Chemical Substance Transport in Soils and Its Effect on Groundwater Quality

by Martin G. Khublarian*

The problems of chemical substance applications in different spheres of industry and agriculture and their effects on groundwater quality and human health are described. Sources of groundwater contamination from industrial and municipal wastes, agricultural pollutants, etc., are listed. The experience in the application of chemical fertilizers and pesticides in the USSR is described. A brief estimation of groundwater salinity is given for various regions of the USSR where irrigation is practiced, as well as the experience in environmental protection. Special attention is given to methods of simulating water seepage and chemical substance transport in soils. Boundary problems for free-surface seepage and dissolved solids transport in porous media are stated, and methods of solution are described in the example of the hydrodynamic theory of seepage and dispersion. Some results of calculations with this method are presented. The influence of groundwater quality on the morbidity of the population is given and the main diseases and associated medical problems are listed.

Introduction

Increased anthropogenic loading on the environment has produced an appreciable disturbance of natural conditions. Considerable amounts of pollutants are released into water and air, causing their contamination. For some chemicals, the rate of release is greater than the rate of removal. As a result, some chemical substances are accumulated, particularly in water and soil.

Pollution of groundwater must be understood to be closely related to that of the whole environment. Moisture in the atmosphere is connected with moisture in surface and groundwaters via the hydrologic cycle. Therefore, it is impossible to prevent groundwater pollution if the atmosphere, surface waters, and soils are subjected to continuous contamination.

Many pollutants are able to penetrate into groundwater aquifers. This situation is even more dangerous than a deficit in the water supply, since unconfined groundwaters—unlike groundwaters in confined aquifers—are not as well protected from pollution. Thus, deterioration of groundwater quality is becoming a matter of great concern.

The main sources of groundwater contamination are municipal, industrial, and agricultural wastes (both solid and liquid), gangue rocks, sludge and slimes, refuse, pesticides, herbicides, effluents from livestock and poultry farms, etc. Pollutants have different migration capacities, toxicities, and other properties. Thus, even low concentrations of highly toxic pesticides can significantly influence cellular behavior, genetics, and metabolism. The ability of pesticides to enter and accumulate in tissues causes contamination of the whole food chain.

Unfortunately, at the present time in the USSR, chemical methods are used to protect agricultural areas and forests from pests and undesirable plants. In 1986, more than 20 million hectares were treated with pesticides, whereas biological methods were applied only on small areas. In the future, the areas where biological methods of protection will be used are to be expanded. These methods are ecologically pure, unlike chemical methods that cause environmental pollution, entailing the annihilation of useful insects, birds, fish, mammals, and the poisoning of people.

Mineral fertilizers, pesticides, and municipal and livestock farm effluents contain heavy metals. Many of these elements such as arsenic, mercury, cadmium, lead, and copper are toxic, even at low concentrations. The main pollutants in livestock farm effluents are nitrogen, phosphorus, and potassium. The migration capacities of potassium and phosphorus are low, so these elements are retained in the upper soil layer; the main contaminants of groundwater are nitrogen and bacteria. Field observations, carried out in Uzbekistan from 1980 to 1985, showed that a loam layer 140 cm deep retained 82.4% of ammonia nitrogen, 90.3% of phosphates, 30% of total nitrogen, and 90% of potassium contained in the effluents (1).

The annual amount of applied fertilizers varies from
10 to 100 kg/ha. These fertilizers contain deleterious substances: nitrogen compounds, sulfates, chlorides, and phosphates. Nitrogen is found in four forms: organic nitrogen, nitrites, ammonium, and nitrates, the latter accumulating in soils. A steady and stable increase of nitrate content in groundwater has been observed. Sometimes it exceeds 50 mg/L, which is the maximum permissible concentration determined by the sanitary standards for drinking water. High nitrate content causes a drop in blood hemoglobin level (methemoglobinemia) that can be fatal in newborn infants.

The danger of organic pollution (humic substances, phenols, hydrocarbons, fatty acids, and lignin) should not be underestimated. In 1985, the USSR agricultural areas totaled 210.3 million hectares, and the application of mineral fertilizers (evaluated on the value of 100% nutrients) was 25,389,000 tons, including 10,951,000 tons of nitrogen fertilizers, 6,837 tons of phosphates, 776,000 tons of phosphoric acid fertilizer, and 6,817,000 tons of potassium fertilizers.

