

**METHODS FOR STUDYING, MAINTANENCE AND PRESERVING ECOSYSTEMS
AND THEIR COMPONENTS**

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**USE OF A NUMERICAL EXPERIMENT IN STUDYING MIGRATION OF DIFFERENT
POLLUTANTS IN THE GROUNDWATER OF THE KALUGA REGION
IN THE AREA OF RADIOACTIVE ZONE**

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The purpose of this article was to use a mathematical modeling in order to study the migration of various pollutants, including radionuclides, from poorly sorbed to highly sorbed ones that travel from groundwater to pressure groundwater through a separating layer, an aquiclude, and has varying permeability. Among others, the field of hydrogeological researches performs search and exploration of groundwater deposits. Search is the first stage which is carried out in unexplored territories, followed by exploration, the second stage, which is performed in the promising territories that were revealed during the first stage.

Our studies follow the first stage, because the territories of our choice, located in the Kaluga Region and affected by the Chernobyl accident, were unexplored. We focused on studying the migration of pollutants from groundwater through the aquiclude of the pressure waters. The direction of our search was determined by the aquiclude's ability to let the pollutants through, which is considered the most unfavorable conditions for groundwater, or its ability to keep the pollutants out, which is considered a favorable condition. However, both of these stages do not exist separately in natural and artificial conditions, because they simply merge together, but, in order to study that, a thorough geological and hydrogeological knowledge of the territory is needed, which we do not possess for the study area. Therefore, our research was carried for both stages: in the first one, the aquiclude was assumed to be permeable, while in the second one it was assumed impermeable.

For each stage, exploratory numerical experiments were carried out using mathematical modeling. The object of those studies was the part of the Kaluga Region, most affected by the accident at the Chernobyl nuclear power plant. Studies concerning the first stage have been already completed and published by our crew (Belousova, Rudenko, 2021a, 2021b), while the results of the second stage and generalizing results of both studies are presented in this article. We studied the migration of various pollutants, including radionuclides, from groundwater through an impermeable aquiclude to the confined aquifer. We used the same profiles that were studied in the first stage, but applied slightly modified scenarios and used different coefficients of pollutant sorption distribution (K_d).

Numerical experiments of the second stage were carried out according to the following scenarios: 1 – (1-3-1), 2 – (1-6-1), 3 – (1-10-1), 4 – (6-60-6), 5 – (26-260-26), 6 – (100-1000-100). The first digit is the K_d value (l/kg) in the 1st layer, the second digit – 2nd layer, the third digit – 3rd layer. This selection of coefficients was determined by the fact that their values were assigned to be higher in the aquiclude than in the upper and lower aquifers.

Each scenario was applied for two conditions: with and without radioactive decay. The starting condition was the contamination degree of groundwater, just like the contamination degree of the ground in the radioactive trace zone of the study area. However, such a spread of contamination by either radionuclides or other pollutants is not actually (in natural conditions) observed in the groundwater of this territory. Pollutant concentrations can be specified in g/l, maximum permissible concentration (MPC) and background concentrations, but we used MPC. K_d of various pollutants were selected from the known values for the Bryansk Region (Belousova, Rudenko, 2021a, 2021b); regarding radionuclides, the K_d values mainly refer to the unsaturated zone of contamination.

We established that the main factors forming the pollutant migration are the radioactive decay of the said pollutants, their sorption properties, and the hydrodynamic dispersion of groundwater flow,

which, in turn, depends on the geological and hydrogeological conditions of the study area and the aquiclude permeability. The studied situation proves that aquicludes cannot ensure a full protection of pressure groundwater from pollution.

Keywords: groundwater, underground confined waters, modeling of migration processes, pollutant, radionuclides, sorption, radioactive decay.

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In this research we studied the pressure groundwater in the part of the Kaluga Region most affected by the accident at the Chernobyl nuclear power plant. Our purpose was to use the method of numerical experiment as part of mathematical modeling to study the migration of various pollutants (from poorly sorbed to highly sorbed), including radionuclides, through groundwater and pressure groundwater.

Numerical experiments of the second stage were carried out according to the following scenarios: 1 – (1-3-1), 2 – (1-6-1), 3 – (1-10-1), 4 – (6-60-6), 5 – (26-260-26), 6 – (100-1000-100). The first digit is the K_d value (l/kg) in the 1st layer, the second digit – 2nd layer, the third digit – 3rd layer. This selection of coefficients was determined by the fact that their values were assigned to be higher in the aquiclude than in the upper and lower aquifers. Each scenario was applied for two conditions: with and without radioactive decay. The previously created MT3D was used to model pollutant migration under each scenario (Zheng, Papadopoulos, 1990). To study the migration using this model, we made two profiles and several individual plots and assessed the ecological condition of groundwater, watershed layer and in pressure groundwater. We used this model to simulate the processes of geofiltration and pollutants migration in the Kaluga Region (Antonov et al., 2013; Belousova, 2015; Belousova, Rudenko, 2021a).

While using the model, we compared each scenario for the pollution development and analyzed the determining factors. We established that the main factors forming the pollutant migration are the radioactive decay of the said pollutants, their sorption properties, and the hydrodynamic dispersion of groundwater flow, which, in turn, depends on the geological and hydrogeological conditions of the study area and the aquiclude permeability.

We discovered that in the case of the impermeable aquicludes, polluted groundwater usually could not get into the confined aquifer at all, while in the case of the permeable ones, pollution could reach the pressure waters. It should be clarified that entirely “impermeable” and “permeable” aquicludes do not exist under natural conditions, because there is a thick layer of confining rocks of a complex lithological structure with industrial and natural disturbances.

The results of our researches on this topic can be used in assessing the ecological conditions of groundwater in different areas and at different scales; in designing and constructing the water intakes for fresh groundwater; in designing and organizing groundwater monitoring in those areas that were affected by the Chernobyl accident (Data on radioactive contamination ..., 2018; Radiation situation..., 2019)..

Modeling of Geological Migration of Pollutants

At the previous stage of our research, we showed that there is a danger of radionuclides polluting groundwater due to their migration from the surface that was contaminated during Chernobyl accident (Belousova, Rudenko, 2020). At the current stage, we consider the possibility of pollution entering the pressure waters from contaminated groundwater.

The *hydrogeological conditions* are characterized by a variety of non-pressure and confined aquifers (Belousova, Rudenko, 2021a, 2021b). Non-pressure aquifers include waters of Quaternary (alluvial, glacial, fluvioglacial, swamp and proluvial horizons), Cretaceous and Jurassic deposits. They all are connected and do not have sustained aquicludes inside their complex.

The previously conducted analysis of the existing groundwater pollution in the Kaluga Region,

showed the chemical pollution in various aquifers. From the Quaternary to the Devonian, every aquifer is polluted and almost each of them contains stable strontium, barium, fluorine, nitrates, chlorides and sulfates.

We analyzed the pollutants according to the degree of their sorption and classified them at the previous stage of our research using literature sources. As the results of that analysis show, the K_d values of many chemical elements significantly exceeded thousands of l/kg ($Ni = 152-5365$ l/kg) due to the lithological composition of the water-bearing rocks and the state of the certain chemical element. To assess the vulnerability of pressure groundwater to pollution coming from groundwater, we used a simplified concept of sorption and divide the elements into 2 categories: poorly sorbed ($K_d = 0-6$ l/kg) and highly sorbed (from 6 to 1000 l/kg). Further below, the range of K_d is explained in detail.

We should emphasize that radionuclide migration was mainly studied in the unsaturated zone before, i.e. in the soils and rocks of the aeration zone, where K_d varies from 1 to >1000 l/kg depending on the lithological composition. Such studies are almost non-existent for groundwater, since it has been believed for some time that groundwater was protected from any radionuclides, even though their insignificant amounts were still found in groundwater of the Bryansk Region.

Thus, ^{137}Cs and ^{90}Sr and other highly sorbed pollutants with a similar range of distribution coefficients, as well as neutral but poorly sorbed pollutants, such as nitrates, sulfates, chlorides and oil products, were chosen for our model to simulate the pollution processes in the groundwater and pressure groundwater.

To model the mass transfer in groundwater, we used MT3D that works on the basis of the MODFLOW transport model (Belousova, Rudenko, 2021a, 2021b). The initial distribution of the pollutants concentration in groundwater was conditionally similar to the surface distribution of radiation in the Chernobyl zone in the Kaluga Region. Their concentration can be determined in g/l, Bq/l, maximum permissible concentration (MPC) or background concentrations; but we prefer to use MPC (Fig. 1). Additionally, it should be noted that such contamination of groundwater in the radioactive zone in the study area is not actually observed.

To study the migration with MT3D (Antonov et al., 2013), we selected 2 profiles: one along the I-I line, from the northeast to the southwest of the study area, and one along the II-II line, from the southwest to the southeast, along the groundwater flow lines stretching from the watershed to the discharge area, i.e. to the river (Fig. 2).

The analysis of the ecological conditions was carried under various scenarios for 4 estimated periods: 30, 60, 100 and 300 years (picked due to the half-life of radionuclides and the duration of water intakes). We considered the following scenarios: with radioactive decay for radionuclides, without the decay for other pollutants, for poorly sorbed pollutants and for highly sorbed pollutants.

Changes in the pollutant concentrations with different K_d without decay for two time periods (30 years, 300 years) and two profiles

Profile I-I, initial pollutant concentrations throughout the individual plots: 1 – 8 MPC, 11 – 6 MPC, 12 – 4 MPC, 13 – 2 MPC, 14 – 4 MPC, 15 – 2 MPC.

30 years after the Chernobyl accident (Table 1; Fig. 3a) the pollutant concentration values in *the 1st layer* are clearly grouped when the K_d is 1-10 (Scenarios 1-3) and 6-1000 (Scenarios 4-6). On the plot No. 1, there are maximum concentrations (7-8 MPC) under Scenarios 4-6 and a drop of MPC down to 6-7 under Scenarios 1-3. Similar situations are observed at plots No. 11 and 14, while at No. 12, 13 and 15, in the area of groundwater discharge, every value of MPC, once equal, would drop down to 2, which indicates a significant role of hydrodynamic dispersion of groundwater flow. The concentrations at any K_d changes little compared to the initial concentrations that were observed before the accident. In *the 2nd layer* (aquiclude; Fig. 3b) the insignificant concentrations

are found at No. 1 (from 0.1 to 0.033 MPC) under Scenarios 1-3, while at No. 11 and 14 they are even lower and do not exceed 0.1 MPC. Other plots only have insignificant traces of pollution. Pollutants with high K_d under Scenarios 4-6 are also found in insignificant concentrations. In *the 3rd layer* there are no pollutants no matter the plot or scenario, which means that they cannot penetrate the aquiclude.

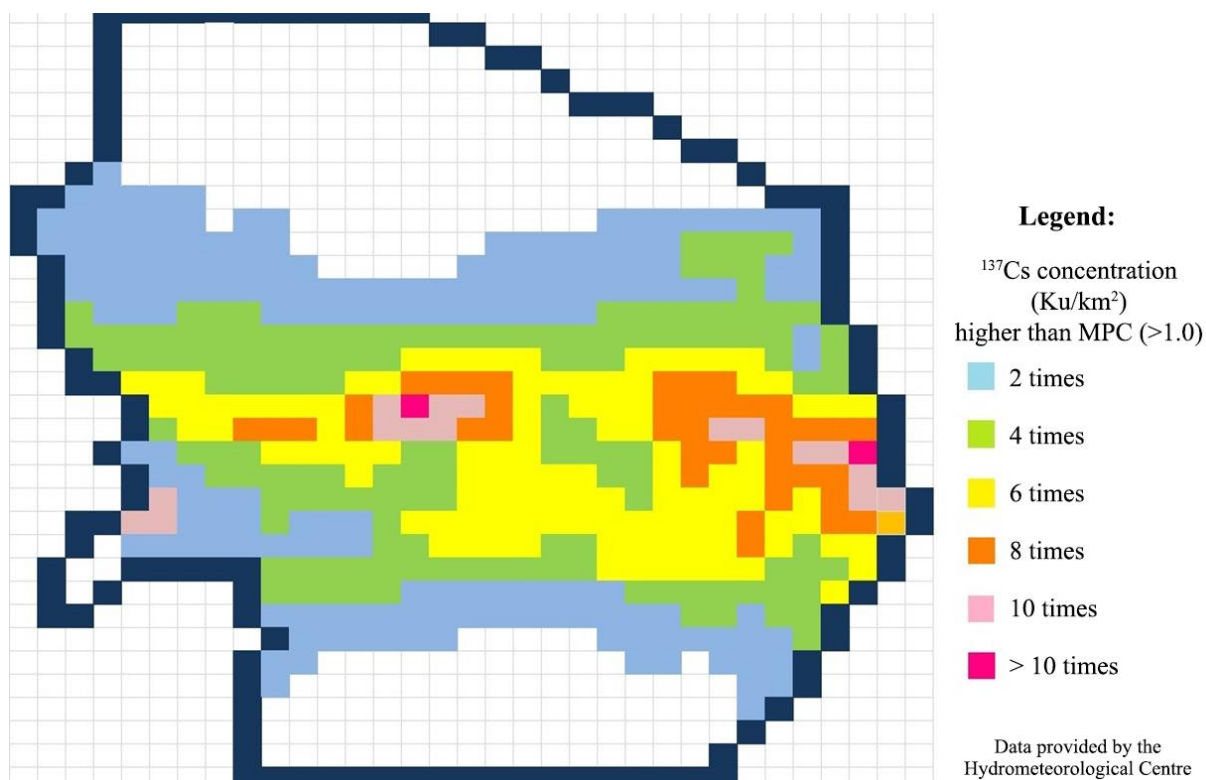


Fig. 1. Cartographic chart of surface contamination with ^{137}Cs radionuclide in the south of Kaluga Region (Map ..., 1991).

300 years after the Chernobyl accident (Table 2; Fig. 3c) pollutants in *the 1st layer* are clearly redistributed according to their K_d : those with low K_d (Scenarios 1-3) migrate more intensely, sometimes reaching the 2nd layer; while the ones with high K_d (Scenarios 4-6) are found in almost the same concentrations. Pollutants with small K_d accumulate in *the 2nd layer* (aquiclude; Scenarios 1-3) up to 3.5 MPC (Fig. 3d), with high concentrations only at the plot No. 11, low ones at No. 1 and 14, and only traces registered at other plots. It should be noted that the maximum concentrations 30 years after the accident shifted from No. 1 to 11 due to the hydrodynamic dispersion of the groundwater flow, because the plot No. 1 is located on the watershed and the flow sources from it, bearing pollutants that have accumulated in it over time. No pollutants are found in *the 3rd layer*.

Profile II-II, initial pollutant concentrations throughout the individual plots: 1 – 8 MPC, 2 – 6 MPC, 3 – 8 MPC, 4 – 12 MPC, 5 – 6 MPC, 6 – 2 MPC, 7 – 2 MPC, 8 – 10 MPC, 9 – 8 MPC, 10 – 12 MPC.

30 years after the Chernobyl accident (Table 1; Fig. 4a) the situation in *the 1st layer* is the same with the I-I profile, with the same differentiation by scenarios, although with an insignificant pollutants concentration from the initial concentration. The concentrations in this layer are high, reaching their maximum of 12 MPC. *The 2nd layer* (Fig. 4b) has the same tendencies with the I-I, i.e. the insignificant accumulation of pollutants under Scenarios 1-3 that do not exceed 0.33 MPC

at the lowest K_d and are considered insignificant at the high K_d . The role of the hydrodynamic dispersion is important in this case as well, because it shifts the maximal concentrations from one plot to another: for example, from No. 8 in the 1st layer to No. 1 in the 2nd layer. No pollutants are found in *the 3rd layer*.

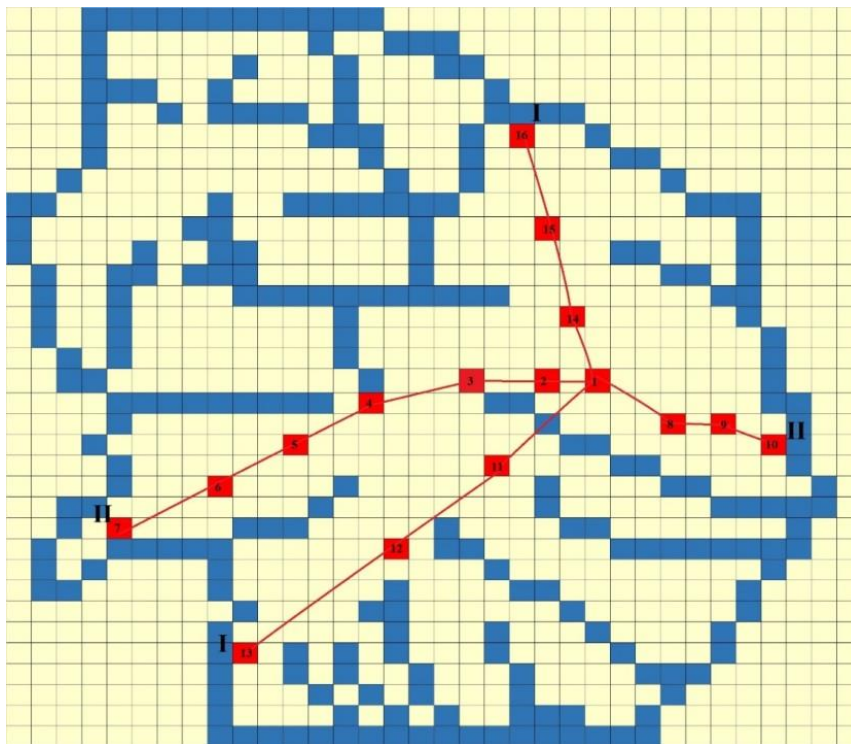


Fig. 2. Schematic location of I-I and II-II profiles, including key plots on the model of the studied object.

