N. M. SHAYAKHMETOV^{2*}, K. A. ALIBAYEVA^{2,1}, D. Y. AIZHULOV¹,

¹Satbayev University, Almaty, Kazakhstan

²Al-Farabi Kazakh National University, Almaty, Kazakhstan

IDENTIFICATION AND RESEARCH OF FACTORS AFFECTING THE OPTIMAL DISTRIBUTION OF WELL FLOW RATES IN SPACE

The paper discusses and research the factors affecting the filtration rate to reduce stagnant zones in the domain and spreading outside the block under consideration. The main hydrodynamic factors in production by In-Situ Leaching are the distribution of permeability in the reservoir and well flow rates. The study of the factors was carried out on the basis of mathematical models using Darcy Law and Law of Conservation of Mass. Calculation was accomplished on a two-dimensional area with an isotropic and non-uniform permeability distribution to determine the effect of permeability on the leached area. The permeability coefficient was distributed respectively over three zones, in the southern part the permeability was low, in the central transition from low to high, respectively, in the northern part there was a highly permeable zone. Three wells were located in the domain, with the production well in the center of the domain. Injection wells are located symmetrically with respect to a horizontal line passing through the center of the area under consideration. The calculation was carried out for three modes of well flow rates with the ratio of the flow rates of the injection wells 0.5 / 0.5, 0.2 / 0.8, 0.8 / 0.2 relative to the flow rate of the production well.

On the basis of comparative analyzes of the obtained results, it is concluded that: at the same flow rates, regardless of the permeability of the zones, the results obtained show that the leaching area in the low-permeability zone is larger in comparison with the high-permeability zone; with an increase in permeability, the shape of the leaching zone tends from round to drop-shaped; with an increase in the flow rate of wells in the radius of the leaching zone, it increases if the flow rate of solutions is much higher than the filtration rate.

Keywords: *In-situ leaching, mathematical modeling, hydrodynamics, well flow rate, flow in porous media*

Introduction. Using of modern mathematical methods is a forced step in the field of mineral extraction by in-situ leaching (ISL). Reducing the volume of uranium deposits that are easy to mine, mining of other metals and minerals that are located in complex geological structures or production of minerals that requires additional technological solutions implies the creation of new mathematical and geophysical approaches for the design and forecasting of the field development process [1]. For example, when mining copper using the ISL method, specialists are faced with the problem of achieving contact between the leaching agent and the extracting metal [2]. Applying of methods for increasing the permeability of the formation that used in the field of oil production is impossible due to the high cost of the methods. Extraction of rare earth minerals, gold and other minerals is also accompanied by such problems as: environmental pollution due to spreading of the leaching solution outside the mined area, clogging of pores due to the high carbonate content of the rock or the choice of the incorrect chemical composition of the leaching agent, low reaction rate

* E-mail корреспондирующего автора: shayakhmetovn@gmail.com

due to features of the mining mineral, etc. [3]. Most of the problems presented can be solved by using the capabilities of modern computer technologies and methods of mathematical modeling, and for the rest of the problems, these methods can be used as tools for choosing certain technological solutions. For example, successful results using of mathematical modeling in ISL processes are represented: for the design of the field in [4-7], for the choice of optimal production methods in [3, 7-9].

One of the most important issues at mineral extraction by the ISL is to determine the optimal flow rates of injection wells in order to achieve minimal spreading beyond the boundaries of the developed area and to reduce dilution by formation waters. The issue requires an integrated approach, consisting of several stages: research and identification of factors that affecting the optimal distribution of well flow rates in space; development of an algorithm for optimizing well flow rates. This paper considers and investigates the factors that affecting the flow rate to reduce stagnation and spreading zones. The main hydrodynamic factors in ISL production are the distribution of permeability in the reservoir and well flow rates.

Problem statement and research methods. The study of the factors was carried out on the basis of mathematical models presented in [10] and using Darcy Law and Mass Conservation Law. By using these laws, the distribution of hydrodynamic head and velocity in the reservoir are calculated:

$$\begin{aligned} \operatorname{div}(\vec{u}\varphi) &= q_{inj_i} \delta(x - x_i, y - y_i) - q_{prod_p} \delta(x - x_i, y - y_i) \\ \vec{u}\varphi &= -k_f \operatorname{grad} h \end{aligned} \quad (1)$$

