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A methodical approach to the selection of candidate wells for limiting water inflow, considered on the example of the Vozeyskoye field in the Komi Republic

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Методический подход к выбору скважин-кандидатов для ограничения водопритока, рассмотренный на примере Возейского месторождения Республики Коми

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field, deposit, water cut, residual mobile reserves, water inflow limitation, candidate wells, geological and technological parameters, Student's t-test, discriminant analysis, posterior probability, water cut source, hydrodynamic connection, tracer studies, Spearman correlation coefficient, velocity indicator movement.

A methodical approach to the selection of candidate wells for measures to limit water inflow is presented, considered on the example of the Carboniferous deposit of the Vozeyskoye field in the Komi Republic.
To determine the list of parameters that affect the effectiveness of measures to limit water inflow, an assessment was carried out using the Student's t-criterion: the average values of geological and technological parameters for classes of effective and inefficient measures obtained from field data were analyzed. Among the analyzed parameters, the statistically significant values were the values of permeability, porosity, net-to-gross ratio, thickness of the water inflow interval, determined by the results of flow metric studies, current reservoir pressure and fluid flow rate before well interventions.
With the help of discriminant analysis, candidate wells of the Carboniferous deposit of the Vozeyskoye field were assigned to the groups of effective or inefficient operations based on a set of statistically significant geological and technological parameters.
Three wells of the Vozeyskoye field have been identified for pilot work to limit water inflow, which belong to an area with a sufficient amount of residual recoverable reserves.
In order to exclude unfavorable conditions for the use of water inflow limitation technologies, sources of flooding in candidate wells were identified. To increase the measures success, it is necessary to exclude from consideration wells, in which excess water flows through cracks and faults. To this end, by calculating the Spearman correlation coefficients, it was found that the hydrodynamic connection between the three candidate wells and the injection well affecting them is characterized as weak, moderate and medium, which excludes the flow of excess water through fractures.

Ключевые слова:
месторождение, залежь, обводненность, остаточные подвижные запасы, ограничение водопритока, скважины-кандидаты, геолого-технологические параметры, *t*-критерий Стьюдента, дискриминантный анализ, апостериорная вероятность, источник обводнения, гидродинамическая связь, трассерные исследования, коэффициент корреляции Спирмена, скорость движения индикатора.

Представлен методический подход к выбору скважин-кандидатов для мероприятий по ограничению водопритока, рассмотренный на примере каменноугольной залежи Возейского месторождения Республики Коми.
Для определения перечня параметров, оказывающих влияние на эффективность мероприятий по ограничению водопритока, проведена оценка при помощи *t*-критерия Стьюдента: проанализированы средние значения геолого-технологических параметров для классов эффективных и неэффективных мероприятий, полученных по промысловым данным. Среди анализируемых параметров статистически значимыми являются значения проницаемости, пористости, песчанистости, толщины интервала водопритока, определенные по результатам потокометрических исследований, текущее пластовое давление и дебит жидкости до проведения мероприятий на скважине.
С помощью дискриминантного анализа осуществлено отнесение скважин-кандидатов каменноугольной залежи Возейского месторождения к группам эффективных или неэффективных работ по совокупности статистически значимых геолого-технологических параметров.
Определены три скважины Возейского месторождения для проведения опытно-промышленных работ по ограничению водопритока, которые относятся к области с достаточным количеством остаточных извлекаемых запасов.
С целью исключения неблагоприятных условий применения технологий ограничения водопритока определены источники обводнения скважин-кандидатов. Для повышения успешности мероприятий необходимо исключать из рассмотрения скважины, поступление избыточной воды в которых происходит по трещинам и разломам. С этой целью расчетом коэффициентов корреляции Спирмена установлено, что гидродинамическая связь между тремя скважинами-кандидатами и влияющей на них нагнетательной скважиной характеризуется как слабая, умеренная и средняя, что исключает поступление избыточной воды по трещинам.

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Introduction

At present, the operation of oil and oil and gas condensate fields in the Komi Republic is accompanied by high volumes of produced water. One of the solutions aimed at reducing watercutting of production wells is the introduction of water inflow limitation technologies (WIL) [1].

The coal deposit of the Voseyskoye field is a priority object for planning measures to limit water inflow since it is characterised by a significant number of highly watered production wells. When selecting candidate wells for water inflow limitation measures it is necessary to adhere to the conditions for obtaining maximum technological and economic effect, taking into account the existing experience in carrying out similar works to reduce the water cut of well products [2].

