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A PROCEDURE FOR EVALUATION OF THE EFFECT OF WATER INJECTION INTO A RESERVOIR ON OIL PRODUCTION ON EXAMPLE OF TOURNAISIAN DEPOSITS OF THE SOSNOVSKOE GAS-OIL FIELD

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РАЗРАБОТКА МЕТОДИКИ ОЦЕНКИ ВЛИЯНИЯ ЗАКАЧКИ ВОДЫ В ПЛАСТ НА ДОБЫЧУ НЕФТИ НА ПРИМЕРЕ ТУРНЕЙСКИХ ОТЛОЖЕНИЙ СОСНОВСКОГО ГАЗОНЕФТЯНОГО МЕСТОРОЖДЕНИЯ

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field, reservoir pressure maintenance system, oil production, water injection, production well, injection well, correlation coefficient, mathematical statistics, regression equation, Student's *t*-criterion, linear discriminant function, slope, optimization, Tournaisian deposits, linear discriminant analysis.

The effect of water injection into a reservoir on oil production for Tournaisian deposits of the Sosnovskoe gas-oil field is evaluated. Statistical methods such as correlation, regression and stepwise discriminant analysis were used. Data on monthly and cumulative oil production, on amount of water injected into the reservoir from four injection and twelve production wells was used. Based on the data, studies have been performed to assess the effect of the volume of monthly water injection into the reservoir on monthly oil production, provided that each injection well affects only nearby producing wells. It was explained why there was no correlation between the parameters of monthly injection and monthly oil production. Then, in order to evaluate the efficiency of water injection into the reservoir, it was decided to use the data from the accumulated volume of water injection and the accumulated volume of oil production. It was found that there is a relationship between the parameters of the accumulated volume of water injection and the accumulated volume of oil production. The greater the accumulated volume of water injection, the greater the accumulated volume of oil production, but the gradients of increase for all wells are individual. Three areas were defined on the graphs. Relationships between the parameters have a high degree of linearity over a certain range. In order to establish the boundaries of those areas where the influence of the values of the accumulated volume of water injection on the accumulated volume of oil production is conditionally homogeneous, linear discriminant analysis was used. Results of the evaluation study show that water injection into the reservoir has a different degree of influence on the production wells. This analysis can be further applied to substantiate workovers and to identify hydrodynamic communication.

Ключевые слова:
месторождение, система поддержания пластового давления, добыча нефти, закачка воды, добывающая скважина, нагнетательная скважина, коэффициент корреляции, математическая статистика, уравнение регрессии, *t*-критерий Стьюдента, линейная дискриминантная функция, угловой коэффициент, оптимизация, турнейские отложения, линейный дискриминантный анализ.

Оценено влияние закачки воды в пласт на добычу нефти для турнейских отложений Сосновского газонефтяного месторождения. Для анализа использованы статистические методы: корреляционный, регрессионный и пошаговый дискриминантный анализ. Использовалась информация по ежемесячной и накопленной добыче нефти, а также закачке воды в продуктивный пласт по четырем нагнетательным и двенадцати добывающим скважинам. На основе этой информации были выполнены исследования по оценке влияния объема месячной закачки воды в пласт на месячную добычу нефти при условии, что каждая нагнетательная скважина оказывает влияние только на близкорасположенные добывающие скважины. Между параметрами месячной закачки и месячной добычи нефти было обосновано отсутствие корреляционной зависимости. Далее для оценки эффективности нагнетания воды в пласт было принято решение использовать информацию о накопленном объеме закачки воды и накопленном объеме добычи нефти. Было установлено, что между параметрами накопленного объема закачки воды и накопленного объема добычи нефти существует зависимость, при увеличении значений накопленного объема закачки воды значение накопленного объема добычи нефти увеличивается, но градиенты повышения для всех скважин индивидуальны. На графиках визуально было выделено три участка, где соотношения между ними обладают на некотором диапазоне высокой степенью линейности. Для установления границ тех участков, где влияние значений накопленного объема закачки воды на накопленный объем добычи нефти условно однородно, был использован линейный дискриминантный анализ. Результаты исследования показывают, что закачка воды в пласт имеет разную степень влияния на добывающие скважины. Данный анализ в дальнейшем можно применять для обоснования проведения геолого-технологических мероприятий и для выявления гидродинамической связи.

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Introduction

Oil industry is of unsurpassed importance for the economy of our country, therefore everything that is currently related to this field is crucial. At the moment, the majority of oilfields are developed using a formation pressure maintenance system [1]. Thus, improving the effectiveness of formation pressure maintenance systems is of utmost importance for all the oil-producing enterprises. In developing an oilfield, it is very important to achieve the highest possible economic effectiveness of oil production, therefore, it is necessary to assess how the implemented formation pressure maintenance system operates [2, 3].

The improvement of methods for analyzing the formation pressure maintenance system is a regular process as it is one of the fundamental and the cheapest method of formation stimulation, while the task of involving poorly drainable formation areas into development is quite challenging [4].

Dealing with the task of evaluating and forecasting the effectiveness of different kinds of flooding system and its control is significantly facilitated, if there is an operating geological and hydrodynamic model in place, however, far from all the development targets have it, as the developing such models is a labour-intensive and quite expensive process. Therefore, this paper makes a special emphasis on the methodology of evaluating the effectiveness of formation pressure maintenance system using readily available oilfield information.

General geological characteristic of sosnovskoye oilfield

Sosnovskoe oilfield was discovered in 1967 by the Well No. 42 as a result of prospecting and exploration drilling.

In administrative terms, the oilfield in located in Ordinsky District of Perm region, 100 km south of the Krai centre – the city of Perm (Fig. 1). The nearest localities include the villages of Orda, Sosnovka and Ashap.

The information about the depth of formation and the ranges of stratigraphic divisions' thickness changes were received as a result of drilling 41 wells, including 11 prospecting and exploration and 30 producing wells.

The surface of crystalline basement is located at the depth of about 7 km submersing in the south-west direction. The basement is represented by crystalline rocks.

The section of Sosnovskoe oilfield represents a sedimentary complex typical of Permian and Bashkir anticlines and Bymsko-Kungurskaya depression and consists predominantly of carbonate rocks. It is favourable in terms of sedimentation conditions and opportunities of hydrocarbon deposits development.

The section contains no Lower Devonian sediments. Middle Devonian sediments with stratigraphic nonconformity rest on Vendian ones. There are no rocks of Cambrian, Ordovician or Silurian ages.

Radaevian sediments rest unconformably on the eroded roof of Tournaisian sediments (no Kosvinsky horizon).

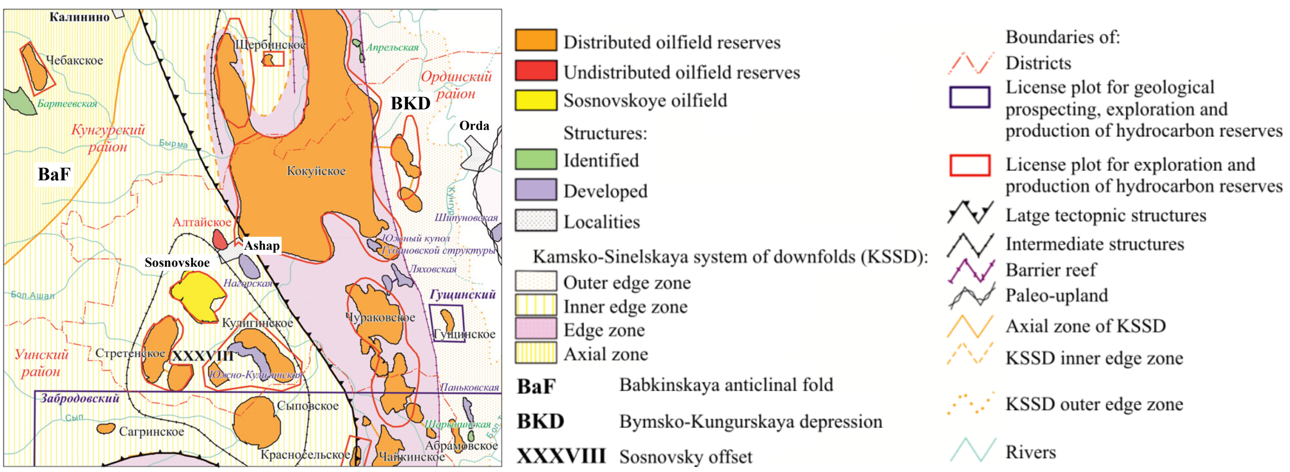

Fig. 1. Extract from the tectonic map of the study area

Mesozoic deposits are not present in the section due to a long break in the sedimentation.

Quarternary deposits are met everywhere and rest with stratigraphic nonconformity on Perm deposits.

In tectonic terms, Sosnovskoe oilfield is located in Babkinskaya anticlinal fold within Sosnovsky offset, in the inner edge zone adjacent to Kamsko-Sinelskaya system of downfolds.

Drilling and well tests have proved the presence of oil-and-gas content in Devonian terrigenous (formation D_0), Upper Devonian and Tournaisian carbonate (formation T_1), Lower and Middle Visean terrigenous (formations Tl_{1a}, Tl_{2a}, Tl_{2b}, Bb_1), Upper Visean Bashkir carbonate (formation Bsh) and Middle Carboniferous terrigenous and carbonate (formation V_3V_4) oil-and-gas bearing complexes.

Production assets under review – T_1.

Brief geological and physical characteristic of T_1: sand content – 0.37 unit fractions, porosity – 0.13 unit fractions, oil-and-gas content – 0.83 unit fractions, permeability (geophysical well logging) – 0.068 μm^2, number of permeable intervals – 5 pcs, gas saturation pressure – 12.11 MPa, current formation pressure – 15.5 MPa. Average formation water cut amounts to 57.6 % with the production of initial recoverable reserves of 10 %. Production asset T_1 ranks first among other production assets of Sosnovskoye oilfield by its reserves (5,376 thousand tons) [5]. The oilfield is at the 3rd stage of development.

Whereas the average formation water cut amounts to 57.6 % with the production of initial recoverable reserves of 10 %, it is necessary to analyze the formation pressure maintenance system of T_1 formation.

