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A New Approach to Mapping of Ground-water Vulnerability to Surface Contamination

A.A. Potapov, V.J. Abramov, and M.N. Kotchneva

Department of Hydrology, Mining Institute,
21 Liniay, 2, St. Petersburg, 199026, Russia

ABSTRACT

Ground water, especially the shallow aquifers, is more vulnerable to anthropogenic influences than any other ecological systems within large urban, industrial and mining regions.

The new methods of mapping of ground water vulnerability to contamination from the surface were developed. It is based on determination of maximum admissible mass of contaminant which may be disposed of one square meter of land surface without risks to ground water quality. The equations for calculation of maximum admissible mass of contaminant are deduced. The main hydrogeological (migration and filtration) parameters used in these equations may be obtained using granulometric composition of soil in unsaturated zone.

The main result of hydrogeological investigations conducted in Komsomolsk-na-Amure industrial region located in the Amur River valley in the Far East of Russia is the map of shallow ground water vulnerability (scale 1:50000) created using this new proposed approach.

Key Words: contamination, ground water vulnerability, mapping

INTRODUCTION

Methods of map construction - "Map of ground water vulnerability to surface contamination" - considered below are performed for reaching the following aims:

- Site assessments keeping in mind ecological safety under industrial and agricultural enterprises design
- Determination of sanitary protection zones for both public and private water supply wellfields including single wells and springs
- Express preliminary forecast of consequences of sudden contaminants spreading over the land surface
- The most vulnerable sites selection under planning of areal ecological sampling

Offered methods mean to use data obtained during hydrogeological survey: hydrogeological maps and sections, maps of hydroisopieses and water table contours, granulometric compositions of water-bearing and impermeable deposits. Taking into account approximate character of the assessments, the authors offer to take transport and filtration parameters of aquifers a priori - according to granulometric composition of water-bearing deposits.

THE MAIN PRINCIPLES OF GROUND WATER VULNERABILITY MAP CONSTRUCTION.

1. Assessments of ground water vulnerability to surface contamination are to make for each aquifer.

2. Different types of hydrogeological sections have been assumed as a basis of areal zonation. The whole variety of natural situations may be reduced to three main migration types of sections (Fig. 1).
   - A-type - shallow unconfined aquifer; unsaturated zone consists of the soils for which initial hydraulic gradient (J_0) is less than 1. In these conditions the convective-dispersional mass-transport will take place together with atmospheric precipitation or with contaminating solution itself - along the Z-axis.
   - B-type - water-saturated deposit with $J_0 < 1$ occurs above the aquifer. In natural conditions mass-transport towards the water table will be mainly realized by means of diffusion mechanism. However, if an intensive water pumping from the aquifer takes place (extreme case - water table fell down below the roof of the aquifer) the vertical convective - dispersional contaminant transport may start.
   - C-type - aquifer, in the top of which the layer with $J_0 > 1$ occurs. The contaminant transport towards aquifer will be the result of molecular diffusion.
   - D-type - there is an interlayer (with $J_0 > 1$) within the deposit which overlie the aquifer. In natural conditions the diffusive mass-transport may only take place. Under intensive water pumping two different situation are possible:
     - Maximum possible hydraulic gradient within low permeable interlayer, which is equal to $J_{max} = (H1 - H2)/m$, will be greater that initial hydraulic gradient (Jo), which is typical for deposits formed this interlayer. In these conditions the vertical convective-dispersional contaminant transport may start. This situation corresponds to the B-type.
     - $J \leq Jo$. Only diffusive mass-transport may occurs under any water pumping. This situation corresponds to the C-type.

3. Within the areas belong to one migration type the zonation may be carried out on the base of two mutually related quantitative criteria:
   - Time, when the first portions (up to 1%) and the main mass (more than 90%) of contaminants will penetration into the aquifer.
   - The maximum admissible mass of contaminant which may be disposed of one square meter of the land surface without any risks for ground water quality (the concentration of the contaminant in any point of the aquifer will not exceed the drinking water standard).