Various schemes and algorithms for selecting candidate wells for work on water inflow limitation are shown in research papers [3–10]. These methods have been used in some fields of the Russian Federation, but the insufficient efficiency of measures to limit water inflow at the fields of the Timan-Pechora oil and gas province indicates the need for further development of methods for selecting candidate wells, which would allow considering a larger number of geological and technological parameters [5, 8].

Development of a methodological approach to the selection of candidate wells using statistical methods

For the selection of candidate wells at the fields under consideration, it is necessary to develop an appropriate methodological approach capable of determining a list of parameters which affect the efficiency of measures on water inflow limitation with regard to local features.

The scheme for selecting candidate wells for water inflow limitation measures is presented in Fig. 1.

In order to comprehensively study the impact of geological and physical parameters on the WIL results, 47 similar measures carried out at the fields of the Komi Republic with various water-insulating compositions were considered.

The first stage of the methodological approach

All measures are divided into two groups according to the results obtained:

1) group 1 – effective measures;
2) group 2 – ineffective measures.

Effective measures include water shut-offs, after which the well shows a decrease in fluid flow rate, and the increase in oil flow rate is greater than or equal to zero. Other measures are classified as ineffective.

From the sample of geological and technological parameters, we analysed those ones which characterise the geological section of the studied wells, properties of produced fluids, design features and operation of the well. Thus, the following independent variables were selected for the analysis: thickness of the water inflow interval determined by flowmetric studies, values of permeability, porosity, compartmentalization, sandiness, effective oil saturated thickness, current reservoir pressure, reservoir temperature, distance from the bottom perforation hole to the oil-water contact (OWC), current density and salinity of produced water, oil viscosity, oil and fluid flow rates and water cut before the WIL measures.

To determine the list of parameters influencing the efficiency of WIL measures, the Student's t-test was evaluated [11–13]: the mean values of geological and technological parameters for the classes of effective and inefficient measures obtained from field data were analysed (Table 1).

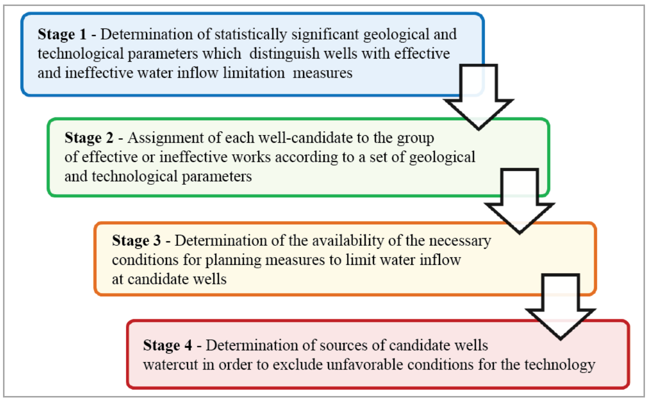

Fig. 1. Scheme of the methodological approach for the selection of candidate wells

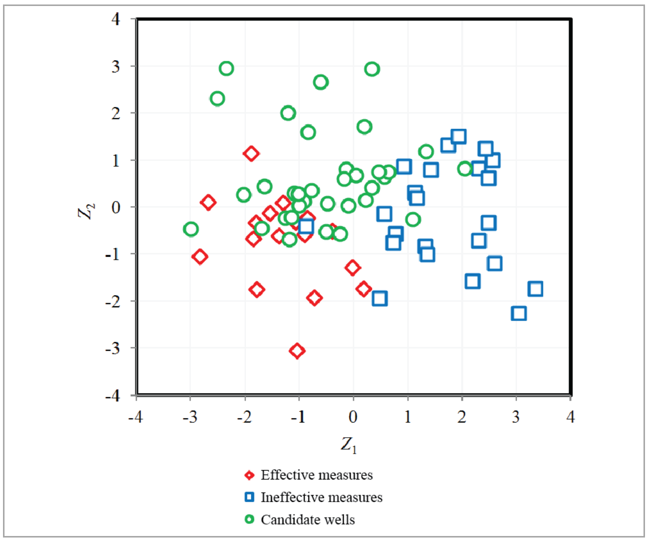

Fig. 2. Scatter diagram of canonical values for pairs of discriminant function values 1 and 2

Among the analysed parameters statistically significant are the values of the thickness of the water inflow interval, permeability, porosity and sandiness, current reservoir pressure, fluid flow rate before the water inflow limitation measure.