For the concentration of the leaching agent, an equation of state for a tracer with advection, hydrodynamic dispersion, injection and production wells is chosen:

$$\begin{aligned} \frac{\varphi \partial c}{\partial t} &= -\vec{u} \operatorname{grad} c + \operatorname{div}(D \operatorname{grad} c) + c^0 q_{inj_i} \delta(x - x_i, y - y_i) - c q_{prod_p} \delta(x - x_p, y - y_p) \\ \vec{u}\varphi &= -k_f \operatorname{grad} h \end{aligned} \quad (2)$$

where, $\vec{u}$ – velocity field; φ – porosity; q_{inj_i} , q_{prod_p} – flow rates of the i-th injection and p-th production wells, respectively; c – reagent concentration in leaching solution; c^0 – reagent concentration in leaching solution at injection wells; k_f – hydraulic conductivity of layer; h – hydraulic head;

Relation between hydraulic head and pressure is defined as:

$$h = \frac{P}{\rho_w \bar{g}} \quad (3)$$

where P – pressure, ρ_w – density of water in standard conditions; $\bar{g}$ – gravitational acceleration.

A rectangular 2D area with a dimension of 200x200 meters with two injection wells and one production well is considered. However, the total computational domain was taken in such a way that the distance from the wells to the boundaries is equal to 10 distances between

the wells. Such a choice of the boundaries of the computational domain is conditioned by the minimization of the effect of the boundaries on the flow in the interwell space. Wells are located along the vertical axis in the center of the area (Figure 1). Diameter of the wells equals to 0.2 m and distance between them is 45 meters.

Figure 1 – Schematic illustration of the computational domain
(Drawing not to scale)

Since this paper studies the effect of layer permeability on the efficiency of field development, the area was divided into three regions with different permeabilities, with the upper y_t and y_b lower boundaries of the block marked with a dashed line (in considering domain) in Figure 1. The first segment is characterized by high permeability k_1 , the second segment is transient and the distribution of permeability k_2 is determined by linear interpolation of the other two segments, the third segment is presented as a region with low permeability k_3 :

$$\begin{aligned}
 k_1 &= 1,574 \cdot 10^{-12} \text{ [m}^2\text{]} \\
 k_2 &= k_1 + \frac{k_3 - k_1}{y_t - y_b} (y - y_b) \\
 k_3 &= 15,74 \cdot 10^{-12} \text{ [m}^2\text{]}
 \end{aligned} \tag{4}$$

On the basis of the following equation, a transformation from the formation permeability to the hydraulic conductivity (k_{fi}) is performed:

$$k_{fi} = \frac{k_i \rho_l g}{\mu_l} \text{ [m/d]}, \quad i = 1 \dots 3 \tag{5}$$

where, k_i – permeability of the i -th segment according to the data specified in (7), ρ_l – density of formation water, g – acceleration of gravity, μ_l – viscosity of formation water.

As the formation water does not differ significantly from water under standard conditions in terms of density and viscosity, the corresponding values for water were taken as characteristics of the formation fluid.

At the initial moment of time, there is no leaching agent in the formation, since it appears in the formation as a result of injection. To track spreading outside the considering domain following boundary conditions was set:

$$\begin{aligned} h(x_w, y, t) &= h_0, h(x_e, y, t) = h_0 \\ h(x, y_n, t) &= h_0, h(x, y_s, t) = h_0 \end{aligned} \quad (6)$$

$$\begin{aligned} \frac{\partial c(x_w, y, 0)}{\partial x} &= 0, \quad \frac{\partial c(x_e, y, 0)}{\partial x} = 0 \\ \frac{\partial c(x, y_n, 0)}{\partial y} &= 0, \quad \frac{\partial c(x, y_s, 0)}{\partial y} = 0 \end{aligned} \quad (7)$$

$$c(x, y, t_0) = 0$$

where, x_e, x_w – east (right hand side) and west (left hand side) boundaries of calculation domain, respectively, y_s, y_n – south (bottom) and north (top) boundaries of calculation domain, respectively. The value of h_0 depends on the depth of the ore body.

Since the equation for the hydrodynamic head is elliptic, the following initial guess is:

$$h(x, y, 0) = 0 \quad (8)$$

The solution of the system of equations (1) is conducted on the basis of the upper relaxation method, where the hydrodynamic head h is known in the first iteration according to the initial approximation (11). Equation (2) with the initial and boundary conditions (9, 10), as well as the distribution of the permeability (7) is solved using an explicit Euler scheme.

Results and analysis. In the result of the study, different flow rates of injection wells are considered while monitoring the effectiveness of these rates in the context of large leaching zones in the target area and smaller spreading zones outside it. By leaching zone means the area of distribution of a solution with a non-zero concentration.

