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Modeling of ^{60}Co migration in the aquifer

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Abstract. In 1985, at Novovoronezh NPP (NVNPP), liquid radioactive waste leaked from the storage facility No2 (SLW-2). The leakage took place along the perimeter of the storage facility from the underpan closed with soil; therefore the leakage has been discovered in about half year, during water sampling from the test boreholes. According to the assessments, a volume of liquid waste released in soil was about 480 m^3 with ~76 and 15 TBq activities of ^{60}Co and ^{137}Cs, respectively. Up to now, the majority of ^{137}Cs amount has been localized at the place of the leakage – in the unsaturated zone at the level of the underpan; ^{60}Co was infiltrated into the aquifer and spread through – ground waters at about 700 meters up to Don River. ^{60}Co occurrence in the river was registered in 1995. The ground water discharge into Don River caused contamination of some part of bottom sediments up to the level of solid radioactive waste. This paper presents the calculation results of ^{60}Co migration via ground waters.

1. CALCULATION MODELS

1.1 Model of contaminants migration

The migration model is based on the transport equation solution

$$\frac{\partial C_t}{\partial t} = \frac{\partial}{\partial x_i}\left[D_{ij}\frac{\partial}{\partial x_j}\left(\frac{C_t}{\rho K_d + \theta}\right) - V_i\frac{C_t}{\rho K_d + \theta}\right] - \lambda C_t + Q, \tag{1}$$

where C_t – activity of solid and liquid components; $D_{ij} = \alpha_t|V|\delta_{ij} + (\alpha_l - \alpha_t)V_iV_j/|V|$– hydrodynamic dispersion coefficient; α_t – transversal_dispersivity, α_l – longitudinal dispersivity, δ_{ij} – Kroneker's delta; V_i – Darcy velocity of ground water; λ – decay constant; Q – source of radionuclide in aquifer; t – time; ρ – rock density; K_d – radionuclide distribution coefficient; θ – moisture content, in saturation θ = n; n – porosity.

1.2 Model of water flow

The water flow model is based on the solution of the hydrostatic potential (pressure) equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial \Psi}{\partial x_j} - \delta_{i3}\rho_w K_{ij}\right) + f, \tag{2}$$

where K_{ij} – hydraulic conductivity coefficient; Ψ – hydrostatic potential (pressure); ρ_w – relative density of ground waters (ρ/ρ_o, $\rho_o = 1000\,\mathrm{kg/m^3}$); f – divergention of the infiltration flux or other water source.

The ground water level is determined by means of solution of the two-dimensional equation:

$$n\frac{\partial h}{\partial t} = \frac{\partial}{\partial x_i}\left(K^a_{ij}H\frac{\partial h}{\partial x_j}\right) + F, \tag{3}$$

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where h – ground water level; H – the aquifer thickness; $H = h - Z$, Z – aquifuge waterproof level; $K_{ij}^{a} = (\int_{Z}^{h} K_{ij} dz)/H$ – hydraulic conductivity averaged by the aquifer thickness; $K_{ij}^{a} H$ – conductivity of the aquifer; F – infiltration flux.

Darcy velocity is determined using the equation:

$$V_i = -K_{ij}\left(\frac{\partial \Psi}{\partial x_j} - \delta_{i3}\rho_w\right). \tag{4}$$

In the equations (1)–(4) summing is assumed by the repeating indexes; these equations are solved numerically by the finite difference method, equations (1), (2) – in three-dimensional form, while (3) – in two-dimensional form.

1.3 Geochemical model

It is assumed that, during the 1985 incident, full amount of ^{60}Co was in anion form. As ^{60}Co in the aquifer is both in the complex anion form, and in the form of the ordinary cation, equation (1) is solved independently for each form.

Complex ^{60}Co anion is transferred into cation during its adsorption with iron hydroxide. This process is accounted in equation (1) through source term:

$$Q = -C_t K_d k_{f2}, \tag{5}$$

where C_t – activity of ^{60}Co in anion form; k_{f2} – cobalt substitution reaction rate in the complex anion by three-valence iron, this value is 0.004 h^{-1}. For ^{60}Co cation, Q value is determined using formula (5), but with "plus" sign.

According to measurements, the sand distribution coefficient of the aquifer is 1.5 l/kg for cation and $2.5 \cdot 10^{-3}$ l/kg for anion. For bottom sediments of Don River and channels the distribution coefficient reaches 1000 l/kg. The hydraulic conductivity of sands at the place of storage facility is 18 m/day, near of Don River – 7 m/day; the longitudinal dispersivity is 10 m, the transversal – 2 m, active porosity – 0.3.

