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Decision-Making Models for In-Situ Leaching Process Control

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Topicality of the research. Technological processes of in-situ leaching by their structure are complex technical multi-coupled systems covering several subsystems (formation-well - pumping stations - reagent concentrations, etc.). All these subsystems are interconnected, and the violation of the technological mode of at least one of the subsystems leads to a shutdown of the entire cycle of operation of the system as a whole. Therefore, at present much attention is paid to progressive methods of development of multicomponent systems, one of which is the in-situ leaching (ISL) method. The ISL method is the most economical and environmentally friendly method compared to other methods, and its use does not result in environmental disturbance. the ISL method is also widely used in the uranium mining industry, which is of extreme economic importance. The demand for energy, of which uranium is the main source, is growing steadily. This reflection reflects the importance of scientific research into the use of efficient methods, particularly the in-situ leaching process, in the production of valuable metals. The dissolution of a useful component in the earth and the subsequent movement of the resulting compounds takes place mainly in accordance with the laws of hydrodynamics, mass transfer and chemical kinetics. Complexity of the process occurring in real underground conditions necessitates development of mathematical models and software to study the whole cycle of the IS process in real conditions and to make decisions in accordance with the management objective. The main purpose of creating a model is to characterise and predict some objects and technological processes. Models based on mathematical interpretation of the problem help in finding necessary information for decision making with the help of certain algorithms. Thus, the development of models for solving analysis and decision making problems in the management of in-situ leaching technological processes in ore mining, as well as the creation of appropriate computational algorithms and software are relevant today.

The purpose of this study is to develop models, methods and software tools for decision-making and analysis in the process control of the drinking water supply process. To achieve this goal, the following tasks should be carried out: system analysis of IS process; data processing using approximate and analytical solutions for forecasting required parameters and checking the reliability of the developed process control model; creating efficient algorithms and software for calculating the main geotechnological indicators of IS process, determining influencing factors on field development management process; determining suitability of mathematical model, algorithm and software tools

The object of the study is ore deposits exploited by the PV method using an acidic solution. The subject of the study is filtration and diffusion actions at PV.

Methods: Fourier, Laplace and Bubnov-Galerkin transform methods as well as finite-difference approximation methods and computational experiment were used to solve the filtration-convection diffusion of the SP process.

Results. Two-dimensional mathematical models of control for decision-making in the process control of the drinking water supply process, taking into account its features, have been developed. Computational algorithms of one- and two-dimensional mathematical models for decision-making in the PV process control tasks have been developed. On the basis of real object data, the adequacy of the developed mathematical models describing the ПВ technological process has been tested. The dynamics of changes in concentration and corresponding different values of parameters affecting the course of the PV technological process has been investigated.

Conclusions. Software tools have been developed for conducting computational experiment and calculation of decision-making parameters in SP process control and visualisation of calculation results.

Keywords: in-situ leaching, useful component, borehole, concentration, optimisation criteria, controls.

The technological processes of in-situ leaching by their structure are complex technical multi- coupled systems, covering several subsystems (formation-well - pumping stations - reagent concentrations, etc.). All these subsystems are interconnected, and the violation of the technological mode of at least one of the subsystems leads to a shutdown of the entire cycle of operation of the system as a whole. Therefore at present much attention is paid to progressive methods of development of multicomponent systems, one of which is the in-situ leaching (ISL) method. The ISL method is the most economical and harmless compared to other methods, and its use does not result in environmental disturbance.

The complexity of the process occurring in real underground conditions necessitates the development of mathematical models and software to study the whole cycle of the process of the HT process in real conditions and to make decisions in accordance with the management objective. The main purpose of creating a model is to characterise and predict some objects and technological processes. Models based on mathematical interpretation of the problem help in finding necessary information for decision making with the help of certain algorithms. Thus, the development of models for solving analysis and decision making problems in the management of in-situ leaching technological processes in ore mining, as well as the creation of appropriate computational algorithms and software are relevant today.