Assessment of impact of water injection into the formation on oil production on the example of tournaisian deposits of Sosnovskoe oil and gas field

The method of assessing the impact of water injection into the formation on oil production for Well 401. The method of assessing the impact of water injection into the formation on the production of oil uses the information about Well 401 for the period from August, 1993, to February, 2016, i.e. for 259 months ($n = 259$).

On the basis of this information we will assess the impact of the monthly volume of water injected into the formation $V^{m}_{H_2O}$ on the monthly oil production V^{m}_{oil}.

For the purposes of the method development, the values of $V^{m}_{H_2O}$ for the injection wells located in different reservoir areas were used. We assume that the injection of water into this well will have an impact on the monthly production of oil by wells 400, 403-405, 474, 475. The change of values of EMBED Equation.DSMT4 in time t is shown in Fig. 2.

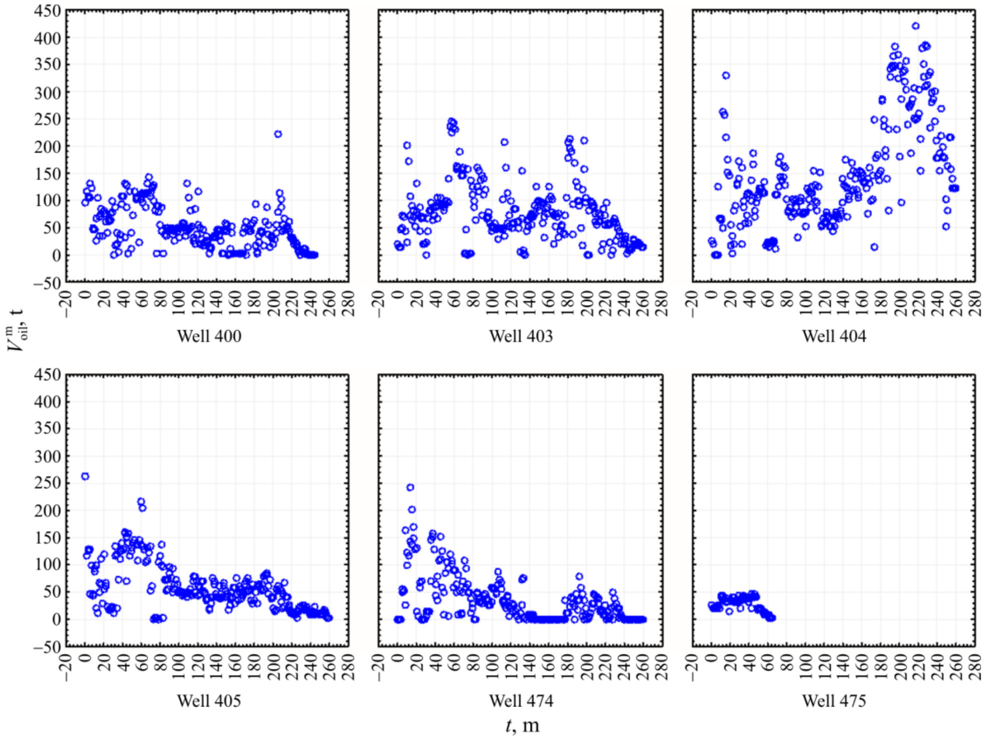

Fig. 2. Change of values of V^{m}_{oil} in time t by wells

The analysis of Fig. 2 shows that the values of V_{oil}^{m} differ materially by well.

The change of values of $V_{H_2O}^{m}$ in time for Well 424 is shown in Fig. 3.

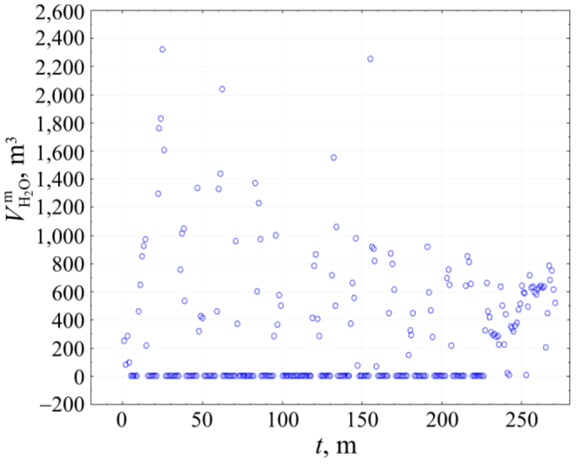

Fig. 3. Change of $V_{H_2O}^{m}$ values in time for Well 424

The change of values of $V_{H_2O}^{m}$ depending on t has quite a complex view.

In order to compare the values of $V_{H_2O}^{m}$ and V_{oil}^{m} for the two reviewed options of impact of the injection wells, correlation fields set out in Fig. 4 were built for the injections wells.

Analyzing Fig. 4, we noted that the values of $V_{H_2O}^{m}$ and V_{oil}^{m} have a weak correlation, i.e. it is impossible to prove in statistical terms the nature of impact of $V_{H_2O}^{m}$ values on V_{oil}^{m} values. Now we are going to prove this statement with the calculations of r and making regression equations. V_{oil}^{m} (oil production for a month, tons) will be a dependent attribute, and $V_{H_2O}^{m}$ (water injection into the formation for a month, m^3) will be an independent factor.

As a result of this method application, the values of r were calculated and regression equations were made for the following options:

a) based on the information about each well;

b) based on the information about all the wells.

The values of r and regression equations of V_{oil}^{m} dependence on $V_{H_2O}^{m}$ in the above options are set out in Table 1.

The analysis of constant and slope term values of a regression equation and r ratio indicates that it is not possible to measure the impact of $V_{H_2O}^{m}$ on V_{oil}^{m} using the provided regression equations. This is especially evident if we look at very low values of r ratios.

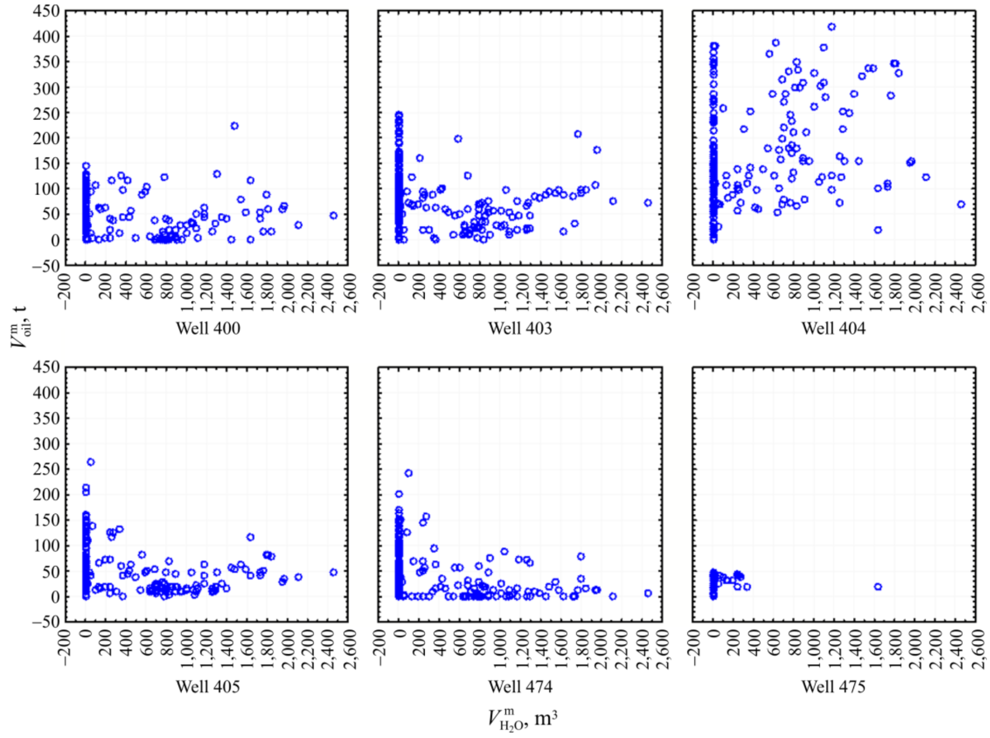

Fig. 4. Field of correlation between $V_{H_2O}^{m}$ and V_{oil}^{m}

Table 1

The constant and slope terms and correlation ratio of regression equation showing the dependence of V_{oil}^{m} on $V_{H_2O}^{m}$ (upper line), dependence of V_{oil} on V_{H_2O} (lower line) for Well 401

Well	Constant	Slope term	Correlation ratio r
400	52.973 5067.247	–0.009 0.142	–0.126 0.851
403	83.907 5796.922	–0.018 0.23	–0.183 0.897
404	126.459 4372.826	0.062 0.435	0.349 0.986
405	67.508 6100,174	–0.026 0.155	–0.323 0.841
474	40.766 4372,232	–0.019 0.077	–0.237 0.75
475	28.31 241.74	–0.001 0.612	–0.016 0.953
All wells	71.603 4701.201	0.0005 0.222	0.0041 0.749

In order to assess the effectiveness of water injection into the formation it is proposed to use the dependence of impact rendered by the accumulated volume of injected water (V_{H_2O}) on the accumulated oil production (V_{oil}) based on the information for 259 months.

The dependencies of V_{oil} on V_{H_2O} for the wells under review are shown in Fig. 5.

It can be seen that as opposed to the previous graphs, in these graphs when the values of V_{H_2O} increase, the values of V_{oil} also go up, however, the gradients are individual for each well. The values of r and regression equations of V_{oil} dependence on V_{H_2O} are set out in Table 1. The values of r are high for all the wells and statistically significant by t criteria, which may indicate an actual impact of V_{H_2O} on V_{oil} across all the wells.

The analysis of dependencies of V_{oil} on V_{H_2O}, set out in Fig. 5, shows that in all the cases within the graph there are three areas, which can be visually observed, where the correlations feature high degree of linearity in a certain range. In order to determine the boundaries of these almost linear sections, where the impact of V_{H_2O} values on V_{oil} is relatively homogenous, we will use the linear discriminant analysis (LDA). The options for the application of statistical methods of analysis in academic research to solve similar tasks are set out in studies [6-23].

Plotting the graph of a linear discriminant function (LDF) is performed in the following manner.