Revealing the influence of the formation permeability on the production area is carried out by changing the ratio of the flow rates of the injection wells to the production wells, while a prerequisite is that the sum of the flow rates of the injection wells is equal to the flow rates of the production well:

$$q_{inj_1} + q_{inj_2} = q_{prod} \quad (9)$$

where, q_{inj_1} – flow rate of a well located in area with low permeability p_1 , relatively q_{inj_2} – flow rate of an injection well located in a highly permeable area.

The study was carried out in three modes with the following ratios of flow rates to injectivity of a production well:

$$\text{Case 1: } q_{inj_1} = q_{inj_2} = 0,5 q_{prod} \quad (13)$$

$$\text{Case 2:} \quad q_{inj_1} = 0,8 q_{prod}, \quad q_{inj_2} = 0,2 q_{prod} \quad (14)$$

$$\text{Case 3:} \quad q_{inj_1} = 0,2 q_{prod}, \quad q_{inj_2} = 0,8 q_{prod} \quad (15)$$

Figure 2 – Leaching front movement
in Case 1 (0.5, 0.5)

As shown in Figure 3, the leaching zone area is larger in the low permeability region. However, the rate of reaching of the reagent to the production well is faster in the high permeable zone. In addition, the shape of the leaching zone tends to a drop-like in the zone with permeability p_3 , respectively, in the zone with permeability p_1 , the shape tends to a circle. This behavior of the forms is explained by the pressure distribution at which the influence of the production well is achieved faster in the zone with high permeability, which in turn increases the flow rate between the injection and production wells in the highly permeable area. According to the Dupuit formula, the pressure distribution in the well depends not only on the well flow rate, but also on the formation permeability, as well as on the pressure on the outline. The outline pressure can also vary due to the presence of wells or other factors such as formation water, etc.

$$q = \frac{2\pi k h_f}{\mu} \frac{P_c - P_w}{\ln \frac{r_c}{r_w}} \quad (10)$$

where h_f – length of well filter, P_c, P_w – outline and well pressure respectively, r_c, r_w – outline and well radius respectively.

In Figure 3 shown the movement of the leaching fronts at the corresponding time t (in days).

The distribution of the y component of the Darcy velocity along the horizontal lines at the coordinates $x = 22.5$ and $x = -22.5$ is shown in Figure 4.

The corresponding results of the movement of the leaching fronts for Cases 2 and 3 are shown in Figures 5-6.

Figure 3 – Movement of the leaching front in case 1 along the vertical line between injection – production – injection wells

Figure 4 – Graph of the variation of the y component of the Darcy velocity in the k_1 and k_3 zones with low and high permeability, respectively.

Figure 5 – Leaching front movement in Case 2 (0.8, 0.2)

Figure 6 – Leaching front movement in Case 3 (0.2, 0.8)

The main indicator of production efficiency in the considering problem is the leaching area. It should be noted that the target zones for production are zones in the interwell space Ω_a (as shown in Figure 7).

Figure 7 – The scheme of zone arrangement

Therefore, all solutions flowing beyond the boundaries of the region Ω_a , that is, into the region Ω_s , are considered redundant. From the above, it is concluded that the scheme is effective in which a smaller volume of spreading solution is achieved beyond the boundaries of the target region Ω_a , with a larger leaching area in the region Ω_a :

$$\begin{aligned} v_{in} &= \iint_{\Omega_a} dx dy \rightarrow \max, \text{ where } c > 0 \\ v_{out} &= \iint_{\Omega_s} dx dy \rightarrow \min, \text{ where } c > 0 \end{aligned} \tag{11}$$

The results of the distribution of leaching areas and their percentage to the entire calculation domain are presented in Table 1.

Table 1 – Distribution of leaching zones for the Cases 1-3 (all values are shown in m^2)

	Case 1 (0.5, 0.5)		Case 2 (0.8, 0.2)		Case 3 (0.2, 0.8)	
Computational domain area, $[m^2]$	40 000					
Target zone area (Ω_a), $[m^2]$	16 000					
Spreading zone area (Ω_s), $[m^2]$	24 000					
Total leaching area ($v_{in} + v_{out}$)	24751	62%	25435	64%	24357	61%
Leaching area inside the target zone (v_{in})	10411	26%	10551	26%	10269	26%
Leaching area outside the target zone (v_{out})	14340	36%	14882	37%	14089	35%

As can be seen from Table 1, the leaching area inside the target zone in all three cases are, on average, similar in percentage. However, the spreading zones vary significantly. Consequently, according to condition (17), the effective area is an area in which the spreading zone is smaller, since the leaching zone is practically identical. Such a condition among the considered cases is achieved in Case 3 with the corresponding flow rates of the injection wells.