The dissolution of a useful component in the subsurface and the subsequent movement of the resulting compounds take place mainly in accordance with the laws of hydrodynamics, mass transfer and chemical kinetics. Complexity of the process occurring in real underground conditions necessitates development of mathematical models and software to study the whole cycle of the IS process in real conditions and make decisions in accordance with the management objective. The main purpose of creating a model is to characterise and predict some objects and technological processes [1]. Models based on mathematical interpretation of the problem help to find necessary information for decision making with the help of certain algorithms [2,3]. A mathematical model of control for decision making in process analysis of DW process is proposed in the following equation showing the nature of change in filtration flow:

$$\frac{\partial}{\partial x}\left(\frac{kh}{\mu}\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{kh}{\mu}\frac{\partial H}{\partial y}\right)+\mu\sum_{i=1}^{N}\delta(x-x_i,y-y_i)Q_i(t)=mh\beta\frac{\partial H}{\partial t} \qquad (1)$$

in the area $G=\{(x,y,t)/\ a<x<b,\quad c<y<d,\quad 0<t\le T_k\}$ satisfying the boundary

$(\alpha\frac{\partial H}{\partial n}+(1-\alpha)H)/_{\Gamma}=\varphi(x,y)$ and initial $H(x,y,0)=H_0(x,y)$ conditions.

After solving problem (1) and determining the head *H*, the filtration rate is found according to

$$\text{Darcy's law:}\quad v_x=-k_1\frac{\partial H}{\partial x},\quad v_y=-k_2\frac{\partial H}{\partial y}$$

The convective diffusion equation is considered to determine the concentration of a useful component in the reservoir:

$$\frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial C}{\partial y}\right)-\frac{\partial(v_x C)}{\partial x}-\frac{\partial(v_y C)}{\partial y}-\gamma(C-C_m)=m\frac{\partial C}{\partial t} \qquad (2)$$

$$\frac{\partial N}{\partial t}=\gamma(C)f(C,N,L,\Gamma),\quad N(x,y,0)=N_0(x,y)$$

in the domain G with initial $C(x,y,0)=C_0$ and boundary , as well as

$(\alpha\frac{\partial C}{\partial n}+(1-\alpha)C)\Big|_{\Gamma}=\psi(x,y,t)$ internal conditions. $C(x,y,t)\big|_{(x,y)=(x_i,y_i)}=C_i,\quad \frac{\partial C}{\partial n}\Big|_{(x,y)=(x_j,y_j)}=0$

The main challenge is to ensure expedient action through the management of the PoE process and the selection of parameters to ensure that the following main objectives are met:

- minimizing reagent inflow through the ore-bearing boundaries of the reservoir;
- ensuring uniform hydrodynamic leaching;
- maximizing the concentration values of the useful component;
- optimum well location.

These objectives are realised by minimising the objective function R by selecting the optimisation criterion (U), i.e. by solving the problem

$$R(U) = \int_0^T \sum_{i=1}^{N_t} [C_i(X,U) - C_{ib}(X,U)]^2 dt, \tag{3}$$
$$R^* = \min_{U\in\Omega} R(U), \quad R(U^*) < \varepsilon,$$
$$U_0 < U < U_n, \quad \Omega = \{\gamma, q_o, q_\kappa\}.$$

Here *C (X, U)* - solution of the problem (1)-(2) at the point (x,y) at a given time *t, Cb(X, U)* - required optimum value of useful component,- given accuracy, *U* - vector with components,- acid concentration in injected solution, *q0, qk* - well flow rates, ν- filtration rate, etc. The following control criteria are introduced to solve this problem[4].

It is necessary to select the sum of well rates

$\overline{Q}$ in the given interval so $0 \le Q \le \overline{Q}$

that the resulting values obtained in the solution boundaries $C(x, y,t)$, corresponding to the given conditions, satisfy the set conditions of minimization of the target function *R(U)*.

On this basis, it is possible to control variations in the concentration limit values:

$$R(\overline{Q}) = \int_0^T \sum_{i=1}^{N_t} [\overline{C}_i(SU_i, \overline{Q}, t) - \overline{C}_{ib}(SU_i, \overline{Q}, t)]^2 dt,$$
$$R^* = \min_{(x,y)\in G} R(\overline{Q}), \quad R(\overline{Q}) < \zeta, \tag{4}$$
$$\overline{Q} = \sum_{i=1}^{N_t} q_i, \qquad q_{\min} \le |q_i| \le q_{\max}.$$

Here *SUi are* the locations of the pumping wells.

