7				5-10 (4)
	28-1-8	34-2-10	71-4-13		10-15 (5)
	29-1-6				3-5 (3)
	30-2-5	44-2/5-12	72-1-7		1-3 (2)
	31-2-7				3-5 (3)
		52-4-12			10-15 (5)
		53-1-6			1-3 (1)
		55-5-10			1-3 (1)
			65-2/4/1-17		>15 (6)

Notes to Table 1: 21-4-8* – the first number is a key plot, the second one is a lithological structure of aeration zone (one-layered, loams), the third one is a sum of weights (scores), made of 3 components: type and lithological soil composition, groundwater depth, lithological structure of aeration zone; 39-2/4/2-13** – the second number is a 3-layered structure of aeration zone (sands, loams, sands), which can also be 2- and 4-layered; the weights of lithological differences of the aeration zone rocks are: tripoli, salica clay, chalk, limestones – (1), sands – (2), sandy loams – (3), loams – (4), clays – (5); protection potential: low (4-8), medium (9-13), high (14-17).

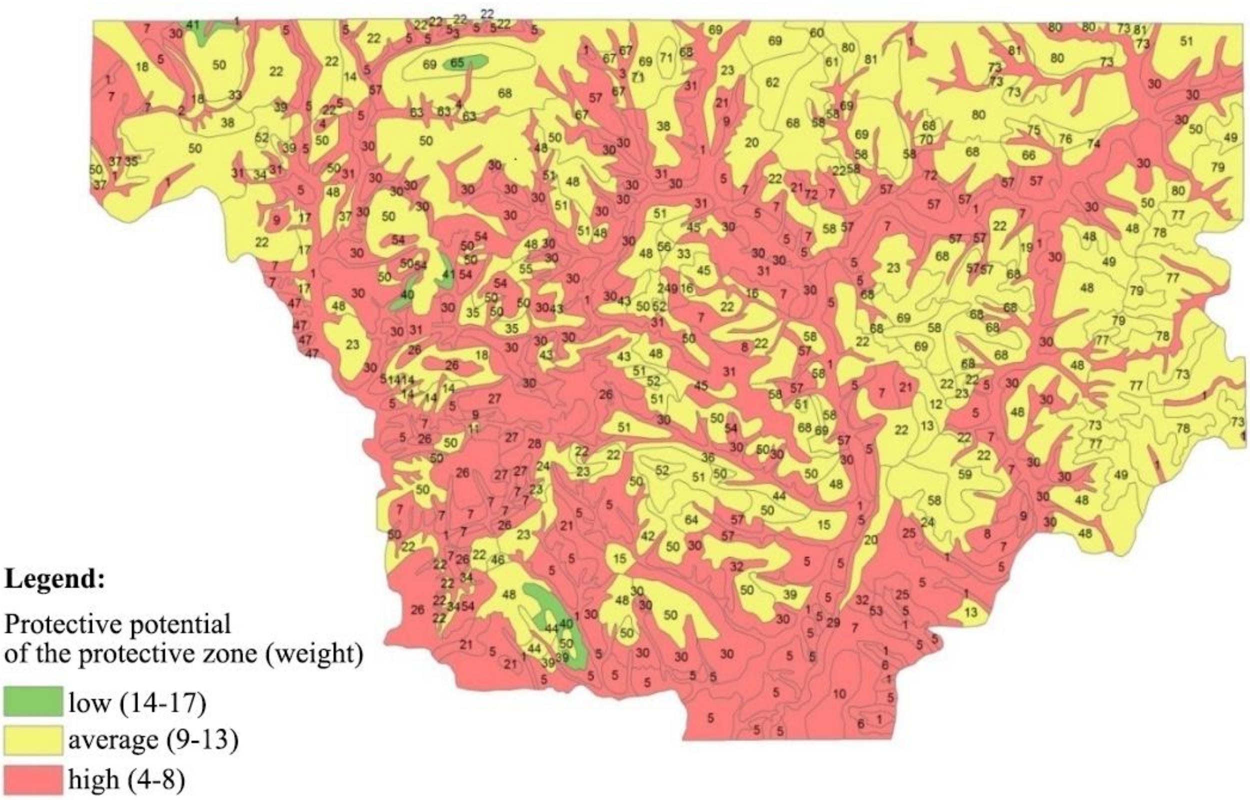

Fig. 1. Schematic map of the protective zone in the south of the Kaluga region (numbers on the map are model sites).

When evaluating the possibility of groundwater contamination with radionuclides, the following factors are taken into account: sorption properties that help to keep the radionuclides in the soils and rocks of the aeration zone; limitation of their penetration intensity to groundwater (up to a complete detention) through the infiltration flow; migratory properties of soils and rocks of the aeration zone that depend on the physical-mechanical, water-physical and filtration characteristics and their mineralogical composition and that characterize the penetration intensity of polluted infiltrating waters into the aeration zone and groundwater; filtration (infiltration) path, i.e. the depth of the aeration zone or the depth of groundwater; half-life of radionuclides.

The groundwater protection from any substance depends on the time that polluted infiltration water needs to reach the aquifer ($t_з$). The time, required for a radionuclide that was dissolved in water to penetrate soil and rocks of the aeration zone with a certain thickness (M), to fill their sorption capacity and then reach groundwater, can be determined using the equation below (Belousova, Rudenko, 2020):

$$t_з = \frac{M \vartheta n}{\upsilon} + \frac{M \vartheta \delta K_p}{W} \quad (1),$$

where θn is a total moisture capacity (in fractions); δ, kg/dm^3 is a volume weight of the soil skeleton; K_p, l/kg is a coefficient of distribution; υ, m/day is a rate of penetration of the infiltration flow (Bindeman, 1963):

$$\upsilon = \frac{1}{\theta}\sqrt[3]{W^2 k_\phi} \quad (2),$$

where θ is a natural rocks moisture (in fractions), W is an infiltration recharge (m/day), k_ϕ is a coefficient of filtration (m/day).

The most toxic of the long-living radionuclides are ^{90}Sr and ^{137}Cs; therefore, protection degree from each of them should be assessed separately.

It is more efficient to make a scale of groundwater natural protection from pollutants depending on T, i.e. the radionuclide half-life. The following categories can be given:

unprotected groundwater: $t_з < T$, $t_з < 30$ years;

poorly protected: $T < t_з < 2T$, 30 years < t < 60 years;

averagely protected: $2T < t_з < 3T$, 60 years < t < 100 years;

relatively protected: $t_з > 3T$, $t_з > 100$ years, 100 years < t < 300 years;

protected: $t_з > 10T$, $t_з > 300$ years.

Allocating categories by the time the pollutant needs to penetrate through the protective zone is an approximate predictive estimation, applied to groundwater pollution by radionuclides.

We assessed water protection from radionuclides using the methodology from our earlier works (Belousova, 2001, 2003, 2005, 2012, 2019; Belousova et al., 2006; Belousova, Rudenko, 2020). It was performed separately for ^{90}Sr and ^{137}Cs. For each of the 81 model sites from the map of the protective zone (Fig. 1) we calculated the time of radionuclides migrating through the protective zone into the groundwater (Table 2), using the formula (1) and taking into account the structure of each site (Table 1) and the zone itself, as well as sorption parameters.

