Computer simulations for assessing the salt regime in irrigated ecosystems in the south of the Aral Sea

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Annotation
The paper considers a computer modelhydrological cycle for predicting the salt regime of soils on a regional scale. A system of interrelated models is proposed that describes the movement of salts along the irrigation network and in zones of incomplete and complete saturation of soils.

Keywords:leaching and vegetation irrigation, irrigation networks, turbulent diffusion, Shezzy coefficient, salt migration.

The problem of salt movement in rivers and irrigation canals
The quality of water in irrigation networks is determined by the concentration of substances contained in it and significantly affects the efficiency of operational flushing and vegetation irrigation. Taking into account all factors in the mathematical description of the problem of water quality in rivers and canals is a great difficulty, not only because of the complexes of hydrodynamic, physicochemical, etc. processes, but also in terms of the complexity of their numerical implementation on a computer.
In this paper, to simplify the description of the distribution of water quality characteristics along the irrigation network, a one-dimensional equation of turbulent diffusion is considered, taking into account the entry of salts (or their release) through the bottom of the canal and other sources.
Mathematical statement. The problem of the movement of salts in rivers and irrigation canals. The turbulent diffusion equation has the following form [2,4]

$$\frac{\partial (ws_1)}{\partial t} = \frac{\partial}{\partial s}\left(\mathrm{E}w\frac{\partial s_1}{\partial s}\right) - \frac{\partial (Qs_1)}{\partial s} + F \qquad (1)$$

where t -time (sec); s - distance along the channel (m); s_1 - mineralization of water in rivers and canals (g / l) , w - cross-sectional area (m ^{2}); E - coefficient of longitudinal dispersion (m ^{2} / sec); Q - flow through the cross section (m ^{3} / sec), F distributed lateral influx of salts (m ^{2} / sec g / l).
The solution of this partial differential equation under the following boundary and initial conditions represents the temporal and spatial distribution of concentration along the direction of water flow

$$\beta_1 s_1 + (1-\beta_1)(Qs_1 - \mathrm{E}w\frac{\partial s_1}{\partial s}) = \phi_5(t) \quad \text{at } s = 0,\ 0 \le t \le t_1 \qquad (2)$$

$$\beta_2 s_1 + (1-\beta_2)(Qs_1 - \mathrm{E}w\frac{\partial s_1}{\partial s}) = \phi_6(t) \quad \text{at } s = l,\ 0 \le t \le t_1 \qquad (3)$$

$$s_1 = s_{10}(s)\ ,\ t = 0,\ 0 \le s \le l \qquad (4)$$

Here ϕ_5, ϕ_6 - well- known functions, $s_{10}(s)$ the initial value of the distribution of salt concentration along the channel downstream, β_1, β_2 -coefficients take values of0 or 1.

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Boundary conditions (2), (3) are taken in the most general form. At $\beta_1 = 1$, we have conditions of the 1st kind at the inlet section of the channels.

$$s_1 = \phi_{51}(t)\ ,\ s = 0,\ 0 \le t \le t_1 \tag{5}$$

This means that in the inlet sections of the river network, where salts enter together with water, salt concentrations are set as a function of time.

At $\beta_1 = 0$, we obtain the salt flow at the inlet sections of the channels as a function of time

$$Qs_1 - \mathrm{E}w\frac{\partial s_1}{\partial s} = \phi_5(t)\ ,\quad \mathrm{s} = 0\ ,\ 0 \le t \le t_1 \tag{6}$$

In a similar way, one can obtain boundary conditions at the outlet sections of the channels.

The situation is somewhat more complicated with the exit points, especially if the salt concentration varies greatly. A more natural condition can be obtained from the assumption that in the outlet section, located at a sufficiently large distance from the place of salt inflow, the role of longitudinal dispersion becomes negligibly small and the salt concentration at this boundary is determined mainly by convective transport. Then the boundary condition following from the made assumption in the outlet section will have the form[4]

$$w\frac{\partial s_1}{\partial t} + Q\frac{\partial s_1}{\partial s} = F\ ,\ s = l\ ,0 \le t \le t_1 \tag{7}$$