4. When vulnerability assessments of the aquifers are being made the worst scenario of contaminant spreading is considered. In connection with that the following assumptions were made by the authors:

- The whole contaminant mass instantly penetrates into the soil from the land surface. Such a problem formulation corresponds to impulse mass injection at the point $Z=1$ (Fig.1), being impermeable (for the substance) boundary in (-Z) direction at the same point $Z=0$.
- Contaminant transport takes place only along Z-axis without its areal spreading by dispersion. This problem formulation corresponds to a great enough contamination spot on the land surface (spot sizes are comparable with the depth to aquifer).
- Contaminants are considered as non-reactive in the sorption processes. It follows from that fact that it is not possible to construct one map of ground water vulnerability to different contaminants with different chemical nature.
- Mass-transport within the unsaturated zone occurs as if it would occur within saturated zone. This position makes the situation very closed to the assessments which take place in flood periods or in case of area inundation. The mass-transport velocity is the highest one in this case.

CALCULATION EQUATIONS

According to the principles presented in the previous part of the article, vertical contaminant transport within the A-type and B-type hydrogeological sections (under intensive ground water pumping) is described by:

$$V_Z(d\,C\,/\,dZ) + D_Z(d^2C\,/\,dZ^2) = n_a(dC\,/\,dt) \ldots\ldots\ldots\ldots \quad (1)$$

The initial condition - delta - Dirak's function d(Z) (impules injection):