In addition, the changes in the leaching area were considered depending on the flow rate of the well located in the zones with the corresponding permeability. The results are shown in Table 2.

Table 2 – Area and its change depending on the flow rate of injection wells

Well flow rate	$0,8 q_{prod}$	$0,5 q_{prod}$	$0,2 q_{prod}$
Change of well flow rate in percentage	100% (changing - 0)	62,5% (changing - 37.5%)	25% (changing - 0.75%)
Injection well located in a low permeable area			
Leaching area	14673	13043	11382
Change of area in percentage of the larger one	100% (changing - 0)	88.9% (changing - 11.1%)	77.6% (changing - 22.4%)
Injection well located in a high permeable area			
Leaching area	12852	11707	10759
Change of area in percentage of the larger one	100% (changing - 0)	91.1% (changing - 8.9%)	83.7% (changing - 16.3%)

Conclusion. Based on comparative analyzes of the obtained results, it is concluded that:

- at the same flow rates, regardless of the permeability of the zones, the results obtained show that in the low-permeability zone, the leaching area is larger in comparison with the high-permeability zone (Figure 3). This is physically explained by the fact that the flow velocity in this zone is much lower than the velocity of solutions in the well, which is calculated from the flow rates of the wells;

- with an increase in permeability, the shape of the leaching zone tends from circle-shaped to drop-shaped. This is explained by the fact that in a low permeable zone the influence of the production well on the injection well is negligible, therefore, the pressure field is distributed according to the Dupuit law, which in turn leads to a uniform distribution of the solution along the radius. The impact of this well will only become noticeable when the area of the circle approaches the production well;

- with an increase in the flow rate of wells, the radius of the leaching zone also increases if the flow rate of solutions is much higher than the flow velocity in porous media. The shape of the leaching zone depends not only on the flow rates of the wells, but also on the permeability in the interwell space. Therefore, when choosing the flow rates of injection wells, it is necessary to take into account the ratio between the well flow rates and permeability;

- based on the above mentioned conclusions, it should be noted that the spreading of solutions outside the technological block increases with decreasing permeability.

Acknowledgments. The study was carried out within the framework of a grant financing project “Digital technology for the efficient positioning and management of technological wells for uranium extraction with In-Situ Leaching method” (AP08052470).

REFERENCES

1 Мендығалиев А.А., Вершков А.Ф., Джартыбаев Н.Б. Развитие и восполнение минерально-сырьевой базы урана Казахстана для обеспечения долгосрочных потребностей урановой отрасли Республики Казахстан // Сборник трудов международной научно-практической конференции актуальные проблемы урановой промышленности. – Алматы, 2019. – т. 1. – С. 31-34. [Mendygaliyev A.A., Vershkov A.F., Dzhartymbayev N.B. Razvitiye i vospolneniye mineral'no-syr'evoy bazy urana Kazahstana dlya obespecheniya dolgosrochnykh potrebnostey uranovoy otrasli Respubliki Kazahstan // Sbornik trudov mezhdunarodnoy nauchno-prakticheskoy konferencii aktual'nye problemy uranovoy promyshlennosti. – Almaty, 2019. – t. 1. – P. 31-34.]

2 Sinclair L., Thompson J. In situ leaching of copper: Challenges and future prospects // Hydro-metallurgy. – 2015. – № 157. – С. 306-324. <https://doi.org/10.1016/j.hydromet.2015.08.022>

3 Kuljabekov A. Analytical and numerical models of chemical leaching with gypsum precipitation in porous media. PhD thesis. – 2014. – 98 с. <https://hal.univ-lorraine.fr/tel-02075294>

4 Шаяхметов Н.М., Құрмансейіт М.Б., Айжулов Д.Е. Исследование оптимальности режимов гексагональной схемы вскрытия при добыче минерала методом подземного скважинного выщелачивания // Комплексное использование минерального сырья. – 2019. – №2. – С. 76-82. <http://kims-imio.kz/wp-content/uploads/2019/06/2019-2-9-1.pdf> [Shayahmetov N.M., Kurmanseyit M.B., Aizhulov D.Y. Issledovanie optimal'nosti rezhimov geksagonal'noj skhemy vskrytiya pri dobyche minerala metodom podzemnogo skvazhinnogo vyshchelachivaniya // Kompleksnoe ispol'zovanie mineral'nogo syr'ya. – 2019. – №2. – P. 76-82.]