A model of the problem of selecting the reagent value γ to maximise the concentration value in the pumping wells within a certain time is as follows:

$$R(\gamma) = \int_0^T \sum_{i=1}^{N_t} [C(SU_i, t, \gamma) - C_b(SU_i, t, \gamma)]^2 dt,$$
$$R^* = \min_{\gamma\in\Omega} R(\gamma), \quad R(\gamma) < \varepsilon, \tag{5}$$
$$0 < \gamma < 10.$$

In order to check the consistency of the proposed mathematical model with the natural processes, the results for the hydrodynamic problem of SP using the Bubnov-Galerkin method have been obtained [7,8].

It is assumed that the filtration flow equation is described by the equation

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} = \frac{1}{\chi}\frac{\partial H}{\partial t} + f(x,y,t) \qquad (6)$$

satisfying the initial $H(x,y,t)\big|_{t=0} = H_0(x,y)$ and boundary conditions. $\left.\frac{\partial H(x,y,t)}{\partial n}\right|_{\Gamma} = 0$

Here: $\chi = \frac{k \cdot K}{m \cdot \mu}$, $f(x,y,t) = \frac{\mu}{kh}\sum_{i=1}^{N} q_i(t)\delta(x - x_i, y - y_i)$.

The analytical solution of this hydrodynamic model is described as follows:

$$H = H_0 + \sum_{n=1}\sum_{m=1} Cos\frac{n\pi x}{a} Cos\frac{m\pi y}{b} V_{nm}(t). \qquad (7)$$

In order to obtain the relevant results of this solution, the head value for the values of the approximate objects has been determined [6].

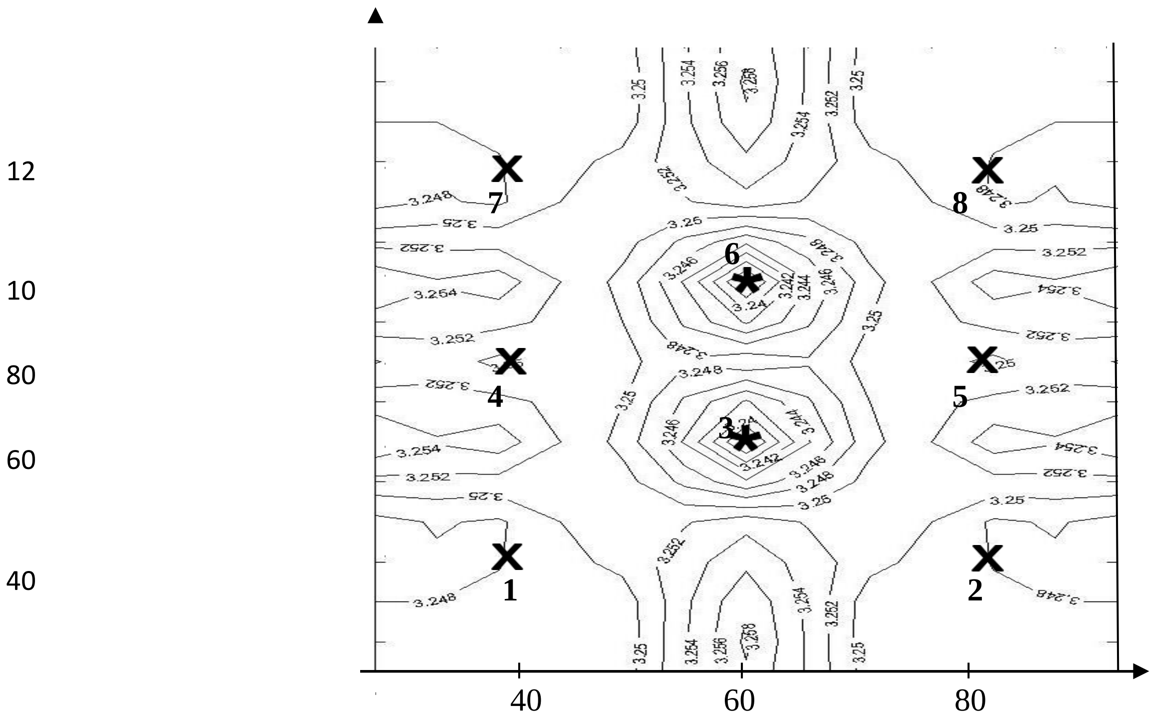
Figure 1 shows the isolines corresponding to the results. The analysis of the results shows that the models proposed for decision making in process control at SP are consistent with the physical properties of the process and can be used in their control process and in data processing.