The river network can be represented as a tree graph. The boundary conditions at the free vertices of the graph were considered above. And in the internal nodes (where mergers or branches occur) of the graph, it is necessary to add conjugation conditions that reflect the equality of flows and distribution of salts

$$\sum_{i=1}^{N_k}\left(Qs_1 - \mathrm{E}w\frac{\partial s_1}{\partial s}\right)_i^k = 0\ ,\ \ s_{11}^k = s_{12}^k = ... = s_{1N_k}^k\ ,\ 0 \le t \le t_1 \tag{8}$$

where N_k is the number of edges included in the k -th node. In those places where there is a concentrated inflow (or discharge of pollution), the boundary conditions are formed in a similar way. If there are hydraulic structures at the nodal points of the river network, then the interface conditions will look like this

$$\sum_{i=1}^{N_k}\left(Qs_1 - \mathrm{E}w\frac{\partial s_1}{\partial s}\right)_i \delta_i = 0\ ,\ \ s_{11}^k = s_{12}^k = ... = s_{1N_k}^k\ ,\ 0 \le t \le t_1 \tag{9}$$

Here Q , is the water consumption in the i -th channel corresponding to the water consumption plan, is the δ_i Dirac function.

To complete the task, it is necessary to determine the quantities F, E . With the help F docking with tasks from other layers can occur. It takes into account the exchange of salt flow due to precipitation, which is defined as follows:

$$F = F_1^1 + F_2^1 \tag{10}$$

Here F_1^1 - characterizes the exchange of salt flow between the river and groundwater; F_2^1 - intake of salts with atmospheric precipitation.

To determine the value, we F_1^1 use the expression

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$$F_1^1 = \begin{cases} d_1 s_3 & npu\ d_1 > 0 \\ d_1 s_1 & npu\ d_1 \le 0 \end{cases} \tag{11}$$

where s_3 is the mineralization of groundwater (g/l). The values d_1 are determined from the problem of planned filtration [6]. Here, the value F_2^1 was not taken into account, since precipitation is negligible $(F_2^1 = 0)$ in this area.

A detailed study of the coefficient of longitudinal dispersion: is very difficult. Therefore, to solve practical problems, given that the transverse dimensions of watercourses are much smaller than the longitudinal ones, we assume that the coefficient E is constant over the free section.

In works [2,4], some empirical formulas for determining the coefficient E obtained for various cases are given. The longitudinal dispersion coefficient was calculated as follows

$$\mathrm{E} = 20,2\sqrt{g}V_k \frac{R}{C_0} \tag{12}$$

where V_k is the average flow velocity, m/s; C_0 - Shezzy coefficient, $м^{\frac{1}{2}} / сек$.

Thus, by setting the boundary conditions in the inlet and outlet sections, internal nodes, as well as the initial conditions throughout the entire section of the river network, it is possible to determine the distribution of salt concentration in the water of river systems in the simulated period.

Equations (1) were approximated using an implicit scheme.

$$\frac{w_{ij+1} + w_{ij}}{2} \cdot \frac{s_{1ij+1} - s_{1ij}}{\triangle t} = E_{i+\frac{1}{2}j+1} \frac{s_{1i+1j+1} - s_{1ij+1}}{\triangle s^2} - \\ -E_{i-\frac{1}{2}j+1} \frac{s_{1ij+1} - s_{1i-1j+1}}{\triangle s^2} - \left[Q_{i+\frac{1}{2}j+1} \frac{s_{1i+1j+1} - s_{1ij+1}}{\triangle s} \alpha 1 + \right. \\ \left. + Q_{i-\frac{1}{2}j+1} \frac{s_{1ij+1} - s_{1i-1j+1}}{\triangle s} (1 - \alpha 1) \right] + F_{ij+1} \tag{13}$$

Here $\alpha 1$, the parameter of the finite difference scheme $(0 \le \alpha 1 \le 1)$

Difference equations (13) together with boundary conditions and conjugation conditions (2)-(9) form a closed system with respect to unknowns s_{1ij+1}. Further, the closed system was solved by the sweep method.