5 Никитина Ю.Г., Поезжаев И.П., Мырзабек Г.А., Разуваева Т.В., Алибаева К.А. Совершенствование схем вскрытия геотехнологических полигонов для оптимизации затрат на добычу урана // Вестник КазНУ. – 2017. – № 6 (124). – С. 54-61. <https://vestnik.satbayev.university/index.php/journal/issue/view/37/36> [Nikitina Yu.G., Poezzhaev I.P., Myrzabek G.A., Razuvaeva T.V., Alibaeva K.A. Sovershenstvovanie skhem vskrytiya geotekhnologicheskikh poligonov dlya optimizatsii zatrat na dobychu urana // Vestnik KazNITU. – 2017. – № 6 (124). – P. 54-61.]

6 Shayakhmetov N.M., Aizhulov D.Y., Alibayeva K.A., Serovajsky S., Panfilov I. Application of hydrochemical simulation model to determination of optimal well pattern for mineral production with In-Situ Leaching // Procedia Computer Science. – 2020. – № 178. – С. 84-93. <https://doi.org/10.1016/j.procs.2020.11.010>

7 Носков М.Д., Истомин А.Д., Кеслер А.Г., Носкова С.Н., Гутцул М.В. Применение математического моделирования для решения геотехнологических и экологических задач при добыче урана способом подземного выщелачивания // Горный информационно-аналитический бюллетень. – 2012. – С. 361-365. <https://cyberleninka.ru/journal/n/gornyy-informatsionno-analiticheskij-byulleten-nauchno-tehnicheskij-zhurnal?i=1077610> [Noskov M.D., Istomin A.D., Kesler A.G., Noskova S.N., Gutcul M.V. Primenenie matematicheskogo modelirovaniya dlya resheniya geotekhnologicheskikh i ekologicheskikh zadach pri dobyche urana sposobom podzemnogo vshchelachivaniya // Gornyy informacionno-analiticheskij byulleten'. – 2012. – P. 361-365.]

8 Алибаева К.А. Численное исследование путей повышения выработки месторождения при добыче минералов методом подземного скважинного выщелачивания. Диссертация

PhD. – 2013. – 92 с. <https://www.geokniga.org/bookfiles/geokniga-chislennoe-issledovanie-putey-povysheniya-vyrabotki.pdf> [Alibaeva K.A. Chislennoe issledovanie putej povysheniya vyrabotki mestorozhdeniya pri dobyche mineralov metodom podzemnogo skvazhinnoogo vyshchelachivaniya. Dissertaciya PhD. – 2013. – 92 p.]

9 Kurmanseit M.B., Shayakhmetov N.M., Tungatarova M.S. GPU Accelerated Modeling of In-Situ Leaching Process and Streamline Based Reactive Transport Simulation // Procedia Computer Science. – 2020. – № 178. – С. 145-152. <https://doi.org/10.1016/j.procs.2020.11.016>

10 Данаев Н.Т., Корсакова Н.К., Пеньковский В.И. Массоперенос в прискважинной зоне и электромагнитный каротаж пластов. – Алматы: Қазақ университеті, 2005. – 180 с. [Danaev N.T., Korsakova N.K., Pen'kovskij V.I. Massoperenos v priskvazhinnoj zone i elektromagnitnyj karotazh plastov. – Almaty: Qazaq universiteti, 2005. – 180 p.]