At present, 250 million hectares (16%) of the world's arable lands are irrigated. In 1986, the area of irrigated lands of the USSR was 20 million hectares. By the year 2000, these areas will be expanded up to 30 to 32 million hectares. Irrigated lands are located mainly in Central Asia, Southern Ukraine, Northern Caucasus, Transcaucasia, and Volga regions.

The construction of large irrigation systems in different regions of the country caused appreciable changes in groundwater level and quality. For example, in the Volga region, the depth of groundwater aquifers is 2 to 10 m, salinity is 0.2 to 15 g/L. Sulfates, chlorides, and sodium compounds are typical constituents of groundwater in the Volga region. On a land plot that has been irrigated for 30 years, salinity of the pore solution increases uniformly from 0.5 to 1.5 g/L to 10 to 15 g/L, as depth increases from 1 to 2 to 8 to 14 m. At a depth of 5 to 7 m the concentration of chloride ion, (Cl⁻) has achieved a value of 8 g/L. At a depth of 10 to 14 m the chloride ion concentration is 9 g/L. Sodium cations prevail in pore solutions: at a depth of 3 to 5 m the average Na⁺ concentration is 1.6 g/L, and at a depth of 5 to 7 m it is 3.0 to 3.5 g/L. Concentrations of calcium, magnesium, and some other elements also increase with increasing depth below the surface.

The construction of the Kara-Kum Canal in Soviet Central Asia (its length is 1200 km; annual runoff is 9 km³) had both positive and negative effects on the environment. Mannmade lakes and drainage systems were constructed and vast lands were irrigated. For the 23-year period of the canal's operation, the total inflow of surface waters into it was 240,933 billion m³. The total input of salts was 142,124 million tons. Infiltrating irrigation waters carried salts from the aeration zone, thus increasing their content in the groundwater.

Zones of groundwater level rise (so-called seepage mounds) appeared under irrigation canals and on irrigated land plots. Thus, in the Ashkhabad region the groundwater level rose by 10 to 15 m; in a 4 to 4.5 km-wide zone along the drainage collection area, the groundwater level rose by more than 15 m. Infiltration lakes appeared in the drainage areas for these canals. Groundwater salinity around them increased by 3 g/L, as compared to the background value, which was explained by intensive evaporation.

The Kara-Kum Canal waters irrigate up to 850,000 hectares of land whereas the total area of irrigated lands in Soviet Central Asia is 6.8 million hectares. Depth, chemical composition, salinity, and other parameters of groundwater are diverse because of the variety of lithologic, geomorphologic and climatic peculiarities, human activities, and many other factors. As a rule, surface water salinity is proportional to the distance between the river and the source of irrigation water (irrigational canal). Similar changes are observed in the salinity of groundwater.

The salinity in the Amudaria River increased to a value of 0.5 to 0.8 g/L and in the Syrdaria River, salinity levels were as high as 1.5 to 1.6 g/L. Groundwater salinity was also subjected to vertical variability. The salinity of water from a sampling bore-hole in the Vakhsh river valley was as follows: 1.5 to 2.48 g/L; 7.5 to 1.80 g/L; 15.0 to 1.90 g/L; 20.0 to 1.13 g/L; 47.0 to 1.69 g/L; 149.0 to 1.06 g/L; 197.0 to 1.15 g/L.

Experience in irrigational system construction and operation is valuable and instructive. Special attention is given to environmental protection problems. Thus, in order to ensure standard salinity in projected irrigational systems in the Volga basin, the impact of the daily release of 2 million m³ of drainage waters (their average salinity being 4 to 7 g/L) is planned and projected for the Urals and Kazakhstan regions. These are regions that are far away from the Volga region, but are connected with that region.

Therefore, predicting seepage phenomena, solute transport in soils, and estimating their effects require models that carefully describe natural processes. Among theoretical models of mass transport in soils are the black box model, the gray box model, structural models, and others. These models are described in great detail in the literature. Because of the specific interest of the author, the present paper deals mainly with structural models. They are based on hydrodynamic principles for describing transient seepage processes and pollutant transport in groundwater.