The second stage of the methodological approach

In the second stage of the proposed methodological approach, after determining the list of parameters influencing the effectiveness of ORP measures, this paper proposes the use of discriminant analysis for further selection of candidate wells. Discriminant analysis is one of the most widely used multivariate methods in statistics and also finds application in geological sciences [14–23].

In order to identify candidate wells by discriminant analysis, in addition to group 1 – effective measures, and group 2 – ineffective measures, a group of candidate wells of the coal deposit of the Wozejskoye field was identified. Thus, the use of discriminant analysis will make it possible to assign each candidate well to the group of effective or inefficient works according to a set of geological and technological parameters that can affect the efficiency of WIL measures, determined by the Student's t-test: thickness of the water inflow interval, permeability, porosity, sandiness, current reservoir pressure, fluid flow rate before the measure.

Table 1

Student's t-test values for geological and technological parameters

Parameter	Average		Student's criterion value / Significance level	Number of observations		Standard deviation	
	group 1	group 2		group 1	group 2	group 1	group 2
thickness of the water inflow interval, m	9.2	14.4	2.13 0.04	14	26	4.1	8.6
Permeability, mD	291.8	76.2	–2.06 0.04	18	25	518.3	78.8
Porosity, %	17.7	15.3	–2.03 0.04	17	28	3.1	4.1
Compartmentalization, units	13.5	17.3	1.10 0.28	17	27	6.9	12.9
Sandiness,fractions of units	0.49	0.38	–3.02 0.03	17	27	0.1	0.1
Effective oil saturated thickness, m	26.9	29.7	0.51 0.61	17	26	16.4	18.1
Current reservoir pressure, MPa	16.0	21.9	2.27 0.03	18	27	7.6	9.3
Temperature, ^{0}C	52.6	63.3	1.46 0.15	19	28	22.8	26.2
Cuttent density of produced water, g/cm^3	1.03	1.03	–1.12 0.27	15	16	0.01	0.01
Current salinity of produced water, mg/l	40741	45728	0.51 0.61	17	27	20654	36597
Oil viscosity, mPa·s	5.1	3.7	–1.00 0.32	17	22	4.5	4.13
Distance from the bottom perforation hole to the OWC, m	32.7	25.8	–0.80 0.43	17	18	29.2	22.1
Fluid flow rate before the event, t/day	174.5	122.6	–2.27 0.02	19	28	66.8	83.0
Oil flow rate before the event, t/day	4.3	5.1	0.44 0.66	19	28	3.2	7.2
Water cut, %	97.3	95.1	0.44 0.66	19	28	2.1	5.3

Table 2

Discriminant analysis data summary table

Parameter	Wilkes' Lambda	Particular Lambda	Tolerance
Thickness of water inflow interval, m	0.38	0.85	0.92
Permeability, mD	0.34	0.94	0.94
Porosity, %	0.41	0.79	0.78
Sandiness,fractions of units.	0.41	0.80	0.88
Current reservoir pressure, MPa	0.37	0.88	0.76
Fluid flow rate before the event, t/day	0.37	0.88	0.88

The following results were obtained during the discriminant analysis: the value of Wilkes lambda is 0.32; the approximate value of the *F*-statistic with the number of degrees of freedom 12 and 130 is 8.2; The *p*-level of significance of the *F*-test is less than 0.00001 (Table 2).

To obtain further results on the discrimination of groups of wells with effective, ineffective measures and candidate wells, a canonical analysis has been carried out. Based on the data on the thickness of the water inflow interval, permeability, porosity, sandiness, current reservoir pressure, and fluid flow rate, the following linear discriminant functions are constructed:

$$Z_1 \text{ (group 1)} = -0.076 \cdot H_{wif} - 0.004 \cdot K_{perm} + 5.422 \cdot K_p + 81.197 \cdot K_{sand.} + 1.43 \cdot P_{res} + 0.05 \cdot Q_f - 89.305;$$

$$Z_2 \text{ (group 2)} = 0.148 \cdot H_{wif} - 0.004 \cdot K_{perm} + 4.553 \cdot K_p + 62.179 \cdot K_{sand.} + 1.339 \cdot P_{res} + 0.034 \cdot Q_f - 64.292,$$

where H_{wif} – the thickness of the water inflow interval determined by the results of flowometric studies, m; K_{perm} – Permeability value, μm^2; K_p – porosity value, fractions of unit; $K_{sand.}$ – fractionsof unit sandiness value, fractions of unit; P_{res} – current reservoir pressure, MPa; Q_f – fluid flow rate before the measure for wells with limited water inflow and current fluid flow rate for candidate wells, t/day

According to these functions it was calculated the values of Z1 and Z2 which for different groups of wells are shown in Fig. 2.