There is a need to apply numerically approximate methods for solving the problem, as analytical solutions are formed only in particular cases with certain constraints[5]. The validity and stability of the results are checked by a computational experiment based on the method of trial functions.

For the task

$$D\frac{\partial^2 C}{\partial x^2} - U\frac{\partial C}{\partial x} - f(x,t) = m\frac{\partial C}{\partial t}, \quad C\big|_{t=0} = 1, \quad C\big|_{x=0} = 1, \quad C\big|_{x=1} = 1$$

results are obtained by numerical approximation using finite-difference schemes. Taking the function $C = e^{xt(x-1)}$ exact solution, the values of this function obtained in the time interval T=0.4 are compared with the numerical values (Table 1).



X - injection wells, * - pumping wells

Figure 1. Diagram of head isolines based on calculation results

Table 1 Table of approximate and exact solutions

X	results obtained by the finite-difference method	Analytical solution $C = e^{xt(x-1)}$	Error
0,00	1,0000000	1,0000000	0,0000000
0,10	0,9647796	0,9646403	0,0001393
0,20	0,9384463	0,9380050	0,0004413
0,30	0,9201964	0,9194313	0,0007652
0,40	0,9094670	0,9084640	0,0010030
0,50	0,9059281	0,9048374	0,0010907
0,60	0,9094709	0,9084640	0,0010069
0,70	0,9202030	0,9194313	0,0007717
0,80	0,9384530	0,9380050	0,0004480
0,90	0,9647832	0,9646403	0,0001429
1,00	1,0000000	1,0000000	0,0000000

The validity of the proposed mathematical models and computational algorithms is shown to perform a numerical analysis of expedient decision-making in the management of the SP process.
Here we propose computational algorithms corresponding to two-dimensional models for solving problem (1)-(2) of decision making in process control. To reduce two-dimensional models to one-dimensional ones, a finite difference method in a variant of direction variables is applied.
In order to check reliability of developed algorithms and software, compliance of calculation results with specified mechanical and physical properties is given [7]. Figure 2 shows distribution of useful component concentration at different moments of time for the case of single-injection x = 450 мand single-outjection x = 400 мwells.

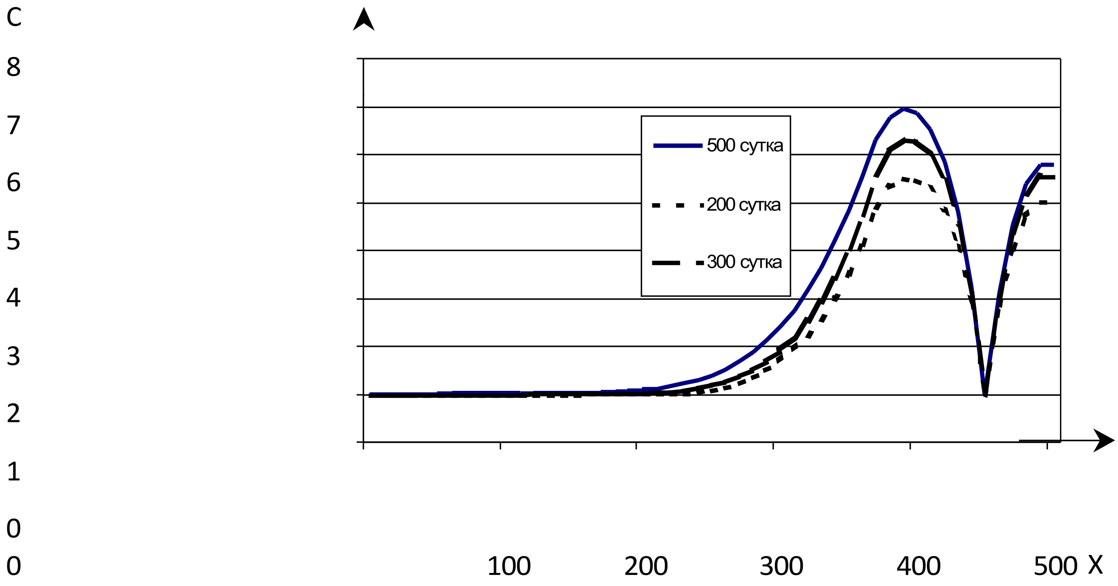


Figure 2. Dynamics of the linear value of the concentration

The reason for the sharp increase in concentration at the right-hand boundary is that the acid lye arrives here very quickly. The left boundary is very far from the injection well and the initial concentration is maintained at the time in question.