If we designate as X_{ij} the value of the variable under number i in the point of observation under number j, taken from the sample within the first correlation interval in respect of V_{oil} and V_{H_2O}, then we will get the matrix W_1 with degree m and n_1 showing the results of observations over this sample:

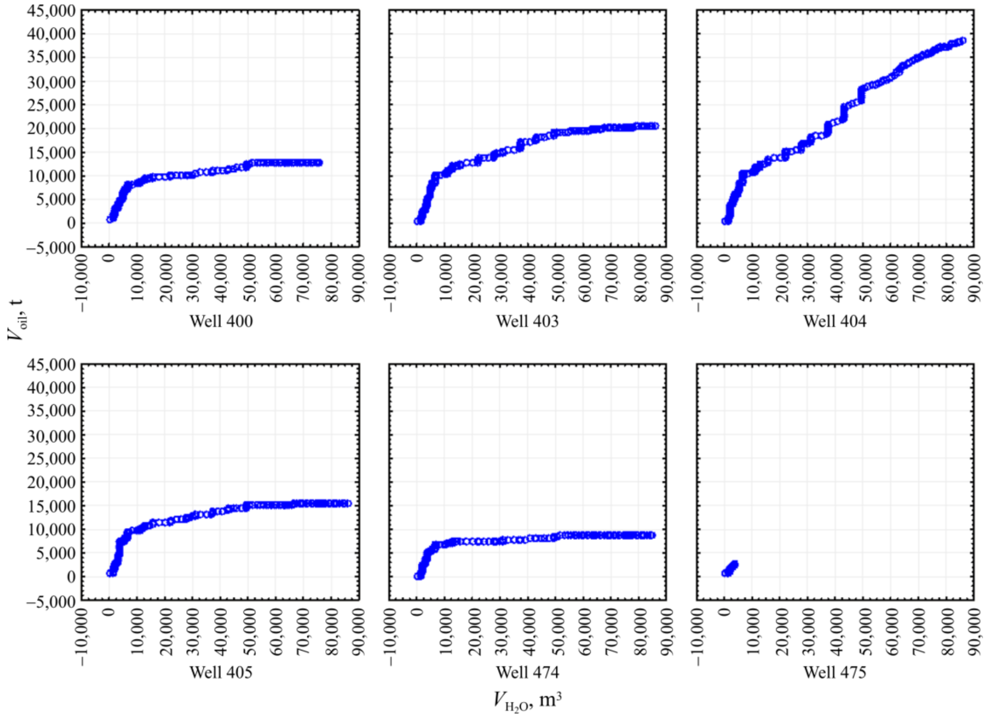

Fig. 5. Change in V_{oil} values depending on V_{H_2O} by well

$$W_1 = \begin{bmatrix} X_{11} & X_{12} & . & X_{1n_1} \\ X_{21} & X_{22} & . & X_{2n_1} \\ . & . & . & . \\ X_{m_1} & X_{m_2} & . & X_{mn_1} \end{bmatrix}.$$

Designating as X_{ij}^1 the result of measuring the variable under number i in the point under number j, taken from the second correlation interval, we will get the matrix W_2 with degree $m \times n_2$:

$$W_2 = \begin{bmatrix} X_{11}^1 & X_{12}^1 & . & X_{1n_2} \\ X_{21}^1 & X_{22}^1 & . & X_{2n_2}^1 \\ . & . & . & . \\ X_{m_1}^1 & X_{m_2}^1 & . & X_{mn_2}^1 \end{bmatrix}.$$

Designating as X_{ij}^2 the result of measuring the variable under number i in the point under number j, taken from the third correlation interval, we will get the matrix W_3 with degree $m \times n_3$:

$$W_3 = \begin{bmatrix} X_{11}^2 & X_{12}^2 & . & X_{1n_2} \\ X_{21}^2 & X_{22}^{21} & . & X_{2n_2}^2 \\ . & . & . & . \\ X_{m_1}^2 & X_{m_2}^2 & . & X_{mn_2}^2 \end{bmatrix},$$

where m is the number of indicators; n_1, n_2, n_3 is the sample volume.

In order to plot LDF, the matrixes of centered sums of squares and shifted products are composed for calculating the sample matrix.

Then, a reverse sample covariance matrix C is found for determining the ratios of the linear discriminant function.

Then, boundary values of discriminant functions (R_0) are determined, which divide the sample into three subsets [24-27].

They are used to calculate linear discriminant functions, to determine the percentage of correct discernment until the entire sample is divided into three non-crossing classes [28-31]. We will now show an example of plotting the linear discriminant function for Wells 400 and 401.

$$Z_1 = 0{,}000478\, V_{H_2O} - 0{,}003641\, V_{oil} + 9{,}87395$$

with $R = 0{,}928$, $\chi^2 = 692{,}49$, $p = 0{,}000000$.

$$Z_2 = -0{,}0003\, V_{H_2O} + 0{,}00064\, V_{oil} - 2{,}22779$$

with $R = 0{,}655$, $\chi^2 = 143{,}18$, $p = 0{,}000000$,

where V_{oil} is the volume of accumulated oil, tons (Q_{oil} accumulated, tons), V_{H_2O} the accumulated injection volume ($Q_{injection}$ accumulated, m^3). The first boundary has V_{H_2O} = 5084 m^3, the second – 43,277 m^3.

Using these boundaries, we have composed regression equations for the dependence of V_{oil} on V_{H_2O} (Table 2). LDFs were also plotted for other wells, which were used to determine the classes' boundaries for the dependence of V_{oil} on V_{H_2O}, within which regression equations were composed (see Table 2) [32-36].

Table 2

Assessment of impact of V_{H_2O} in the injection well 401 on V_{oil} in producing wells 400, 403-405, 474, 475

Interval of values V_{H_2O}, m^3	Constant	Slope term	Correlation ratio r
Well 400			
0-5,084	174.805	1.066	0.951
5,084-43,277	7,008.907	0.113	0.914
Over 43,277	10,673.574	0.034	0.819
Well 403			
0-5,084	–990.09	1.380	0.956
5,084-58,426	7,835.362	0.228	0.973
Over 58,426	17,682.610	0.034	0.978
Well 404			
0–3,942	–1,524.131	1.897	0.899
3,942–43,277	6,267.128	0.373	0.976
Over 43,277	9,846.542	0.349	0.989
Well 405			
0-3,942	–850.407	1.521	0.956
3,942-57,535	7,821.541	0.153	0.950
Over 57,535	14,066.0569	0.019	0.992
Well 474			
0-3,942	–1,193.225	1.388	0.874
3,942-50,735	5,666.771	0.064	0.833
Over 50,735	8,123.062	0.011	0.891
Well 475			
0-1,780	–3,351.323	2.584	0.754
1,780-3,107	535.3272	0.545	0.967
Over 3,107	1,519.468	0.272	0.654

It can be seen that the impact of V_{H_2O} on V_{oil} of the Well 401 is different in the highlighted intervals. We note that for all the wells the minimum impact is observed in the third interval (minimum slope term) and maximum – in the first.

The dependence of accumulated oil production on the accumulated injection in the third interval is presented in Fig. 6.

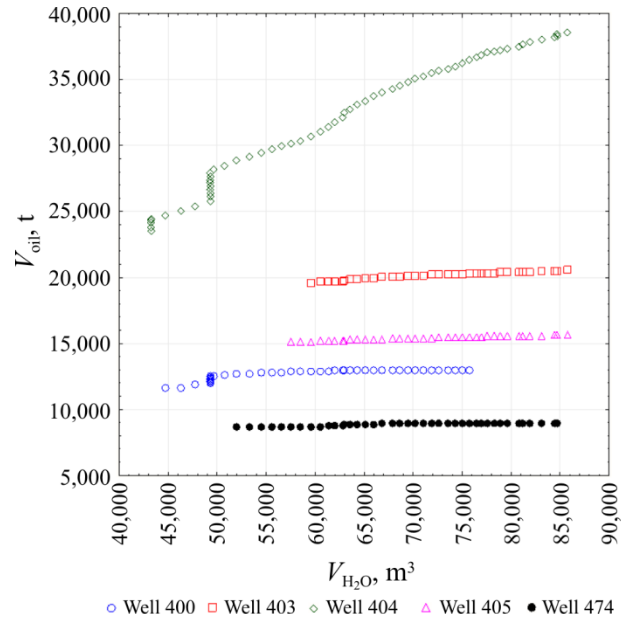

Fig. 6. Change in the values of V_{oil} depending on V_{H_2O} in the third interval

Regression equations between injection well 401 and producing wells:

Well 400: $V_{oil} = 10{,}673.574 + 0.0338\,V_{H_2O}$;

Well 403: $V_{oil} = 17{,}682.6099 + 0.034\,V_{H_2O}$;

Well 404: $V_{oil} = 9{,}846.5421 + 0.3493\,V_{H_2O}$;

Well 405: $V_{oil} = 14{,}066.0569 + 0.0188\,V_{H_2O}$;

Well 474: $V_{oil} = 8{,}123.0623 + 0.0107\,V_{H_2O}$.

Having analyzed the obtained graph and regression equation, we can say that the highest slope term is featured by the Well 404 (0.3493) and the lowest – by Well 474 (0.0107). The slope term of other wells ranges from 0.0188 to 0.034.

Method of assessing the impact of water injection into the formation on oil production for Well 407. The method of assessing the impact of water injection into the formation on the production of oil uses the information on Well 407 for the period from July, 1993, to June, 2015, i.e. for 264 months ($n = 264$).

On the basis of this information we will assess the impact of the monthly volume of water injected into the formation $V^{m}_{H_2O}$ on the monthly oil production V^{m}_{oil}.

For the purposes of the method development, the values of $V^{m}_{H_2O}$ for the injection wells located in different reservoir areas were used. We assume that the injection of water into this well will have an impact on the monthly production of oil by wells 403, 405, 474, 475, 478. The change of values of V^{m}_{oil} in time t is shown in Fig. 7.