300 years after the accident (Table 2; Fig. 4c) the pollutants in *the 1st layer* are redistributed the same way according to their K_d : those with low K_d (Scenarios 1-3) migrate more intensely and reach the 2nd layer in insignificant amount; while the ones with high K_d (Scenarios 4-6) are found in almost the same concentrations. Insignificant concentrations of pollutants with small K_d accumulate in *the 2nd layer* (Scenarios 1-3) up to 0.22 MPC (Fig. 4d); however, insignificant accumulations can be seen everywhere aside from the plots No. 5-7, where it's almost zero. It should be noted that in this case the maximal concentrations shifted as well from one point to another due to the hydrodynamic dispersion of groundwater flow. No signs of accumulations were found in *the 3rd layer*.

In addition to the aforementioned periods, we carried out calculations for 60 and 100 years, the results of which can be found in Tables 1 and 2.

Changes in the pollutant concentrations with different K_d with decay for two time periods (30 years, 300 years) and two profiles

Profile I-I, initial pollutant concentrations throughout the individual plots: 1 – 8 MPC, 11 – 6 MPC, 12 – 4 MPC, 13 – 2 MPC, 14 – 4 MPC, 15 – 2 MPC.

30 years after the accident (Table 1; Fig. 5a) there are the same tendencies of pollutants in *the 1st layer* forming groups according to their K_d , as it was observed for the pollutants with decay in the same layer. However, their concentration is twice as low (3.5 MPC) due to them reaching one half-life (which equals 30 years for radionuclides).

Table 1. Change in concentration of highly sorbed pollutants in groundwater, watershed and pressure water during their migration (30 and 60 years).

Profile No.	Plot No.	Kd 1-3-1				Kd 1-6-1				Kd 6-60-6			
		decay		no decay		decay		no decay		decay		no decay	
		Layer No.											
		1	2	1	2	1	2	1	2	1	2	1	2
		30 years											
I	13	0.989	0.00015	1.967	0.00020	0.989	0.00008	1.966	0.00010	0.867	0.00001	1.990	0.00001
	12	1.985	0.00037	3.945	0.00073	1.985	0.00028	3.945	0.00037	1.736	0.00003	3.990	0.00004
	11	2.891	0.00527	5.746	0.00695	2.891	0.00266	5.645	0.00351	2.589	0.00031	5.950	0.00036
	1	3.491	0.02430	6.938	0.03180	3.491	0.01230	6.938	0.01610	3.387	0.00148	7.786	0.00172
	14	1.890	0.00465	3.757	0.00613	1.890	0.00235	3.757	0.00309	1.719	0.00027	3.952	0.00032
	15	0.963	0.00033	1.913	0.00044	0.963	0.00017	1.913	0.00022	0.863	0.00002	1.983	0.00002
	16	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000
II	7	0.957	0.00066	1.902	0.00087	0.957	0.00033	1.901	0.00044	0.862	0.00039	1.980	0.00005
	6	0.976	0.00017	1.940	0.00045	0.976	0.00009	1.940	0.00012	0.865	0.00001	1.988	0.00001
	5	2.928	0.00033	5.829	0.00043	2.928	0.00017	5.819	0.00022	2.595	0.00002	5.965	0.00002
	4	5.873	0.00439	11.670	0.00581	5.873	0.00222	11.627	0.00293	5.193	0.00025	11.937	0.00030
	3	3.870	0.00075	7.691	0.00098	3.870	0.00038	7.691	0.00050	3.454	0.00004	7.940	0.00005
	2	2.814	0.02070	5.559	0.02730	2.814	0.01050	5.593	0.00014	2.575	0.00123	5.920	0.00143
	1	3.491	0.02430	6.938	0.03180	3.491	0.01230	6.938	0.01610	3.387	0.00148	7.786	0.00172
	8	4.635	0.02040	9.212	0.02685	4.635	0.01030	9.212	0.01300	4.283	0.00120	9.845	0.00141
	9	3.887	0.01470	7.726	0.01943	3.887	0.00743	7.726	0.00980	3.457	0.00086	7.947	0.00100
	10	5.771	0.02050	11.470	0.02712	5.771	0.01040	11.470	0.01300	5.176	0.00120	11.897	0.00141
		60 years											
I	13	0.489	0.00024	1.933	0.00043	0.490	0.00012	1.933	0.00022	0.377	0.00001	1.978	0.00002
	12	0.985	0.00079	3.890	0.01344	0.985	0.00040	3.890	0.00068	0.755	0.00004	3.979	0.00007
	11	1.381	0.00805	5.454	0.01424	1.381	0.00406	5.453	0.00719	1.118	0.00046	5.892	0.00075
	1	1.474	0.03560	5.820	0.06137	1.474	0.01800	5.819	0.03100	1.428	0.00216	7.530	0.00953
	14	0.898	0.00637	3.545	0.01063	0.897	0.00322	3.545	0.00537	0.741	0.00036	3.909	0.00057
	15	0.462	0.00049	1.826	0.00086	0.462	0.00025	1.825	0.00043	0.373	0.00003	1.965	0.00005
	16	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000
II	7	0.458	0.00097	1.808	0.00167	0.458	0.00049	1.808	0.00084	0.372	0.00006	1.962	0.00009
	6	0.476	0.00026	1.882	0.00045	0.476	0.00013	1.882	0.00023	0.375	0.00001	1.976	0.00002
	5	1.428	0.00048	5.640	0.00083	1.428	0.00024	5.640	0.00042	1.125	0.00003	5.929	0.00004
	4	2.870	0.00662	11.335	0.01164	2.870	0.00334	11.335	0.00587	2.252	0.00037	11.870	0.00061
	3	1.866	0.00118	7.367	0.00213	1.865	0.00060	7.367	0.00107	1.494	0.00007	7.875	0.00012
	2	1.313	0.03050	5.185	0.05309	1.313	0.01540	5.185	0.02080	1.107	0.00180	5.896	0.00287
	1	1.474	0.03560	5.820	0.06137	1.474	0.01800	5.819	0.03100	1.428	0.00216	7.530	0.00953
	8	2.134	0.03020	8.425	0.05249	2.134	0.01520	8.425	0.02652	1.836	0.00170	9.679	0.00286
	9	1.875	0.02280	7.406	0.04060	1.875	0.01150	4.405	0.02052	1.496	0.00130	7.883	0.00213
	10	2.773	0.03040	10.950	0.05296	2.773	0.01540	10.950	0.02674	2.238	0.00170	11.793	0.00279
	13	0.989	0.00005	1.966	0.00006	0.843	0.00000	1.990	0.00000	0.842	0.00000	1.998	0.00000

Continuation of Table 1.

Profile No.	Plot No.	K _B 1-10-1				K _d 100-1000-100				K _d 26-260-26			
		decay		no decay		decay		no decay		decay		no decay	
		Layer No.											
		1	2	1	2	1	2	1	2	1	2	1	2
		30 years											
I	12	1.985	0.00017	3.945	0.00022	1.686	0.00000	3.990	0.00000	1.684	0.00001	3.998	0.00001
	11	2.891	0.00160	5.745	0.00211	2.528	0.00002	5.990	0.00002	2.524	0.00007	5.988	0.00008
	1	3.491	0.00739	6.938	0.00969	3.366	0.00009	7.980	0.00010	3.350	0.00035	7.949	0.00040
	14	1.890	0.00141	3.757	0.00186	1.685	0.00002	3.990	0.00002	1.681	0.00006	3.998	0.00007
	15	0.963	0.00010	1.913	0.00013	0.843	0.00000	1.990	0.00000	0.841	0.00000	1.996	0.00001
	16	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000
II	7	0.957	0.00020	1.901	0.00027	0.843	0.00000	1.990	0.00000	0.841	0.00001	1.995	0.00001
	6	0.976	0.00005	1.940	0.00007	0.843	0.00000	1.990	0.00000	0.841	0.00000	1.997	0.00000
	5	2.928	0.00010	5.819	0.00013	2.528	0.00000	5.990	0.00000	2.525	0.00000	5.991	0.00001
	4	5.873	0.00134	11.672	0.00176	5.056	0.00002	11.990	0.00002	5.051	0.00006	11.985	0.00007
	3	3.870	0.00026	7.691	0.00030	3.370	0.00000	8.000	0.00000	3.366	0.00001	7.985	0.00001
	2	2.814	0.00631	5.592	0.00830	2.527	0.00008	5.990	0.00009	2.520	0.00129	5.981	0.00033
	1	3.491	0.00739	6.938	0.00969	3.366	0.00009	7.980	0.00010	3.350	0.00035	7.949	0.00040
	8	4.635	0.00620	9.212	0.00816	4.210	0.00008	9.990	0.00009	4.199	0.00028	9.963	0.00021
	9	3.887	0.00448	7.726	0.00591	3.371	0.00005	7.990	0.00006	3.367	0.00020	7.987	0.00017
	10	5.771	0.00625	11.470	0.00824	5.055	0.00007	11.990	0.00009	5.047	0.00028	11.975	0.00033
		60 years											
I	13	0.489	0.00007	1.933	0.00013	0.355	0.00000	1.990	0.00000	0.354	0.00000	1.997	0.00001
	12	0.985	0.00024	3.891	0.00041	0.710	0.00000	3.990	0.00000	0.709	0.00001	3.995	0.00002
	11	1.381	0.00245	5.453	0.00433	1.065	0.00003	5.990	0.00005	1.060	0.00011	5.974	0.00018
	1	1.473	0.01080	5.819	0.01870	1.420	0.00013	7.970	0.00022	1.400	0.00051	7.887	0.00083
	14	0.898	0.00194	3.545	0.00323	0.710	0.00002	3.990	0.00003	0.707	0.00009	3.978	0.00013
	15	0.462	0.00015	1.825	0.00026	0.355	0.00000	1.990	0.00000	0.354	0.00001	1.992	0.00001
	16	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000
II	7	0.458	0.00029	1.808	0.00051	0.355	0.00000	1.990	0.00001	0.353	0.00001	1.991	0.00002
	6	0.477	0.00008	1.882	0.00014	0.355	0.00000	1.990	0.00000	0.354	0.00000	1.995	0.00001
	5	1.428	0.00015	5.640	0.00025	1.065	0.00000	5.990	0.00000	1.060	0.00001	5.983	0.00001
	4	2.870	0.00201	11.335	0.00354	2.130	0.00002	11.990	0.00004	2.126	0.00009	11.969	0.00014
	3	1.866	0.00036	7.367	0.00065	1.420	0.00000	7.990	0.00001	1.410	0.00002	7.970	0.00003
	2	1.313	0.00931	5.185	0.01620	1.064	0.00011	5.980	0.00017	1.050	0.00042	5.967	0.00067
	1	1.473	0.01080	5.819	0.01870	1.420	0.00013	7.970	0.00022	1.400	0.00051	7.887	0.00083
	8	2.133	0.00919	8.425	0.01590	1.773	0.00011	9.970	0.00017	1.760	0.00041	9.923	0.00067
	9	1.875	0.00694	7.405	0.01236	1.420	0.00008	7.990	0.00013	1.420	0.00030	7.972	0.00050
	10	2.774	0.00925	10.953	0.01610	2.129	0.00011	11.980	0.00017	2.120	0.00040	11.951	0.00065

Notes to Tables 1-2: the 3rd layer is not included, because the values at the key plots were zero.

The hydrological dispersion is also present here, affecting mostly the pollutants with the lower K_d , as well as their accumulation that happens after they flow into the nearby computational cells; however, the dispersion does not affect the highly sorbed pollutants too much. **The 2nd layer** (aquiclude) is similar (Fig. 5b) to the Layer 2 of the I-I, with lower concentrations: plot No. 1 without decay – 0.032 MPC, with decay – 0.024 MPC, which means that aquiclude accumulates less of poorly sorbed pollutants with decay, while the highly sorbed ones leave traces. No pollutants were found in **the 3rd layer**.

300 years after the accident (Table 2; Fig. 5c) the pollutants with high K_d (Scenarios 4-6) are almost entirely absent in **the 1st layer** (up to < 0.001 MPC), while the amount of ones with lower K_d (Scenarios 1-3) is insignificant (up to 0.004 MPC).

Therefore, we can affirm that radioactive pollutants with different K_d undergo the almost complete decay. The concentration of pollutants in **the 2nd layer** (Fig. 5d) increases slightly compared to the ones 30 years after the accident: for example, the concentration of poorly sorbed pollutants reached 0.025 MPC at the plot No. 1 after 30 years, increasing to 0.042 MPC after 300 years, which cannot be considered a significant value, but can indicate the traces of these pollutants in the aquiclude. No pollutants were found in **the 3rd layer**.

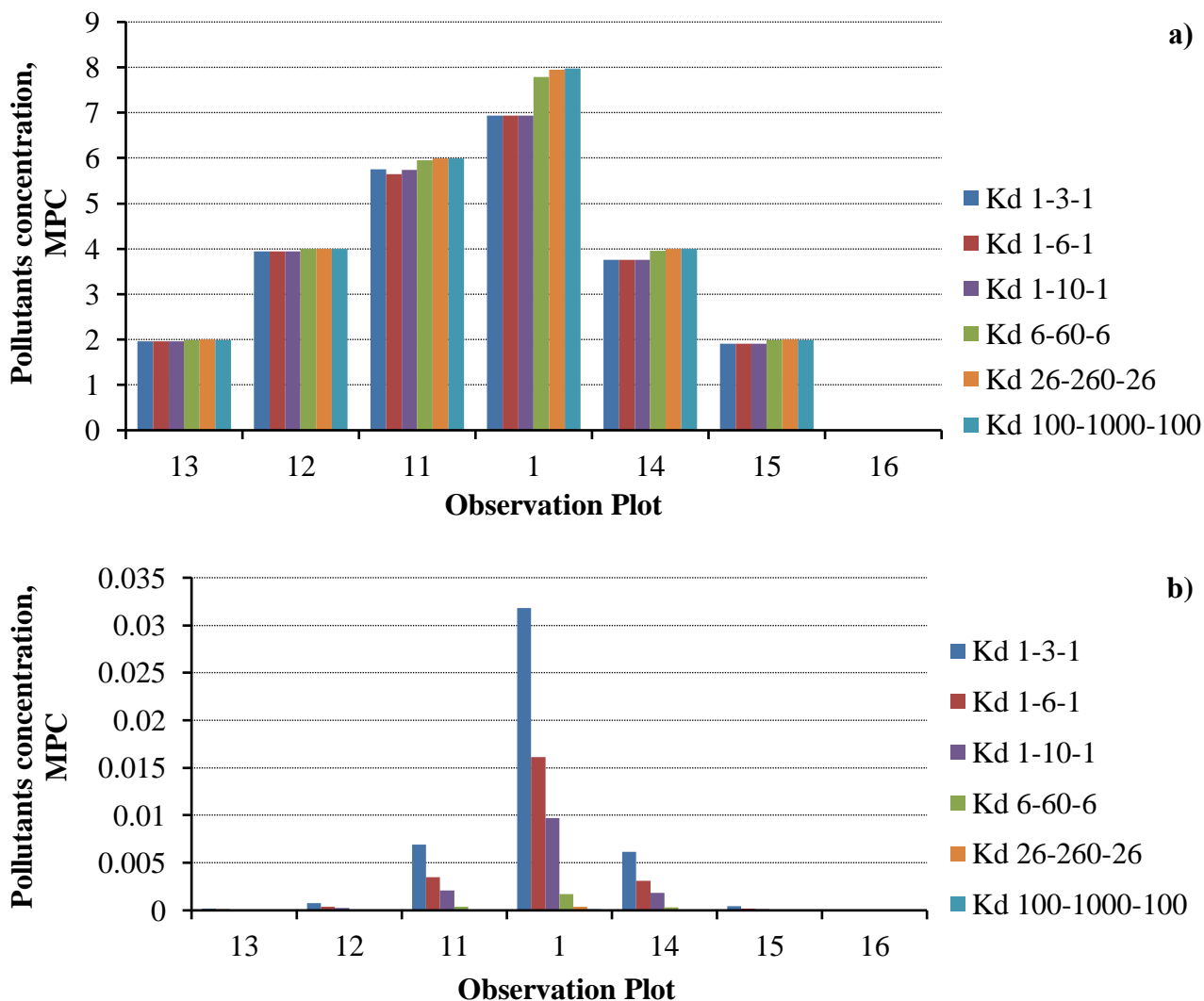


Fig. 3a, b. Distribution of pollutant concentrations for different K_d , Profile I-I: a) 30 years, Layer 1 without decay; b) 30 years, layer 2 without decay.