Figure 3 shows that the symmetric change in concentration value of the two-dimensional model corresponds to the computational algorithm and the program created for the physical and mechanical process variations.

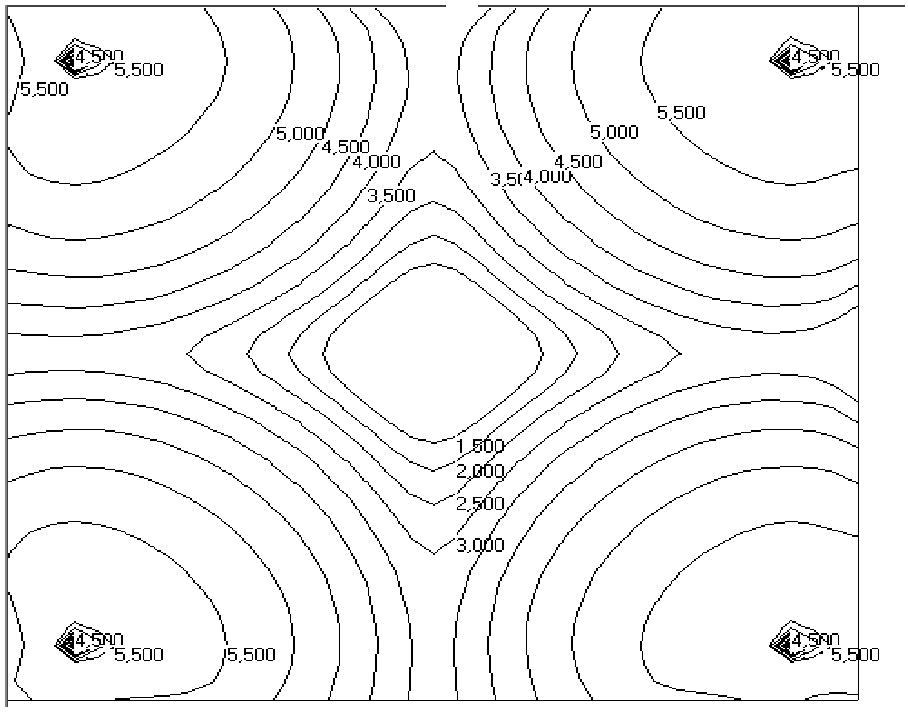


Figure 3. Isolines corresponding to concentrations at the centre of the pumping well for 90 days.

Usually, the first step is to break down the blocks of an arbitrary deposit that is mined using the method, taking into account its known characteristics, and then to approve the individual mining in succession.

So, in order to make the necessary decisions for the management of the process at PoE, the following tasks are carried out:

- a systematic study of the object of PoE;
- data processing;
- mathematical modelling;
- creating computational algorithms;
- object-oriented programming;
- getting the results on a computer;
- systematic analysis of the results for decision-making in process management;
- Establishing a database for decision-making and describing how to use it.

Several specific decision-making problems for expedient control of the SP process are considered here and the influence of several parameters on the change in concentration is investigated. The following are some of them. First, the dynamics of the concentration value is determined by changing the flow rate of the injection well. In the case where there are four injection wells and one injection well located at (5 , 5), results were obtained for different values of flow rate in the injection well [8]. Calculation results were analysed for T = 91; 200 days. The results of the analysis for 91 days are shown in Figure 8, which shows a graph of the relationship between the flow rate value in the pumping well and the concentration value at points (10,10) and (10,20).
From the results obtained, it can be concluded that the concentration value at points further away from the injection well increases faster than at points close to the injection well. The reason for this is the increased flow rate in the injection well.