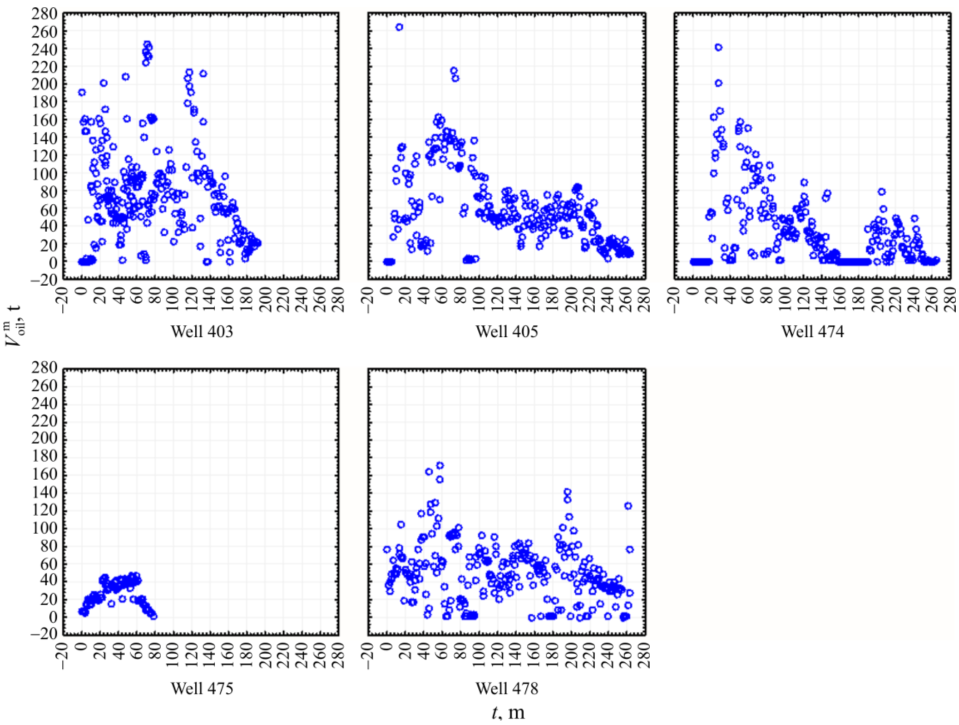

Fig. 7. Change of values of V^{m}_{oil} in time t by wells

It is seen that the values of V_{oil}^{m} vary significantly by well.

The change of values of $V_{H_2O}^{m}$ in time for Well 407 is shown in Fig. 8.

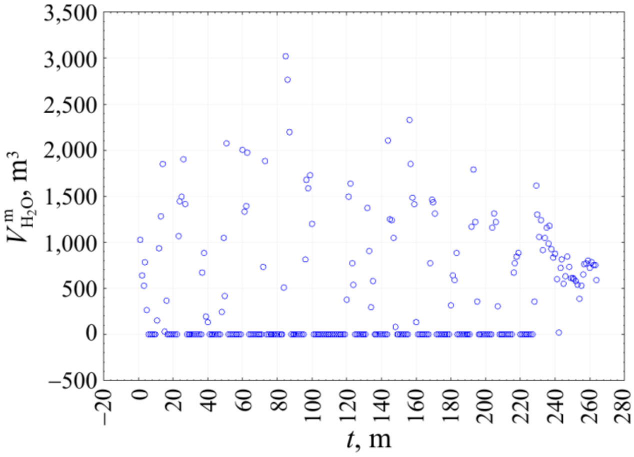

Fig. 8. Change of values of $V_{H_2O}^{m}$ in time for the Well 407

According to Fig. 8, the dependence of $V_{H_2O}^{m}$ values on *t* has a quite complicated form.

In order to compare the values of $V_{H_2O}^{m}$ and V_{oil}^{m} for the two reviewed options of impact of the injection wells, correlation fields set out in Fig. 9 were built for the injections wells.

The values of $V_{H_2O}^{m}$ and V_{oil}^{m} have a weak correlation, i.e. it is impossible to prove in statistical terms the impact of $V_{H_2O}^{m}$ values on V_{oil}^{m} values. Now we are going to prove this statement with the calculations of r and making regression equations V_{oil}^{m} (oil production for a month, tons) will be a dependent attribute, and $V_{H_2O}^{m}$ (water injection into the formation for a month, m^3) will be an independent factor.

As a result of this method application, the values of *r* were calculated and regression equations were made for the following options:

Based on the information about each well;

b) based on the information about all wells.

The values of *r* and regression equations of V_{oil}^{m} dependence on $V_{H_2O}^{m}$ in the above options are set out in Table 3.

The analysis of the constant and slope terms of a regression equation and *r* ratio indicates that it is not possible to measure the impact of $V_{H_2O}^{m}$ on V_{oil}^{m} using the provided regression equations. This is especially evident if we look at very low values of *r* ratios.

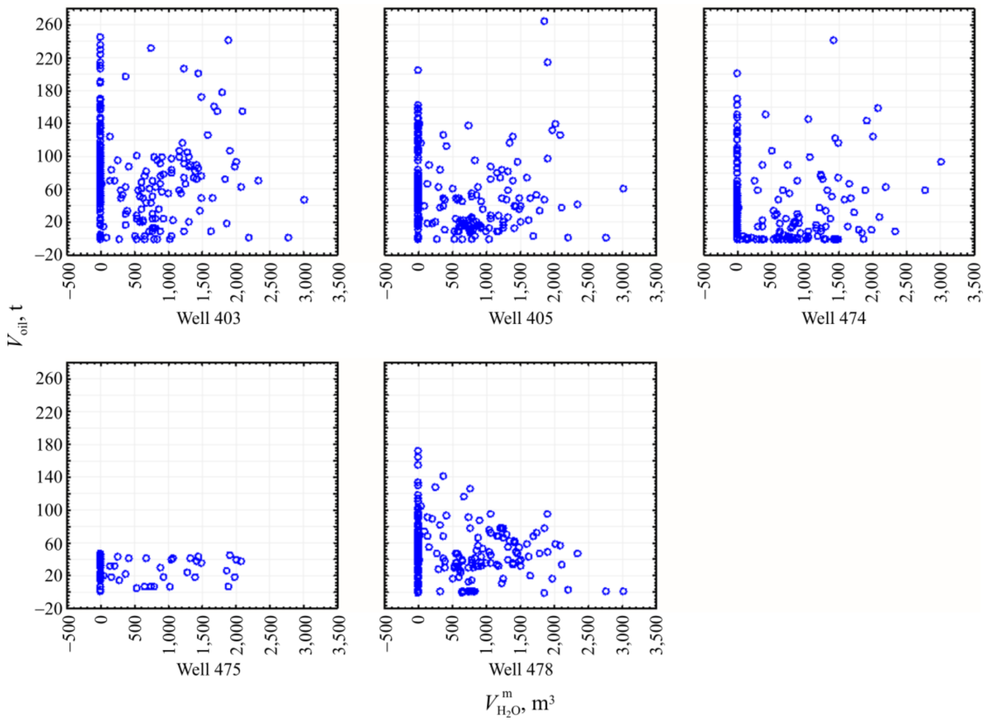

Fig. 9. Correlation plot of $V_{H_2O}^{m}$ and V_{oil}^{m}

Table 3

Constant and slope terms and correlation ratio of regression equation showing the dependence of V^{m}_{oil} on $V^{m}_{H_2O}$ (upper line), dependence of V_{oil} on V_{H_2O} (lower line) for Well 407

Well	Constant	Slope term	Correlation ratio r
403	79.540 –534.195	–0.005 0.210	–0.063 0.990
405	62.82 1,060.251	–0.009 0.1539	–0.128 0.974
474	31.497 1,414.276	0.005 0.084	0.081 0.930
475	24.855 379.986	0.003 0.079	0.131 0.978
478	54.048 2,296.74	0.008 0.127	–0.153 0.990
All wells	54.647 741.962	0.004 0.148	–0.048 0.888

In order to assess the effectiveness of water injection into the formation, it is proposed to use the dependence of impact rendered by the accumulated volume of injected water (V_{H_2O}) on the accumulated oil production (V_{oil}) based on the information for 264 months. The dependencies of V_{oil} on V_{H_2O} for the wells under review are shown in Fig. 10.

The analysis of information in Fig. 10 allowed concluding that as opposed to the previous graphs, in these graphs when the values of V_{H_2O} increase, the values of V_{oil} also go up, however, the gradients are individual for each well. The values of r and regression equations of V_{oil} on V_{H_2O} are set out in Table 4. The values of r are high for all the wells and statistically significant by t criteria, which may indicate an actual impact of V_{H_2O} on V_{oil} across all the wells.

The analysis of dependencies of V_{oil} on V_{H_2O} set out in Fig. 10, shows that in all the cases within the graph there are three areas, which can be visually observed, where the correlations feature high degree of linearity in a certain range. In order to determine the boundaries of these almost linear sections, where the impact of V_{H_2O} values on V_{oil} is relatively homogenous, we will use the linear discriminant analysis [37-41].

Example of plotting the linear discriminant function for Wells 403 and 407:

$$Z_1 = -0.000146\,V_{H_2O} - 0.001917\,V_{oil} + 9.669477$$

with $R = 0.943$, $\chi^2 = 643.21$, $p = 0.000000$;

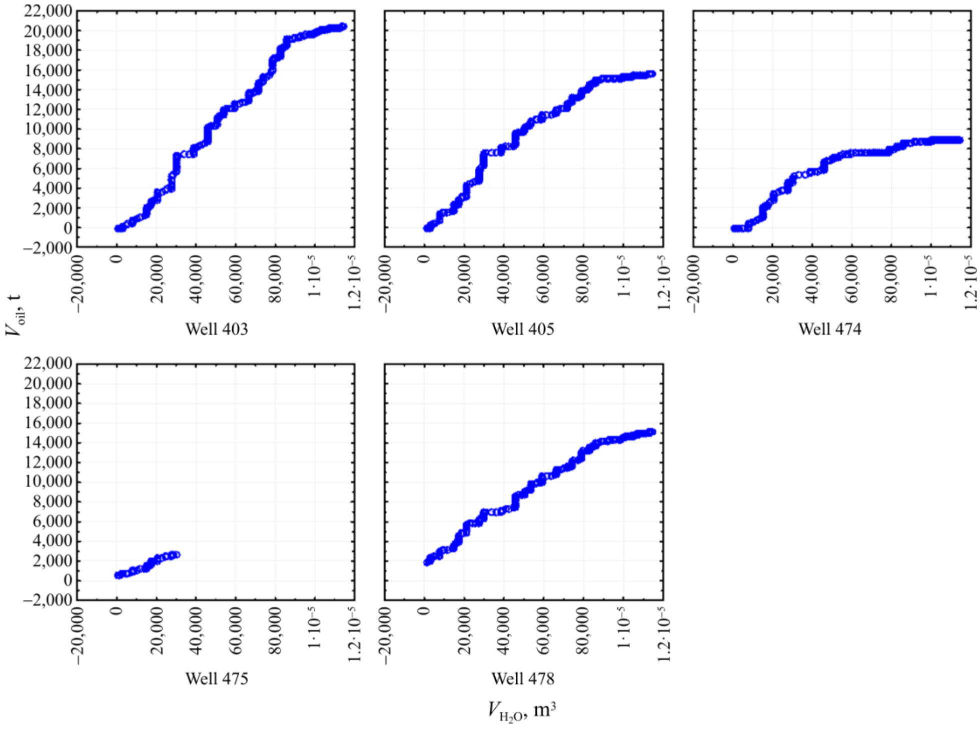

Fig. 10. Change in V_{oil} values depending on V_{H_2O} by well

$$Z_2 = -0.00024\,V_{H_2O} + 0.0018\,V_{oil} - 3.54019$$

with R = 0.338, χ^2 = 31.74, p = 0.000000, where V_{oil} is the volume of accumulated oil, tons (Q_{oil} accumulated, tons) and V_{H_2O} is the accumulated injection volume ($Q_{injection}$ accumulated, m^3).