Isothermal groundwater and pollutant transport can be described by the following system of governing equations as

\[ V = \frac{k}{\mu} (\text{grad} \ P + \rho g \text{grad} \ Z) \]  
\[ \frac{\partial \rho C}{\partial t} - \text{div} (\rho V) = 0 \]  
\[ \frac{\partial \rho C}{\partial t} + \text{div} (CV) = \text{div} \left[ \frac{D_p \text{ grad } C}{\rho} \right] \]  
\[ \rho = \rho(C); \quad \mu = \mu(C) \]
Here V is seepage velocity; K is the coefficient of permeability; μ is dynamic viscosity; m is porosity; P is fluid pressure; g is the acceleration of gravity; Z is the vertical coordinate; t is time; ρ is the density of the solution; D is the second-rank tensor of dispersion; and C is pollutant concentration in groundwater.

Solutions of these equations are possible at assigned parameter values and boundary conditions for certain conditions. Assuming that the density and viscosity of the solutions do not depend on the concentration (which is observed when the concentration varied within a narrow range), the hydrodynamic problem can be considered independently. Then the concentration can be determined from the obtained values of seepage velocity.

**Hydrodynamic Theory of Seepage**

The theoretical basis of the model is described elsewhere (5,6). For nonuniform porous media according to the linear form of Darcy's law, the two-dimensional seepage velocity profile with a free boundary is described by an elliptic equation for head, H as

\[
\frac{\partial}{\partial x} \left[ K_x(X,Y) \frac{\partial H}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K_y(X,Y) \frac{\partial H}{\partial y} \right] = 0
\] (5)

Seepage velocity components and the free surface \( Y = \phi(X,t) \) are determined as

\[
V_x = -K_x(X,Y) \frac{\partial H}{\partial x}, \quad V_y = -K_y(X,Y) \frac{\partial H}{\partial y}
\] (6)

\[
m \frac{\partial \phi}{\partial t} = -K_y(X,Y) \frac{\partial H}{\partial y} + K_x(X,Y) \frac{\partial H}{\partial x} = E(X,Y,t)
\] (7)

where \( K_x \) and \( K_y \) are the coefficients of permeability in the X and Y directions; \( E(X,Y,t) \) is the function that describes free-surface infiltration and evaporation. The initial condition is

\[
\phi(X,0) = F(X) \quad 0 \leq X \leq L
\] (8)

For the lower boundary, which, in general, has an arbitrary contour and recharge rate, the boundary condition is given as

\[
\frac{\partial H}{\partial x} = Q(x,t)
\] (9)

where \( N \) is the inner normal to the boundary domain. Vertical boundary conditions at \( X = 0 \) and \( X = L \), can be different depending on the concrete statement of the problem. If \( X = L \), then

\[
\frac{\partial H}{\partial x} = 0 \quad 0 \leq Y \leq B_n
\]

\[
H = B \quad \text{for} \quad B_n < Y < B
\]

\[
H = Y \quad \text{for} \quad B < Y \leq \phi(0,t)
\] (10)

where \( B_n \) is the distance between the water body bottom and the selected zero plain (or zero line, in the case when the horizontal impermeable layer is the lower boundary); and \( B \) is the distance between the zero plain and the level line of the surface water body. This value generally depends on time.

If \( Y = 0 \), either symmetry is observed, e.g., \( \partial H/\partial x = 0 \), or the values of head or flow are to be assigned. Boundary conditions for other cases are described elsewhere (7).

The solution of this nonlinear boundary value problem can be obtained with the present generation computers. Complex hydrogeological media, characterized by non-uniformity and the presence of stratified layers of different permeability, can be investigated only with the help of hydrodynamic models. In cases when the domain under consideration is uniform, the seepage layer is thin, its spatial variations are minimal, and flow dynamics are studied over vast areas. Only then can the hydraulic theory of unconfined seepage be applied. In this case, seepage can be described by the quasi-linear Boussinesq equation. It should be noted that this equation results from the vertical averaging of the continuity equation and the application of free-surface conditions to Darcy's law (8).

**Unsaturated-Saturated Seepage**

This problem can be solved by two methods described in the scientific literature. The first method consists of using the equation of moisture transport in unsaturated media and the Boussinesq equation for free-surface saturated seepage. The other method requires the development of a coupled mathematical model.