The problem of the movement of salts in groundwater. Here we consider the dynamics of mass transfer processes in non-pressure filtration flows with the influx of dissolved substances during infiltration feeding. As a rule , the process of migration of substances dissolved in water during filtration of non-pressure waters can be described by the following equation [1,3,4,5,7]

$$\mu H \frac{\partial s_3}{\partial t} = \frac{\partial}{\partial x}\left(H D_x \frac{\partial s_3}{\partial x} \right) + \frac{\partial}{\partial y}\left(H D_y \frac{\partial s_3}{\partial y} \right) - V_x \frac{\partial s_3}{\partial x} - V_y \frac{\partial s_3}{\partial y} + J \tag{14}$$

where t - time (day); x, y - coordinates in the horizontal direction (m) ; s_3 - mineralization of ground waters (g/l); V_x, V_y, D_x, D_y - filtration rate and coefficients of convective diffusion along the axes x and(y m/ day and m2 / day); H - elevation of the groundwater surface relative to the comparison plane (m); μ - coefficient of undersaturation; J - intensity of the volume of salts (m/ day g/l).

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Equation (13) represents the migration of salts in the hydraulic theory of geochemical processes. The values V_x, V_y, H are determined from the problem of planned filtration [6].

Here, the problem of groundwater mineralization is considered on a regional scale. Therefore, when studying the process of mass transfer, we assume that the diffusion terms $\frac{\partial}{\partial x} D_x \frac{\partial s_3}{\partial x}, \frac{\partial}{\partial y} D_y \frac{\partial s_3}{\partial y}$ much less than the convective flow of salts i.e.

$$\frac{\partial}{\partial x} D_x \frac{\partial s_3}{\partial x} \ll V_x \frac{\partial s_3}{\partial x}, \quad \frac{\partial}{\partial y} D_y \frac{\partial s_3}{\partial y} \ll V_y \frac{\partial s_3}{\partial y}$$

This assumption is well justified at large Peclo values [7,8], which are determined by the equality $pe = \frac{Vl_\phi}{D}$ (V - filtration rate, l_ϕ - characteristic length of the filtration path).

In this case, equation (13) will be described as

$$\mu \frac{\partial s_3}{\partial t} = -V_x \frac{\partial s_3}{\partial x} - V_y \frac{\partial s_3}{\partial y} + F_3 \quad (15)$$

For a unique solution of equation (14), we add to it the initial and boundary conditions.

$$s_3 = s_{30}(x, y),\ t = 0,\ (x, y) \in G \quad (16)$$

$$\beta_3 s_3 + (1-\beta_5) V s_3 = \phi_9(x, y, t), \quad 0 \le t \le t_1,\ (x, y) \in \Gamma \quad (17)$$

Here $\phi_9(x, y, t)$ are known functions, $s_{30}(x, y)$ is the initial distribution of groundwater salinity, β_5 is a coefficient that takes the values 0 or 1.

Note that from condition (16), varying the parameters β_5 (0 ,1), we obtain different boundary conditions at the boundaries of the filtration region Γ.

At $\beta_5 = 1$, the salt concentration is given at the boundary as a known function in time

$$s_3(x, y, t) = \phi_{91}(x, y, t), \quad 0 \le t \le t_1,\ (x, y) \in \Gamma \quad (18)$$

where ϕ_{91} specifies the change in groundwater salinity during the considered time interval.

When $\beta_5 = 0$ at the boundary of the filtration area, the convective salt flow is set

$$V s_3 = \phi_{92}(x, y, t), \quad 0 \le t \le t_1,\ (x, y) \in \Gamma \quad (19)$$

Boundary conditions (1 8) can be used at the boundary with a liquid continuous medium (sea, lake, river, etc.), where there is a given distribution of salt concentration.

If the boundary passes through a river or irrigation networks, then in condition (18) the value $\phi_{91}(x, y, t)$ is expressed in the following form

$$\phi_{91}(x, y, t) = \begin{cases} \gamma_1 d_1^r s_1 & npu\ \ d_1^r \le 0 \\ \gamma_1 d_1^r s_3 & npu\ \ d_1^r > 0 \end{cases}$$

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Here γ_1 , is the dimension matching factor.

At the watershed boundary, the boundary conditions can be given as

$$\frac{\partial s_3}{\partial \vec{n}} = 0 \tag{20}$$

This reflects the fact that the speeds of movement of groundwater and salts in this section are the same, and therefore the concentration gradient is equal to zero.