Maps of groundwater protection from pollution with ^{90}Sr (Fig. 2a) and ^{137}Cs (Fig. 2c) are compiled on the basis of the map of the protection zone. When they were compared, it showed that ^{90}Sr is the more dangerous for groundwater, because it can cover vast areas of the aquifer in a short period of about <5 years.

The map of groundwater protection from ^{90}Sr (Fig. 2a) demonstrates that about 50% of the territory is not protected from pollution, while 20% is poorly protected, another 20% (mainly in the north) is relatively protected, 5% is protected and 5% more is averagely protected.

However, the situation with ^{137}Cs is different (Fig. 2c): the unprotected groundwater can be found only along the narrow strip along river channels, the poorly protected ones are found in the northwest valleys of several small rivers, the moderately protected are located on the high river terraces, and the relatively protected adjoin the watersheds. The relatively protected and protected ones are dominant.

Thus, assessment of the time this radionuclide needs to penetrate the protective zone makes it possible for us to provide an approximate predictive estimate of the groundwater pollution with this extremely dangerous substance.

Groundwater vulnerability to pollution is the ratio of the real industrial load of the study area to the natural protection of groundwater. The ^{137}Cs vulnerability map is based on the map of industrial load, compiled for the same radionuclide (Fig. 3a; Map of radioactive contamination ..., 1995), which includes the distribution of ^{137}Cs pollution over the ground surface, and the map of groundwater protection against ^{137}Cs (Fig. 2c). We do not have any data for other radionuclides.

The following categories of groundwater vulnerability to ^{137}Cs were identified: catastrophically vulnerable, extremely vulnerable, highly vulnerable, vulnerable, slightly vulnerable, relatively invulnerable, invulnerable. The last category is conditional due to the fact that pollution can reach areas with initially invulnerable groundwater with the help of the seepage flow that comes from the areas with vulnerable groundwater.

Figure 3a shows the industrial load (density of ^{137}Cs surface fallout) after the Chernobyl Accident.

Figure 3 in and Tables 3 and 4 show vulnerability of groundwater to ^{137}Cs in the radioactive trace immediately after the accident: the extremely vulnerable groundwater is found in the separate areas in the middle reaches of the Resseta River; highly vulnerable is in the river valleys in the center of the radioactive trace; moderately vulnerable is along the valleys of rivers, tributaries, ravines and in the east, near the Vytebet River; slightly vulnerable is along the watersheds of the rivers; almost invulnerable is at the periphery of the radioactive trace; invulnerable is on the high river terraces and sometimes on the watersheds.

Table 2. Penetration time of ^{90}Sr and ^{137}Cs radionuclides into groundwater.

№ of a model site	Time – $t_з$				
	$t_з$ (neutral), pollutants (year)	Radionuclides			
		$t_з$ ^{90}Sr (year)	$\sum t_з$ ^{90}Sr (year)	$t_з$ ^{137}Cs (year)	$\sum t_з$ ^{137}Cs (year)
1	**2**	**3**	**4**	**5**	**6**
1	0.01	3.7	3.71	21.3	21.31
2	0.05	8.5	8.55	40.1	40.15
3	0.05	8.49	8.54	40.06	40.11
4	0.07	10.35	10.42	43.99	44.06
5	0.4	8.21	8.61	76.5	76.9
6	0.4	8.21	8.61	76.5	76.9
7	0.07	15.5	15.58	149	149.08
8	0.07	15.5	15.58	149	149.08
9	0.14	28.16	28.3	275.99	276.13
10	0.14	28.16	28.3	275.99	276.13
11	0.07	8.74	8.81	119.81	119.88
12	0.23	28.2	28.43	144.45	144.68
13	0.48	57.6	58.08	292.5	292.98
14	0.27	34.7	34.97	195.5	195.77
15	0.34	49.1	49.44	176.3	176.64
16	0.72	101.8	102.52	359.8	360.52
17	0.23	101.00	102.52	144.45	144.68
18	0.48	33.1	33.58	292.5	292.98
19	0.48	33.1	33.58	292.5	292.98
20	0.27	109.76	110.03	717.62	717.89
21	0.42	48.1	48.52	212.43	212.85
22	0.87	99.7	100.58	436.05	436.93
23	0.3	35.22	35.52	156.53	156.83
24	3.98	420.67	424.65	1826.81	1830.79
25	0.12	155.1	155.22	379.4	379.52
26	0.25	325.6	788.5	325.85	788.75
27	0.48	623.9	624.38	1504.51	1504.99
28	1.13	1476.23	1477.39	3550.2	3551.33
29	0.25	325.6	325.85	788.5	788.75
30	0.04	8.21	8.25	76.5	76.55
31	0.08	15.5	15.58	149	149.08
32	0.08	15.54	15.62	155.4	155.48
33	0.15	28.23	28.38	282.34	282.49
34	0.24	46.4	46.64	463.73	463.97
35	0.23	28.24	28.47	150.81	151.04
36	0.23	28.24	28.47	150.81	151.04
37	0.48	57.7	58.18	298.9	299.38
38	0.48	57.7	58.18	298.9	299.38
39	0.17	21.6	21.77	128.15	128.32
40	0.36	44.7	45.06	257.2	257.56

Continuation of Table 2.

1	2	3	4	5	6
41	0.1	29.76	29.86	138.85	138.95
42	0.07	57.2	57.27	183.8	183.87
43	0.3	49.11	49.41	176.32	176.62
44	0.3	49.2	49.5	182.7	183
45	0.63	101.9	102.53	366.2	366.83
46	0.55	58.8	59.35	390.4	390.95
47	0.2	22.4	22.6	106.98	107.18
48	0.4	48.2	48.6	218.8	219.2
49	0.4	48.2	48.6	218.8	219.2
50	0.88	99.8	100.68	442.4	443.28
51	1.7	190.11	191.81	833.74	835.44
52	2.8	319.1	321.9	1392.8	1395.6
53	0.13	155.2	155.33	385.75	385.88
54	0.26	325.65	325.91	794.9	795.16
55	0.6	90.1	90.7	282.52	283.12
56	1.2	188.2	189.4	210585	210586.2
57	0.08	8.6	8.68	86	86.08
58	0.12	15.85	15.97	158.55	158.67
59	0.12	15.85	15.97	158.55	158.67
60	0.12	9.13	9.25	129.3	129.42
61	0.19	16.98	17.17	250.03	250.22
62	0.31	30.3	30.61	455.22	455.53
63	0.27	28.56	28.89	153.98	154.25
64	0.24	70.87	71.11	232.2	232.54
65	1.62	573.33	574.95	1783.96	1785.58
66	0.26	18.11	18.37	341.5	341.76
67	0.27	28.56	28.89	153.98	154.25
68	0.92	100.12	101.04	445.6	446.52
69	0.58	61.4	61.98	277.9	277.48
70	1.72	190.4	192.12	836.91	838.63
71	2.9	319.44	322.34	1395.95	1398.24
72	0.165	155.5	155.665	388.92	389.09
73	0.11	10.8	10.91	90.9	91.01
74	0.17	11.9	12.07	177.5	177.67
75	0.28	20.3	20.58	346.4	346.68
76	0.39	28.7	29.09	515.2	515.59
77	0.49	50.7	51.19	226.8	227.19
77a	0.46	48.44	48.9	221.95	222.41
78	0.49	50.7	51.19	226.8	227.19
79	0.95	102.3	103.25	450.45	451.35
80	0.95	102.3	103.25	450.45	451.35
81	0.55	626.5	627.05	920.54	921.09