Н. М. ШАЯХМЕТОВ², К. А. АЛИБАЕВА^{2,1}, Д. Е. АЙЖУЛОВ¹

¹Сатпаев университеті, Алматы, Қазақстан

²әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан

КЕҢІСТІКТЕГІ ҰҢҒЫМАЛАРДЫҢ ШЫҒЫНЫНЫҢ ТАРАЛУЫНЫҢ ОҢТАЙЛЫЛЫҒЫНА ӘСЕР ЕТЕТІН ФАКТОРЛАРДЫ АНЫҚТАУ ЖӘНЕ ЗЕРТТЕУ

Бұл жұмыста өлі зоналар мен технологиялық блоктың сыртына ағу зоналарын азайту үшін фильтрация жылдамдығына әсер ететін факторлар қарастырылады және зерттеледі. Жерасты ұңғымалы шаймалау әдісімен өндіру барысында негізгі гидродинамикалық факторлар ретінде өткізгіштіктің қабаттағы таралуы мен ұңғымалардың шығыны қарастырылады. Зерттеу Дарси заңы мен массаның сақталу заңына негізделген математикалық модель арқылы жүргізілді. Өткізгіштіктің сілтісіздендіру ауданына әсерін анықтау үшін есептеу өткізгіштік коэффициентінің изотропты және гетерогенді үлестірімді екі өлшемді аймақта жүргізілді. Өткізгіштік коэффициенті үш зонаға үлестірілді, оңтүстік бөлігінде өткізгіштік төмен, центрде төменнен жоғарыға өзгертін өтпелі, сәйкесінше солтүстік бөлікте жоғары өткізгіштік зона орналасады. Зерттелетін аймақта үш ұңғыма орналастырылды, өндіретін ұңғыма аймақтың центрінде қойылды. Айдау ұңғымалары аймақтың центрі арқылы өтетін горизонталь сызығына симметриялы түрде орналастырылды. Есептеу, ұңғымалардың шығындарының үш режимінде, өндіру ұңғымасының қабылдағыштығына қатысты айдау ұңғымаларының дебиттерінің келесі қатынастарымен: 0.5/0.5, 0.2/0.8, 0.8/0.2 жүргізілді.

Алынған нәтижелердің салыстырмалы талдау негізінде келесі тұжырымдамалар қортылды: зоналардың өткізгіштігіне тәуелсіз ұңғымалардың шығындары бірдей болған жағдайда, нәтижелер, жоғары өткізгіштікті зонамен салыстырғанда, өткізгіштігі төмен зонада шаймалау аймағының ауданы үлкен екені көрсетілді; өткізгіштіктің өсуімен шамалау зонасының формасы дөңгелектен тамшы формалы түрге ұмтылады; ертінділерді енгізу жылдамдығы фильтрация жылдамдығынан әлде қайда үлкен болған жағдайда, ұңғыманың дебиты өскен сайын шаймалау зонасының радиусы өседі.

Түйін сөздер: жерасты ұңғымалы шаймалау, математикалық модельдеу, гидродинамика, ұңғыма шығыны, фильтрация

Н. М. ШАЯХМЕТОВ², К. А. АЛИБАЕВА^{2,1}, Д. Е. АЙЖУЛОВ¹

¹Сатпаев университет, Алматы Казахстан

²Казахский национальный университет им. аль-Фараби, Алматы, Казахстан

ИССЛЕДОВАНИЕ ФАКТОРОВ, ВЛИЯЮЩИХ НА ОПТИМАЛЬНОСТЬ РАСПРЕДЕЛЕНИЯ РАСХОДОВ СКВАЖИН В ПРОСТРАНСТВЕ

В данной работе рассматриваются и исследуются факторы, влияющие на скорость фильтрации для уменьшения застойных зон и растекания за пределы технологического блока. Основными гидродинамическими факторами при добыче методом подземного скважинного выщелачивания являются распределение проницаемости в пласте и расходов на скважинах. Исследование факторов проводилось на основе математических моделей, использующих законы Дарси и сохранения массы. Вычисление проводилось на двумерной области с изотропным и неоднородным распределением проницаемости для определения влияния проницаемости на площадь выщелачивания. Коэффициент проницаемости был распределен по трем зонам, в южной части проницаемость была низкой, в центральной переходной – от низкой к высокой соответственно, на северной части была расположена высокопроницаемая зона. В исследуемой области были расположены три скважины, при этом добывающая скважина находилась в центре области. Закачивающие скважины расположены симметрично относительно горизонтальной линии, проходящей через центр рассматриваемой области. Вычисление проводилось для трех режимов расходов скважин с соотношением дебитов закачивающих скважин 0.5/0.5, 0.2/0.8, 0.8/0.2 относительно от приемистости добывающей скважины.

На основе сравнительных анализов полученных результатов можно сделать вывод: при одинаковых расходах, вне зависимости от проницаемости зон, полученные результаты показывают, что в низкопроницаемой зоне площадь выщелачивания больше в сравнении с высокопроницаемой областью; с увеличением проницаемости форма зоны выщелачивания стремится от круглой к каплевидной; при увеличении дебита скважин в радиус зоны выщелачивания увеличивается, если скорость подачи растворов значительно больше скорости фильтрации.

Ключевые слова: подземное скважинное выщелачивание, математическое моделирование, гидродинамика, расход скважин, теория фильтрации.