To close the problem of salt transfer in groundwater, it is necessary to define a function F_3 which consists of the following terms

$$F_3 = \frac{(F_3^I + F_3^{II} + F_3^{III} + F_3^{IV})}{H} \tag{21}$$

where F_3^I is the change in the concentration of salts as a result of the dissolution of their solid phase, F_3^{II} is the exchange of salt flow between the zone of incomplete and complete saturation; F_3^{III} - inflow of salt flow from irrigation canals (or outflow of salt flow); F_3^{IV} - selection of salts by vertical drainage.

In this area, the toxic component of salts is chlorine, which, as a rule, completely dissolves. Therefore, sorption processes can be neglected $F_3^I = 0$ when predicting changes in groundwater salinity, which is characterized by chloride salinization.

To calculate the value F_3^{II} , the following dependence is used [5,8,9]

$$F_3^{II} = (\theta_5 s_3 - \theta s_n^I)\frac{\partial H}{\partial t} + k\left(\frac{\partial \psi}{\partial Z} - 1\right)s_2 + \theta D\frac{\partial s_2}{\partial Z} \tag{22}$$

where

$$s_n^I = \begin{cases} s_2 \quad npu \quad \dfrac{\partial H}{\partial t} > 0 \\ s_3 \quad npu \quad \dfrac{\partial H}{\partial t} < 0 \end{cases}$$

From equation (21), at , $s_2 = s_3 = const$ we obtain dependence (20),

The quantities F_3^{III} and F_3^{IV} are calculated as follows

$$F_3^{III} = \begin{cases} \varepsilon_{KH} s_1 \quad npu \quad \varepsilon_{KH} > 0 \\ \varepsilon_{KH} s_3 \quad npu \quad \varepsilon_{KH} < 0 \end{cases} \tag{23}$$

$$F_3^{IV} = \varepsilon_{ck} \cdot s_3$$

The solution of the above migration equations (14) under the initial and boundary conditions (15) - (19) makes it possible to obtain a picture of changes in the salt concentration in groundwater. Thus, to establish at what distance and during what time the mineralized waters can move in the aquifer.

For the numerical solution of equation (15), the splitting method was used. As a result, the original equation is

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split into two equations in terms of spatial variables

$$\mu \frac{\partial \xi}{\partial t} = -V_x \frac{\partial \xi}{\partial x} + \frac{1}{2} F_3, \xi^l = s_3^l, t_l \le t \le t_{l+1} \quad (24)$$

$$\mu \frac{\partial \eta}{\partial t} = -V_y \frac{\partial \eta}{\partial y} + \frac{1}{2} F_3, \eta^l = \xi^{l+1}, t_l \le t \le t_{l+1} \quad (25)$$

We notice that

$$s_3(x, y, t) = \eta(x, y, t_{l+1}) \quad (26)$$

The solution of equation (24) is used as the initial condition for solving equation (25).

In this case, using the implicit scheme of finite-difference approximation, we rewrite equations (24), (25) on a uniform grid.

To solve the systems of equations (24), (25), the running calculation method was used.

Results of numerical calculations and their discussion. The initial data (initial conditions and design parameters) of the problem were taken from the study of the Aral Hydrogeological Expedition, the Karakalpak Scientific Research Institute of Agriculture (KKNIIZ), the Karakalpak branch of SANIIRI, as well as the Karakalpak hydrogeological reclamation expedition.

The results of predictive calculations on the water-salt regime of soils and grounds on a part of the Kyzketken irrigation system, with an area of 672 sq. km, were obtained . The study area is irrigated by the Kyzketken canal system, which takes water from the Amudarya River. Kyzketken is divided into branches: Kuvanyshdzharma and Kegeyli.

The irrigation system is characterized by the following parameters: total number of sites in the river network SN =4; step along the axis S , □S =2000 m; section length.

The initial distributions of discharges and their salinity along the length of the Amudarya river , the channels Kyzketken, Kuvanyshdzharma , Kegeyli are taken constant $Q = 2100$ m/sec; $s_1 = 0,9 г/л$; Q \u003d 170 m ^{3}/ s; s_1 =0.9 g/l; Q \u003d 90m ^{3}/ sec; $s_1 = 0,9 г/л$ Q \u003d 80 m ^{3}/ s; $s_1 = 0,9 г/л$ respectively for each.