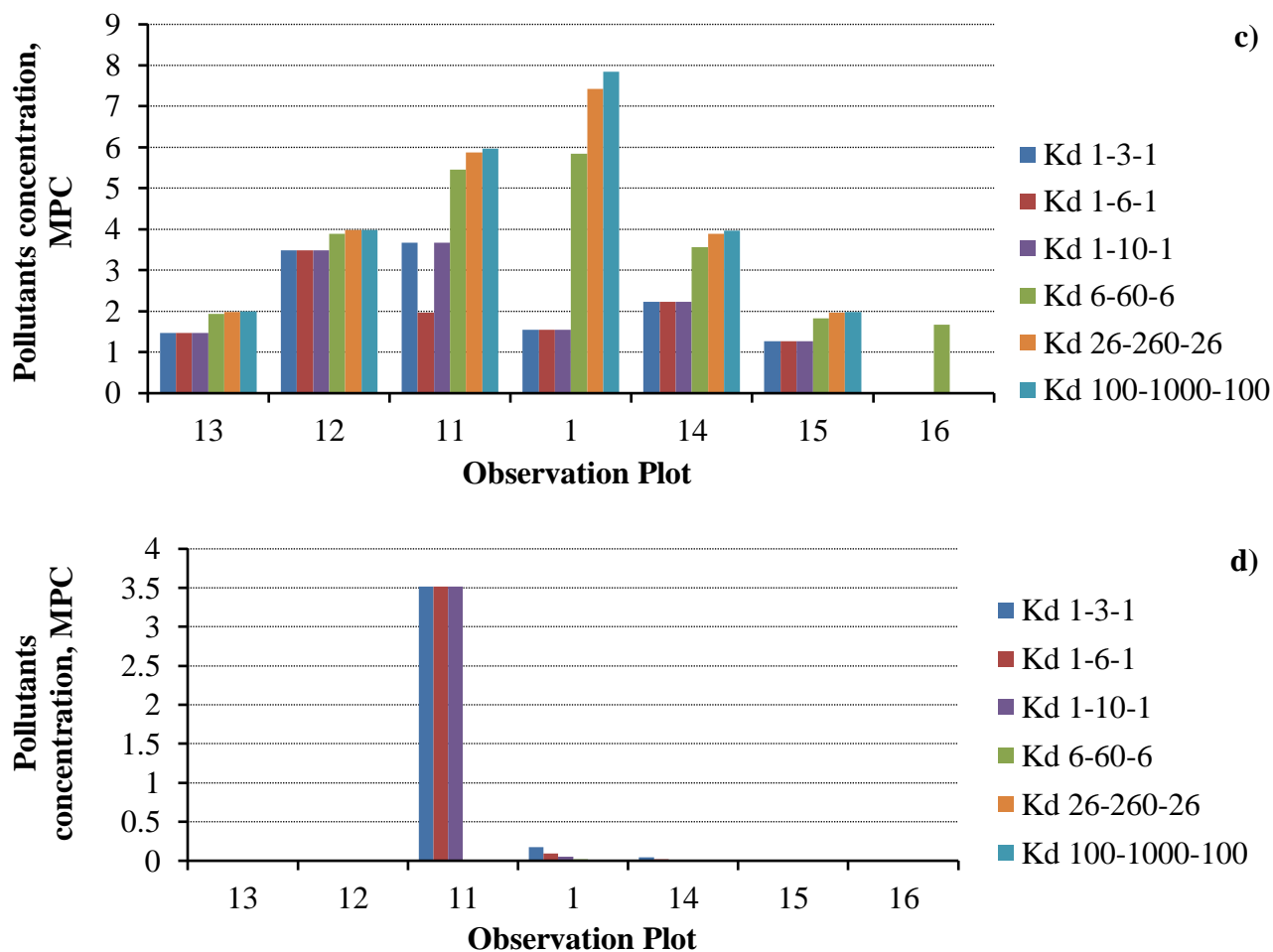


Fig. 3c, d. Distribution of pollutant concentrations for different Kd, Profile I-I: c) 300 years, Layer 1 without decay; d) 300 years, Layer 2 without decay.

Profile II-II, initial pollutant concentrations throughout the individual plots: 1 – 8 MPC, 2 – 6 MPC, 3 – 8 MPC, 4 – 12 MPC, 5 – 6 MPC, 6 – 2 MPC, 7 – 2 MPC, 8 – 10 MPC, 9 – 8 MPC, 10 – 12 MPC.

30 years after the accident (Table 1; Fig. 6a) the general tendencies of the radioactive pollutants distribution in *the 1st layer* are the same with the non-radioactive ones (Fig. 4a). The only difference is the concentration values which are twice lower for the radioactive pollutants: plot No. 4 – 12 MPC (no decay) and 6 MPC (decay), with the same picture at other plots due to the one half-life of the radionuclides. In addition, there is a shift of maximal concentrations that were registered for the pollutants with high Kd and no decay, as well as for the ones with decay and low Kd. This is due to hydrological dispersion that actively brings pollutants with low Kd from the nearby cells, instead of those with higher Kd. *The 2nd layer* (Fig. 6b) mostly accumulates the poorly sorbed pollutants that come from the 1st layer (up to 0.025 MPC) and has traces of highly sorbed ones. No pollutants were found in *the 3rd layer*.

300 years after the accident (Table 2; Fig. 6c) *the 1st layer* has the same tendencies and changes with the layer from the I-I, however the concentration of poorly sorbed pollutants at the plot No. 1 has dropped from 12 to 0.009 MPC due to ten half-lives of the radionuclides. The poorly sorbed pollutants in *the 2nd layer* (Fig. 6d) have increased insignificantly under Scenarios 1-3 at the plot No. 1 – up to 0.04 MPC compared to 0.024 MPC after 30 years (Fig. 6b); however, only the traces of highly sorbed ones were found. No pollutants were found in *the 3rd layer*.

Table 2. Change in concentration of highly sorbed pollutants in groundwater, watershed and pressure water during their migration (100 and 300 years).

Profile No.	Plot No.	Kd 1-3-1				Kd 1-6-1				Kd 6-60-6			
		decay		no decay		decay		no decay		decay		no decay	
		Layer No.											
		1	2	1	2	1	2	1	2	1	2	1	2
		100 years											
I	13	0.191	0.00027	1.891	0.00066	0.191	0.00014	1.891	0.00033	0.110	0.00002	1.978	0.00003
	12	0.386	0.00100	3.820	0.00241	0.386	0.00050	3.820	0.00112	0.220	0.00005	3.965	0.00013
	11	0.524	0.00926	5.193	0.02200	0.524	0.00468	5.193	0.01111	0.325	0.00510	5.837	0.00119
	1	0.503	0.04010	4.978	0.09000	0.503	0.02030	4.977	0.04570	0.406	0.00244	7.309	0.00551
	14	0.328	0.00808	3.246	0.01900	0.328	0.00408	3.246	0.00959	0.214	0.00046	3.844	0.00105
	15	0.177	0.00058	1.725	0.00137	0.174	0.00029	1.725	0.00069	0.108	0.00003	1.944	0.00007
	16	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000
II	7	0.170	0.00116	1.690	0.00274	0.170	0.00059	1.690	0.00138	0.107	0.00007	1.937	0.00015
	6	0.183	0.00031	1.810	0.00073	0.183	0.00015	1.809	0.00037	0.109	0.00002	1.962	0.00004
	5	0.548	0.00058	5.419	0.00139	0.551	0.00029	5.419	0.00070	0.327	0.00003	5.884	0.00007
	4	1.106	0.00781	10.934	0.01870	1.060	0.00394	10.943	0.00945	0.655	0.00043	11.790	0.00099
	3	0.709	0.00132	7.018	0.00313	0.709	0.00066	7.018	0.00158	0.433	0.00002	7.803	0.00017
	2	0.480	0.03560	4.748	0.08360	0.479	0.01810	4.747	0.04233	0.319	0.00204	5.738	0.00470
	1	0.503	0.04010	4.978	0.09000	0.503	0.02030	4.977	0.04570	0.406	0.00244	7.309	0.00551
	8	0.769	0.03490	7.608	0.08130	0.769	0.01770	7.607	0.04111	0.528	0.00200	9.493	0.00462
	9	0.709	0.02590	7.017	0.06200	0.709	0.01310	7.016	0.03134	0.435	0.00140	7.828	0.00319
	10	1.010	0.03590	10.018	0.08490	1.012	0.01820	10.010	0.04291	0.648	0.00200	11.661	0.00464
		300 years											
I	13	0.002	0.00031	1.477	0.002	0.002	0.00031	1.477	0.00097	0.000	0.00002	1.936	0.00011
	12	0.004	0.00108	3.483	0.006	0.004	0.00108	3.483	0.00313	0.001	0.00006	3.896	0.00033
	11	0.004	0.00927	3.673	3.520	0.004	0.00927	1.962	3.51700	0.001	0.00055	5.463	0.00368
	1	0.003	0.04170	1.550	0.177	0.003	0.04170	1.547	0.09070	0.001	0.00260	5.848	0.01580
	14	0.002	0.00857	2.229	0.041	0.002	0.00857	2.223	0.02000	0.001	0.00048	3.571	0.00260
	15	0.001	0.00063	1.262	0.004	0.001	0.00063	1.262	0.00183	0.000	0.00003	1.832	0.00022
	16	0.000	0.00000	0.000	0.000	0.000	0.00000	0.000	0.00000	0.000	0.00000	1.676	0.00000
II	7	0.001	0.00126	1.739	0.007	0.001	0.00126	1.739	0.00362	0.000	0.00007	1.817	0.00042
	6	0.002	0.00034	1.849	0.002	0.002	0.00034	1.849	0.00105	0.000	0.00002	1.887	0.00012
	5	0.005	0.00064	4.401	0.004	0.005	0.00064	4.401	0.00185	0.001	0.00003	5.656	0.00021
	4	0.009	0.00859	8.548	0.052	0.009	0.00859	8.550	0.02610	0.002	0.00045	11.360	0.00298
	3	0.005	0.00147	5.262	0.093	0.005	0.00147	5.262	0.00471	0.001	0.00008	7.387	0.00056
	2	0.004	0.03760	2.723	0.195	0.004	0.03760	2.716	0.09960	0.001	0.00220	5.213	0.01360
	1	0.003	0.04170	1.550	0.177	0.003	0.04170	1.547	0.09070	0.001	0.00260	5.848	0.01580
	8	0.005	0.03720	4.210	0.190	0.005	0.03720	4.201	0.09600	0.001	0.00210	8.476	0.01350
	9	0.006	0.02830	5.261	0.174	0.006	0.02830	5.257	0.08843	0.001	0.00150	7.415	0.01050
	10	0.006	0.04000	6.209	0.209	0.006	0.04000	6.206	0.10600	0.002	0.00210	10.998	0.01350
	13	0.191	0.00008	1.890	0.00020	0.101	0.00000	1.990	0.00000	0.100	0.00000	1.995	0.00001

Continuation of Table 2.

Profile No.	Plot No.	Kd 1-10-1				Kd 100-1000-100				Kd 26-260-26			
		decay		no decay		decay		no decay		decay		no decay	
		Layer No.											
		1	2	1	2	1	2	1	2	1	2	1	2
100 years													
I	12	0.386	0.00030	3.820	0.00073	0.202	0.00000	3.990	0.00001	0.202	0.00001	3.990	0.00003
	11	0.525	0.00282	5.193	0.00669	0.303	0.00003	5.980	0.00007	0.301	0.00012	5.961	0.00028
	1	0.503	0.01226	4.976	0.02756	0.402	0.00015	7.950	0.00035	0.396	0.00057	7.831	0.00133
	14	0.328	0.00246	3.246	0.00578	0.202	0.00003	3.990	0.00006	0.200	0.00010	3.963	0.00025
	15	0.174	0.00018	1.725	0.00042	0.101	0.00000	1.990	0.00000	0.100	0.00001	1.987	0.00002
	16	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000
II	7	0.171	0.00035	1.690	0.00083	0.101	0.00000	1.990	0.00009	0.100	0.00002	1.984	0.00003
	6	0.183	0.00009	1.809	0.00022	0.101	0.00000	1.990	0.00000	0.100	0.00000	1.990	0.00001
	5	0.547	0.00018	5.419	0.00042	0.303	0.00000	5.990	0.00000	0.302	0.00001	5.972	0.00002
	4	1.106	0.00237	10.943	0.00569	0.607	0.00003	11.980	0.00006	0.604	0.00010	11.950	0.00023
	3	0.709	0.00040	7.018	0.00095	0.404	0.00000	7.980	0.00001	0.402	0.00002	7.953	0.00004
	2	0.479	0.01090	4.747	0.02550	0.303	0.00012	5.980	0.00029	0.300	0.00048	5.937	0.00110
	1	0.503	0.01226	4.976	0.02756	0.402	0.00015	7.950	0.00035	0.396	0.00057	7.831	0.00133
	8	0.769	0.01060	7.607	0.02477	0.505	0.00012	9.960	0.00028	0.500	0.00047	9.878	0.00109
	9	0.709	0.00791	7.016	0.01800	0.404	0.00009	7.990	0.00021	0.400	0.00033	7.958	0.00077
	10	1.012	0.01090	10.017	0.02585	0.606	0.00012	11.980	0.00028	0.603	0.00047	9.917	0.00108
300 years													
I	13	0.002	0.00009	1.476	0.00059	0.000	0.00000	1.990	0.00001	0.000	0.00000	1.984	0.00003
	12	0.004	0.00033	3.483	0.00188	0.000	0.00000	3.990	0.00002	0.000	0.00001	3.975	0.00008
	11	0.004	0.00856	3.672	3.51600	0.001	0.00003	5.965	0.00023	0.001	0.00013	5.869	0.00088
	1	0.002	0.01300	1.544	0.05480	0.001	0.00016	7.847	0.00100	0.001	0.00060	7.430	0.00410
	14	0.002	0.00262	2.227	0.01249	0.000	0.00003	3.972	0.00016	0.000	0.00010	3.894	0.00063
	15	0.001	0.00019	1.262	0.00410	0.000	0.00000	1.980	0.00001	0.000	0.00001	1.959	0.00005
	16	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000	0.000	0.00000
II	7	0.001	0.00038	1.739	0.00218	0.000	0.00000	1.980	0.00003	0.000	0.00002	1.955	0.00010
	6	0.002	0.00010	1.365	0.00063	0.000	0.00000	1.990	0.00001	0.000	0.00000	1.973	0.00005
	5	0.005	0.00019	4.401	0.00112	0.001	0.00000	5.980	0.00001	0.001	0.00001	5.917	0.00005
	4	0.009	0.00262	8.548	0.01575	0.002	0.00003	11.960	0.00018	0.002	0.00010	11.846	0.00070
	3	0.005	0.00045	5.262	0.01136	0.001	0.00000	7.960	0.00004	0.001	0.00002	7.851	0.00013
	2	0.003	0.01170	2.713	0.06000	0.001	0.00013	5.948	0.00087	0.001	0.00050	5.804	0.00332
	1	0.002	0.01300	1.544	0.05480	0.001	0.00016	7.847	0.00100	0.001	0.00060	7.430	0.00410
	8	0.005	0.01150	4.198	0.05845	0.001	0.00013	9.890	0.00087	0.001	0.00049	9.617	0.00332
	9	0.006	0.00873	5.255	0.05339	0.001	0.00009	7.960	0.00066	0.001	0.00035	7.858	0.00251
	10	0.006	0.01190	6.205	0.06396	0.002	0.00013	11.935	0.00084	0.001	0.00049	11.755	0.00378

Changes in the pollutant concentrations with different Kd

Scenario 1-6-1, Profile I-I. 30 years after the accident the distribution of pollutant concentrations **without decay** changed insignificantly in *the 1st layer* compared to the initial

concentrations (Fig. 7a). For example, the initial 8 MPC at the plot No. 1 dropped to 7 MPC, then to 6 MPC after 60 years, to 5 MPC after 100 years and finally to 1.5 MPC after 300 years, the latter change being the result of the hydrological dispersion of the groundwater flow. The concentration of pollutants **with decay** halved at all plots (Fig. 7a) after 30 years, i.e. after one half-life of radionuclides, affected by the groundwater dispersion: the initial 8 MPC at the plot No. 1 dropped to 3.5 MPC after 30 years, but it should have been 4 MPC instead, which means that a 0.5 MPC decrease was the result of dispersion as well, i.e. of the pollutants flowing into nearby cells. The same trend was observed at other plots of this profile, and only minor traces of pollutants were found over 300 years.