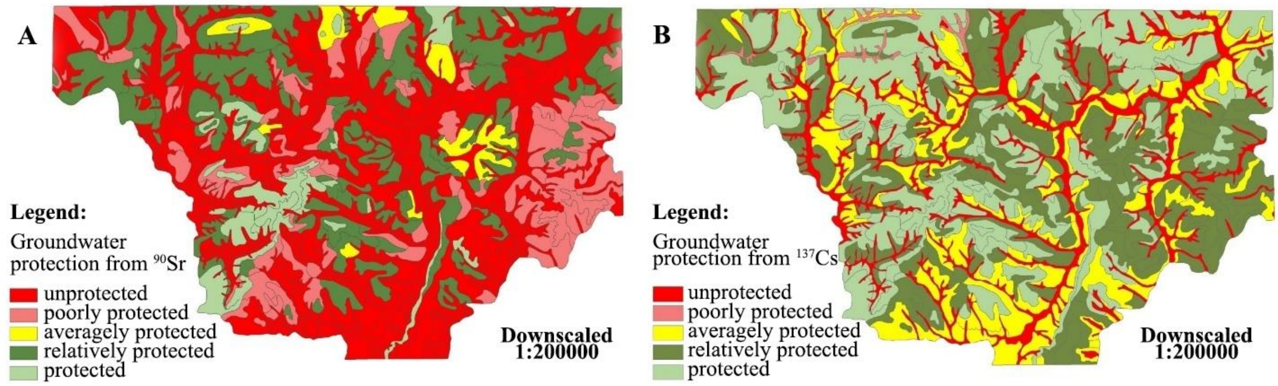

Fig. 2. Schematic maps of groundwater protection from ^{90}Sr (a) and ^{137}Cs (b) in the south of the Kaluga region.

The described approach to the mapping of the groundwater natural protection from radioactivity can be used for compiling similar maps to assess pollution by other highly toxic and low toxic pollutants.

Methodology for assessing protection of subterranean waters (confined waters) from pollution

This stage of our research is about approaches to assessment of subterranean *confined waters* protection from pollution and their vulnerability to it, which is important for estimation of the ecology of drinking subterranean waters, usually located in the confined aquifers below the groundwater horizons.

Just like the assessment of groundwater protection from pollution, the assessment of confined subterranean waters protection has its own features. The main difference is to define the confined water protection zone, which consists of two levels as well.

1) The first one is groundwater itself or other confined aquifers, located above the studied aquifer horizon. They have a dual effect on confined waters, i.e. if they flow into the lower confined aquifer, they can become a source of pollution for it; or if the lower confined aquifer flows into them, they become a protection zone for the confined waters.

2) The second one is an impervious stratum or an aquiclude that separates confined water from groundwater.

A protective zone is a two-level zone that consists of an overlying aquiferous horizon and an aquiclude that separates the said horizons. This zone shields confined subterranean waters from pollution that comes from the overlying horizon.

Protection is its ability of the protective zone to prevent pollutants penetration from the overlying horizon into subterranean confined waters for a certain period of time.

Natural protective potential is the ability of the geological environment to keep pollution in the protective zone. It depends on the lithological, filtration, hydrodynamic and sorption properties of rocks.

Medium-scale assessment of the confined subterranean waters protection from pollution

We assessed the protection of confined subterranean waters that were located below the groundwater horizon in the territory of the Kaluga Region, in the radioactive trace left from the Chernobyl Accident. The scale was 1:200000.

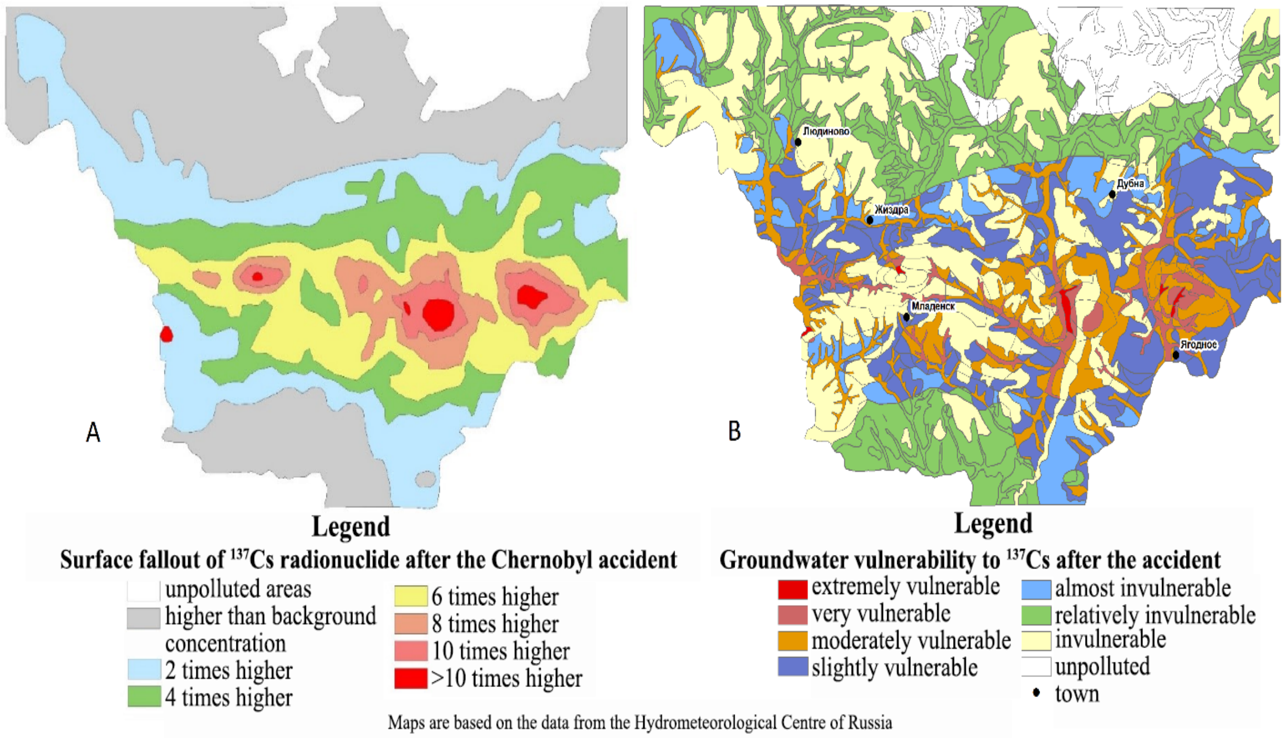

Fig. 3. Schematic maps of industrial load of the density of ^{137}Cs surface fallout (a) and groundwater vulnerability to ^{137}Cs contamination (b) after the Chernobyl Accident.

Table 3. Groundwater vulnerability to ^{137}Cs pollution after the Chernobyl Accident.

Protection degree (weight)	**Industrial load Cs^{137} (Ku/km^2) concentration of the ground surface (weight)**						
	> 10 (6)	**8-10 (5)**	**6-8 (4)**	**4-6 (3)**	**2-4 (2)**	**1-2 (1)**	**< 1 (0)**
(4) Unprotected $T_3 < 30$ years	10*	9	8	7	6	5	Relatively vulnerable
(3) Poorly protected $30 < T_3 < 60$ years	9	8	7	6	5	4	
(2) Averagely protected $60 < T_3 < 100$ years	8	7	6	5	4	3	
(1) Relatively protected $100 < T_3 < 300$ years	7	6	5	4	3	2	
(0) Protected $T_3 > 300$ years	Invulnerable						

Notes to Table 3: 2-10* – weight values of vulnerability.