For the coefficients of molecular diffusion D_m and hydrodynamic dispersion λ , the values are taken constant $(\mathrm{D}_m = 10^{-4}\ \text{м}^2/\text{сут},\ \lambda = 0,5 м)$.

The main parameters included in the model of the channel flow and their salinity are the channel width (B) and the channel bottom elevation (Z_g). Their values were set in the initial and final sections equal to B = 880, 770 m; Z_g = 71, 64 m. for the Amudarya river ; B = 90, 80 m; Z_g =71.68 m for Kyzketken; B =45.45 m ; Z_g \u003d 68, 64 m for the Kuvanyshdzharma canal ; B = 35, 35 m; Z_g = 68, 64 m. for the Kegeyli channel . At the remaining grid nodes along the channel, they are transferred by interpolation. The value of the Manning roughness coefficient is taken equal to n_0 = 0.03; bottom slope l = 0.0002; vertical filtration coefficient k_B = 0.24 m/ day. The initial conditions were water discharges and levels, as well as their mineralization in each section, the boundary conditions in the upper section-hydrograph and their changes in mineralization, in the lower section, the slope of the water surface and the mineralization gradient of the channel flow, equal to zero.

The initial mineralization value $s_3(x, y)$ is presented in the form of an isoline map (see Fig. 1.). All these data

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will be transferred for each node of the computational grid in the plan by interpolation.