From the data of Fig. 2 we can see that the values of Z1 and Z2 are quite well separated within the studied groups of wells 1 and 2.

The discriminant analysis is concluded with a table of posterior probability values, i.e. the belonging of the candidate wells to one of the two groups. It was revealed that out of 32 candidate wells of the Voseyskoye field 21 wells belong to the group with effective measures and are recommended for further study (Table 3).

The third stage of the methodological approach

In the course of the third stage of the proposed methodological approach, three wells of the Vozeyskoye field – No D-1, D-2, D-3, located in the injection center of well No N-1, which have the necessary conditions for planning measures to limit water inflow, were identified among the wells selected as a result of the analysis of a posteriori probability (Table 4). These wells are prime candidates for pilot work to test WIL technologies [1].

Table 3

Value of a posterior probabilities
for candidate wells of the Vozeyskoye field

No of Candidate Well	Group 1 – effective measures	Group 2 – ineffective measures
406	0.326035	0.673965
556	0.996727	0.003273
1518	0.000000	1.000000
1550	0.513518	0.486482
1576	0.999996	0.000004
1585	0.003120	0.996880
1626	0.971031	0.028969
1638	0.029492	0.970508
1660	0.614557	0.385443
1661	0.000018	0.999982
Д-1	0.968902	0.031098
1679	0.999304	0.000696
Д-2	0.892074	0.107926
1698	0.995537	0.004463
1709	0.311543	0.688457
1712	1.000000	0.000000
1727	0.994948	0.005052
1728	0.531812	0.468188
1731	0.983361	0.016639
1736	0.999697	0.000303
1743	0.002321	0.997679
1746	0.994934	0.005066
Д-3	0.998603	0.001397
1764	0.872952	0.127048
1784	0.476227	0.523773
1837	0.020571	0.979429
1844	0.898820	0.101180
1873	0.123866	0.876134
1879	0.075779	0.924221
1ОЦ	0.999313	0.000687
2ОЦ	1.000000	0.000000
5ОЦ	0.999999	0.000001

Table 4

Parameters of candidate wells of Vozeyskoye field [1]

Geological and technological parameters	№ D-1	№ D-2	№ D-3
Well category by fund	Production	Production	Production
Method of operation	ЭЦН	ЭЦН	ЭЦН
Object of development	C2-3	C2-3	C2-3
Reservoir pressure, MPa	12.5	14	15.6
Reservoir temperature, ^{0}C	37	37	40
Production casing diameter, mm	146	146	146
Perforation intervals, m	1791–1804.6	1699.8–1707.2	1690–1696 1700.4–1712
Plugback depth, m	1843	1773.2	1766.3
Current depth, m	1815.8	1744.6	1754
Pressurisation of production casing to pressure, MPa	13	10	10
Oil flow rate, tonnes/day	2	1.4	0.82
Fluid flow rate, m^3/day	86	50	97
Water cut, %	98	91.5	99
Residual recoverable reserves, kt	38.2	25.8	23.8

Table 5

Application of Spearman's correlation coefficient
to describe Hydrodynamic Connection Significance

Spearman correlation coefficient value	Characteristics of the significance of connectivity	Presumed presence of fractures connecting wells
$R_s < 0.1$	Almost no connectivity observed	No
$0.101 < R_s < 0.3$	Weak connectivity	No
$0.301 < R_s < 0.5$	moderate connectivity	No
$0.501 < R_s < 0.7$	Medium significance connectivity	No
$0.701 < R_s < 0.9$	Strong connectivity	Yes
$0.901 < R_s < 1.0$	Very strong connectivity	Yes

The fourth stage of the methodological approach

According to the world experience of water inflow limitation [24–28], there are a number of intractable problems in the treatment of fractures connecting production and injection wells. First of all, there are difficulties in determining the volume of injection, since the size of the fractures is unknown. In addition, the injected water-insulating composition can plug productive cracks, and after injection, there is a high probability of the composition being carried out of the reservoir. Therefore, in order to increase the success of measures to limit water inflow and eliminate the above-mentioned problems, it is necessary to exclude from consideration wells with excessive water inflow through fractures and faults.

Since there is a strong heterogeneity in the permeability of the matrix and fracture components in the coal deposit of the Voseyskoye field, determining the source of watering of candidate wells in order to exclude unfavourable conditions for water shut-off technologies is an urgent task.