The hydrogeological conditions show that the unconfined aquifers (groundwater and confined aquifers of fresh groundwater) are separated by the Upper Jurassic area-persistent aquiclude.

Protective zone of confined waters and its mapping. To create this map it is necessary to study its *first level* and assess how much the ground aquifer complex influences the pollution of the confined aquifer complex. This influence is estimated by the value of water transmissibility (*km*), or the ability to filter polluted waters and the levels difference of the first and second aquifers ($H_1 - H_2$), which ensures the intensity and direction of the flow between the complexes.

Table 4. Degree of groundwater vulnerability to ^{137}Cs contamination

Vulnerability degree	**Weight**	**Color**
Unpolluted		
Invulnerable	$T_3 > 300$ years	
Relatively vulnerable	< 1	
Barely vulnerable	2-1	
Slightly vulnerable	4-3	
Mildly vulnerable	6-5	
Highly vulnerable	8-7	
Extremely vulnerable	10-9	

The *second level* of the protective zone is characterized by the aquiclude parameters, such as a coefficient of filtration ($k_ф$) and depth (m_0). Due to the lack of data about the lithological structure of the aquiclude, its coefficient of filtration was considered constant for the overall depth, changed only for different scenarios.

Thus, we used three following indices to assess the protective potential: *km*, $k_ф$, m_0 (Table 5).

Table 5. Potential of the protective zone.

km **(m^2/day) [5] – weight**	**m_0 – aquiclude depth (m) [3] – weight**			**$H_1 - H_2$ – difference between the layers of the first and second aquiferous complexes (m) [5] – weight**
	10 – 30 [1]	**0 – 10 [3]**	**0.0 [6]**	
0 -10 [1]	3	5	8	1-10 [1]
10 -20 [2]	5	7	10	10 – 20 [2]
20 -50 [3]	7	9	12	20 – 40 [3]
50 – 100 [4]	9	11	14	40 – 60 [4]
100 – 500 [5]	11	13	16	> 60 [5]
500 – 1000 [6]	13	15	18	0.0 [6]
Legend:				
	– high protective potential (weight is 0-5)			
	– average (5-10)			
	– low (10-15)			
	– extremely low (15-18)			
	– extremely high; area where groundwaters are not the source of pollution for the confined waters, and their depth is below the piestic depth of confined waters			

The assessment was carried out as follows. Each index was assigned a weight in ascending order, depending on the deterioration of their protective properties. An increase of *km* causes a deterioration of the protective properties, meaning that the polluted waters in the groundwater flow are filtered faster and reach the aquiclude quicker, therefore, the weight increases as the protective properties decrease (it also applies to the level difference ($H_1 - H_2$)); however, the weight value m_0 increases as the aquiclude depth decreases. Then the values of the 3 indices are summed up and the potential of the protective zone is determined: high (weight is 0-5), average (5-10), low (10-15), extremely low (15-18), extremely high (the latter is added specifically for the area where groundwater is not a source of confined water pollution, with their level located below the piestic level of confined water).

The results of this assessment are shown in Table 5.

The model sites are mapped on the schematic map of the protective zone (Fig. 4), with different structure of their protective zones, according to 3 indices and their protective potential (Table 5). Their description is given in the explication to the map in Table 6.

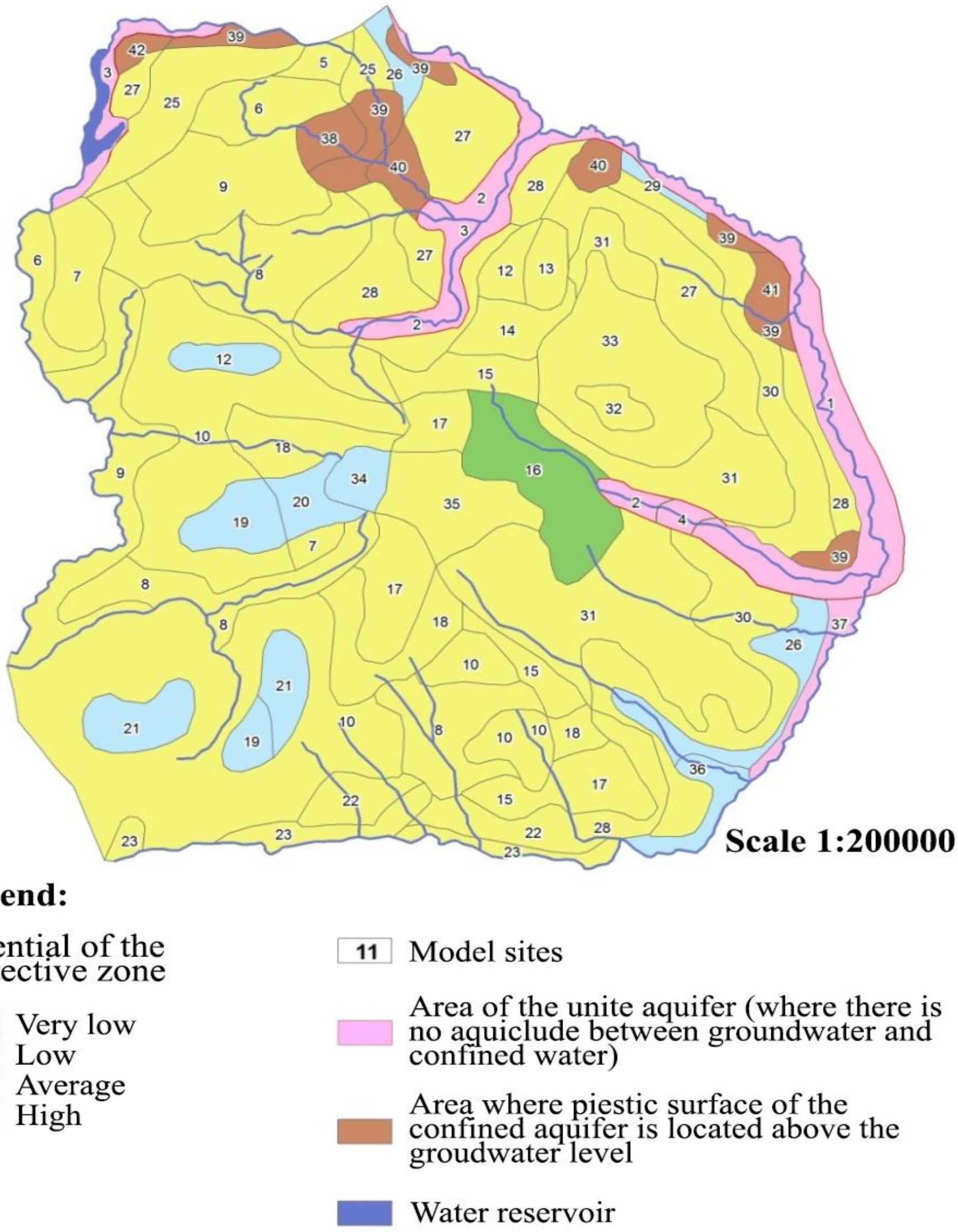

Fig. 4. Schematic map of the protective zone for confined waters.