Based on these functions, the values Z_1 and Z_2 were calculated, and they were further used to determine the boundaries of classes in respect of the ratio of V_{oil} to V_{H_2O}.

The first boundary has the value of V_{H_2O} = 30,187 m^3, the second = 71,595 m^3. Using these boundaries, we have composed regression equations for the dependence of V_{oil} on V_{H_2O} (see Table 4). LDFs were also plotted for other wells, which were used to determine the classes' boundaries for the dependence of V_{oil} on V_{H_2O} within which regression equations were composed (see Table 2).

Table 4

Assessment of impact of V_{H_2O} in the injection well 407 on V_{oil} in producing wells 403, 405, 474, 475, 478

Interval of values V_{H_2O}, m^3	Constant	Slope term	Correlation ratio r
Well 403			
0-30,187	–839.435	0.191	0.978
30,187-71,595	991.844	0.189	0.980
Over 71,595	5,703.416	0.139	0.911
Well 405			
0-27,569	–582.34	0.197	0.978
27,569-63,580	1,752.795	0.161	0.976
Over 63,580	6,764.785	0.085	0.918
Well 474			
0-20,873	–835.455	0.1745	0.956
20,873-68,849	1,941.655	0.093	0.961
Over 68,849	4,972.493	0.038	0.945
Well 475			
0-5,630	567.945	0.045	0.858
5,630-17,088	369.914	0.069	0.942
Over 17,088	913.695	0.059	0.957
Well 478			
0-17,088	1,762.347	0.128	0.959
17,088-53,669	2,861.668	0.117	0.972
Over 53,669	4,788.573	0.098	0.966

It can be seen that the impact of V_{H_2O} on V_{oil} of Well 407 is different in the highlighted intervals. We note that for wells 403, 405, 474, 478 the minimum impact is observed in the third interval (minimal slope term) and maximum – in the first. For well 475, the minimum impact is observed in the first interval, and maximum – in the second.

The graph showing the changes of $V_{нефти}$ values depending on the value of V_{H_2O} in the third interval is shown in Fig. 11.

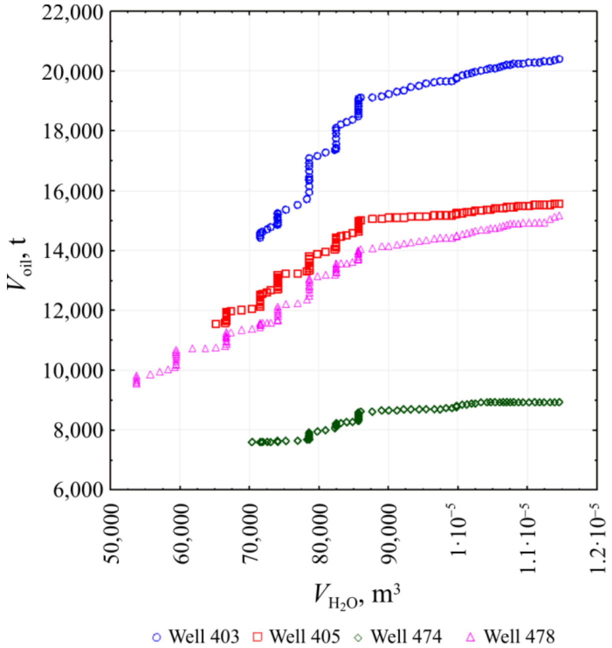

Fig. 11. Change in the values of V_{oil} depending on V_{H_2O} in the third interval

Regression equations between injection well 407 and producing wells:

Well 403: $V_{oil} = 5{,}703.4162 + 0.139\,V_{H_2O}$;

Well 405: $V_{oil} = 6{,}764.7847 + 0.0845\,V_{H_2O}$;

Well 474: $V_{oil} = 4{,}972.4927 + 0.0377\,V_{H_2O}$;

Well 478: $V_{oil} = 4{,}788.5732 + 0.0977\,V_{H_2O}$.

Having analyzed the obtained graph and regression equation, we can say that the highest slope term is featured by Well 403 (0.139) and the lowest – by Well 474 (0.0377). The slope term of other wells ranges from 0.0845 to 0.0977.

The method of assessing the impact of water injection into the formation on oil production for Well 424. The method of assessing the impact of water injection into the formation on the production of oil uses the information on Well 424 for the period from August, 1993, to February, 2016, i.e. for 271 months (n = 271).

On the basis of this information we will assess the impact of the monthly volume of water injected into the formation $V^{m}_{H_2O}$ on the monthly oil production V^{m}_{oil}.

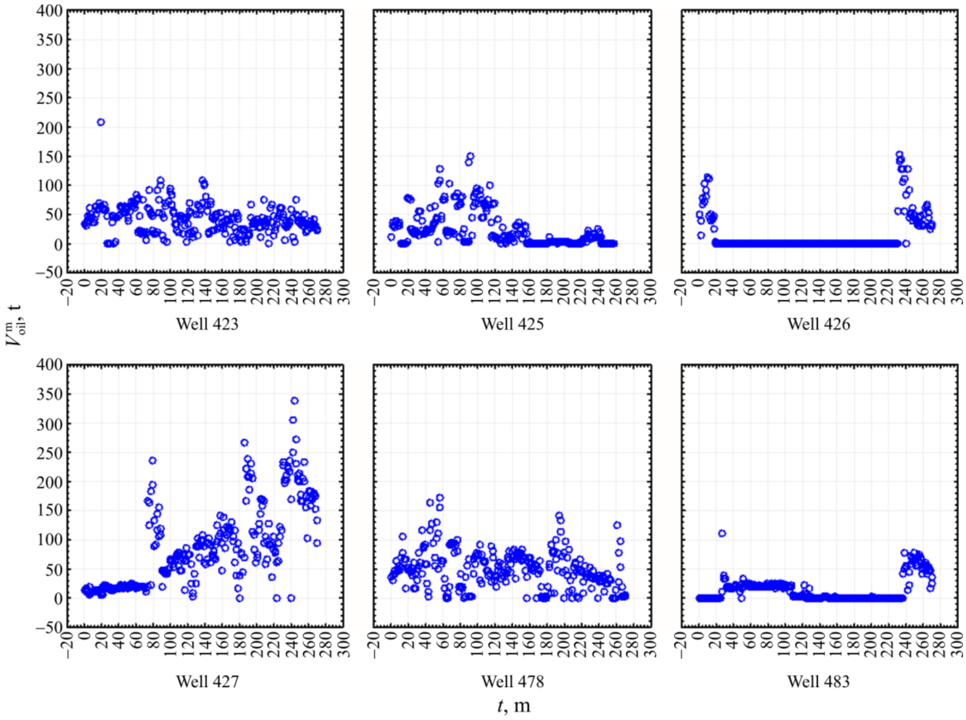

Fig. 12. Change of values of V^{m}_{oil} in time t by wells

For the purposes of the method development, the values of $V^{m}_{H_2O}$ for the injection wells located in different reservoir areas were used. We assume that the injection of water into this well will have an impact on the monthly production of oil by wells 210, 423, 425, 427, 478, 483.

The change of values of V^{m}_{oil} is time t is shown in Fig. 12.

It is seen that the values of V^{m}_{oil}, tons, vary significantly by well.

The change of values of $V^{m}_{H_2O}$ in time for Well 424 is shown in Fig. 13.

The change of values of $V^{m}_{H_2O}$ depending on t has quite a complex view.

In order to compare the values of $V^{m}_{H_2O}$ and V^{m}_{oil} for the two reviewed options of impact of the injection wells, correlation plots set out in Fig. 14 were built for the injections wells.

The values of $V^{m}_{H_2O}$ and V^{m}_{oil} have a weak correlation, i.e. it is impossible to prove in statistical terms the impact of $V^{m}_{H_2O}$ values on V^{m}_{oil} values. Now we are going to prove this statement with the calculations of r and composing regression equations. V^{m}_{oil} (oil production for a month, tonnes) will be a dependent attribute and $V^{m}_{H_2O}$ (water injection into the formation for a month, m^3) will be an independent factor.

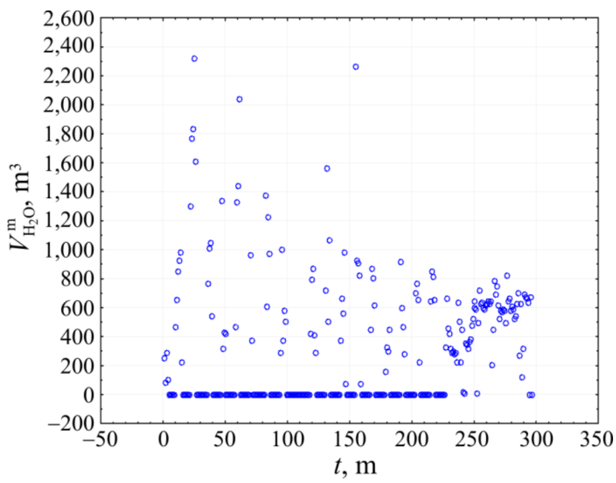

Fig. 13. Change of values of $V^{m}_{H_2O}$ in time for Well 424

As a result of this method application, the values of r were calculated and regression equations were made for the following options:

a) based on the information about each well;

b) based on the information about all the wells.