$$C\,(Z,0) = (m/n_a)\,d\,(Z) \ldots\ldots\ldots \quad (2a)$$

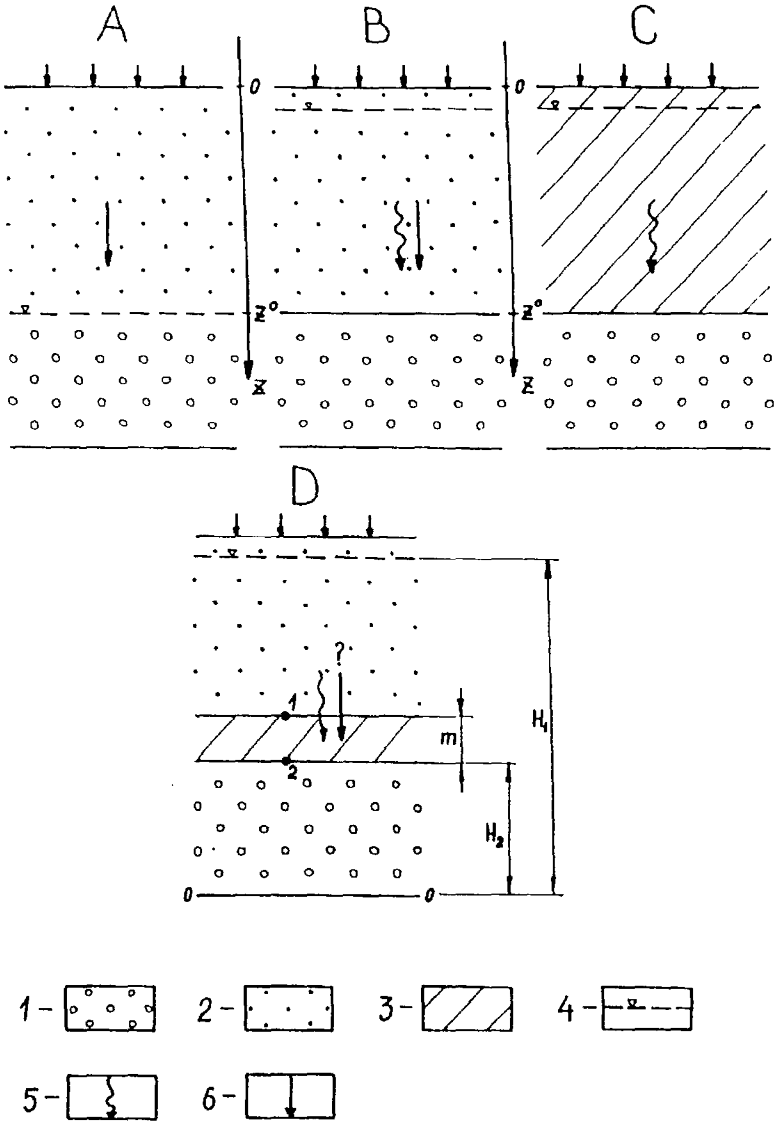

FIGURE 1. Migration types of hydrogeological sections.

1 - aquifer, which vulnerability to surface contaminant is being in consideration; 2 - deposits with initial hydraulic gradient < 1; 3 - deposits with initial hydraulic gradient > 1; 4 - ground water table; 5 - direction of diffusion contaminant transport; 6 - direction of convection - dispersion contaminant transport.

Boundary conditions:

$$\lim C(Z,t) = 0; \qquad z \to \infty \tag{2b}$$

$$\int_0^{\infty} C(Z,t)\, dZ = m/n_a, \tag{2c}$$

where $C(Z,t)$ - concentration of contaminant (g/m^3, mg/L), which is a function of the depth (Z,m) and time (t, days); v_z - vertical flow velocity, m/day; D_z - longitudinal dispersion coefficient (m^2/day); n_a - active porosity; m - contaminant mass, disposed over the land surface, g/m^2.

For the C-type hydrogeological section the same equation is:

$$D_m(d^2 C/d Z^2) = n(d C / d t) \tag{3}$$

with the same initial and boundary conditions but if n_a is changed by n. In this case: n - total porosity; D_m - diffusion coefficient (m^2/day).

For the B-type hydrogeological section (natural conditions) the differential equation of mass-transport corresponds to the equation (3) with changing n by n_a and D_m by $D_{z(t)}$ (transversal dispersion coefficient along the Z-direction under the condition of horizontal flow).

All presented parameters belong to the layer overlain the described aquifer.

We've deduced the solution of the equation (1) with the boundary conditions (2):

$$C(Z,t) = 1/2(m/n_a)\left[\frac{2}{\sqrt{\pi\,(D_z/n_a)t}}\, exp\left(-\frac{(Z-(v_z/n_a)\,t)^2}{4\,(D_z/n_a)t}\right) - (v_z/D_z)\, exp\,(v_z\, Z/D_z)\, erfc\left(\frac{Z+(v_z/n_a)t}{\sqrt{4(D_z/n_a)t}}\right)\right] \tag{4}$$

The solution of the equation (3) with boundary conditions (2) can be easily found by the superposition methods using well-known solution concerning the instant (impules) source with an unlimited diffusion:

$$C(Z,t) = \frac{m/n}{\sqrt{\pi\,(D_m/n)t}}\; exp\left(-\frac{Z^2}{4\,(D_m/n)t}\right). \tag{5}$$

To evaluate mass of contaminant reached aquifer during the time - t, the authors have used the following equation:

$$m_t = n\int_{Z_o}^{\infty} C\,(Z,t)\; d\,z, \tag{6}$$

where m_t - mass of contaminant, which reached aquifer during the time t after the contaminant spilling, g/m^3; Z_o - depth to ground water occurrence, m.

Thus, value of contaminant mass reached aquifer in per cent from the total mass of contaminant disposed on the land surface $m_t(\%) = (m_t/m)100$ is: - for the A-type and the B-type hydrogeological sections (under intensive ground water pumping):

$$m_t(\%) = 50\left[\; erfc\left(\frac{Zo-(vz/na)t}{\sqrt{4(D_z/n_a)t}}\right) + \right.$$

$$\left. + \,exp\left(\frac{v_z\,Z_o}{D_z}\right)\; erfc\left(\frac{Z_o-(v_z/n_a)t}{\sqrt{4(D_z/n_a)t}}\right)\right] \tag{7}$$