In *the 2nd layer* (aquiclude; Fig. 7b) pollutants **without decay** were found only after 300 years (3.5 MPC at the plot No. 1), with only insignificant concentrations observed for previous periods (Tables 1, 2). Concentrations **with decay** (Fig. 7c) were very insignificant after 300 years: 0.042 MPC at No. 1, ranging from 0.012 to 0.02 MPC for earlier periods and never exceeding 0.005 MPC at other plots, which means that only traces of pollutants are present there.

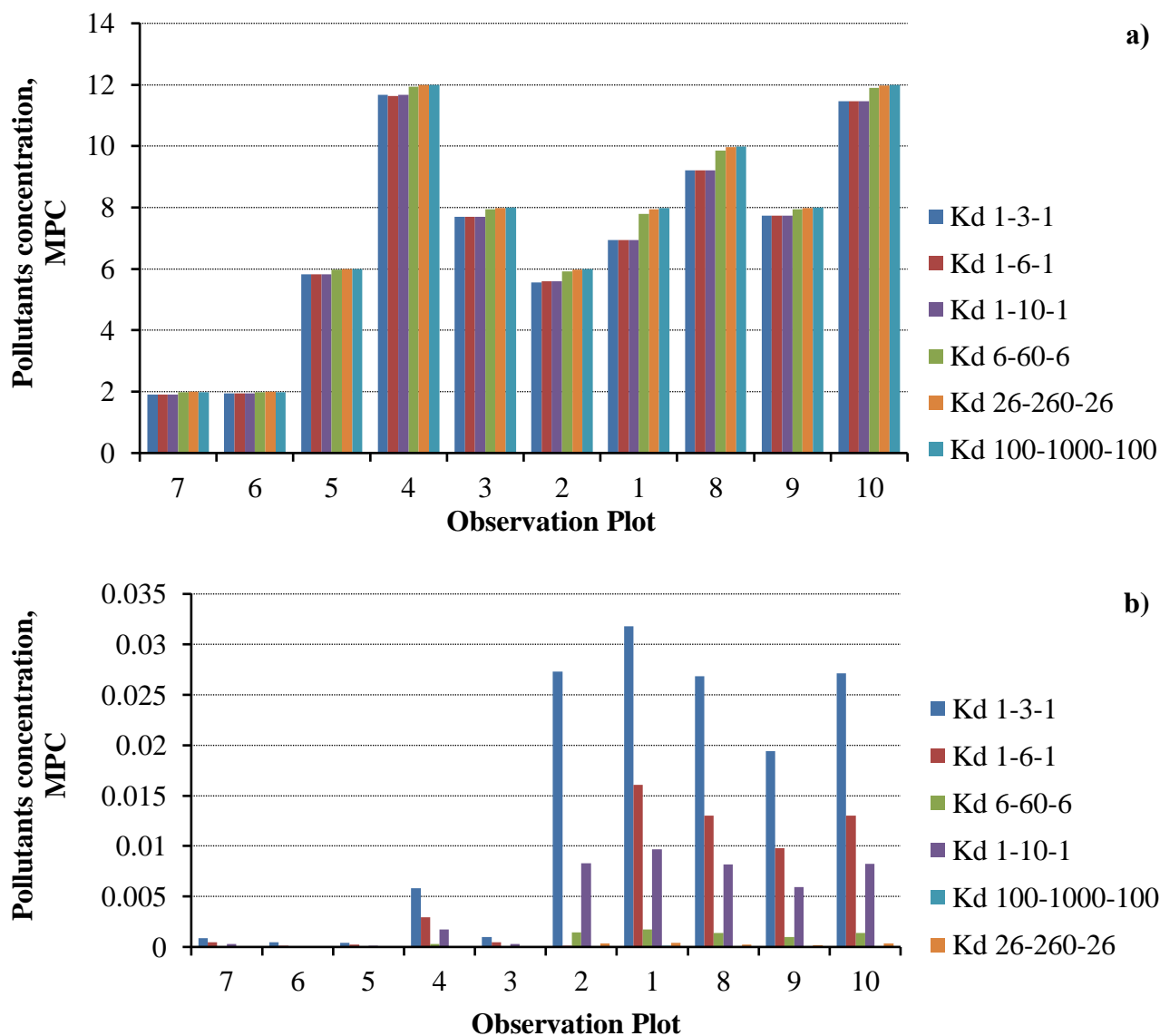


Fig. 4a, b. Distribution of pollutant concentrations for different Kd, Profile II: a) 30 years, Layer 1 without decay; b) 30 years, Layer 2 without decay.

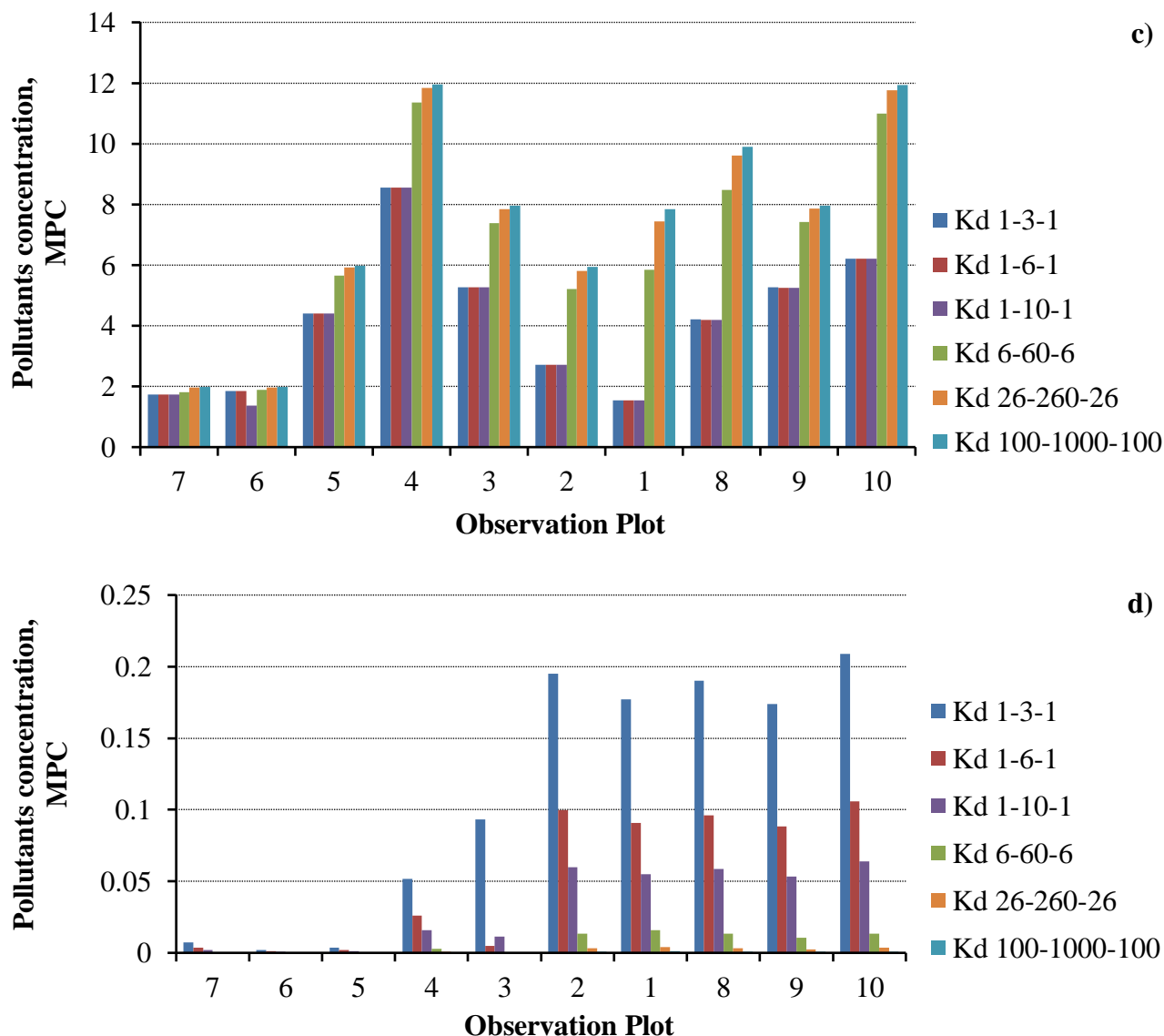


Fig. 4c, d. Distribution of pollutant concentrations for different Kd, Profile II: c) 300 years, Layer 1 without decay, d) 300 years, Layer 2 without decay.

Profile II-II. Distribution of pollutants (Fig. 8a) **with** and **without decay** in *the 1st layer* is mostly similar to those in the same layer of I-I (Fig. 7a). However, we registered differences in *the 2nd layer* (Fig. 8b). While the maximal concentrations for every period were noted at the plot No. 4 in *the 1st layer* (Fig. 8a), they shifted to No. 2 (Fig. 8b) due to increasing hydrological dispersion. However, the maximum of pollutants **without decay** in the 2nd layer of II-II decreased from 3.5 (Fig. 7b) to 0.1 MPC (Fig. 8b) compared to the same layer of I-I, while the pollutants **with decay** decreased from 0.04 to 0.02 MPC. Pollutants **with decay** accumulate and increase over time: for example, at the plot No. 1 there is 0.01 MPC 30 years after the accident, but 0.04 MPC 300 years after the accident. Pollutants **without decay** accumulate as well: No. 10 – 0.04 MPC after 30 years, but 0.11 MPC after 300 years. It should be noted that these accumulations are insignificant and considered to be only traces of pollution.

Scenario 1-10-1, Profile I-I. Changes in the pollutant concentrations **with** and **without decay** are very insignificant (Table. 1, 2) in *the 1st layer* (Fig. 9) and similar to the changes under Scenario 1-6-1. However, after 300 years pollutants **without decay** reach 3.7 MPC at the plot No. 11

compared to 2 MPC under Scenario 1-6-1 (Fig. 7a), which can be the result of hydrological dispersion over a long period of calculations. The situation in the 2nd layer is almost the same.

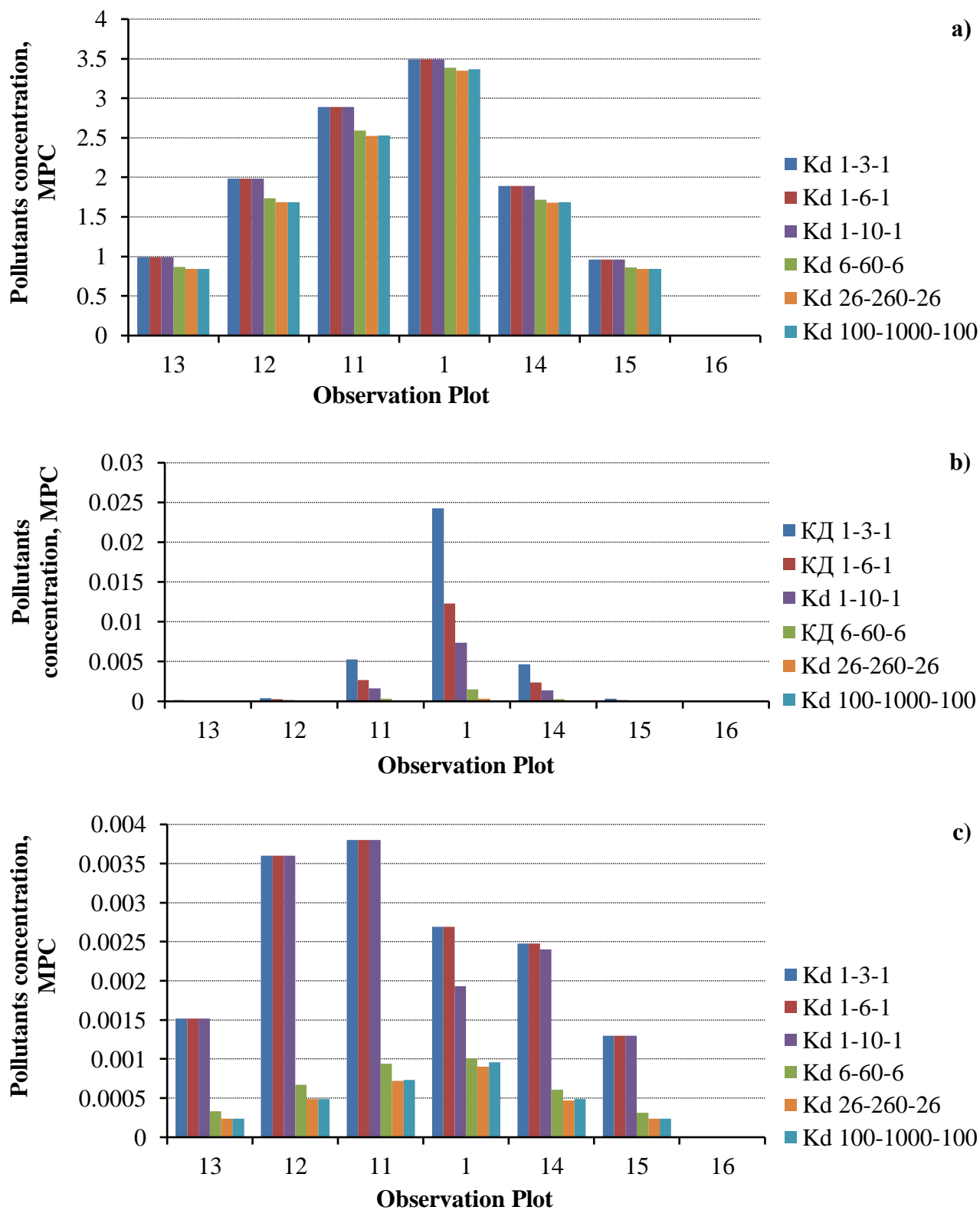


Fig. 5a, b, c. Distribution of pollutant concentrations for different Kd, Profile I: a) 30 years, Layer 1 with decay; b) 30 years, Layer 2 with decay; c) 300 years, Layer 1 with decay;

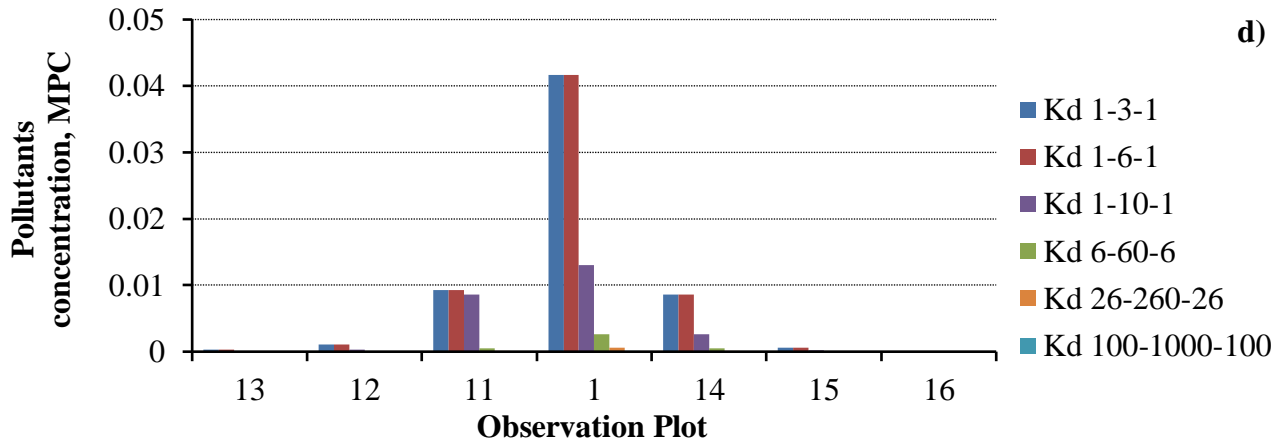


Fig. 5d. Distribution of pollutant concentrations for different Kd, Profile I: d) 300 years, Layer 2 with decay.