Table 6. Explication to the schematic map of the protective zone for confined waters.

No. of the model site	**Weights of the indices (1) – No. of the indices on a digitized model site**			**∑ sum of the weights**	**Protective potential**
	m_0	***km***	***$H_1 – H_2$***		
1	6	6	6	18	very low
2	6	3	6	15	very low
3	6	5	6	17	very low
4	6	4	6	16	very low
5	1	4	2	7	average
6	1	5	2	8	average
7	1	3	4	8	average
8	1	4	3	8	average
9	1	5	3	9	average
10	1	4	4	9	average
11	1	4	5	10	low
12	1	4	2	7	average
13	1	2	3	6	average
14	1	3	2	6	average
15	1	3	3	7	average
16	1	1	3	5	high
17	1	1	4	6	average
18	1	3	4	8	average
19	1	5	5	11	low
20	1	3	5	9	low
21	1	5	4	10	low
22	1	2	3	6	average
23	1	2	4	7	average
24	1	2	5	8	average
25	3	4	2	9	average
26	3	5	2	10	low
27	3	3	2	8	average
28	3	4	2	9	average
29	3	4	6	13	low
30	3	2	2	7	average
31	3	3	3	9	average
32	3	4	4	11	average
33	3	4	3	10	low
34	3	3	5	11	low
35	3	1	4	8	average
36	3	6	2	11	low
37	3	6	6	15	very low
38	**1**	**5**	**0 (from -1 to -10)**	**6**	very high
39	**3**	**5**	**0 (from -1 to -10)**	**8**	very high
40	**3**	**3**	**0 (from -1 to -10)**	**6**	very high
41	**3**	**6**	**0 (from -1 to -10)**	**9**	very high
42	**3**	**4**	**0 (from -1 to -10)**	**7**	very high

The schematic map (Fig. 4) shows that there are areas in the valleys of the Bolva, Resseta and Zhizdra Rivers with an extremely low protective potential, because their confined and groundwater are not separated by an aquiclude. They make a unified aquifer complex. In the smaller areas the piesric level of the confined aquifer complex is slightly higher than the level of the groundwater aquifer, which determines the absence of any flow of contaminated groundwater into the confined ones. Most of the territory, however, has an average protective potential of the confined aquifer complex, while the low and high ones were found only in the small areas.

Subterranean pressure waters and their protection from pollution. Since the radionuclides are the main pollutants in the study area of the radioactive trace in the Kaluga Region, we assessed the migration intensity of ^{90}Sr and ^{137}Cs from groundwater to pressure water. However, in this example we use only ^{137}Cs (Belousova, Rudenko, 2021a, 2021b)

The migration intensity of strongly sorbed pollutants (radionuclides) (Table 7) was calculated according to equation (1) and equation (2). The following parameters were used, common for aquiclude rocks such as clay: δ – volume weight of the soil skeleton, equal to 1.8 kg/dm^3, ϑ (n) – porousness, equal to 0.2. Figure 5 shows the time the pollutants need to migrate at K_p = 26 l/kg and K_p = 1000 l/kg, which matches the interval of values of the coefficient of distribution for ^{137}Cs. The maximal migration time of 1,080,078 years was calculated at K_p = 1000 l/kg, W = 0.01 m/year and the aquiclude depth equal to 30 m (Fig. 5b). The minimal migration time of 3,758 years was calculated at K_p = 26 l/kg, W = 0.025 m/year and the aquiclude depth equal to 10 m (Fig. 5c).

Table 7. Time of penetration of strongly sorbed substances, including ^{90} Sr and ^{137} Cs, through the aquiclude.

W **(m/year)**	***M*** **(m)**	^{90}**Sr**				^{137}**Cs**			
		K_p (l/kg)	$t_{з}$ (year)	$t_{н}$ (year)	$t_{з} + t_{н}$ (year)	K_p (l/kg)	$t_{з}$ (year)	$t_{н}$ (year)	$t_{з} + t_{н}$ (year)
0.01	1	6	216	3	219	26	936	3	939
		200	7200	3	7203	1000	36000	3	36003
0.025	1	6	86	1	87	26	374	1	375
		200	2880	1	2881	1000	14400	1	14401
0.01	5	6	1080	13	1093	26	4680	13	4693
		200	36000	13	36013	1000	180000	13	180013
0.025	5	6	432	7	439	26	1872	7	1879
		200	14400	7	14407	1000	72000	7	72007
0.01	10	6	2160	26	2186	26	9360	26	9386
		200	72000	26	72026	1000	360000	26	360026
	30	6	6480	78	6558	26	28080	78	28158
		200	216000	78	216078	1000	1080000	78	1080078
0.025	10	6	864	14	878	26	3744	14	3758
		200	28800	14	28814	1000	144000	14	144014
	30	6	2592	42	2634	26	11232	42	11274
		200	86400	42	86442	1000	432000	42	432042

If we consider the ecology of radionuclides migration and the fact that after 10 half-lives (about 300 years) the said radionuclides decay almost entirely, then it is safe to assume that during their lifetime both radionuclides will never get into the confined waters of the study area. However, if the aquifer depth decreases and reaches 1.0 m, then only ^{90}Sr will reach the pressure water: in 219 years at K_p = 6 l/kg and W = 0.01 m/year, or in 87 years at K_p = 6 l/kg and W = 0.025 m/year (Fig. 5). Besides, other pollutants with coefficients close to the mentioned values can flow into pressure waters in various periods of time, up to several million years; for example, it can happen with Ni at K_p = 5500 l/kg.

Results and some recommendations

A step-by-step guide for a complex methodology for assessing the protection of groundwater and pressure subterranean water from pollution and their vulnerability to it. It is significant to note the features and structure of the complex assessment. As it was noted above, its structure primarily depends on the pollution source, its location and one specific pollutant, the groundwater protection from which is being assessed. Therefore, there can be two options of the structure: 1) the source of pollution is located on the ground surface, in the soil (Fig. 6a); 2) the contaminated subterranean (ground) waters are the source of pollution (Fig. 6b).

Further below we will describe the stages of the *first option* of protection assessment (Fig. 6a).

1) Mapping the total area, contaminated by the given pollutant (layer 1a). In our case it was ^{137}Cs radionuclide, which distribution area in the radioactive trace in the Kaluga Region was the only one of interest, rather than the ratio “quantity – intensity” of contamination it caused.

2) Mapping the groundwater protective zone (layer 2a) that shows the geological and hydrogeological structure of the soil cover and the aeration zone. This method is described above and shown in Figure 1. This map is the basis for any further assessments.

3) Mapping the groundwater protection from contamination by a given pollutant (layer 3a). This method is described above and shown in Figure 2.

4) The map of groundwater vulnerability to ^{137} Cs (Fig. 3c) is compiled on the basis of the industrial load map and groundwater protection map, both created for ^{137} Cs (Fig. 2c) as there is no data for other radionuclides. This method is described above and shown in Figure 3c. For this step two maps were required: the map of industrial load (layer 1a), which shows the intensity of the load, i.e. its quantitative characteristic (however, the data is available only for ^{137}Cs, which is shown in Figure 3a), and the map of protection (layer 2a) shown in Figure 2c.

This concludes our assessment of groundwater protection from ^{137}Cs contamination and their vulnerability to it. Further below we will describe the assessment of protection and vulnerability of pressure subterranean waters. Since we used the study area of pressure subterranean waters for mathematical modeling of pollution processes at the site, the area was smaller than the radioactive trace where the groundwater flow had been studied, limited by the Bolva, Resseta and Zhizdra Rivers.