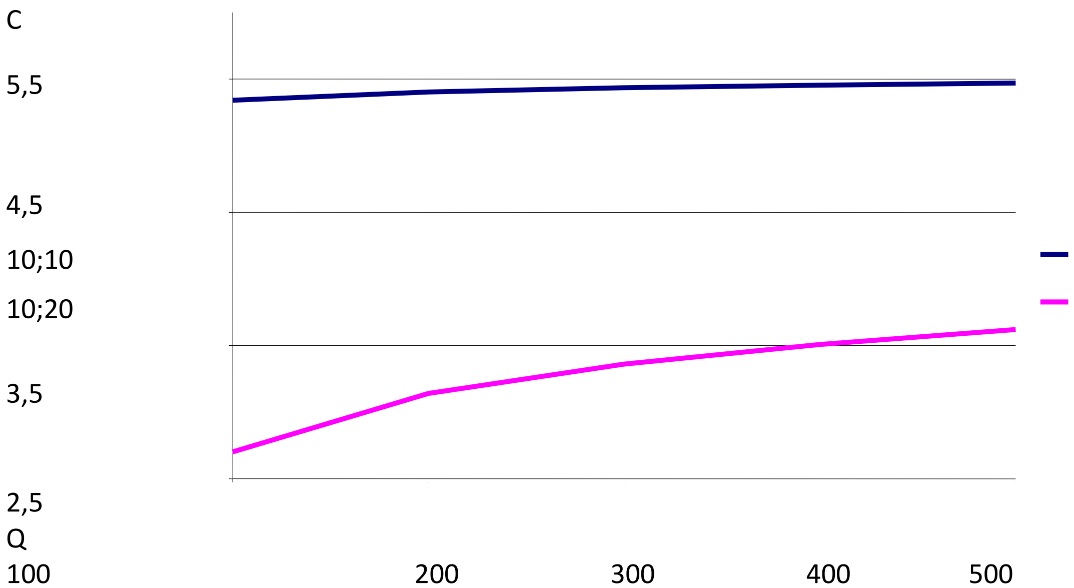


Figure 4. Calculated values of concentration change for different flow rates over time

It is required to control SP process so that in pumping wells after 360 days average concentration of useful component reaches maximum (i.e. Csr = 9.4mg/m) by selection of criteria of acid concentration in injected reagent. To solve the problem from real factors, the limits of variation of acid concentration () in the injected solution were determined. In our data the dimensionless value of this parameter ( ) is defined in the range 0.05·10-7 < < 0.5.10-7.
To achieve this goal, we solve problem (1) - (3) for different values of . The values were selected by dividing in half the interval of variation of this parameter. Problem (1)-(3) was solved for seven values of , and the results are given in Table 2. For = 0.05, 0.075,..., 0.5, (1)-(2) was solved and concentration values over the whole field were calculated. Concentration values of useful component in the pumping wells are given in columns 3-7, respectively, in Table 2. Based on these values, the condition (3) of optimum control of WP process was checked. Each time the result is compared with the required (set) value of concentration (second column). This process continues until the specified accuracy (=10-1) is met. In our example, this condition is fulfilled at step five.

Table 2

Concentration of useful component in pumping wells

No. of the well.	Optimal	0,05	0,078	0,092	0,106	0,162	0,275	0,5
1	9,398	7,665	8,905	9,251	9,487	9,887	9,995	10,000
2	9,383	7,642	8,882	9,232	9,474	9,883	9,994	10,000
3	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
4	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
5	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
6	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
7	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
8	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
9	9,381	7,638	8,880	9,230	9,473	9,883	9,994	10,000
10	9,398	7,665	8,905	9,251	9,487	9,887	9,995	10,000
11	9,383	7,642	8,882	9,232	9,474	9,883	9,994	10,000
12	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
13	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
14	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
15	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
16	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
17	9,379	7,634	8,876	9,227	9,471	9,882	9,994	10,000
18	9,381	7,638	8,880	9,230	9,473	9,883	9,994	10,000
Average.	9,382	7,639	8,880	9,231	9,473	9,883	9,994	10

Due to the complexity of the SP process, the parameters are not selected simultaneously, but individually. The hydrodynamic parameters are selected using a hydrodynamic model for the SP process. Here the output parameters, or the hydrodynamic objective of minimising the values of the flowing fluid at the boundary, are given. The dynamic values applied in the previous design are used as experimental values. The kinetic parameters are then selected. In this case, the output parameters or last objective is to maximise the values of the pumping well concentration.

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