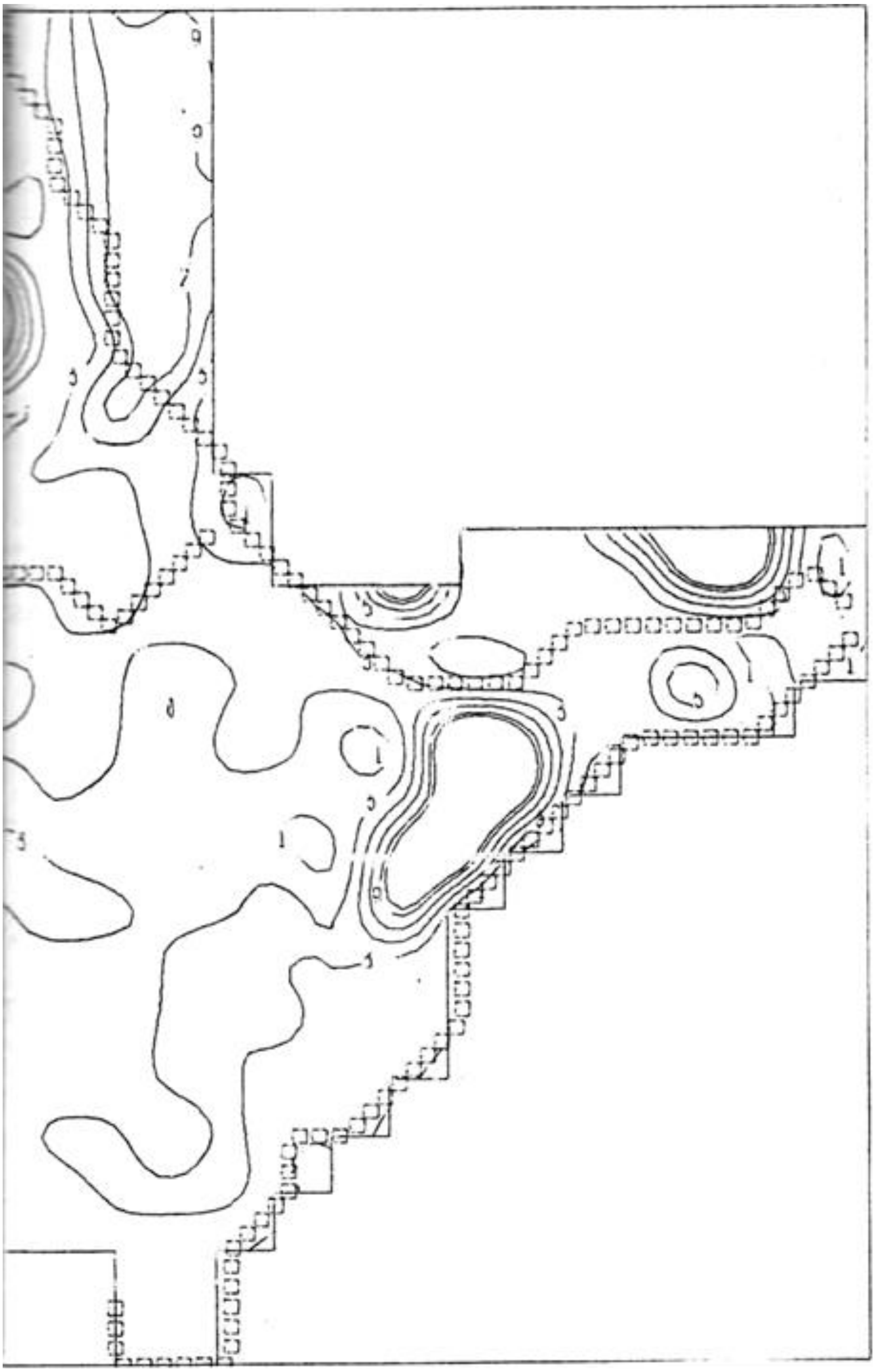

Fig. 1. Map of the isoline of groundwater mineralization at $t = 0$

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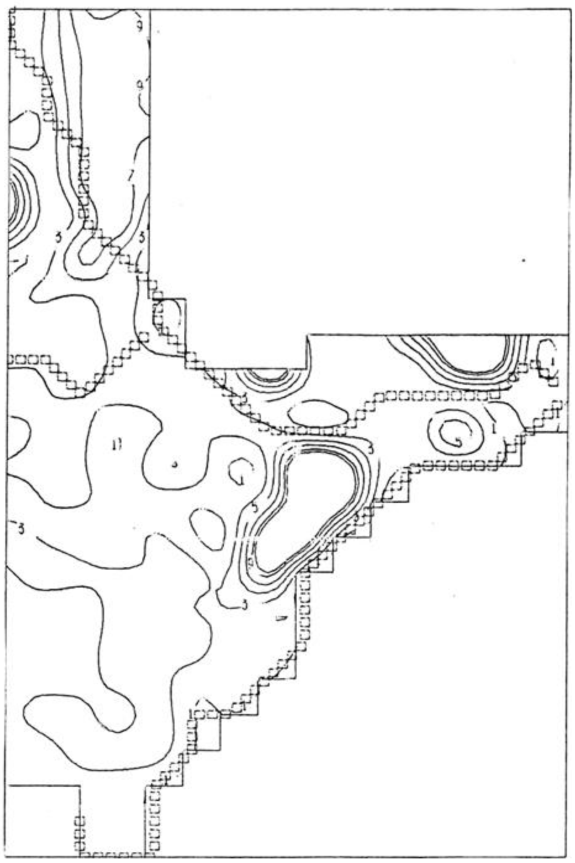
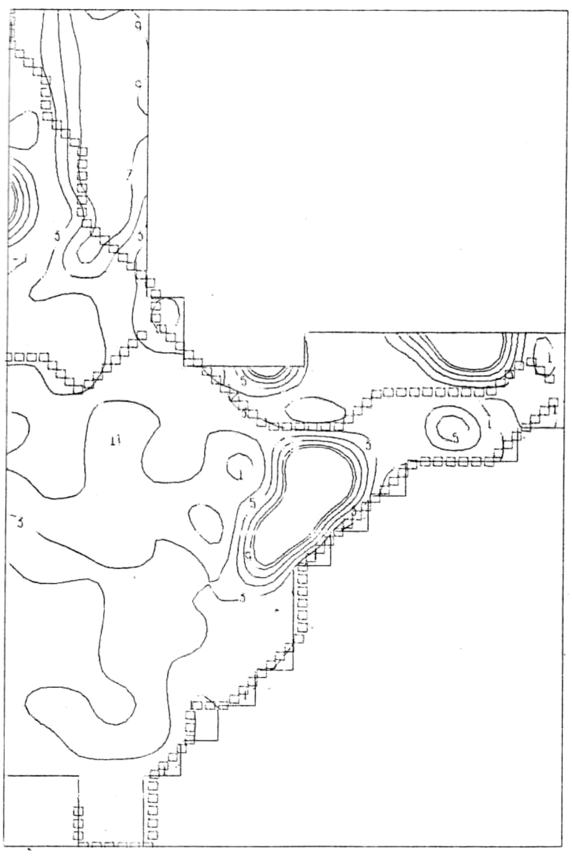


Rice. 4.2.24. Map of the isoline of groundwater mineralization **(60th** day of the process).