5) Mapping the protective zone for confined subterranean waters (layer 5a). This method is described above and shown in Figure 4. This map is made of two levels: the first characterizes the interaction between the ground and confined aquifer horizons; the second characterizes the structure of the aquiclude between these horizons.

6) Mapping the confined subterranean waters protection from ^{137}Cs (layer 6a). This method is described above and shown in Figure 5. It is similar to the methodology for assessing the groundwater protection from pollution and uses the same equations. However, when used for confined waters, one member of its equation, *W* (infiltration groundwater recharge), should be replaced with the groundwater flow to confined waters, or the observations data on confined waters levels should be used, which can be quite problematic. Otherwise, it is possible to use the values, expressed in shares of infiltration recharge, as shown in Figure 5. Besides, the data on the coefficients of sorption distribution (K_p) of a certain pollutant for the studied object is usually

absent, and, therefore, we used various values of this index according to the literary sources that we used in our previous researches (Belousova, Rudenko, 2021a, 2021b).

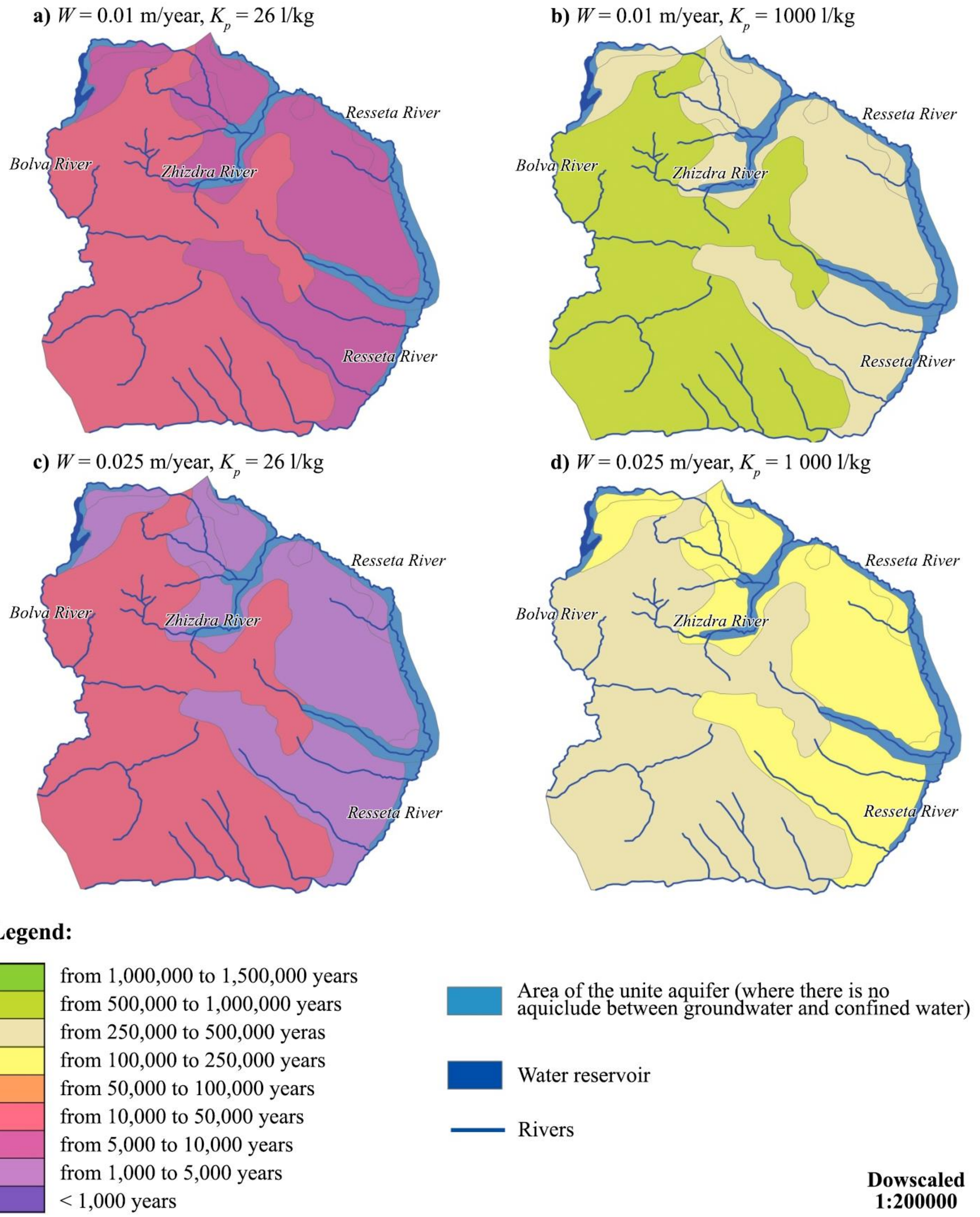

Fig. 5. Scaled down schematic map of the penetration time of strongly sorbed substances, including ^{137}Cs, through a separate layer (aquiclude) at different values of *W* and K_p.

7) Compiling the final map of the subterranean confined waters protection (layer 7a) from a pollution source, located on the surface. For that the migration time required for a pollutant to reach groundwater and confined water are summed up. In our case, this map is not required for ^{137}Cs due to the already mentioned migration times.

8) The final stage is to build a map of the vulnerability of subterranean confined waters to pollution (layer 8a) by overlaying the map of industrialload (layer 1a, the quantitative parts of the load) and the final map of the confined waters protection (layer 7a). In our case, this map is not required as well.

The *second option* (Fig. 6b) is a shortened version of the first one due to the deeper pollution source that reached down to the groundwater horizon. It includes the following steps.

1) Mapping of the industrial load, i.e. compiling a map of groundwater pollution by a certain pollutant (^{137}Cs), which shows the area of pollution distribution and its intensity (layer 1b).

2) Mapping the protective zone (layer 2b), similar to step 5 of the first option.

3) Mapping the subterranean confined waters protection from a given pollutant (layer 3b), similarly to step 6 of the first option.

4) Mapping the confined waters vulnerability to pollution by a given pollutant (layer 4b), similar to step 4 of the first option.