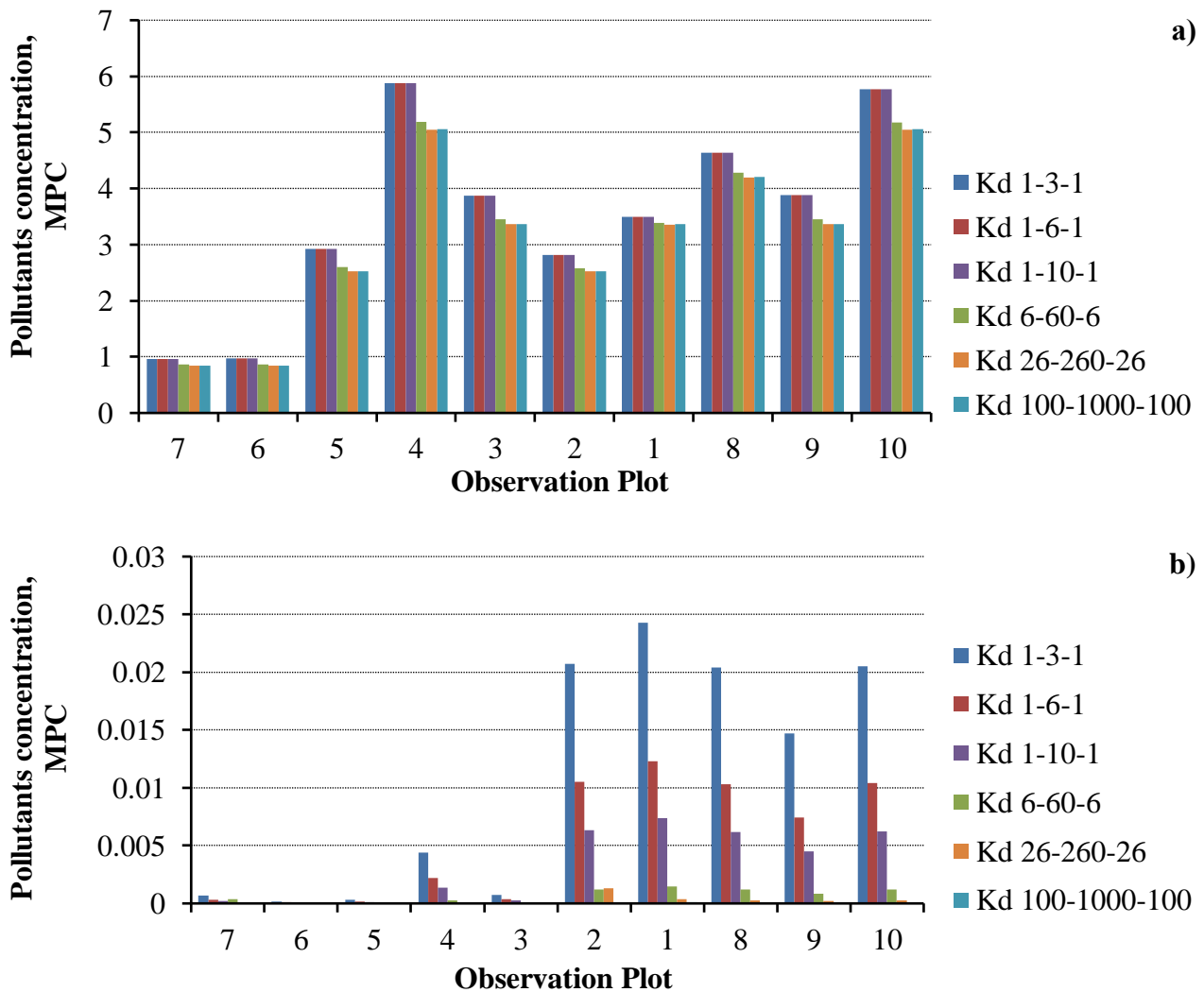


Fig. 6a, b. Distribution of pollutant concentrations for different Kd, Profile II: a) 30 years, Layer 1 with decay; b) 30 years, Layer 2 with decay.

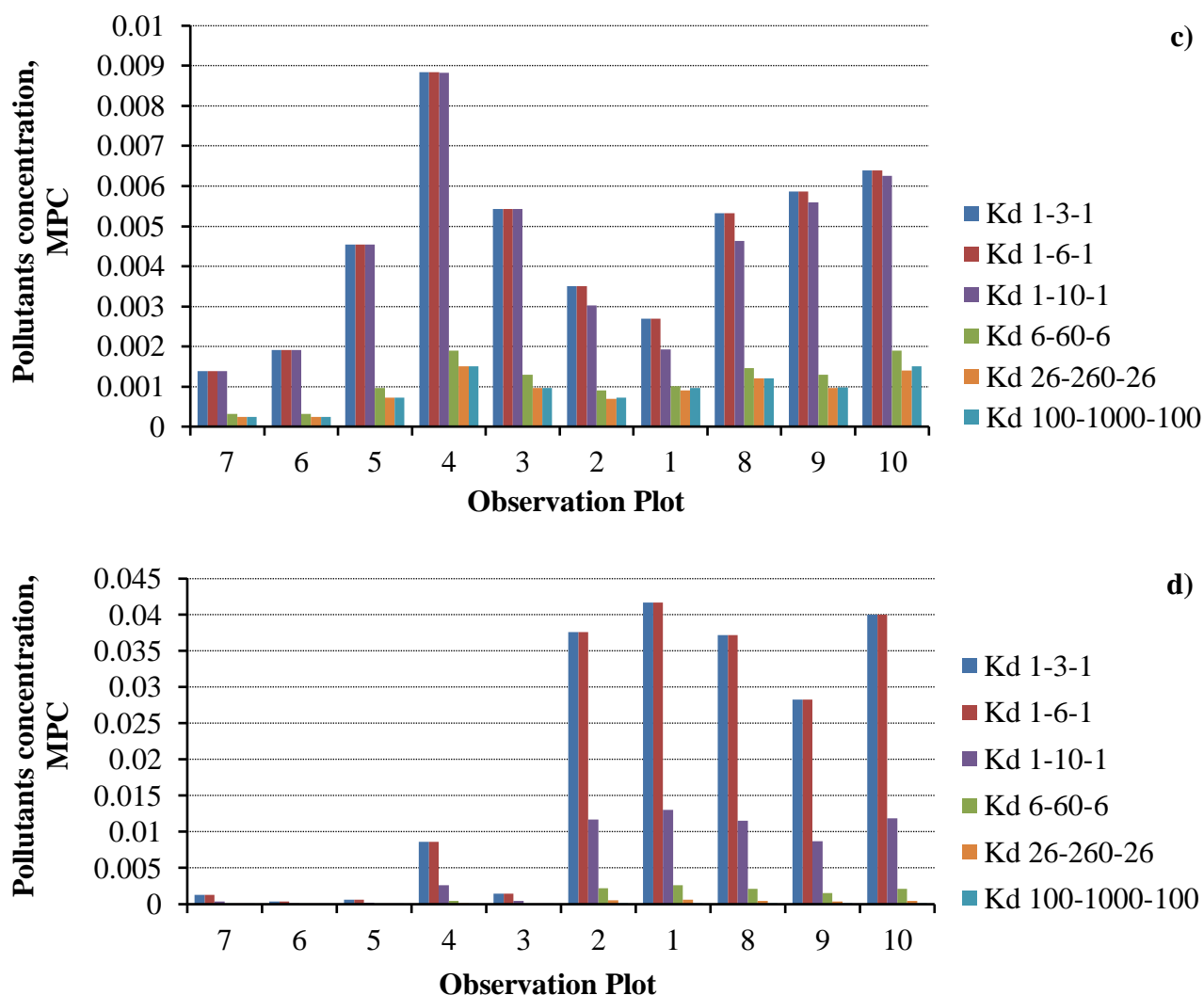


Fig. 6c, d. Distribution of pollutant concentrations for different Kd, Profile II: c) 300 years, Layer 1 with decay; d) 300 years, Layer 2 with decay.

Profile II-II. Changes in pollutants concentrations **with** and **without decay** in *the 1st layer* (Fig. 10a) are very insignificant (Tables 1, 2) and similar to those under Scenario 1-6-1. However, 60 years after the accident, the value **without decay** reached 6.7 MPC at the plot No. 9 compared to 4.2 MPC under Scenario 1-6-1 (Fig. 7a), due to the dispersion of the underground glow. *The 2nd layer* is quite similar to the 1st, i.e. its pollutants **with decay** accumulate and increase over time (Fig. 10b): for example, there was 0.006 MPC at the plot No. 1 after 30 years, but 0.013 MPC after 300 years. Pollutants **without decay** accumulate as well, from 0.008 MPC at No. 10 after 30 years to 0.065 MPC after 300 years.

Comparing this data with the previous scenario, we can say that accumulation decreased due to a better confinement that prevents them from penetrating onto the aquiclude. For example, **without decay** there was 0.11 MPC at No. 10 after 300 years under Scenario 1-6-1, but 0.065 MPC under Scenario 1-10-1; **with decay** there was 0.04 MPC under Scenario 1-6-1, but 0.012 MPC under Scenario 1-10-1.

Scenario 6-60-6, Profile I-I. The concentration of pollutants **without decay** decreases insignificantly in *the 1st layer* (Fig. 11a) compared to their starting values: for example, from 7.8 MPC at the plot No. 1 after 30 years compared to the initial 8 MPC and to 3.5 MPC **with decay**

(due to decay itself). These numbers indicate that pollutants are well-confined in the 1st layer due to the increased sorption at high K_d values in both layers.

The concentrations decrease in *the 2nd layer* (Fig. 11b): **without decay** there is 0.016 MPC at No. 1 after 300 years, but 3.5 MPC under Scenario 1-6-1 (Fig. 7b); **with decay** there is 0.0025 and 0.042 MPC under Scenario 1-6-1 (Fig. 7B).

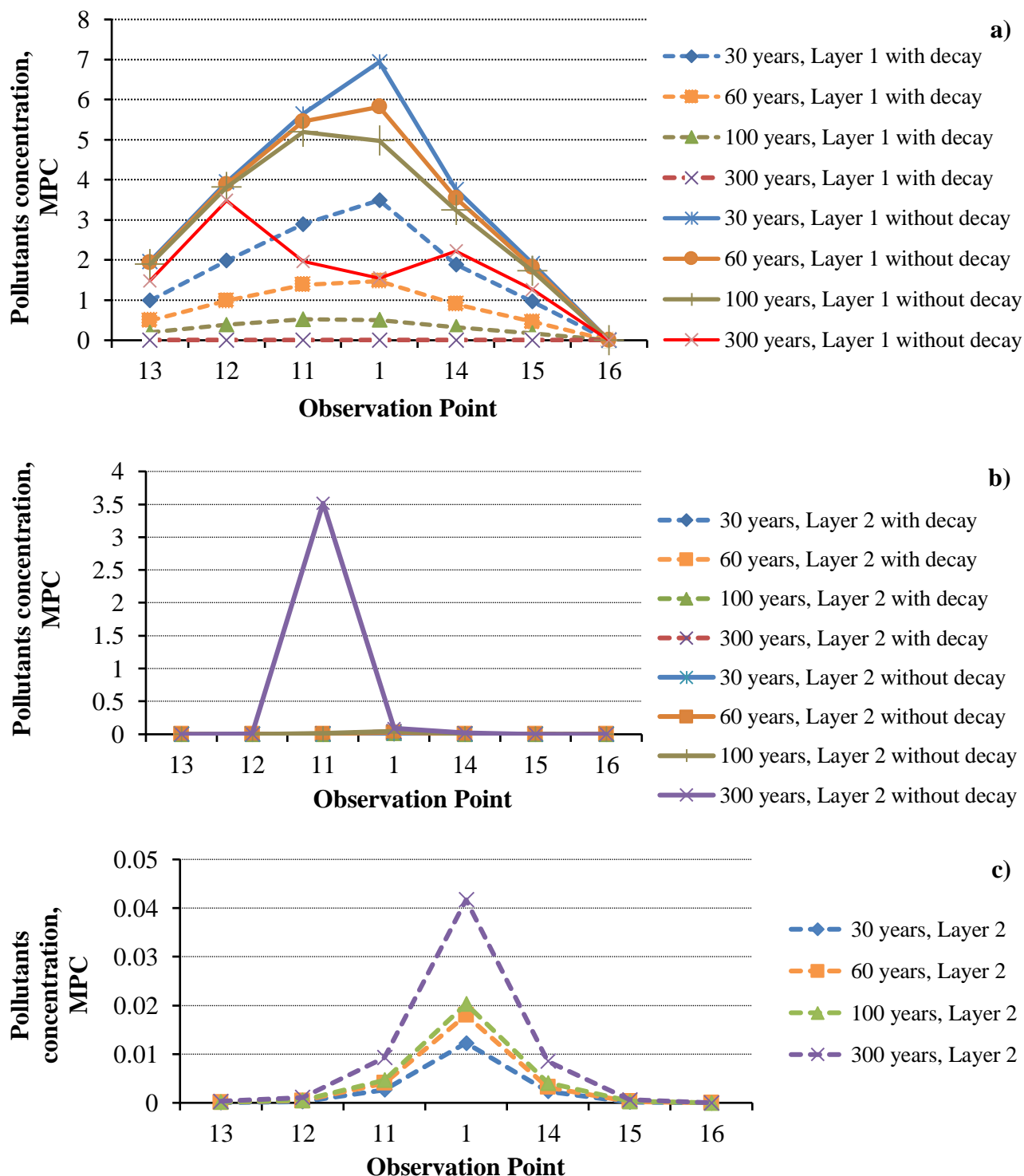


Fig. 7. Scenario K_d 1-6-1, distribution of pollutant concentrations over time: a) Profile I; b) Profile I, Layer 2 without decay; c) Profile I, Layer 2 with decay.

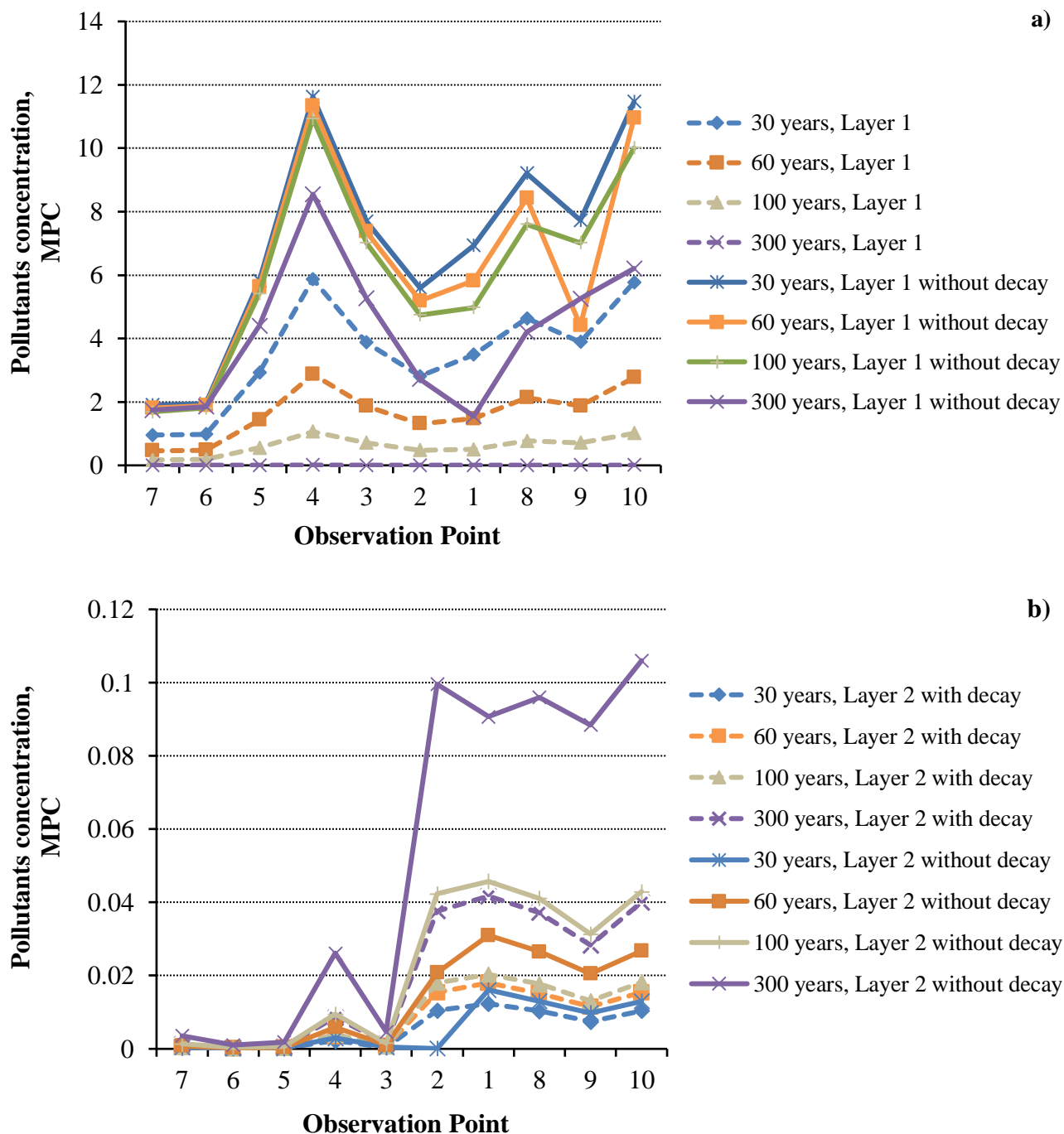


Fig. 8. Scenario Kd 1-6-1, distribution of pollutant concentrations depending on time: a) Profile II, Layer 1, b) Profile II, Layer 2.