We consider both of these methods, as follows:

**Case 1.** For a one-dimensional case, the Boussinesq equation is given as:

\[
m \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left[ kh \frac{\partial h}{\partial x} \right] + E(x,t)
\] (11)

where \( h \) is head; \( K \) is the coefficient of permeability; and \( E \) is the term describing the source of flow.

The initial and boundary conditions for the saturated zone are

\[
h(X,0) = f(X) \quad 0 < X < L
\]

\[
h(0,t) = h_0(t) \quad t > 0
\]

\[
\frac{\partial h}{\partial x} \mid_{x=L} = 0 \quad t > 0
\] (12)

The one-dimensional equation of transient moisture transfer is

\[
C(P) \frac{\partial P}{\partial t} = \frac{\partial}{\partial z} \left[ K(P) \left\{ \frac{\partial P}{\partial z} + 1 \right\} \right]
\] (13)

where \( C(P) \) is the coefficient describing the water-holding capacity or storativity of the aquifer; \( K(P) \) is the
coefficient of permeability for the unsaturated zone; and P is liquid pressure.

Initial and boundary conditions for Eq. (13) are

\[
P(Z,0) = \xi(Z) \quad 0 \leq Z \leq Z_0
\]

\[
P(0,t) = 0 \quad t > 0
\]

\[
\frac{\partial P}{\partial Z}|_{Z=Z_0} = \frac{R}{K(P)} - \frac{1}{t > 0}
\]

where R is the infiltration flow rate through the soil surface \((R > 0)\) or the evaporation rate \((R < 0)\).

If the effect of vegetation is to be taken into account, a term describing water absorption by the plant roots must be included in Eq. (13). The algorithm for the solution of this problem, the coupling of the two equations and the analysis of the results are described in (9). It can be concluded from this investigation that the methods give satisfactory results for simulation startup. When the inflow to the water surface is small, the lateral component in the unsaturated flow domain is negligible and the Boussinesq approximation hypothesis of Dupuit-Forschheimer is valid. For these cases a coupled model will be an effective, approximate solution of the unsaturated-saturated seepage problem, since the solution of practical problems using the rigorous model requires extensive computer time.

**Case 2.** A rigorous coupled mathematical model of two-dimensional unsaturated-saturated seepage is

\[
\frac{\partial W}{\partial t} = \frac{\partial}{\partial x} \left[ K(\psi) \frac{\partial \psi}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K(\psi) \frac{\partial \psi}{\partial y} \right] + \frac{\partial}{\partial t} \frac{\partial \psi}{\partial \psi}
\]

where \(W\) is moisture content, and \(\Psi\) is moisture tension.

On the boundary between the saturated and unsaturated zones the pressure is atmospheric, \((\Psi = 0)\), which allows us to determine the position of the depression curve as

\(a)\) in the unsaturated zone:

\[
\psi = 0 \quad \frac{\partial W}{\partial \psi} = 0 \quad K = K(\psi)
\]

\(b)\) in the saturated zone:

\[
\psi > 0 \quad \frac{\partial W}{\partial \psi} = 0
\]

\[
K = K_0 = \text{const. or} \quad K = K(X,Y)
\]

\(\Psi\) determines the free-surface position.

The following relation is assumed between \(K\) and \(\Psi\):

\[
K = K_0 \left[ \frac{1}{1 - A \Psi^2} \right] \quad \psi < 0
\]

\[
1 \quad \psi > 0
\]

where \(K_0\) is the saturated permeability coefficient and \(A\) is a constant for the soil type. Analyses of modern approaches to the problem of water and salt transfer simulation in soils are given in (10).

Many investigations (11–13) have dealt with the problems of unsaturated-saturated seepage. Algorithms for Eq. (15) have been developed and numerous examples of calculations have been given. In addition to the computational difficulties, the authors were faced with lack of knowledge of \(dW/d\Psi\) and the relationship for \(K(\psi)\).

The use of a rigorous model of unsaturated-saturated seepage is advisable when the groundwater aquifer is close to the root zone and is subjected to large-scale vertical variations, thus endangering the plants’ growth and in some cases, causing their destruction. This model is also important in studying the interaction of surface and groundwater, as well as chemical substance transport in the domain. In the case of surface waters, when the water body bottom is covered by a layer of silt that has runoff from agricultural activities, it can represent an additional source of contamination to underlying groundwaters. The hydrodynamics of these processes are described in Khublarian et al. (14,15).