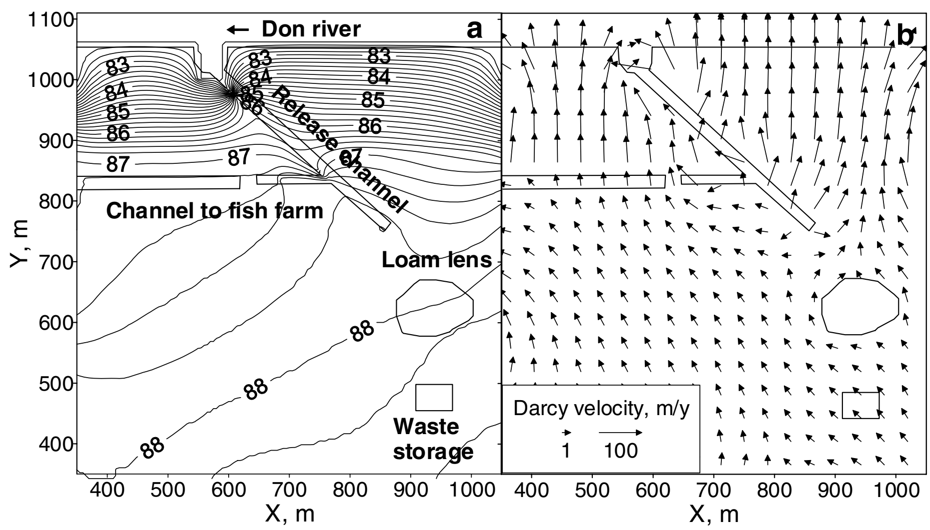

Figure 1. Calculation of ground water flow, a – absolute height of ground water table (m), b – vectors of Darcy velocity (m/year).

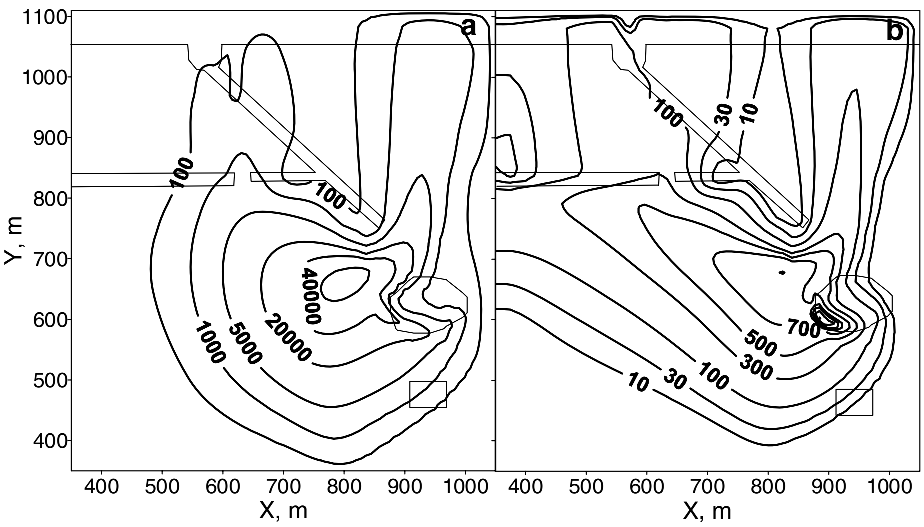

Figure 2. Calculated activity distribution of ^{60}Co anion form in ground waters (kBq/kg), a – since 7 years after the incident, b – 18 years.

2. RESULTS AND CONCLUSION

Figure 1 shows the results of ground water flow. According to Figure 1, contaminant migration is significantly depended by the system of channels, as well as the lenses of low permeable loamy soil discovered in the course of hole-boring and showered in Figure 1.a.

Figure 2 shows ^{60}Co anion form distribution. In terms of the calculations, we may conclude that there are three main paths of the contaminant migration into the river:

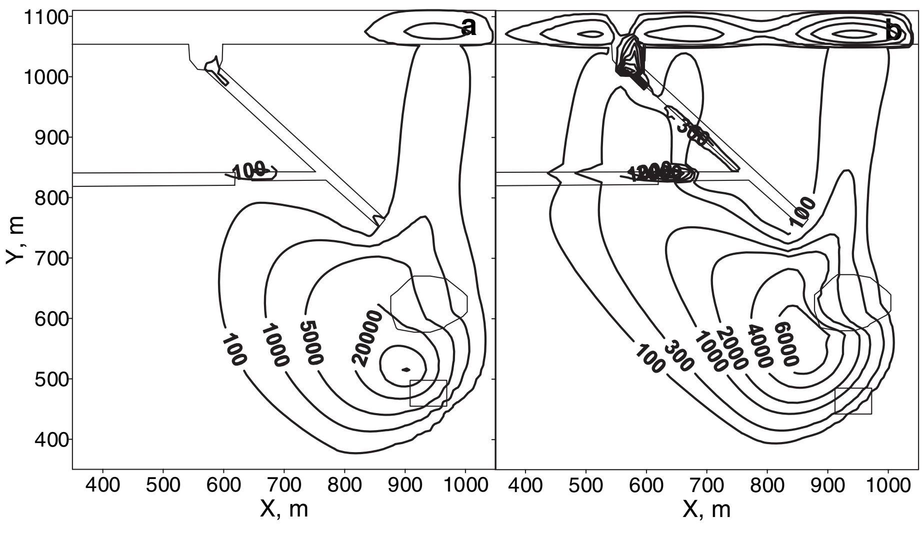

Figure 3. Calculated activity distribution of ^{60}Co cation form in soils (kBq/kg), a – since 7 years after the incident, b – 18 years.