Profile II-II. Just like in the I-I, the concentration of pollutants **without decay** slightly decrease in *the 1st layer* (Fig. 12a) compared to the initial values for all studied periods. For example, **without decay** it is 11.8 MPC at the plot No. 12 after 30 years compared to the initial 12 MPC; **with decay** it is 5.5 MPC (due to decay itself). These figures indicate that pollutants are well confined in the 1st layer due to an increasing role of sorption at high Kd in both layers. In *the 2nd layer* (Fig. 12b) the concentrations decrease: **without decay** it is 0.016 MPC at the plot No. 1 after 300 years, but 3.5 MPC under Scenario 1-6-1 (Fig. 7b); **with decay** it is 0.0015 and

0.042 MPC under Scenario 1-6-1 (Fig. 7c). In general, there is a trend similar to Scenario 1-6-1; however, the concentration **without decay** increased up to 0.009 MPC at No. 1 after 60 years due to the influence of hydrological dispersion where the groundwater supply is located (Fig. 2).

Further consideration of the model results for Scenarios 26-260-26 and 100-1000-100 is meaningless, because all pollutants are concentrated in the 1st layer, practically reaching zero in the 2nd (aquiclude; Tables 1, 2), which indicates the complete impermeability of the aquiclude within the studied profiles.

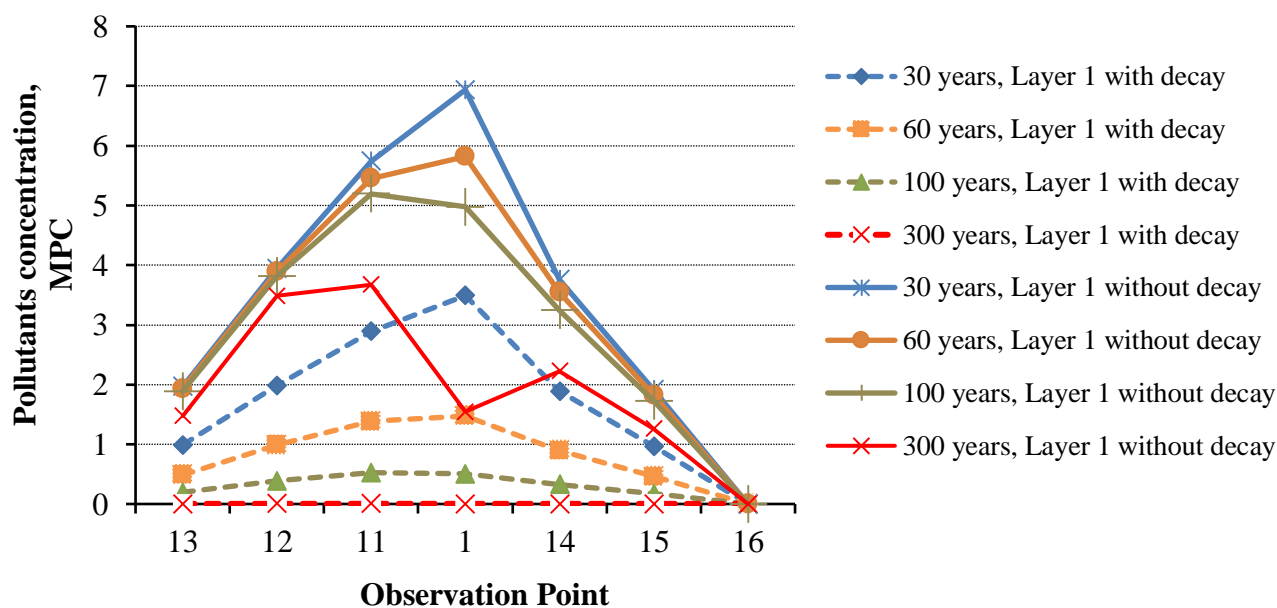


Fig. 9. Scenario Kd 1-10-1, distribution of pollutant concentrations depending on time, Profile I, Layer 1.

Discussion of results obtained during areal modeling

The results of areal modeling of pollutants migration in the study area are shown in Figure 13. We carried out modeling according to two scenarios: 1-3-1 for poorly sorbed pollutants and 100-1000-100 for highly sorbed ones, with and without decay, for the 1st layer (groundwater) and the 2nd layer (aquiclude), for two estimated periods of 30 and 300 years.

For this experiment, the surface contamination with ^{137}Cs radionuclide that appeared in the south of the Kaluga Region after the Chernobyl accident was taken as the initial contamination of groundwater. The Figure 1 shows that it consists of 2 isolated sections, western and eastern, within the radioactive zone, where the concentration of ^{137}Cs exceeds the MPC by more than 10 times.

Migration of poorly sorbed pollutants under Scenario 1-3-1 without decay throughout the study area (Fig. 13.1). **30 years after**, the configuration of areal pollution is still preserved in *the 1st layer* (Fig. 13.1A), but its maximum decreases to 9 MPC; in *the 2nd layer* (Fig. 13.1B) it changes greatly, appearing mainly in the eastern section and decreasing to 0.045 MPC.

300 years after, the pollution configuration changes greatly in *the 1st layer* (Fig. 13.1C), mainly remaining in the western section, while its maximum decreases to 7 MPC. In *the 2nd layer* (Fig. 13.1D) it also changes greatly, appearing mainly in the eastern section and increasing to 0.8 MPC compared to the initial concentration after 30 years.

Migration of highly adsorbed pollutants under Scenario 100-1000-100 without decay (Fig. 13.2). **30 years after**, the pollution configuration in *the 1st layer* (Fig. 13.2A) practically

matches the initial one (Fig. 1), and its maximum exceeds 10 MPC. In *the 2nd layer* (Fig. 13.2B), it changes greatly, appearing mainly in a small part of the eastern section and decreasing to 0.0003 MPC.

300 years after, the configuration changes slightly in *the 1st layer* (Fig. 13.2C), and its maximum decreases to 9 MPC. However, in *the 2nd layer* (Fig. 13.2D) it changes noticeably, appearing mainly in the eastern section and increasing to 0.04 MPC compared to the initial concentration after 30 years.

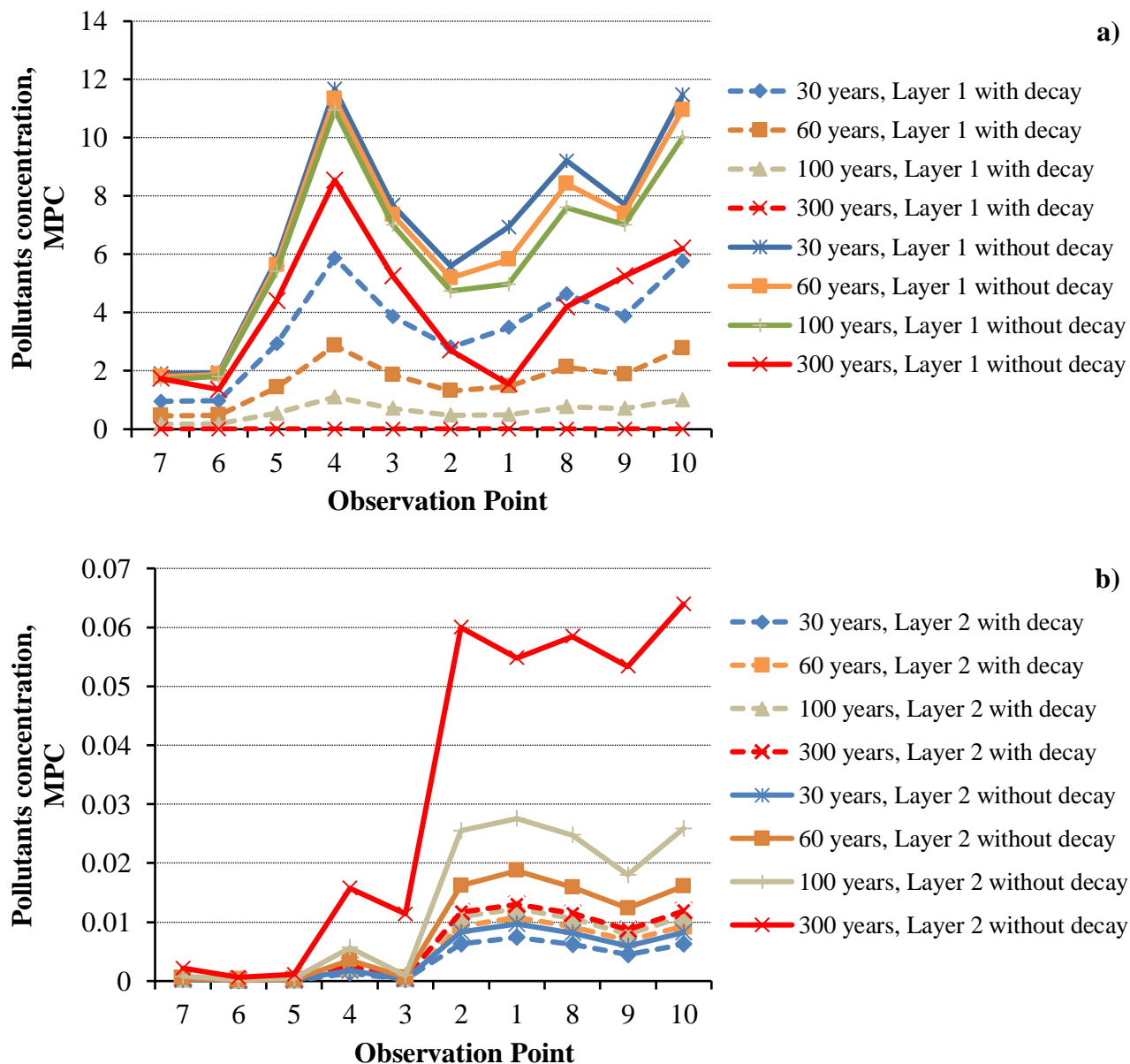


Fig. 10. Scenario Kd 1-10-1, distribution of pollutant concentrations depending on time, Profile II: a) Layer 1, b) Layer 2.

Migration of highly sorbed pollutants under Scenario 1-3-1 with decay (Fig. 13.3). **30 years after**, the configuration of areal pollution remains in *the 1st layer* (Fig. 13.3A), but its maximum decreases to 4.5 MPC. In *the 2nd layer* (Fig. 13.3B) it changes greatly, appearing mainly in the eastern section and decreasing to 0.02 MPC.

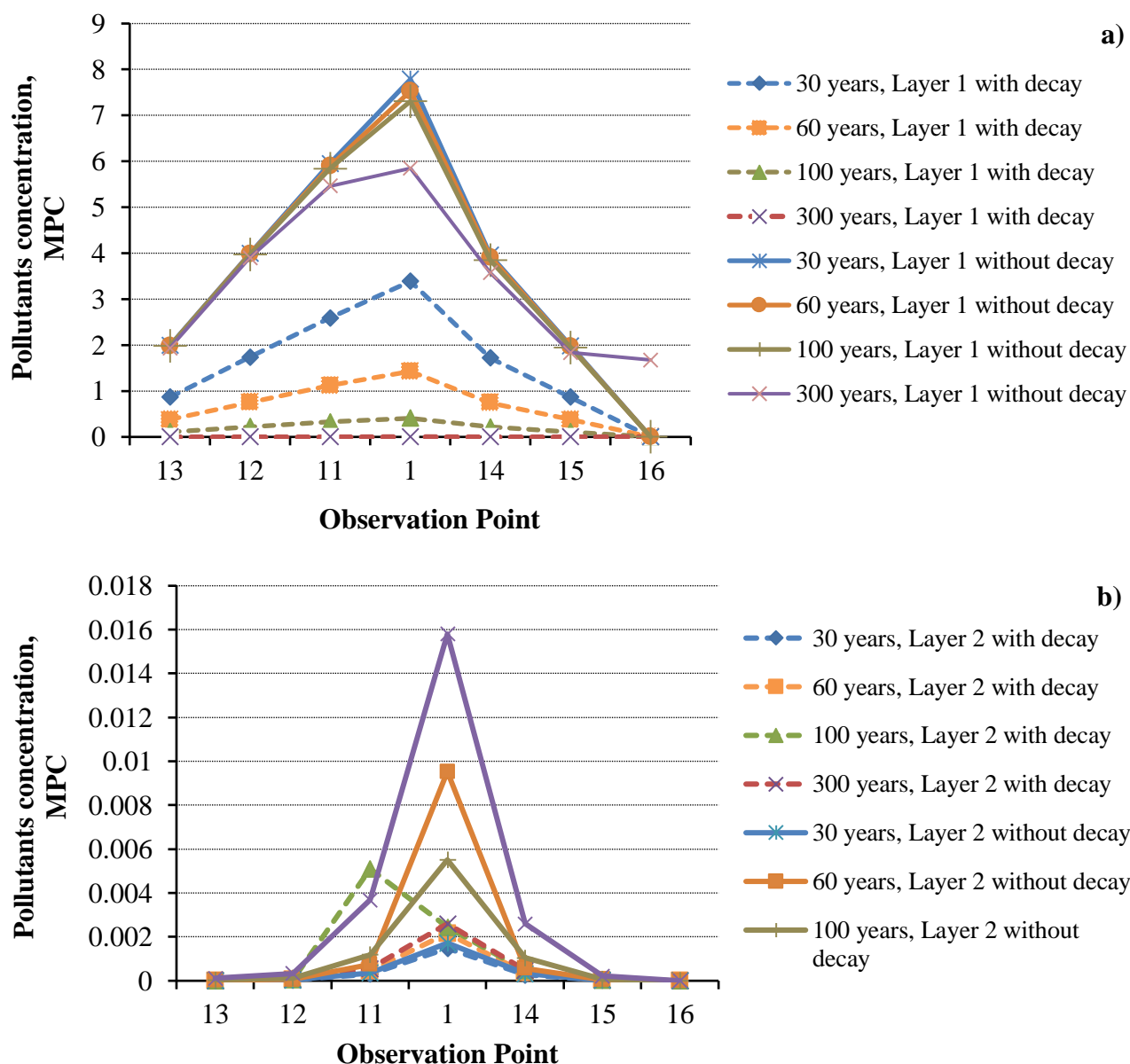


Fig. 11. Scenario Kd 6-60-6 Distribution of pollutant concentrations depending on time, Profile I: a) Layer 1, b) Layer 2.

300 years after, the pollution configuration in *the 1st layer* (Fig. 13.3C) changes greatly, with insignificant pollution in a limited part of the eastern section – up to 0.02 MPC compared to the initial 0.004 MPC. It changes greatly in *the 2nd layer* (Fig. 13.3D), appearing mainly in the eastern section; its area decreases compared to the initial area after 30 years, and its MPC increases to 0.04.

Migration of highly sorbed pollutants under Scenario 100-1000-100 with decay (Fig. 13.4). **30 years after**, the areal pollution configuration in *the 1st layer* (Fig. 13.4A) practically matches the initial one (Fig. 1), but its maximum exceeds 3.6 MPC; in *the 2nd layer* (Fig. 13.4B) it changes greatly, appearing mainly in an insignificant part of the eastern section and decreasing to 0.0003 MPC.

300 years after, the configuration changes slightly in *the 1st layer* (Fig. 13.4C), and its maximum decreases to 0.0009 MPC; in *the 2nd layer* (Fig. 13.4G), however, it changes greatly, appearing mainly in the eastern section and dropping to 0.0004 MPC.