The values of r and regression equations of V^{m}_{oil} dependence on $V^{m}_{H_2O}$ in the above options are set out in Table 5.

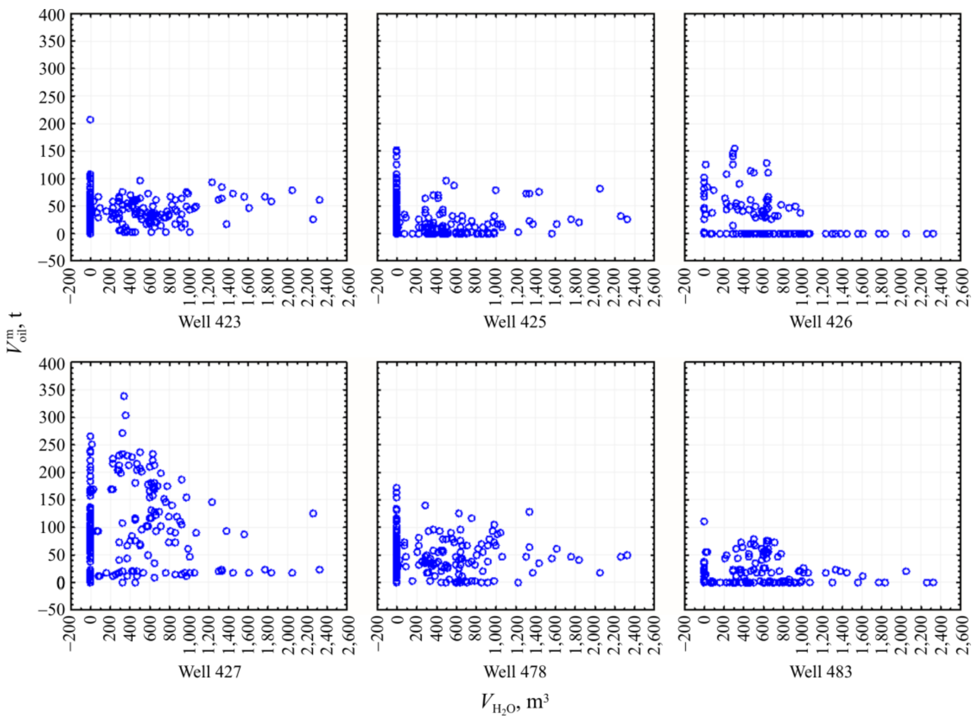

Fig. 14. Correlation plot of $V^{m}_{H_2O}$ and V^{m}_{oil}

Table 5

Absolute and corner terms and correlation ratio of regression equation showing the dependence of V^{m}_{oil} on $V^{m}_{H_2O}$ (upper line), dependence of V_{oil} on V_{H_2O} (lower line) for Well 424

Well	Constant	Slope term	Correlation ratio r
423	41.059 1,514.586	0.0026 0.162	0.046 0.993
426	12.186 3,257.244	0.005 0.023	0.005 0.681
483	12.946 643.638	0.005 0.042	0.104 0.941
427	85.255 –4,321.115	0.0128 0.337	0.079 0.957
425	24.601 1,110.278	–0.005 0.108	–0.07 0.937
478	51.725 1,527.189	–0.007 0.199	–0.092 0.994
All wells	38.205 568.990	0.003 0.147	0.0023 0.642

The analysis of the values of constant and slope terms of a regression equation and r ratio indicates that it is not possible to measure the impact of $V^{m}_{H_2O}$ on V^{m}_{oil} using the provided regression equations. This is especially evident if we look at very low values of r ratios.

In order to assess the effectiveness of water injection into the formation, it is proposed to use the dependence of impact rendered by the accumulated volume of injected water (V_{H_2O}) on the accumulated oil production (V_{oil}) based on the information for 271 months.

The dependencies of V_{oil} on V_{H_2O} for the wells under review are shown in Fig. 15.

It can be seen that as opposed to the previous graphs, in Fig. 15 when the values of V_{H_2O} increase, the values of V_{oil} also go up, however, the gradients are individual for each well. The values of r and regression equations of V_{oil} on V_{H_2O} are set out in Table 6. The values of r are high for all the wells and statistically significant by t criteria, which may indicate an actual impact of V_{H_2O} on V_{oil} across all the wells.

The analysis of dependencies of V_{oil} on V_{H_2O} set out in Fig. 15, shows that in all the cases within the graph there are three areas, which can be visually observed, where the correlations feature in a certain range high degree of linearity. In order to determine the boundaries of these almost linear sections, where the impact of V_{H_2O} values on V_{oil} is relatively homogenous, we will use the linear discriminant analysis.

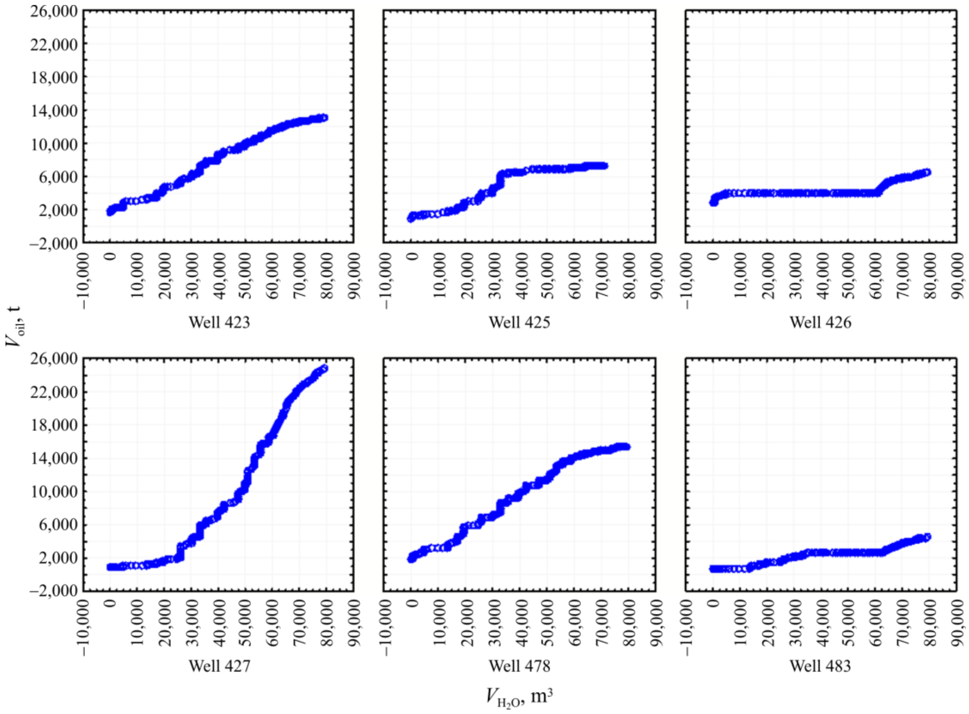

Fig. 15. Change of V_{oil} values depending on V_{H_2O} by wells

Example of plotting the linear discriminant function for Wells 423 and 424:

$$Z_1 = -0.000208\,V_{H_2O} + 0.000728\,V_{oil} + 5.89479$$

with $R = 0.943$, $\chi^2 = 707.431$, $p = 0.000000$;

$$Z_2 = -0.0005\,V_{H_2O} + 0.00285\,V_{oil} - 2.87433$$

with $R = 0.679$, $\chi^2 = 165.59$, $p = 0.000000$.

Based on these functions, the values Z_1 and Z_2 were calculated, and they were further used to determine the boundaries of classes in respect of the ratio of V_{oil} to V_{H_2O}.

Close to the first boundary, V_{H_2O} = 33,029 m^3, and close to the second boundary – to 71,261 m^3.

Using these boundaries, we have composed regression equations in respect of dependence of V_{oil} on V_{H_2O}. LDFs were also plotted for other wells, which were used to determine the classes' boundaries for the dependence of V_{oil} on V_{H_2O}. within which regression equations were composed (see Table 6).

It can be seen that the impact of V_{H_2O} on V_{oil} of Well 424 is different in the highlighted intervals. We note that the minimum impact is observed in the first interval for Wells 427 and 483, and in the third interval – for Wells 423, 425 and 478, in the second – for Well 426

Table 6

Assessment of impact of V_{H_2O} in injection well 424 on V_{oil} in producing wells 423, 425, 426, 427, 478, 483

Interval of values V_{H_2O}, m^3	Constant	Slope term	Correlation ratio r
Well 423			
0-33,029	1,670.640	0.142	0.983
33,029-71,261	2,232.123	0.152	0.995
Over 71,261	8,735.536	0.055	0.997
Well 425			
0-30,293	730.656	0.102	0.949
30,293-49,389	2,333.654	0.101	0.828
Over 49,389	5,763.419	0.0213	0.961
Well 426			
0-722	2,627.573	0.730	0.612
722-63,501	3,850.544	0.002	0.376
Over 63,501	–609.562	0.09	0.979
Well 427			
0-13,643	881.735	0.026	0.968
13,643-53,500	–4,865.397	0.31	0.984
Over 53,500	–10,613.584	0.462	0.991
Well 478			
0-22,736	1,947.028	0.149	0.941
22,736-69,281	973.125	0.215	0.993
Over 69,281	10,638.89	0.06	0.942
Well 483			
0-24,779	492.676	0,041	0.933
24,779-68,189	1,661.532	0,02	0.806
Over 68,189	–2,481.698	0,09	0.992

(minimum slope term). The maximum impact is observed in the first interval for Wells 425 and 426, in the second – for Wells 427 and 483 (maximum slope term).

The graph showing the changes of V_{oil} values depending on the value of V_{H_2O} in the third interval is shown in Fig. 16.