**Chemical Substance Transport**

The above models allow us to study seepage processes in the soil, predict their changes, and solve the problem of solute transport in nonuniform media, because the seepage flow is the main carrier of chemical pollutants in the porous media. The equation of pollutant transport has been given in Eq. (3). At present there are many investigations dealing with theoretical substantiation and validation of the solute transport equation and critical analysis of the model’s sphere of application. These papers also present suitable boundary conditions and suggest analytical or numerical methods for their solution.

Migration of chemical contaminants from agricultural fields takes place mainly through the aeration zone. The equation of transport in this zone is given as

\[
\frac{\partial (WC)}{\partial t} + \text{div} (CV) = \text{div} (D \text{ grad } C)
\]

where \(W\) is moisture content, determined from the equation of moisture transfer. The statement of the problem of water and salt transport, numerical methods for their solution and results of calculations are given by Watson and Jones (16,17).

Let us now state the boundary problem for the equation, describing water and salt transport in a porous medium, for which the hydrodynamic problem of free-boundary seepage has been investigated (Fig. 1). The two-dimensional transient equation of convective transport in saturated porous media is

\[
\frac{\partial (WC)}{\partial t} + \text{div} (D(V) \frac{\partial C}{\partial X}) = \text{div} (D(V) \frac{\partial C}{\partial Y})
\]

\[
- V_X \frac{\partial C}{\partial X} - V_Y \frac{\partial C}{\partial Y}
\]

(20)
The coefficient of hydrodynamic dispersion $D(V)$ depends on the seepage velocity and certain parameters of porous media (5) and is given as

$$D(V) = D_m + \beta |V|^{\alpha} \quad 1 \leq \alpha \leq 2 \quad (21)$$

where $D_m$ is the coefficient of molecular diffusion; $\beta$ is the coefficient that is a function of the structure of the porous media, and $\alpha$ is an exponent, usually $1 \leq \alpha \leq 2$ (18).

The initial condition for Eq. (20) is

$$C(X,Y,0) = C_0(X,Y) \quad (22)$$

The boundary conditions are

a) Flow by dispersion does not exist across the boundary zones, and the boundary is impermeable for water and salts.

$$D \frac{\partial C}{\partial N} = 0 \quad (23)$$

where $N$ is the normal to the boundary.

b) Salt concentration on the boundary between the water body and the porous medium is equal to its concentration in the water body:

$$C = C_f \quad (24)$$

c) The following condition can be assigned for the zone where the solute flows out of the porous media into the surface water body:

$$C = C_B, \quad D \frac{\partial C}{\partial N} = 0 \quad (25)$$

On the free surface,

$$D \frac{\partial C}{\partial N} = E_N(C - C_{Inf}) \quad (26)$$

where $E_N = E/\sqrt{1 + (dV/dx)^2}$ is the value of infiltration per unit length of free surface; and $C_{Inf}$ is the concentration of dissolved solids in infiltrating water.

When infiltration does not take place ($E = 0$) and $\partial C/\partial N = 0$. This means that dissolved solids move together with the free surface.

The problem, stated by Eqs. (5), (7), and (20) was solved numerically with the help of the computer. These equations were solved successively. Once the position of the free surface is known the hydraulic head value is found from Eq. (5). Changes in the concentration are determined from Eq. (20), taking into account seepage velocity [Eq. (6)]. Then the new position of the free boundary at the subsequent moment of time was determined from Eq. (19), etc.

Approximate forms of Eqs. (5) and (20) were developed with finite difference techniques and solved by the alternating direction implicit (ADI) method; Eq. (5) on the basis of a longitudinal transverse run scheme; and Eq. (20) on the basis of totally implicit splitting scheme (19,20).