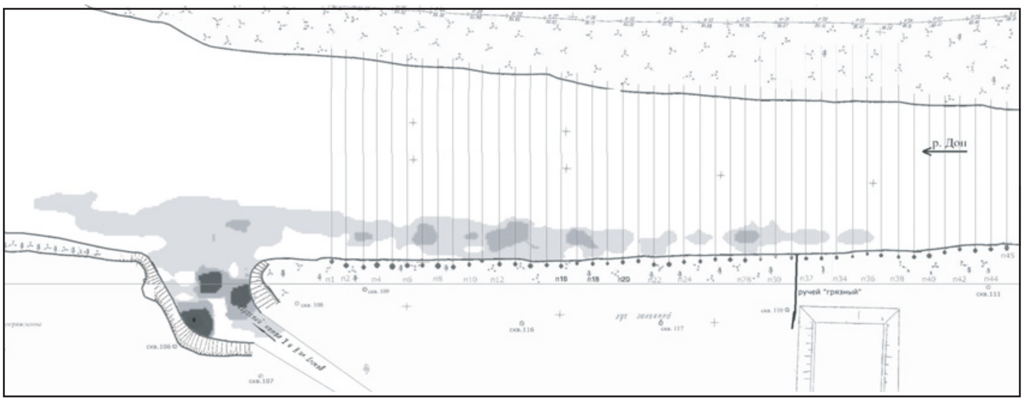

Figure 4. Measured ^{60}Co activity distribution in bottom sediments of Don River.

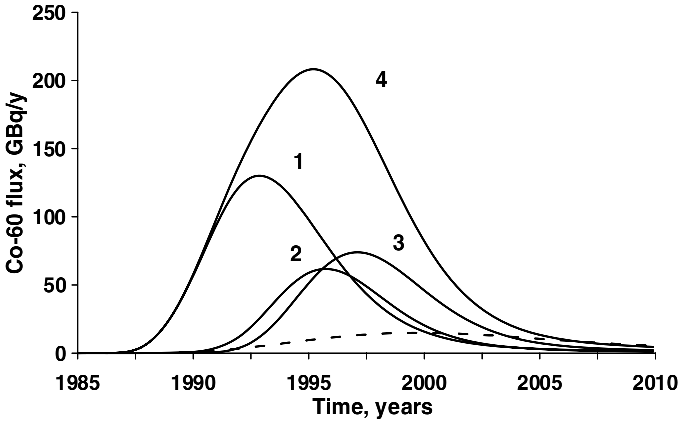

Figure 5. Calculation of ^{60}Co flux into Don River. 1 – ^{60}Co anion entry at the section located 300 m higher than the waste channel mouth, 2 –150 m higher, 3 – in the waste channel mouth, 4 – total ^{60}Co anion flux. The dotted line indicates total ^{60}Co cation flux.

– entry into Don River above the waste channel mouth in 300 m – across the channel to the fish farm below the dam;
– the last flow is subdivided into the stream to Don River in approximately 150 m higher than the mouth and the stream into the channel mouth.

Figure 3 shows ^{60}Co distribution in the cation form. Because of the sand sorption, almost full amount of ^{60}Co in cation form is concentrated close to the storage facility, both in 7 years after the incident, and in 18 years; while its anion form is located mainly in front of the natural barriers: loam lens and channels, entering from these places into Don River. Thus, ^{60}Co distributions for cation and anion forms are rather different.

Before the beginning of numerical experiments, according to experimental data, it was assumed that there is the only last path of ^{60}Co inflow into the river, in the waste channel mouth, which causes contamination of bottom sediments. Later, discovering of ^{60}Co in bottom sediments above the waste channel mouth confirms the calculation results; Figure 4 shows the observed ^{60}Co distribution in bottom sediments of Don River.

Figure 5 shows time dependence of ^{60}Co flux – into Don. The flow calculations accounted that, according to experimental data, ^{60}Co entry into Don was about $\sim 5 \cdot 10^{10}$ Bq/year. The calculations are presented for three sections, characterizing, according to Figure 2, three main directions of contaminated ground water streams. It is obvious that firstly (in 1990) ^{60}Co entered into Don approximately 300 m higher than the waste channel mouth; and then (since 1995) it has entered through the waste channel mouth. This fact had been registered.

The public dose due to the liquid waste leakage of 1985 can be evaluated on the base of calculated ^{60}Co entry into Don. This dose assessment used GENII [1] model for the critical group of fishermen and members of their families, whose fish intake is 50 kg per year. According to the calculations, maximum dose to the critical group of the population is about 10 times lower than 10 μSv/year dose of minimum significance. Thus, we can conclude that the incident at Novovoronezh NPP did not cause the public exposure excess the authorized limits; this dose permanently decreases because of reduction of ^{60}Co entry into Don River.

References

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