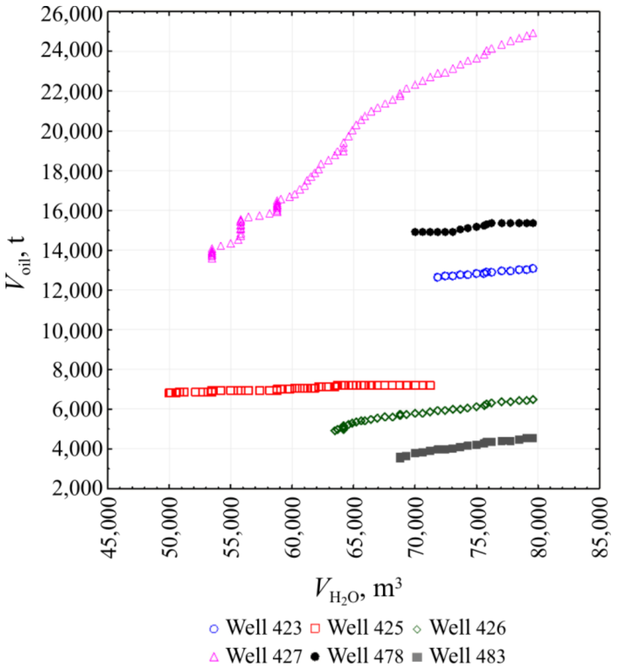

Fig. 16. Change in the values of V_{oil} depending on V_{H_2O} in the third interval

Regression equations between injection well 424 and producing wells:

Well 423: $V_{oil} = 8{,}735.5356 + 0.0545\,V_{H_2O}$;

Well 425: $V_{oil} = 5{,}763.4186 + 0.0213\,V_{H_2O}$;

Well 426: $V_{oil} = –609.5622 + 0.0905\,V_{H_2O}$;

Well 427: $V_{oil} = –10{,}613.5839 + 0.4615\,V_{H_2O}$;

Well 478: $V_{oil} = 10{,}638.8898 + 0.0604\,V_{H_2O}$;

Well 483: $V_{oil} = –2{,}481.6977 + 0.0891\,V_{H_2O}$.

Having analyzed the obtained graph and regression equation, we can say that the highest slope term is featured by Well 427 (0.4615) and the lowest – by Well 425 (0.0213). The slope term of other wells ranges from 0.0545 to 0.0905.

The method of assessing the impact of water injection into the formation on oil production for Well 472. The method of assessing the impact of water injection into the formation on the production of oil uses the information on the Well 472 for the period from July, 1993, to February, 2015, i.e. for 260 months ($n = 260$).

On the basis of this information, we have assessed the impact of the monthly volume of water injected into the formation $V^{m}_{H_2O}$ on the monthly oil production V^{m}_{oil}.

For the purposes of the method development, the values of $V^{m}_{H_2O}$ for the injection wells located in different reservoir areas were used. We assume that the injection of water into this well will have

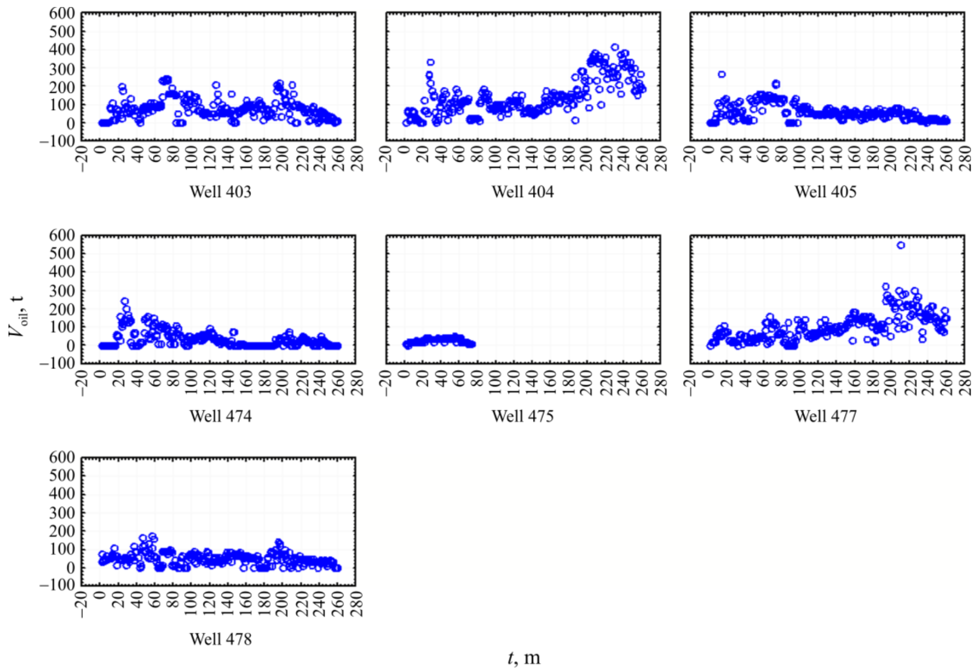

Fig. 17. Change of values of V^{m}_{oil} in time t by wells

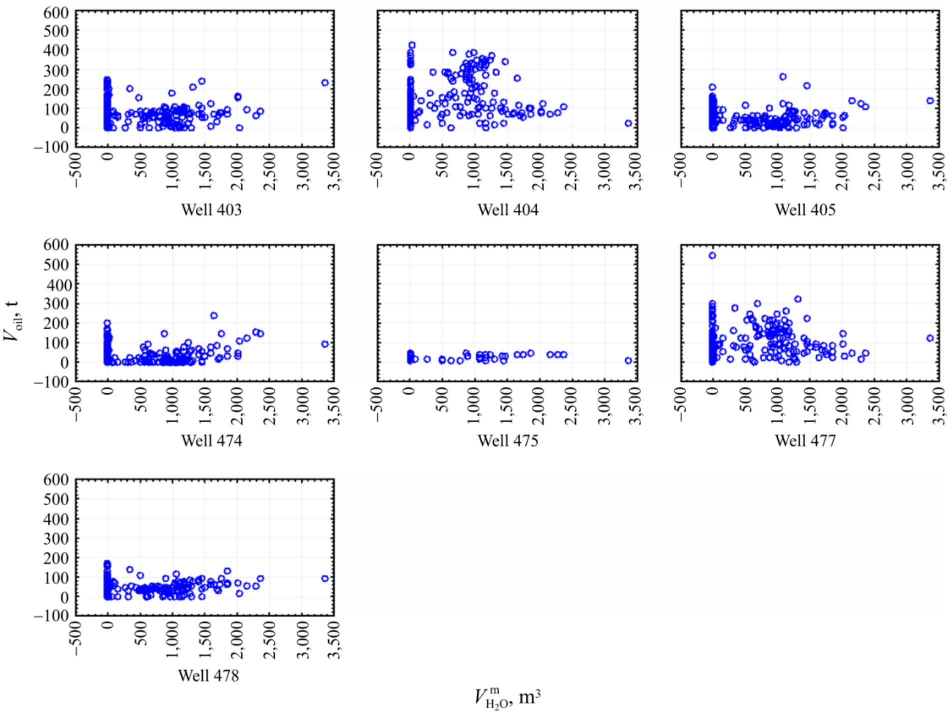

Fig. 19. Field of correlation between $V^{m}_{H_2O}$ and V^{m}_{oil}

an impact on the monthly production of oil by wells 403-405, 474, 475, 477, 478. The change of values of V^{m}_{oil} is time t is shown in Fig. 17.

The analysis of Fig. 17 shows that the values of V^{m}_{oil} by wells differ materially.

The change of values of $V^{m}_{H_2O}$ in time for Well 424 is shown in Fig. 18.

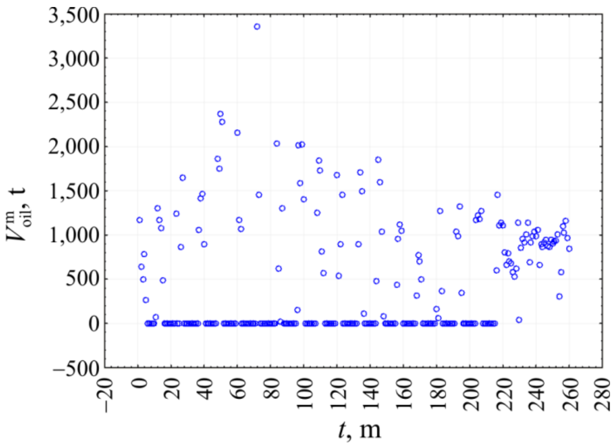

Fig. 18. Change of values of $V^{m}_{H_2O}$ in time for Well 472

The change of values of $V^{m}_{H_2O}$ depending on t has quite a complex view.

In order to compare the values of $V^{m}_{H_2O}$ and V^{m}_{oil} for the two reviewed options of impact of the injection wells, correlation fields set out in Fig. 19 were built for the injections wells.

The values of $V^{m}_{H_2O}$ and V^{m}_{oil} have a weak correlation, i.e. it is impossible to prove in statistical terms the impact of $V^{m}_{H_2O}$ values on V^{m}_{oil} values. Now we are going to prove this statement with the calculations of r and making regression equations. We will take V^{m}_{oil}, as a slope term and $V^{m}_{H_2O}$ as a constant.

As a result of this method application, the values of r were calculated and regression equations were made for the following options:

a) based on the information about each well;

b) based on the information about all the wells.

The values of *r* and regression equations of V^{m}_{oil} dependence on $V^{m}_{H_2O}$ in the above options are set out in Table 7.

The analysis of the values of constant and slope terms of a regression equation and *r* ratio indicates that it is not possible to measure the impact of $V^{m}_{H_2O}$ on V^{m}_{oil} using the provided regression equations. This is especially evident if we look at very low values of *r* ratios.

In order to assess the effectiveness of water injection into the formation, it is suggested to use the following dependencies

Table 7

Absolute and corner terms and correlation ratio of regression equation showing the dependence of V_{oil}^{m} on $V_{H_2O}^{m}$ (upper line), dependence of V_{oil} on V_{H_2O} (lower line) for Well 472

Well	Constant	Slope term	Correlation ratio *r*
403	81.348 –519.835	0.007 0.204	–0.083 0.988
404	129.69 –3,658.375	0.026 0.315	0.167 0.974
405	64.540 1,023.096	–0.011 0.151	–0.151 0.974
474	29.808 1,345.355	0.01 0.083	0.146 0.938
475	26.884 501.645	0.001 0.071	0.066 0.988
477	100.175 –3,635.677	0.006 0.246	0.046 0.964
478	50.446 2,306.813	–0.00006 0.124	–0.001 0.988
All wells	54.647 741.962	–0.004 0.148	–0.048 0.888

of impact of the accumulated water injection volume (V_{H_2O}) on the accumulated oil production volume (V_{oil}) based on the information for 260 months. The dependencies of V_{oil} on V_{H_2O} for the wells under review are shown in Fig. 20.