The following standard dimensionless variables were used in the solution of the problem:

$$h = \frac{H}{B_S}, \quad x = \frac{X}{B_S}, \quad y = \frac{Y}{B_S}, \quad \varphi = \frac{\phi}{B_S}$$

$$l = \frac{L}{B_S}, \quad \beta = \frac{\beta}{B_S}, \quad \beta_n = \frac{\beta_n}{B_S}, \quad r = \frac{R}{B_S} \quad (27)$$

$$\tau = \frac{t}{\tau}, \quad \nu_x = \frac{\nu X}{K_m}, \quad \nu_y = \frac{\nu Y}{K_m}, \quad d(V) = \frac{d(V)}{B_S K_m}$$

Here $B_S$ is the distance between the permeable layer and the earth's surface; the coefficients of infiltration and seepage are related to the maximum $K_m$ value of the coefficient of permeability in the domain. Various problems representing certain physical processes were investigated.

Figure 1 presents a case of a horizontal drainage canal, parallel to the irrigational canal, with water levels being different in both the canals. Free-surface seepage and pollutant transport occur through the soil layer, separating the two canals. The soil layer is represented by the two-dashed lines.

The plots in case 1 of Figure 1 present the results of calculating free-surface position, hydraulic head values at $\tau = 0.5$ (head iso-lines), and values of dissolved solids content (concentration isolines) at $\tau = 0.5$ and $\tau = 2.5$ ($\tau$ is time, dimensionless). The values for porosity and permeability coefficient in the upper, middle, and lower layers are

$$m_u = 0.5 \quad K_u = 1.0$$

$$m_m = 0.25 \quad K_m = 0.1 \quad (28)$$

$$m_l = 0.25 \quad K_l = 1.0$$

The initial position of the free surface is $\phi_o = 1$, the coefficient of hydrodynamic dispersion is $D = 0.001 + [V]$ and the initial concentration of the pore solution is $C_o = 0$. When $\tau > 0$, the solution concentration in the irrigational canal is $C_r = 1.0$.

Case 2 of Figure 1 shows that liquid flow moves from the source of contamination (the zone of high pressure, $P_h = 0.4$) to the open channel. The source of pollution is in the permeable layer ($K_m = 1.0$), located between the two impermeable ones ($K_1 = K_u = 0.1$); $\phi_o = 0.8$; $D = 0.001; C_o = 0$; and, $C_r = 1.0$.

The above examples illustrate the significant role of porous media characteristics on the transport dynamics of water and solutes. That is why the assumption that physico-chemical parameters such as permeability having constant values at all positions are not always justified. However, the value of these models is that a large number of hydrogeological settings can be examined very quickly. This makes it possible to determine exposure concentrations of toxic chemicals in drinking waters derived from groundwater for many combinations of system parameters. These models make it possible to examine the impact on groundwater quality of agricultural practices and waste management activities by taking into account the interaction of hydrogeological
characteristics of the subsurface and the chemical properties of the pollutant.

Environmental pollution and the deterioration of sanitary conditions of surface and groundwater decrease drinking water quality, which becomes unsatisfactory in some of the regions. According to Soviet Water Legislation, groundwater as a source of drinking water is given first priority. However, groundwater quality, as mentioned above, is deteriorating. This is caused by increased anthropogenic loading, manifesting itself in the inflow of polluted waters into groundwater aquifers. Other activities that cause adverse effects on groundwater quality are pumping of toxic effluents into the subsurface (deep-well injection), the burial of toxic wastes in unsaturated zones, etc.

The influence of the human factor on spreading of noninfectious diseases among the population is determined by this type of pollution. These diseases are numerous and include practically all types of ailments. They include chronic cardiovascular and nervous system diseases, diseases of the digestive and blood-forming organs, disturbance in fetal development, genetic afflictions, allergies and cancer. Bacterial pollution, caused by violation of water disinfection technology, results in outbreaks of infectious gastric and intestinal diseases such as diarrhea, paratyphoid diseases, viral hepatitis, typhoid fever, dysentery, salmonellosis, and other waterborne diseases.

Most frequently, waterborne diseases occur in regions of intensive agricultural development, particularly in Soviet Central Asia. Sanitary conditions of the region cannot but affect human health, with the main problem being gastric and intestinal infectious diseases. For example, morbidity from typhoid fever in Central Asia is higher than anywhere else in the USSR. Blood diseases and disturbance in both fetal development and childbirth possibly caused by herbicides or pesticides migrating into groundwater resources used for drinking water are widespread in this region.