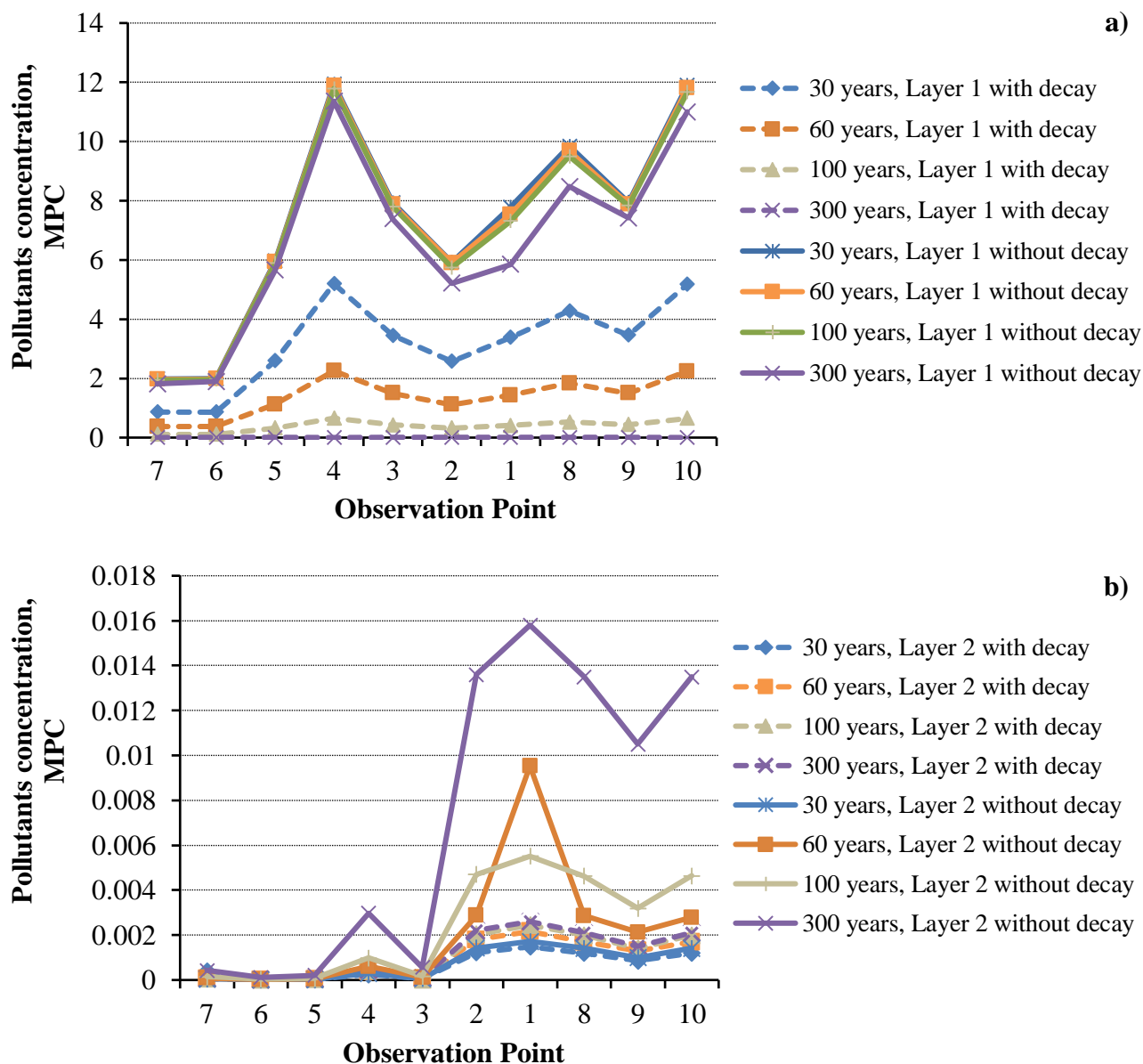


Fig. 12. Scenario Kd 6-60-6, distribution of pollutant concentrations depending on time, Profile II: a) Layer 1, b) Layer 2.

Therefore, poorly sorbed pollutants **without decay** remain in the western section after 300 years in the 1st layer, while pollutants of the eastern section tend to migrate and their insignificant amounts can be found in the 2nd layer (aquiclude).

Highly sorbed pollutants **without decay** remain in both areas in the 1st layer, with slightly different concentration compared to the ones after a 30-year period; in the 2nd layer their insignificant concentrations occupy a small part of the eastern section.

Poorly sorbed pollutants **with decay** are practically absent in the study area, but their traces can be found in the 1st layer of the eastern section, forming a small area in the 2nd layer in insignificant concentrations.

Highly sorbed pollutants **with decay** remain in both areas in the 1st layer, and their concentration significantly differs from the 30-year period, decreasing to 0.0009 MPC, which is considered small, meaning those are only traces. In the 2nd layer, their insignificant concentrations

occupy a small area of the eastern section.

This indicates that ^{137}Cs and ^{90}Sr radionuclides will completely decay within 10 half-lives.

Comparison current results with the previous research stage

Further below we consider specificity of the pollutant migration through a permeable aquiclude that we studied on the previous stage of this research (Belousova and Rudenko, 2021a, 2021b) and the one studied at the current stage. Modeling results of both stages are shown as 3D maps in Figure 14.

To study the permeable aquiclude (Fig. 14A), we set K_d equal for all three layers (6-6-6), while for the impermeable aquiclude (Fig. 14B), we set K_d higher than its values in the groundwater of the 1st and 3rd layers (1- 3-1).

With the *permeable aquiclude* (Fig. 14A), the migration of pollutants **without decay** occurs in all layers over 300 years. In the 1st layer (groundwater) MPC does not exceed 4; in the 2nd layer pollutants accumulate intensively up to 4 MPC; in the 3rd layer (pressure waters) accumulation is up to 2 MPC in some areas.

With the *impermeable aquiclude* (Fig. 14B) **without decay** the intensity of migration varies greatly in all layers over 300 years. In the 1st layer there are significant concentrations above 5 MPC; in the 2nd layer this process is very isolated, its area decreases, and its MPC drops to 3; in the 3rd layer this process is limited and the concentrations are insignificant – up to 0.05 MPC. It should be noted that pollutant migration was not found in any of the points of the 3rd layer of both profiles.

Conclusions

The object of our studies was the part of the Kaluga Region, most affected by the accident at the Chernobyl nuclear power plant.

There is almost no experimental data on the radionuclides migration in the saturated zone (groundwater) and their parameters, and only some parts of the Bryansk Region were explored superficially in the radioactive zone caused by the accident. However, they mostly belong to the unsaturated or protective zone. Therefore, instead of field or laboratory studies, we chose numerical experiments and carried them out for the region.

Numerical experiments study the migration of pollutants in the saturated zone, i.e. their flow from groundwater through the aquiclude to pressure groundwater. In this study, we considered both ^{137}Cs and ^{90}Sr and other pollutants, from poorly sorbed to highly sorbed ones, found in the pressure waters of the studied territory.

To simulate the process of mass transfer in groundwater, the MT3D model based on MODFLOW was chosen. Along with flow hydrological dispersion, this model takes into account the sorption of pollutants and radioactive decay.

Given that geological, hydrogeological and hydrogeochemical data concerning the studied object do not guarantee a sufficient reliability of our forecasts, especially in the case with aquicludes, the study was carried out in two stages. Results of the first stage (migration of through a permeable aquiclude) have been already completed and published by our crew (Belousova, Rudenko, 2021a, 2021b), while the results of the second (migration through an impermeable aquiclude) are given in this article.

Numerical experiments of the second stage were carried out according to the following scenarios: 1 – (1-3-1), 2 – (1-6-1), 3 – (1-10-1), 4 – (6-60-6), 5 – (26-260-26), and 6 – (100-1000-100), where the first digit is the K_d value (l/kg) in the 1st layer, the second digit – 2nd layer, the third digit – 3rd layer. This set of coefficients was determined by the fact that their values were assigned to be higher in the aquiclude than in the upper and lower aquifers. Each scenario was applied for two conditions: with and without radioactive decay.

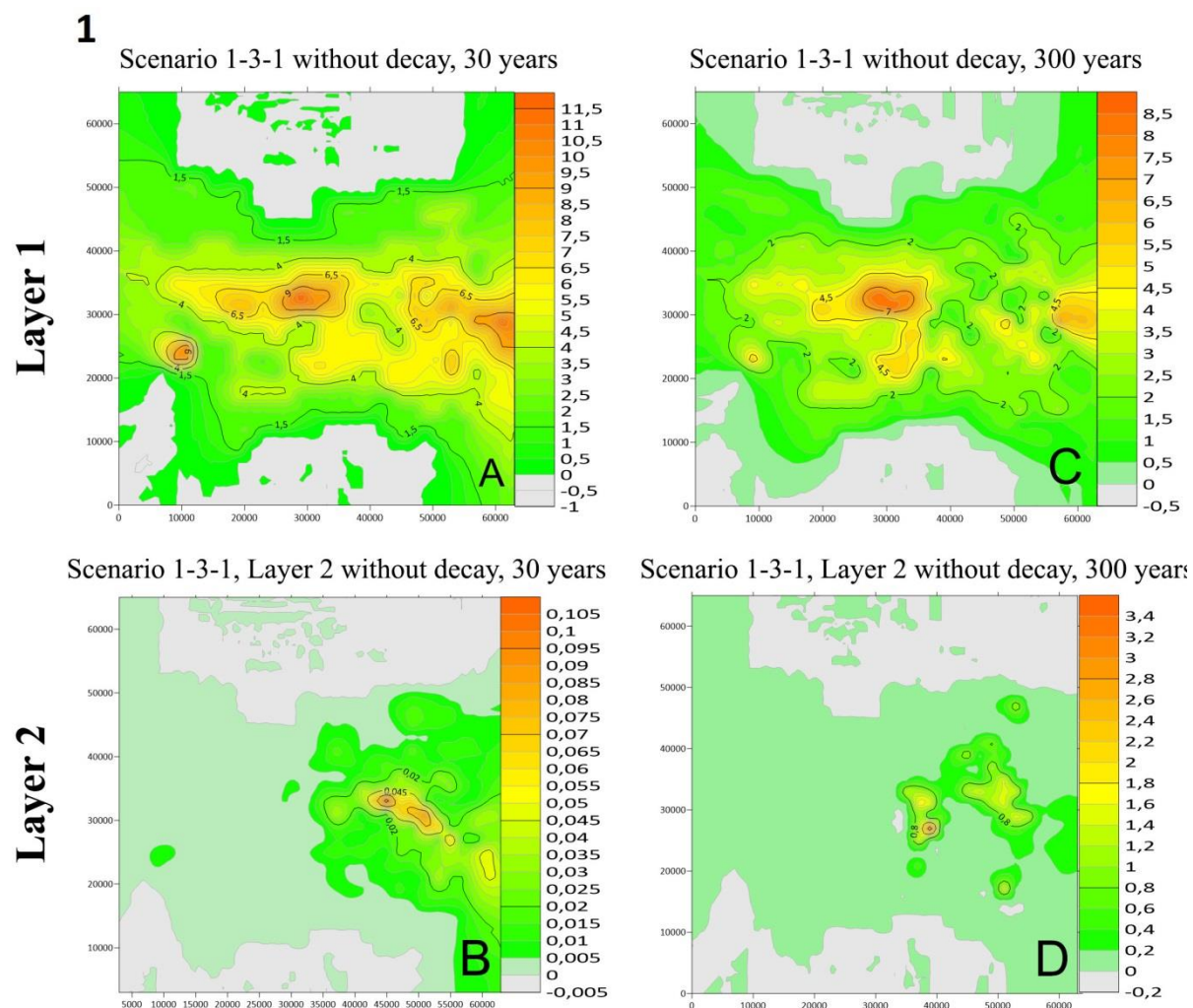


Fig. 13.1. Cartographic chart of the distribution of concentrations of we poorly akly sorbed (Scenario 1-3-1) and highly sorbed (Scenario 100-1000-100) pollutants in the simulated area with/without decay.

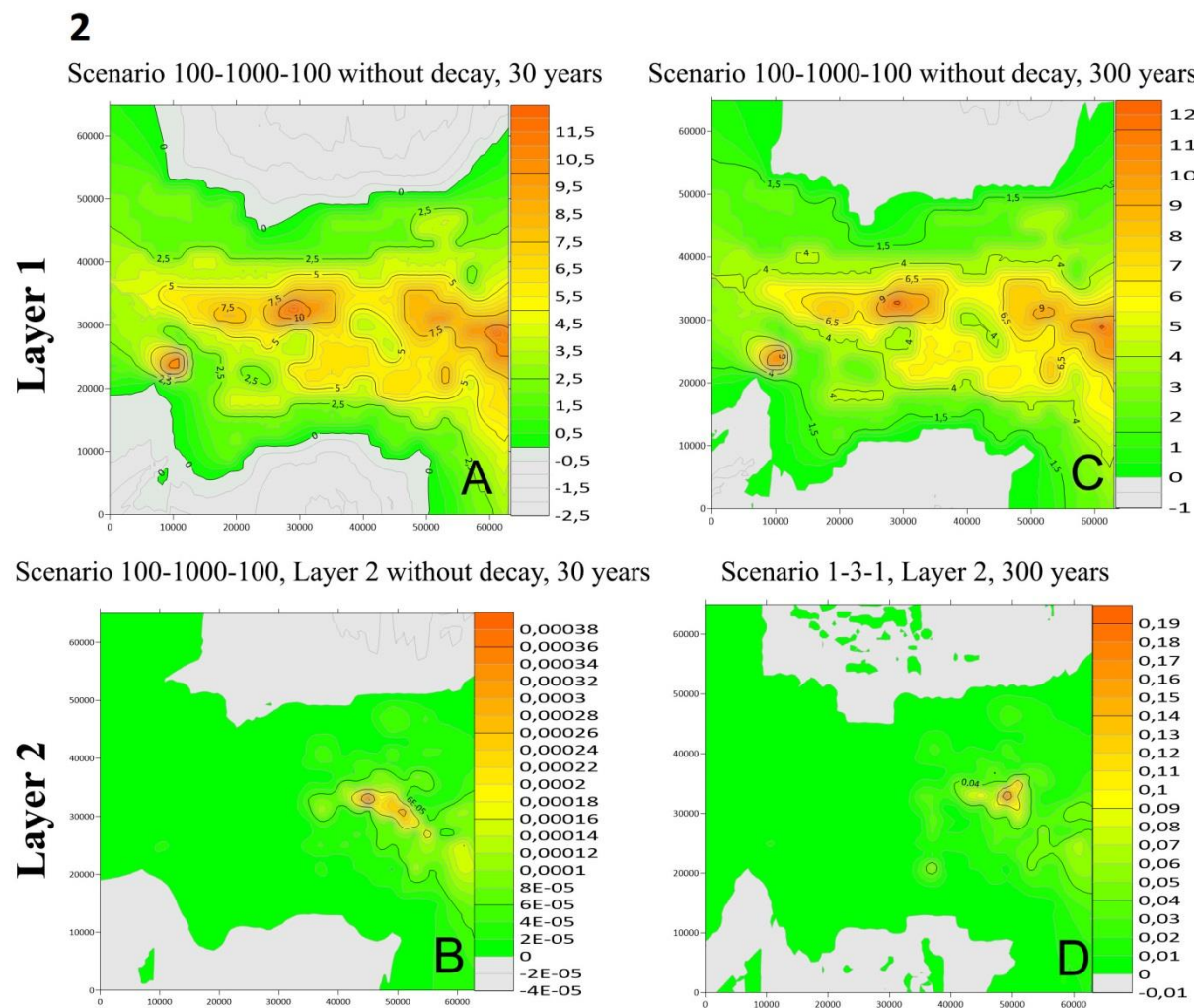


Fig. 13.2. Cartographic chart of the distribution of concentrations of poorly sorbed (Scenario 1-3-1) and highly sorbed (Scenario 100-1000-100) pollutants in the simulated area with/without decay.

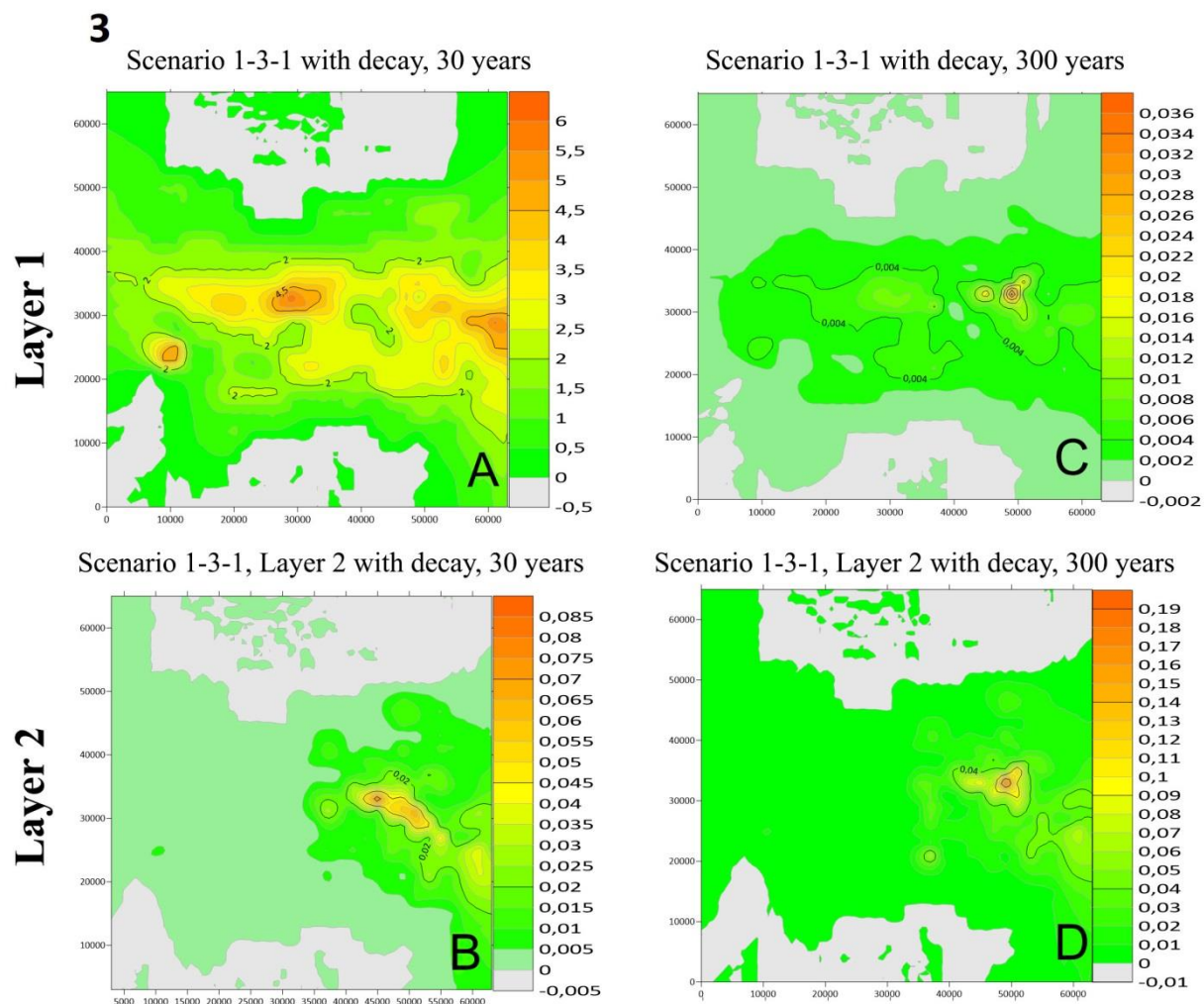


Fig. 13.3. Cartographic chart of the distribution of concentrations of poorly sorbed (Scenario 1-3-1) and highly sorbed (Scenario 100-1000-100) pollutants in the simulated area with/without decay.