One of the indicators of the character of water inflow to candidate wells from injection wells is the presence and significance of hydrodynamic connection between production and injection wells. Area hydrodynamic methods: tracer surveys and sonar are considered to be the most common and informative methods of research [29–39]. However, it should be noted that area studies are expensive and time-consuming. This limits the use of this type of survey to assess the hydrodynamic connection between wells before each water shut-off works.

At the selected test site, including production wells No D-1, D-2, D-3 and injection well No N-1, areal hydrodynamic studies were not carried out, thus, the assessment of the degree of hydrodynamic connectivity capable of detecting fractures and faults between wells is proposed to carry out according to the appropriate method of mathematical statistics – Spearman's rank correlation method. Spearman's rank correlation method makes it possible to determine the presence and closeness of the correlation between two series of compared quantitative indicators [40–44]. To apply these methods for candidate wells, in addition to the data of monthly production it is also involved data on injection into injection wells.

For the coal deposit of the Voseyskoye field, Spearman correlation coefficients were calculated for 17 injection centres, including 50 pairs of production and injection wells. In this work, Y is taken as the injectivity of the injection well, m^3/day, while X is the fluid flow rate of the candidate wells under study, m^3/day, taken over the entire injection period.

In order to identify the possibility of using Spearman's correlation coefficients as a tool for assessing the significance of the hydrodynamic relationship between the wells of the Carboniferous deposit of the Vozeyskoye deposit, a relationship was established between these coefficients and the results of tracer studies was established by correlation analysis.

For this purpose, the first array includes the results of calculating Spearman's correlation coefficients for pairs of wells in the kitchen area, in the second – the results of determining the maximum velocity of the indicator for similar wells. The results of the correlation analysis are presented in Fig. 3.

From Fig. 3 we can see a rather high correlation between the Spearman correlation coefficients and the values of the maximum velocity of movement of the of the indicator (R = 0.8). Since the time and velocity of the indicator movement during tracer studies are among the basic parameters characterising the presence and significance of

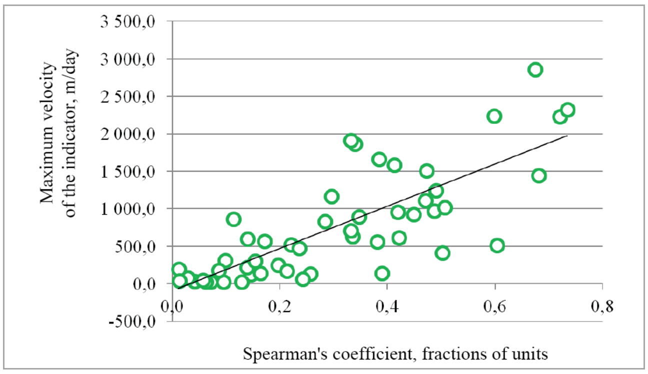

Fig. 3. Results of the correlation analysis

Table 6

Spearman correlation coefficients calculation data

No of Candidate Well	No of injection well	p	Characteristics of the significance of connectivity
Д-1	H-1	0.68	Medium significance connectivity
Д-2	H-1	0.31	Moderate connectivity
Д-3	H-1	0.20	Weak connectivity

hydrodynamic connection, we can conclude that the use of Spearman correlation coefficients in the Voseyskoye field is also capable of establishing a connection between wells.

Table 5 shows the intervals of possible Spearman's rank correlation coefficients, corresponding characteristics of the significance of hydrodynamic connection between wells and the presumed presence of fractures connecting production and injection wells. The correspondence of the significance of wells connectivity to the values of Spearman correlation coefficients is shown in [45].

Table 6 shows the results of Spearman correlation coefficient calculation for the pairs of candidate wells and injection well No. H-1.

The calculation of Spearman correlation coefficient revealed that the pair of wells № D-3 – № H-1 is characterised by weak connectivity, the pair of wells № D-2 – № H-1 – moderate hydrodynamic connection, the pair of wells № D-1 – № H-1 – connectivity of medium significance, what excludes the entry of excess water through the fractures connecting the injection and production wells.

Conclusion

On the example of the coal deposit of the Voseyskoye field it is shown the methodological approach to the selection of candidate wells based on the study of the influence of various geological and technological parameters of wells on the effectiveness of water inflow limitation measures. The methodological approach consists of four stages and allows analysing a large number of candidate wells, which is especially relevant for large production facilities and fields of the Komi Republic.

With the help of the proposed methodological approach it is possible to identify the sources of well watering in order to exclude unfavourable conditions for water shut-off technologies.

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