Rice. 4.2.25. Groundwater Mineralization Contour Map (80th day of the process).

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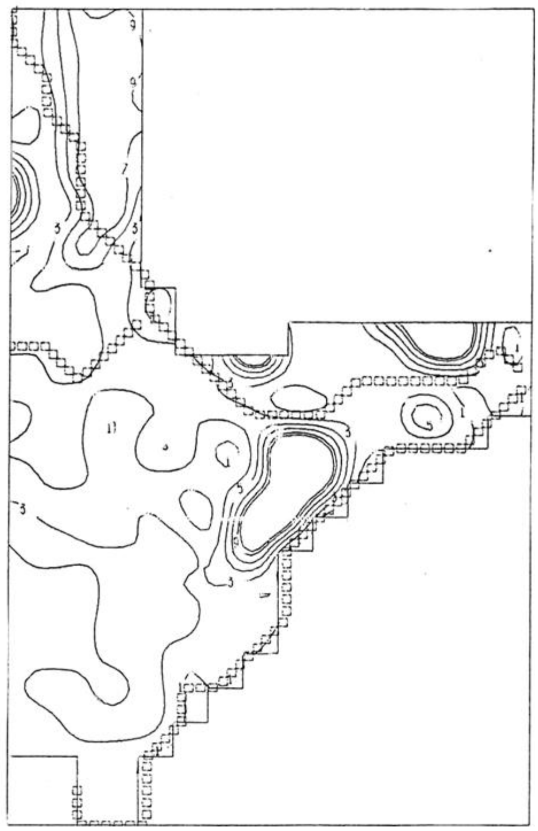
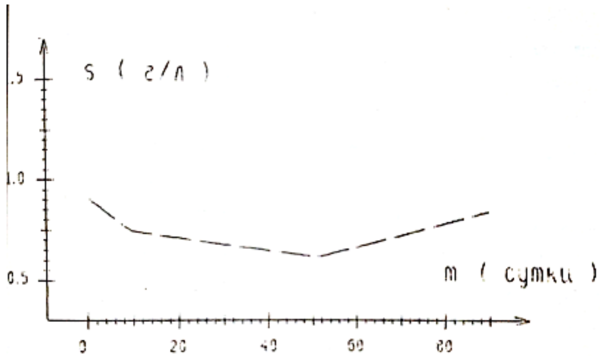


Rice. 4.2.26. Groundwater Mineralization Contour Map

(90th day of the process).



Rice. 4.2.27. Changes in the mineralization of the Amudarya river

As can be seen from the results, there is a change in the mineralization of groundwater in the area between the Amudarya River and the Kegeyli canals. According to its lithological composition, this site belongs to the channel deposits, characterized by a high filtration coefficient. Therefore, here the supply of groundwater depends not only on the irrigation regime, but also on filtration from the Amudarya River, which contributes to the transfer of salts from solonchaks. With a decrease in the flow of the Amudarya river, the transfer of salts decreases accordingly. In the area between the Kegeyli and Kuvanyshdzharma canals, during the growing season, there was no significant change in the mineralization of groundwater. The supply of groundwater from the main canals of Kegeyli and Kuvanyshdzharma is insignificant, because According to its lithological composition, this area belongs to lacustrine deposits characterized by a low filtration coefficient.
Carry out reclamation measures in the area between the Amu Darya River and the Kegeyli canals to intercept the salts carried from the solonchaks. This will prevent the accumulation of salt content in the groundwater of the underlying irrigated massifs.
Thus, a mathematical tool has been developed, consisting of a complex of models. It can be used to simulate various options for reclamation measures aimed at improving the state of irrigated lands.

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