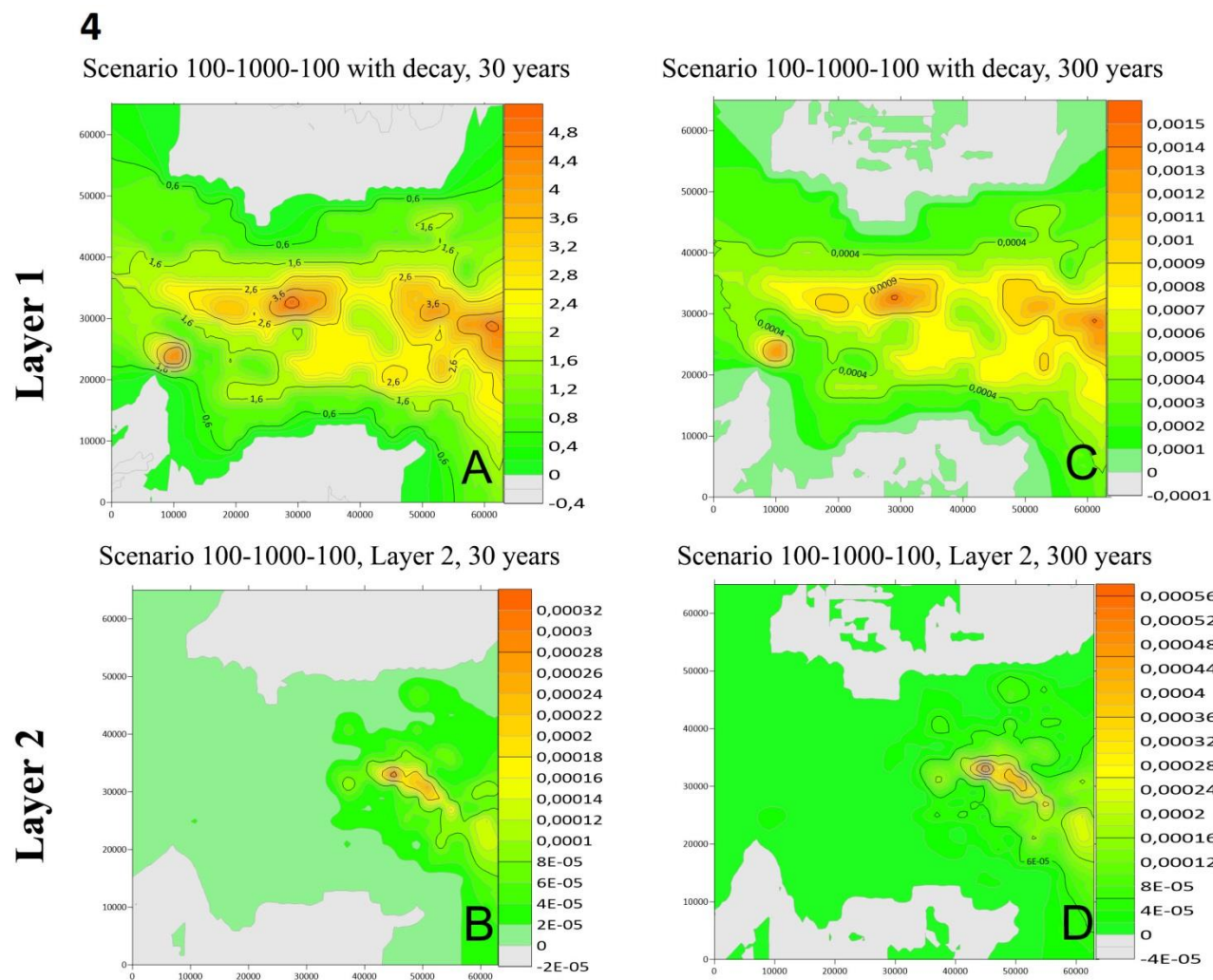


Fig. 1.4. Cartographic chart of the distribution of concentrations of poorly sorbed (Scenario 1-3-1) and highly sorbed (Scenario 100-1000-100) pollutants in the simulated area with/without decay.

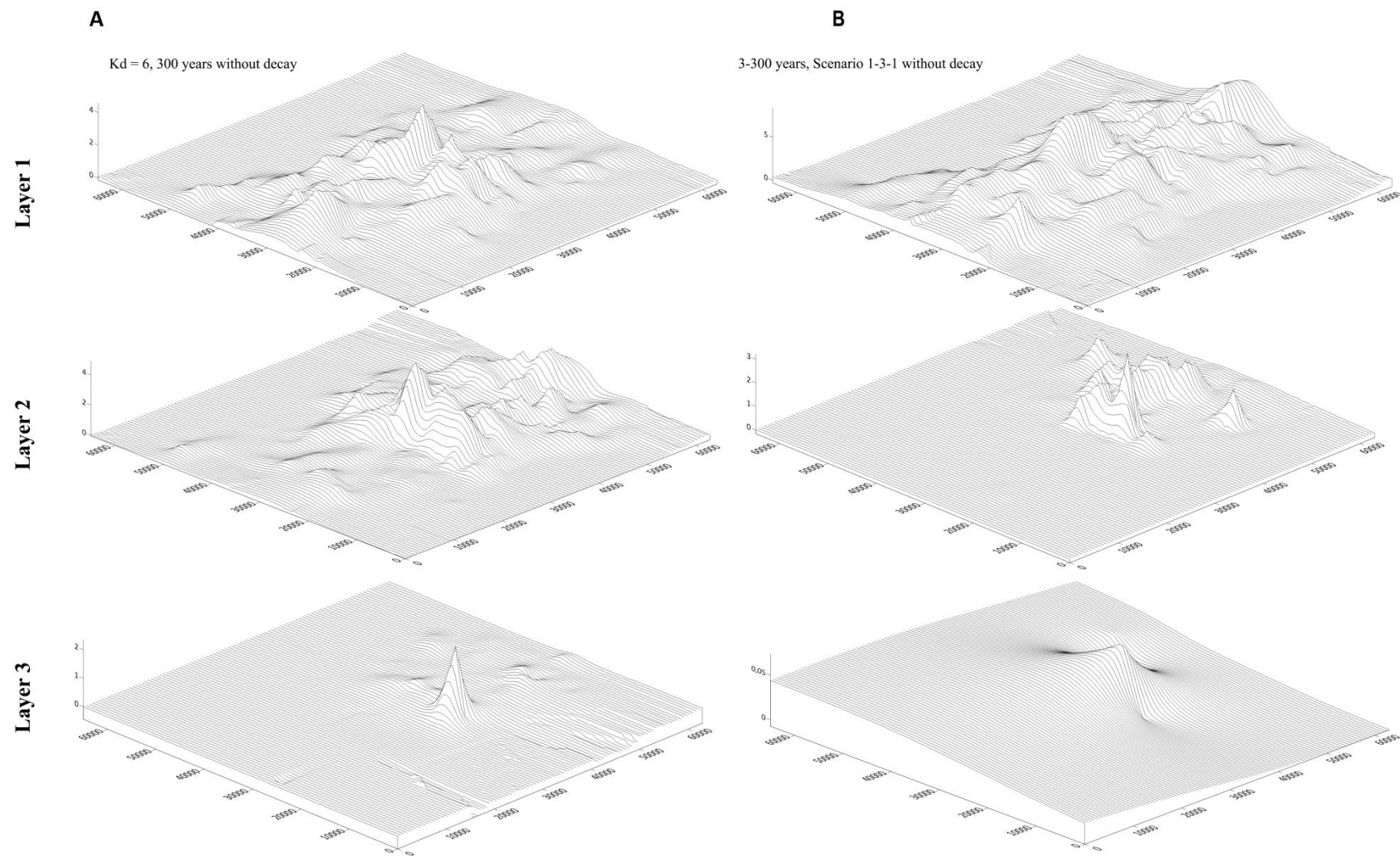


Fig. 14. Comparison of scenarios with permeable (A) and impermeable (B) aquiclude.

The degree of groundwater contamination was taken as the initial conditions, similar to the contamination degree of the surface in the radioactive zone of the study area. However, such a wide spread of contamination by radionuclides or other pollutants is not observed in the groundwater under natural conditions in this area. The pollutants concentration can be determined in g/l, Bq/l, maximum permissible concentration (MPC) or background concentrations; but we prefer to use MPC. Coefficients of pollutant sorption distribution (K_d) of various pollutants were selected from the known values for the Bryansk Region (Belousova, Rudenko, 2021a, 2021b); the radionuclides K_d values mainly refer to the unsaturated zone of contamination.

Analysis of the modeling results obtained during the numerical experiments was carried out for 2 profiles and for the studied territory, using maps.

We established that, as K_d increases, the high concentration of pollutants remains in groundwater, while poorly sorbed pollutants with minimal K_d can partially remain in the aquiclude. It should be noted that in the 3rd layer (pressure waters) pollutants were not found at all, although they appear at other plots.

According to K_d values, we found out that at $K_d \geq 60$ l/kg, pollutants cannot penetrate into the aquiclude, i.e. the aquiclude is almost impermeable. For radionuclides, the radioactive decay plays the main role in their migration: for example, 30 years after the accident at the Chernobyl nuclear power plant, the concentration of ^{137}Cs and ^{90}Sr decreased by half, because 30 years is their actual half-life; therefore, in the next 300 years they will completely decay. For non-radioactive pollutants, the process is different: they accumulate in the aquiclude and penetrate into pressure waters, significantly worsening the local ecology, while other long-lived radionuclides (such as plutonium-209) have a half-life of 24,095 years and will pose a severe danger in those areas of the nuclear fuel fallout (such is the area of the Chernobyl nuclear power plant itself).

The main factors forming the pollutants migration are their radioactive decay, their sorption properties and, finally, the hydrological dispersion of groundwater flows, which in turn depends on the geological and hydrogeological conditions of the area.

Results of both research stages. With the *permeable aquiclude*, the migration of pollutants without decay occurs in all layers over 300 years. With the *impermeable aquiclude* without decay the intensity of migration varies greatly in all layers over 300 years: in the 1st layer there are significant concentrations found; in the 2nd layer this process is very isolated, its area and concentration decrease; in the 3rd layer this process is limited.

However, neither of these aquicludes can exist separately under natural conditions, because usually confining strata is like a patchwork quilt, since it is made of several areas with both impermeable and permeable aquicludes. Aquicludes cannot be impenetrable throughout their entire length, because they contain natural disturbances, such as lenses, permeable rocks, neotectonic cracks, and artificial disturbances, such as drilling wells.

Therefore, in order to study the processes of pollutant migration and predict their further development under complex hydrogeological conditions, it is necessary to study thoroughly the geological and hydrogeological structure, as well as the hydrogeochemical conditions of the chosen objects territories, and to conduct experimental studies of mass transfer in order to parameterize all the processes causing it, for the further numerical modeling and forecasting of the development of the real ecological situation at the research areas.

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УДК 556.383/388:504(571.1)

ИСПОЛЬЗОВАНИЕ ЧИСЛЕННОГО ЭКСПЕРИМЕНТА ПРИ ИЗУЧЕНИИ МИГРАЦИИ РАЗЛИЧНЫХ ЗАГРЯЗНЯЮЩИХ ВЕЩЕСТВ В ПОДЗЕМНЫХ ВОДАХ КАЛУЖСКОЙ ОБЛАСТИ В ЗОНЕ РАДИОАКТИВНОГО СЛЕДА

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Цель статьи – изучение методом математического моделирования процессов миграции различных, от слабо до сильно сорбируемых загрязняющих веществ (ЗВ), включая радионуклиды, из грунтовых в напорные подземные воды через раздельный слой – водоупор различной степени проницаемости. В практике гидрогеологических исследований существует такое направление, как поиски и разведка месторождений подземных вод. Первая стадия – поиск, осуществляется на практически неизученных территориях, а вторая – разведка, ограничивается территориями, где по данным первой стадии выявляют перспективные территории.

Данные исследования можно отнести к первой, поисковой стадии, когда изученность территории в рамках заданной тематики практически отсутствует для выбранной территории Калужской области, пострадавшей от аварии на Чернобыльской атомной электростанции (ЧАЭС). Поиск был сосредоточен на изучении миграции загрязняющих веществ в грунтовых водах, а из них – через водоупор в напорных водах. Направление поиска определялось способностью водоупоров пропускать через себя ЗВ с одной стороны (самые неблагоприятные для подземных вод условия), а с другой – не пропускать ЗВ (благоприятные условия). В природных и в техногенных условиях оба случая не существуют по отдельности (они сливаются), что требует хорошей геолого-гидрогеологической изученности территории, отсутствующей для изучаемой местности. Наши исследования были проведены по обоим направлениям поисковых исследований, для первого случая водоупор принимался проницаемым, для второго – непроницаемым.

Для каждого типа поисковой стадии были проведены как бы разведочные численно-экспериментальные исследования (численный эксперимент) с применением математического моделирования. Объектом исследований является часть территории Калужской области, наиболее пострадавшая от аварии на ЧАЭС. Исследования по первому направлению были завершены и опубликованы ранее (Белоусова, Руденко, 2021а, б). Результаты второй стадии и обобщающие результаты исследований обоих поисковых направлений приводятся в настоящей статье. На данном этапе продолжается исследование процессов миграции различных ЗВ, включая радионуклиды, из грунтовых вод в напорный водоносный горизонт через непроницаемый водоупор по тем же разрезам, что и для первого направления, но по несколько измененным сценариям и с другим набором коэффициентов распределения сорбции ЗВ (K_d).

Численные эксперименты второго этапа проводилось по следующим сценариям: 1 – (1-3-1), 2 – (1-6-1), 3 – (1-10-1), 4 – (6-60-6), 5 – (26-260-26), 6 – (100-1000-100). Первая цифра – значение K_d (л/кг) в первом слое, вторая – во втором слое, третья – значение в третьем слое. Такой подбор коэффициентов распределения обусловлен заданием их значений на порядок больше в водоупоре, чем в верхнем и нижнем водоносных горизонтах.

Каждый сценарий проводился для двух условий: с радиоактивным распадом и без распада. За начальные условия была принята степень загрязнения грунтовых вод по аналогии со степенью загрязнения поверхности земли в зоне радиоактивного следа на изучаемой территории, хотя в природных условиях на этой территории в грунтовых водах такого распространения загрязнения ни радионуклидами, ни другими ЗВ не наблюдается. Концентрации ЗВ могут быть заданы в г/л, ПДК, фоновых концентрациях; в нашем случае использовались ПДК. Коэффициенты распределения сорбции различных ЗВ подбирались из известных значений для территорий Брянской области (Белоусова, Руденко, 2021а, 2021б),

для радионуклидов значения K_d в основном относятся к ненасыщенной зоне.

Установлено, что главными факторами формирования процессов миграции ЗВ являются в первую очередь радиоактивный распад ЗВ, во вторую – сорбционные свойства ЗВ, а в третью – гидродисперсия потоков подземных вод, которая в свою очередь зависит от геолого-гидрогеологических условий изучаемой территории и степени проницаемости водоупора. Рассмотренная ситуация свидетельствует о том, что водоупоры не являются полной гарантией, обеспечивающей защищенность напорных подземных вод от загрязнения.

Ключевые слова: грунтовые воды, подземные напорные воды, моделирование процессов миграции, загрязняющее вещество, радионуклиды, сорбция, радиоактивный распад.

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