It can be seen that as opposed to the previous graphs, in Fig. 20 when the values of V_{H_2O} increase, the values of V_{oil} also go up, however, the gradients are individual for each well. The values of r and regression equations of V_{oil} on V_{H_2O} are set out in Table 8. The values of *r* are high for all the wells and statistically significant by *t* criteria, which may indicate an actual impact of V_{H_2O} on V_{oil} across all the wells.

The analysis of dependencies of V_{oil} on V_{H_2O} set out in Fig. 20, shows that in all the cases within the graph there are three areas, which can be visually observed, where the correlations feature in a certain range high degree of linearity. In order to determine the boundaries of these almost linear sections, where the impact of V_{H_2O} values on V_{oil} is relatively homogenous, we will use the linear discriminant analysis.

Example of plotting the linear discriminant function for Wells 403 and 472:

$$Z_1 = -0.00023\,V_{H_2O} + 0.000941\,V_{oil} + 3.899984$$

with $R = 0.942$, $\chi^2 = 760.4577$, $p = 0.000000$;

$$Z_2 = 0.000174\,V_{H_2O} - 0.001254\,V_{oil} + 2.145452$$

with $R = 0.732$, $\chi^2 = 196.9258$, $p = 0.000000$.

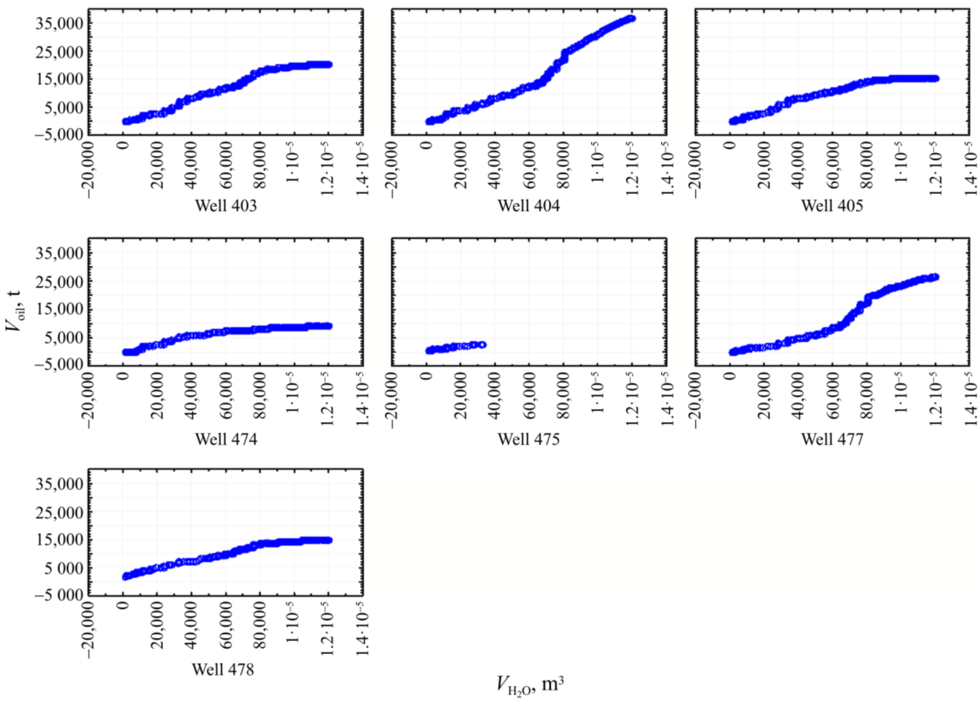

Fig. 20. Change in V_{oil} values depending on V_{H_2O} by well

Based on these functions, the values Z_1 and Z_2 were calculated, and they were further used to determine the boundaries of classes in respect of the ratio of V_{oil} to V_{H_2O}.

The first boundary has the value of V_{H_2O} = = 33,029 m^3, the second – of 71,595 m^3. Using this information, we have composed regression equations for the dependence of V_{oil} on V_{H_2O} (see Table 8). LDFs were also plotted for other wells, which were used to determine the classes' boundaries for the dependence of V_{oil} on V_{H_2O} within which regression equations were composed.

Table 8

Assessment of impact of V_{H_2O} in injection well 472 on V_{oil} in producing wells 403-405, 474, 475, 477, 478

Interval of values V_{H_2O}, m^3	Constant	Slope term	Correlation ratio r
Well 403			
0-45,932	–1,087.158	0.221	0.980
45,932-100,403	–2,016.843	0.232	0.979
Over 100,403	16,070.244	0.036	0.973
Well 404			
0-39,673	–581.660	0.215	0.989
39,673-80,967	–7,428.683	0.339	0.957
Over 80,967	–3,801.333	0.346	0.995
Well 405			
0-45,932	–609.042	0.212	0.988
45,932-95,653	1,784.522	0.150	0.985
Over 95,653	13,354.822	0.018	0.994
Well 474			
0-41,258	–571.296	0.162	0.987
41,258-88,637	3,863.416	0.053	0.956
Over 88,637	7,274.674	0.015	0.967
Well 475			
0-11,236	491.402	0.064	0.963
11,236-19,679	602.126	0.072	0.939
Over 19,679	723.364	0.062	0.894
Well 477			
0-68,288	–859.575	0.149	0.981
68,288-80,967	– 24,166.504	0.522	0.969
Over 80,967	2,835.772	0.204	0.986
Well 478			
0-39,673	1,785.563	0.145	0.996
39,673-98,498	1,065.275	0.146	0.984
Over 98,498	11,398.578	0.03	0.985

It can be seen that the impact of V_{H_2O} on V_{oil} of Well 424 is different in the highlighted intervals. We note that for wells 403, 405, 474, 475 and 478 the minimum impact is observed in the third interval (minimal slope term) and maximum – in the second. For Well 404, the minimum impact is observed in the first interval, and maximum – in the third. For Well 477, the impact is maximum in the second interval and minimum – in the first.

The graph showing the changes of V_{oil} values depending on the value of V_{H_2O} in the third interval is shown in Fig. 21.

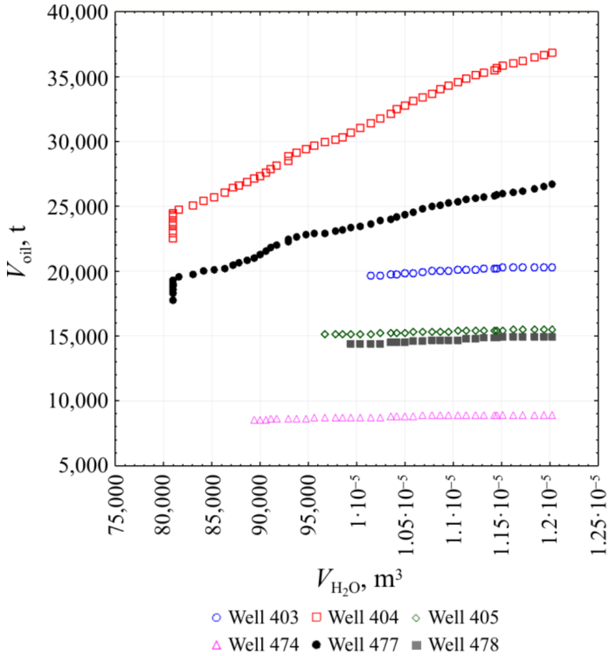

Fig. 21. Change in the values of V_{oil} depending on V_{H_2O} in the third interval

Regression equations between injection well 472 and producing wells:

Well 403: $V_{oil} = 16{,}070.2439 + 0.0359\,V_{H_2O}$;

Well 404: $V_{oil} = -3{,}801.3332 + 0.3456\,V_{H_2O}$;

Well 405: $V_{oil} = 13{,}354.8221 + 0.0182\,V_{H_2O}$;

Well 474: $V_{oil} = 7{,}274.674 + 0.0146\,V_{H_2O}$;

Well 477: $V_{oil} = 2{,}835.7721 + 0.2035\,V_{H_2O}$;

Well 478: $V_{oil} = 11{,}398.5776 + 0.03\,V_{H_2O}$.

Having analyzed the obtained graph and regression equation, we can say that the highest slope term is featured by Well 404 (0.3456) and the lowest – by Well 474 (0.0146). The slope term of other wells ranges from 0.0182 to 0.2035.

As a result of the performed research the following recommendations may be formulated for the optimization of oil production from T_1 of Sosnovskoe oilfield.

13 production enhancement operations were performed in respect of producing well pool for 1997-2014. The leading technology in terms of implementation volume is the formation reperforation with further treatment of wellbore area with acid agent preventing emulsification (four recovery enhancement operations were performed, average initial growth amounted to 4.9 tonnes/day with specific incremental production of 2,529.6 tonnes). Besides, one recovery enhancement operation was carried out according to hydroacoustic effect technology (initial growth amounted to 5.0 tonnes per day with the specific incremental production of 1,286.9 tonnes).

The highest efficiency in terms of specific incremental oil production per well (5,010.9) is achieved by radial drilling. Therefore, it is recommended for oil production optimization.

Based on the results of analyzing the graphs of changes in V_{oil} values depending on V_{H_2O} values, in the third interval, it is recommended that Wells 404, 427 and 477 continue working in the same mode. For Wells, on which water injection into the formation has insignificant effect (403, 405, 423, 426, 478 и 483), radial drilling is recommended. Wells 400, 425 and 474 were abandoned in 2016 because of water cut close to 100 %.

Conclusions

In view of the above, the statistical analysis was used to assess the impact of water injection into the formation on oil production on the example of Tournaisian deposits of Sosnovskoe oil and gas field. The research results show that the analysis described in the paper may be applied to assess the impact of water injection into the formation on oil production and provide a rationale for carrying out recovery enhancement operation and to identify hydrodynamic relations. This method of assessment shall be further applied to further development targets.

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