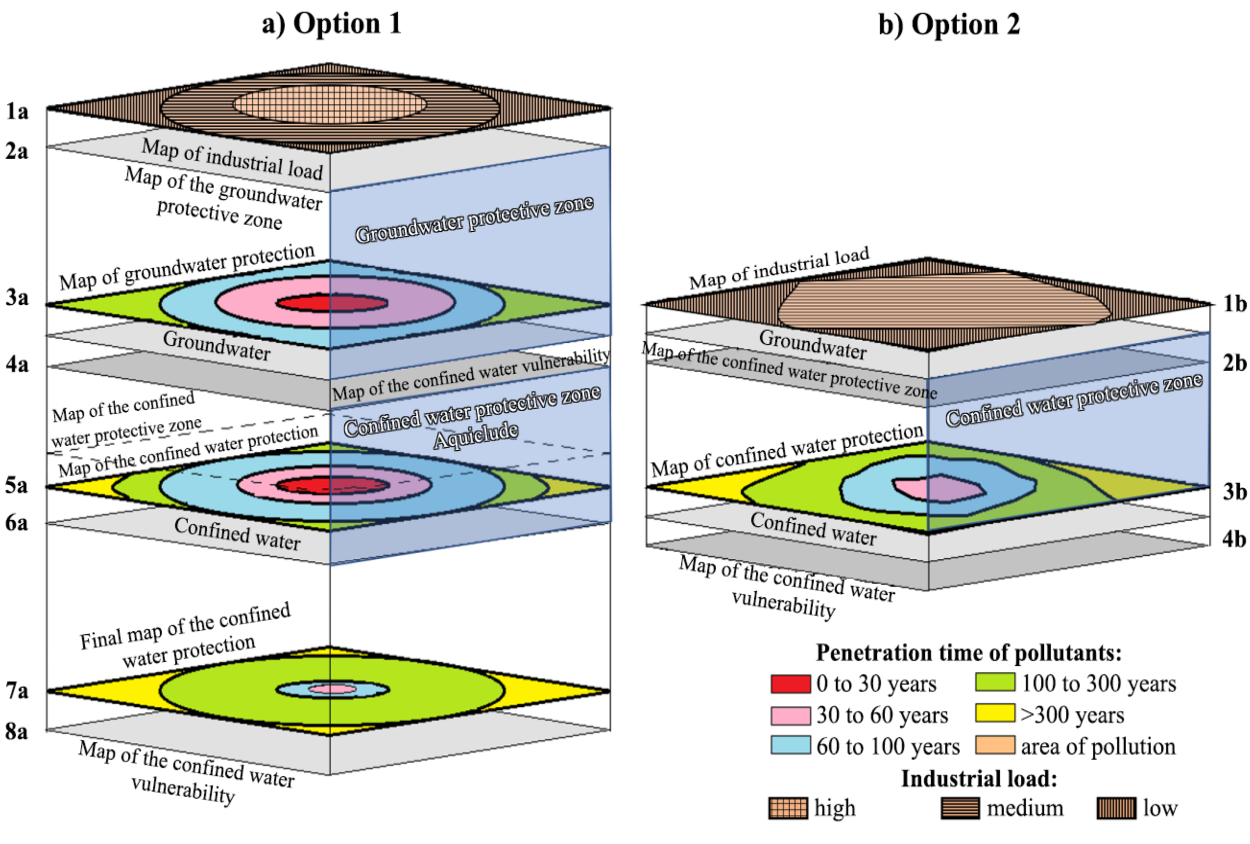

Fig. 6. Scheme of two options of the comprehensive methodology for assessing the groundwater protection from pollution and their vulnerability to it.

Specificity of the complex assessment of the groundwater and subterranean confined waters protection from pollution and their vulnerability to it. The first option of the aforementioned complex assessment is intended to be used for any type of pollution, rather than for our case exclusively. Therefore, we assessed the protection of subterranean waters of the confined aquifer from contamination by neutral, weakly and strongly sorbed pollutants, with different coefficients of distribution and recharge values (according to steps 5 and 6 of the first option of our methodology).

If the data on the pollutants penetration times are evaluated (Tables 7, 8), it can be seen that the penetration times can be less than 300 years at K_p being lower than 10 l/kg, which is typical for poorly sorbed pollutants. The period of 300 years determines 10 half-lives of the main radionuclides in the radioactive trace and is limiting when the protection is assessed. In that case it is necessary to estimate protection and vulnerability acceding to all stages of the first option, as well as the second option. If the pollutant is not a radionuclide, and especially if it is a neutral pollutant, then the intensity scale of the industrial load can be changed relative to other constraints, such as the operation time of water intake. But if the pollutant is a strongly sorbed substance with K_p higher than 10 l/kg, then we can skip the last two steps of the first option, as shown above, but follow every step of the second option, and, if the pollutant is not a radionuclide, the scale of industrial load can be changed as well.

Table 8. Penetration time of a poorly sorbed substance through the aquiclude.

W (m/year)	M (m)	K_p (l/kg)	$t_з$ (year) – second term of equation (3)	$t_н$ (year) – first term of equation (3)	$t_з + t_н$ (year)
0.01	1	0.5	18	3	21
0.025	1	0.5	7	1	8
0.01	5	0.5	90	3	93
0.025	5	0.5	36	1	37
0.01	10	0.5	180	26	206
0.025	10	0.5	70	26	96
0.01	30	0.5	540	78	618
0.025	30	0.5	210	78	288
0.01	1	1	36	3	39
0.025	1	1	14	1	15
0.01	5	1	180	13	193
0.025	5	1	70	7	77
0.01	10	1	360	26	386
0.025	10	1	140	26	166
0.01	30	1	1080	78	1158
0.025	30	1	420	78	498
0.01	1	3	108	3	111
0.025	1	3	42	1	43
0.01	5	3	540	13	553
0.025	5	3	210	7	217
0.01	10	3	1080	26	1106
0.025	10	3	420	26	496
0.01	30	3	3200	78	3278
0.025	30	3	1216	78	1294

It should be also noted that the calculation of radionuclides penetration time takes into account their lifespan, which is 300 years both for ^{90}Sr and ^{137}Cs. Any higher time value is not applicable for them. The change in their surface fallout that happens with each half-life period is not taken into account, because the calculation is carried out for a certain period, or, in our case, for the period after the Chernobyl Accident. However, if other pollutants with high K_p are estimated, then all lifespans exceeding 300 years are taken into account.

Every assessment we mentioned before were carried out using the model-cartographic method; calculations and mapping were carried out using the analytical method according to the our equation and methodology (Belousova, 2001, 2003, 2005, 2012, 2019; Belousova et al., 2006, 2019; Belousova, Rudenko, 2020; Rudenko, Belousova 2021). To estimate the adequacy of our results, a mathematical modeling of the migration processes was performed using the MT3D for various pollutants, from weakly sorbed to strongly sorbed radioactive ones, as well as non-radioactive ones (Belousova, Rudenko, 2021a, 2021b). The modeling was carried according to the second option (Fig. 6b), for various scenarios, instead of the real ones, because there is no data on the latter. When comparing the results of modeling the pollutant migration processes according to various scenarios, we can note the following features.

The strongly sorbed pollutants significantly decrease in the first layer (groundwater) by the 300-year period, as well as their accumulation in the aquiclude; two lenses of polluted water form in the third layer.

The strongly sorbed pollutants with radioactive decay follow a different scenario. By the 300-year period there are some traces of pollution left in groundwater and aquiclude, while in confined waters their concentration is $0.027 – 3{\cdot}10^{-20}$ MAC.

Poorly sorbed pollutants migrate with higher intensity, and by the 300-year period only an insignificant amount of about 0-2.0 MAC is left in groundwater, while the same amount accumulates in the aquiclude; one lens of polluted water forms in confined waters.

The main factors that form the migration processes of pollutants are as follows: their radioactive decay; their sorption properties (the higher K_p is, the slower the pollutant will get into the confined subterranean waters, but the time factor reduces their chances to remain uncontaminated); the hydrodispersion of subterranean water flows, which depends on the geological and hydrogeological conditions of the study area.

Thus, the aquiclude is highly important for the pollutants migration from groundwater to confined water. It protects the latter from surface pollution and from contaminated groundwater, while being a potential source of pollution for confined subterranean waters.