- for the B-type hydrogeological section (natural conditions):

$$m_t(\%) = 100\;\; erfc\left(\frac{Zo}{\sqrt{4(D_{z(t)}/n_a)t}}\right) \tag{8}$$

- for the C-type hydrogeological section:

$$m_t(\%) = 100\;\; erfc\left(\frac{Zo}{\sqrt{4(D_m/n)t}}\right) \tag{9}$$

Assessment method of the maximum admissible mass of contaminant which may be disposed of one square meter of the land surface without any risk for ground water quality (m_{ad}) is based on determination of the maximum possible concentration C_{max} in the Z_o-point. The time t_{max}, when $C = C_{max}$ in the Z_o-point, is determined from the equation:

$$dC\,(Z_o,t)/dt = 0 \qquad (10)$$

For the solution (4):

$$t_{max} = Z_o^2/2\{(D_z/n_a) + (v_z/n_a)Z_o\} \qquad (11)$$

When $(v_z Z_o)/D_z \gg 1$, the solution (11) becomes simpler:

$$t_{max} = Z_o/(v_z/n_o) \qquad (11a)$$

Our evaluations have shown that the difference between the concentrations C_{max}, calculated using equations (11) and (11a) when $(v_z Z_o/D_z) = 10$, does not exceed 10%.

Analyzing the equation (11a), we've found, that when $(v_z Z_o/D_z) > 1.5$ the value of the second item in the equation (4) is approximately equal to a half of the first one with accuracy up to 5%.

Then for the A-type and the B-type hydrogeological sections (when an intensive ground water pumping from the aquifer takes place):

$$C_{max} = C_{dws}, \qquad (12)$$

$$m_{ad} = aC_{dws}, \qquad (13)$$

where C_{dws} - maximum admissible concentration (drinking water standard) of the contaminant in ground water (g/m^3, mg/L); a - coefficient of the admissible mass of contaminant (m), which can be found from the equation:

$$a = 2n_a\sqrt{(\pi D_z Z_o)/v_z} \qquad (14)$$

For the solution (5):

$$t_{max} = Z_o^2/2(D_m/n). \qquad (15)$$

Then for the B-type hydrogeological section (natural conditions) taking into consideration the equations (12) and (13) we have:

$$a = n_a Z_o \sqrt{0,5\pi}\ \ exp\ (0,5) \qquad (16)$$

and for the C-type:

$$a = n Z_o \sqrt{0,5\pi}\ \ exp\ (0,5). \qquad (17)$$

It should be noted that:

$$v_z = K_z\ J, \qquad (18)$$

where K_z - hydraulic conductivity along the vertical direction (m/day); J - hydraulic gradient which value may be taken equal 1 both under free vertical filtration for the A-type and under forced filtration for the B-type (as the worst situation). Thus, in the equations (7) and (14) the parameter K_z should be used instead of the parameter v_z.

MAP OF GROUND WATER VULNERABILITY FOR THE AREA OF KOMSOMOLSK-na-AMURE CITY

Fragment of the map of ground water vulnerability to surface contamination within the Komsomolsk-na-Amure City area is shown in Figure.2.

The a-coefficient is specified for each sites with different ground water vulnerability to surface contamination. This coefficient means a maximum admissible mass of contaminant which may be disposed of one square meter of the land surface without any risk to ground water quality.

As to the deeper aquifers, just some of them (most significant) were considered. On Figure 1, it is alQ_{IV} aquifer.

Geological and hydrogeological features of the area are reflected on the hydrogeological sections (Figure 3).

CONCLUSIONS

The presented map allows to evaluate clearly the conditions of aquifer vulnerability to surface contamination.

The most part of the study area belongs to the A migration type. Moreover, all mass of contaminant within this area reaches shallow aquifer for less than 30 days.