Thus, the present situation necessitates paying greater attention to environmental protection. Between 1986 and 1990 (the 12th five-year period) 15 billion ru-
bles have been allocated by the State for environmental protection, whereas between 1976 and 1985 (the 10th and 11th five-year periods) only 22 billion rubles were allocated for environmental protection projects.

REFERENCES
1. Deviatkin, E. L. Some aspects of groundwater pollution by livestock effluents in foothill valleys [in Russian]. In: Groundwater Resources and Their Protection from Exhaustion and Pollution, Tashkent, 1986, pp. 78–82.
2. Faibishenko, B. A. Water and Salinity Regime of Soils in Irrigation [in Russian]. Moscow, 1986.
3. Kozlovskiy, E. A. (Ed.) Hydrogeological Base of Groundwater Protection [in Russian]. Moscow, 1984.
4. Kats, D. M. Influence of Irrigation on Groundwater [in Russian]. Moscow, 1976.
5. Bear, J., Zaslavsky, D., and Irmay, S. Physical Principles of Water Percolation and Seepage. UNESCO, Paris, 1968.
6. Polubarinova-Kochina, P. Ya. Theory of Groundwater Movement [in Russian]. Moscow, 1977.
7. Khublarian, M. G., Churmaev, O. N., and Yushmanov, I. O. Numerical solution of a hydrodynamic problem of seepage and convective diffusion [in Russian]. Water Resour. (Vodnye Resursy) 4(1): 133–143 (1979).
8. Khublarian, M. G. Analysis of hydrodynamic problems of seepage and substance transport [in Russian]. In: Methods of Analysis and Procession Hydrogeological Data for Groundwater Resources Forecasting. Tallin, 1984, pp. 56–64.
9. Pikul, H. F., Street, R. U., and Remson, I. A numerical model based on coupled one-dimensional Richards and Boussinesq equations. Water Resour. Res. 10(2): 295–302 (1974).
10. Nielsen, D. R., van Genuchten, M. Th., and Biggar, J. W. Water flow and solute transport processes in the unsaturated zone. Water Resour. Res. 22(9): 89–108 (1986).
11. Todsen, M. Numerical solution of two-dimensional saturated/unsaturated drainage models. J. Hydrol. 30(4): 311–326 (1973).
12. Freeze, A. Three-dimensional transient saturated-unsaturated flow in a groundwater basin. Water Resour. Res. 7(2): 347–366 (1971).
13. Davidson, M. R. Numerical calculation of saturated-unsaturated infiltration in a cracked soil. Water Resour. Res. 21(5): 709–714 (1985).
14. Khublarian, M. G., Putyrskiy, V. E., and Frolov, A. P. Modelling of interrelated water flows in the system “unsaturated-saturated soil river” [in Russian]. In: Proceedings of the International Symposium on Groundwater Monitoring and Management, March, 23–28, 1986, Dresden, GDR, 1986, pp. 1–13.
15. Khublarian, M. G., Putyrskiy, V. E., and Frolov, A. P. Mathematical modeling of surface and groundwater interaction [in Russian]. Water Resour. (Vodnye Resursy) 4: 31–40 (1987).
16. Watson, K. K., and Jones, M. J. Hydrodynamic dispersion during absorption in a fine sand. 1. The constant concentration case. Water Resour. Res. 18(1): 91–100 (1982).
17. Watson, K. K., and Jones, M. J. Hydrodynamic dispersion during absorption in a fine sand. 2. The constant flux case. Water Resour. Res. 18(5): 1433–1443 (1982).
18. Guvanasen, V., and Volker, R. R. Simulating mass transport in unconfined aquifers. Proceedings of the American Society for Civil Engineers, J. Hydraulics Div. 107(4): 461–477 (1981).
19. Khublarian, M. G., Churmaev, O. M., and Yushmanov, I. O. Analysis of a hydrodynamic problem of seepage and convective diffusion in non-uniform and anisotropic porous media [in Russian]. Water Resour. (Vodnye Resursy) 3: 23–29 (1984).
20. Khublarian, M. G., and Yushmanov, I. O. Groundwater quality appraisal. In: Hydrogeology in the Service of Man. Memoires of the 18th Congress of the International Association of Hydrogeologists, Part 3. Cambridge, 1986, pp. 119–126.