The data that we obtained using the model-cartographic method (Table 7) do not contradict the modeling data (Belousova, Rudenko, 2021a 2021b), although they are still different. According to the first method, the difference is the time of pollutant penetration; according to the second one, it is the concentration of pollutants. The data on the migration of strongly sorbed pollutants with decay shows that their concentrations exceed any possible values and are equal to $0.027 – 3{\cdot}10^{-20}$ MAC in the third layer, i.e. confined subterranean waters (Belousova, Rudenko, 2021a 2021b). The migration time of ^{137}Cs is also extremely long, being more than 300 years, which indicates that the confined waters will not be contaminated by this radionuclide during its lifespan (300 years) (Belousova, Rudenko, 2021a 2021b).

The complex assessment of the protection and vulnerability of groundwater and pressure subterranean waters makes it possible to make preliminary calculations and predict the changes in the ecology of groundwater and pressure subterranean waters at any given moment or time intervals, depending on the particular task. For example, it can be used for assessment of radionuclides pollution up to 300 years, with a step of 30 years (for other pollutants these periods may vary). Besides, it can provide forecasts for ecological changes under climate change. In this methodology only the average annual amount of precipitation is responsible for the climate, affecting such a hydrogeological parameter as infiltration feeding or *W*, as well as the groundwater flow from one aquifer to another, associated with *W*.

This problem can be easily solved using our unified method for assessing the groundwater protection from pollution (Belousova, Rudenko, 2018), which allows to make many assessments of protection at various values of infiltration recharge, or values of coefficients of sorption distribution, or while changing both values at once. Therefore, we can consider many scenarios of climate change and give a preliminary assessment of ecological changes of subterranean waters, whenever they are contaminated with various pollutants. Modern GIS-technologies make it easy to compile a large amount of maps of the groundwater and pressure subterranean waters protection and vulnerability under the climate change and the chemical composition of pollutants.

Recommendations on the application of a complex methodology for assessing the protection of ground and pressure subterranean waters from pollution and their vulnerability to it. This complex methodology was developed for preliminary forecasting of changes in the ecological state of groundwater and pressure subterranean waters, and therefore needs some recommendations for its further application.

1) This methodology should be used for routine and standard hydrogeological studies of objects and territories (including the radioactive trace from the Chernobyl Accident), where groundwater contamination is possible.

2) It should be used at the preliminary stages in the design of facilities that may pose a risk of environmental pollution, such as nuclear power plants and chemical, basic, oil, agriculture and other enterprises.

3) It should be used to design the fresh subterranean water intakes.

4) It should be used to design the structure of groundwater monitoring for all of the aforementioned enterprises and objects.

The scientific and practical efficiency of this methodology increases significantly if it is applied in its unified form, which is especially important under the modern climate change, the forecasts of which are not highly reliable these days. The methodology makes it possible to estimate in advance and then compile a large amount of maps of subterranean waters protection from pollution and their vulnerability to it for various climate scenarios (taking into account the changing values of W), for conditions of pollution (for various K_p) and for both indices at once. Then from the numerous maps (or an album) some options can be chosen that match the current year best, according to the average annual precipitation in the study area and a specific pollutant. This will increase the efficiency of environmental protection measures in case of emergencies at the study sites.

Conclusions

The developed complex methodology for assessing the protection and vulnerability of groundwater and confined groundwater offers two approaches. The first one is used when the source of pollution is located on the ground, while the second one is used when the pollution source is located in the groundwater or when the pollution is spread over a large area. This methodology has a number of advantages and can be widely applied for the environmental and hydrogeological researches. Its distinguishing features are listed below.

1) The previously developed methodology can be used as a complex methodology for confined groundwater, with the exception of some features, such as the differences in the compilation of the maps of the protection zone and restrictions in the compilation of the final map, as well as the corresponding map of vulnerability that is based according on the first approach (Fig. 3a) and is used for radioactive substances with $K_p > 6$ l/kg, since the higher values protect the confined water throughout the entire territory for the entire lifetime of ^{137}Cs. Besides, we studied the properties of the aquiclude that separates these soil horizons. We found out that the lithological structure and the nature of pollution can determine whether it is impermeable, slightly permeable or quite permeable

for pollutants, as well as if it can become a potential source of pollution for confined waters.

2) This methodology can be applied for any cases of contamination with neutral, weakly sorbed and strongly sorbed pollutants, with/without radioactive decay.

3) Its effectiveness increases when using its unified version, especially when using it for environmental problems under the climate change and for groundwater contamination with various pollutants.

4) It is a preliminary forecast of the changes in the ecology of the studied objects, especially for the object of this article, studied in the radioactive trace of the Chernobyl Accident, when the theory suggests that each half-life of a radionuclide (i.e. 30 years for ^{137}Cs) its fallout density decreases two times, while its life span is limited to ten half-lives (300 years).

5) It is advised to use the said methodology for environmental hydrogeological studies in the polluted areas, such as the Chernobyl trace, for designing the environmentally hazardous industrial and agricultural facilities, for designing the intakes of fresh underground water and for environmental monitoring.

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КОМПЛЕКСНАЯ МЕТОДИКА ОЦЕНКИ ЗАЩИЩЕННОСТИ И УЯЗВИМОСТИ ГРУНТОВЫХ И НАПОРНЫХ ПОДЗЕМНЫХ ВОД ОТ РАЗЛИЧНЫХ ЗАГРЯЗНЯЮЩИХ ВЕЩЕСТВ И ЕЕ АПРОБАЦИЯ НА ЧАСТИ ТЕРРИТОРИИ КАЛУЖСКОЙ ОБЛАСТИ В ЗОНЕ РАДИОАКТИВНОГО СЛЕДА ОТ АВАРИИ НА ЧАЭС

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Объектом научных исследований являются грунтовые и напорные подземные воды на части территории Калужской области, наиболее пострадавшей от аварии на Чернобыльской атомной станции (ЧАЭС). Целью исследований была разработка комплексной методики для оценки защищенности и уязвимости грунтовых и напорных подземных вод к загрязнению различными веществами, включая радионуклиды. Методика была впоследствии опробована в Калужской области – в зоне радиоактивного следа от аварии на ЧАЭС.

Ранее проведенные нами исследования по оценке защищенности и уязвимости подземных вод, начавшиеся практически сразу после аварии и следовавшие оригинальной авторской методике, были полностью сконцентрированы на изучении только грунтовых вод, первом от поверхности земли водоносном горизонте. Настоящие исследования направлены на комплексное совместное изучение этой проблемы относительно грунтовых и напорных подземных вод, залегающих ниже грунтового водоносного горизонта.

В зависимости от расположения источника загрязнения подземных вод рассмотрено два подхода для решения поставленной задачи. Первый предполагает размещение источника загрязнения на поверхности почв, как это наблюдалось после аварии на ЧАЭС. Второй вариант предполагает размещение источника загрязнения в грунтовых водах или их площадное загрязнение; в этом случае количество объектов изучения уменьшается, и он становится частным случаем первого подхода.

Результаты научных исследований и предложенная методика могут быть использованы при оценке экологического состояния подземных вод на различных территориях страны в различных масштабах; при проектировании и строительстве водозаборов пресных питьевых подземных вод; при проектировании и организации мониторинга за подземными водами в районах, пострадавших от аварии на ЧАЭС. Результаты исследований являются новыми и значимыми для дальнейших работ.

Ключевые слова: грунтовые воды, подземные напорные воды, загрязняющие вещества, защищенность и уязвимость подземных вод от загрязнения, радионуклиды, сорбция, время миграции.

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