However, as for the main aquifer (alQ_{II}) used for drinking purposes the first portions of contaminant will not reach water level earlier than in 1000 days (even within the sites with very high level of ground water vulnerability). The harmless mass of contaminant for alQ_{II} aquifer is also high enough: it is more than 9 kg/m^2 for Cl-ion (with maximum admissible concentration of Cl_2- in ground water - 350 mg/l); and it is more than 0.75 g/m^2 (without sorption) for Pb (with maximum admissible concentration of Pb in ground water - 0.03 mg/l).

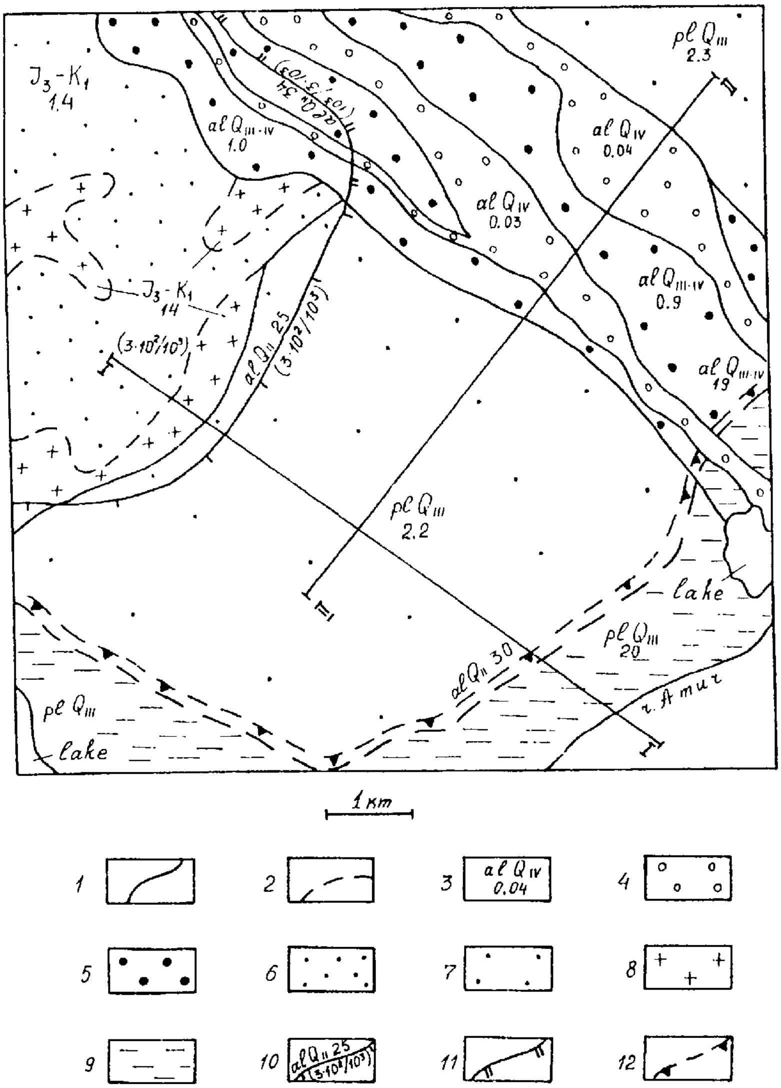

FIGURE 2. Fragment of the map of ground water vulnerability to surface contamination within the Komsomolsk-na-Amure City area.

1 - aquifer boundaries; 2 - boundaries of the sites with different vulnerability levels within one aquifer; 3 - aquifer index; 4 -7 - sites with the A-type of hydrogeological section (time, when more than 90% of contaminant mass will reach aquifer: 4 - 1 day, 5 - 3 days, 6 -10 days and 7 - 30 days); 8,9 - sites with the B-type and the C-type of hydrogeological sections respectively (time, when more than 1% and 50% of contaminant mass will reach aquifer: 8 - 10^3 days and 10^4 days, 9 - 10^4 days and 10^5 days respectively); 10 -12 - boundaries of the sites with different vulnerability levels within the main exploited aquifer (alQII), hydrogeological sections of the B-type - 10,11 and the C-type -12 (time, when more than 1% and 50% of contaminant mass will reach aquifer: 10 - 10^3 days and 10^4 days, 11 - $3*10^3$ days and $3*10^4$ days, 12 - 10^5 days respectively); For the sites with the B-type hydrogeological sections (8,10,11) time when more than 1% and 50% of contaminant mass will reach aquifer is shown in brackets taking into consideration an intensive using of the aquifer.

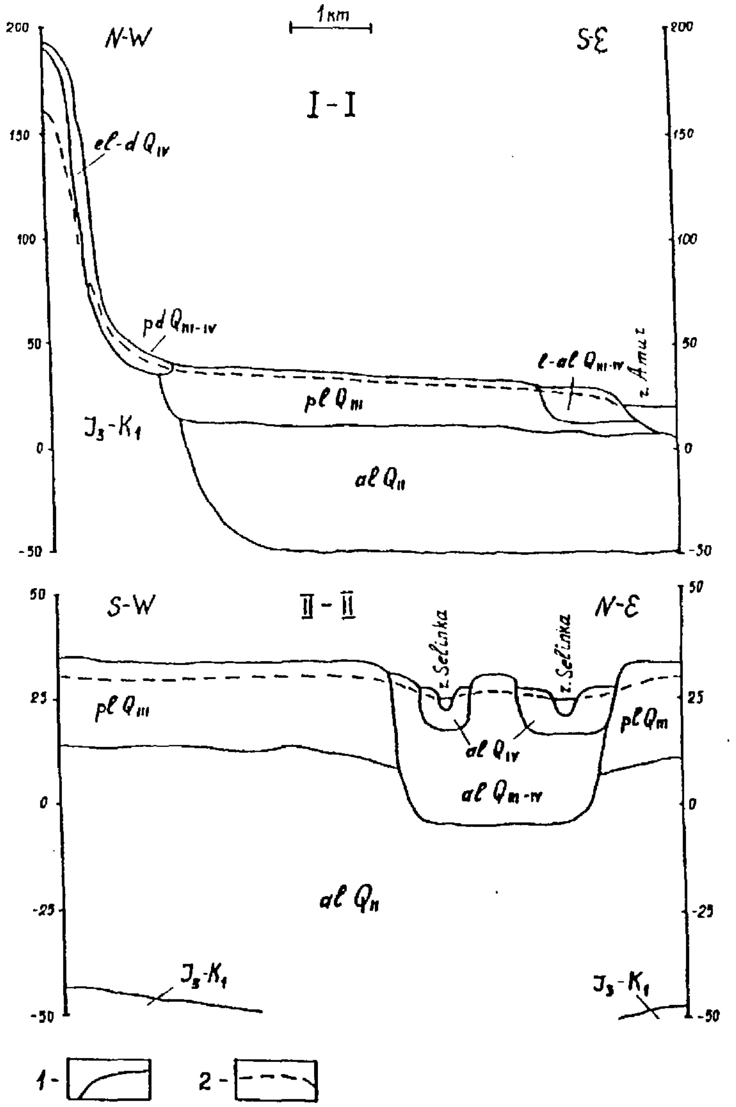

FIGURE 3. Hydrogeological sections along the lines I-I and II-II (see Fig. 2)

1 - geological boundaries; 2 - water table; el-dQIV - eluvial and deluvial deposits (rock debris with loam and clay sand); alQIV - alluvium (gravel sand); alQIII-IV - alluvium (boulder-gravel deposits with clay sand); pdQIII-IV- proluvium and deluvial deposits (rock debris with loam and clay sand); l-alQIII-IV - lacustrine - alluvium deposits (clay sand and clay); plQIII - proluvium of detrital cone (boulder-gravel deposits with clay sand and sand); alQII - alluvium (sand and clay sand); J3-K1 - terrigenous deposits (argillite, siltstone and fractured sandstone).