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# USE OF PROBABILISTIC AND STATISTICAL METHODS FOR DETERMINATION OF THE SOURCES OF WATER FLOW IN CANDIDATE WELLS FOR WATER SHUT-OFF WORKS (ON EXAMPLE OF THE VISEAN RESERVOIR OF THE PERM REGION FIELD)

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# ИСПОЛЬЗОВАНИЕ ВЕРОЯТНОСТНО-СТАТИСТИЧЕСКИХ МЕТОДОВ ДЛЯ ОПРЕДЕЛЕНИЯ ИСТОЧНИКОВ ОБВОДНЕНИЯ СКВАЖИН-КАНДИДАТОВ ДЛЯ ВОДОИЗОЛЯЦИОННЫХ РАБОТ (НА ПРИМЕРЕ ВИЗЕЙСКОГО ОБЪЕКТА МЕСТОРОЖДЕНИЯ ПЕРМСКОГО КРАЯ)

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Today, the problem of production of surplus associated water is particularly actual because of transition of fields to the final stages of development. Water shut-off works are the main method to combat the increased water cut of wells of modern fields. One of the most important stages in water shut-off works is the selection of candidate wells and determination of their sources of water inflow which depend on the geological structure of an oil reservoir and well technical state. Technical reasons of water inflow to wells include leakage of a production string and annular circulation. Geological reasons include lift of water-oil contact to the bottom hole, breakthrough of water along the productive formation, fractures between wells or formations.

The article discusses production wells of the Visean reservoir of the Perm region field with shut-off works done. Wells are divided according to the most common sources of water inflow into two groups such as a breakthrough in the productive formation of pumped or aquifer water. To analyze the average values of geological and technological parameters of the two groups of wells obtained from the field data the Student's *t*-criterion is used. Among the analyzed parameters the distance from the lower perforation to the water-oil contact, formation thickness and thickness of the interval of water inflow are statistically significant.

To determine the sources of water inflow for 19 candidate wells of the Visean reservoir of the Perm region field a discriminant analysis is performed. Based on the table of values of a posteriori probabilities, it is revealed that 4 wells of 19 candidate wells for water shut-off works are flooded due to breakthroughs of pumped water through the productive formation, 4 wells are flooded by aquifer water. The 11 remaining candidate wells are likely to have another source of water.

В настоящее время проблема добычи избыточной попутно-добываемой воды стоит особенно остро по причине перехода объектов месторождений на заключительные стадии разработки. Водоизоляционные работы являются основным способом борьбы с повышенной обводненностью скважин современных месторождений. Один из важнейших этапов реализации водоизоляционных работ – подбор скважин-кандидатов и определение их источников обводнения, которые зависят от геологического строения нефтяной залежи и технического состояния скважины. К техническим причинам обводнения скважин относятся негерметичность эксплуатационной колонны и заколонная циркуляция, к геологическим причинам – подъем водонефтяного контакта к интервалу вскрытия пласта, прорыв воды по продуктивному пласту, трещины между скважинами или пластами.

В данной статье рассмотрены добывающие скважины визейского объекта одного из месторождений Пермского края с выполненными водоизоляционными работами. Скважины разделены на две группы согласно наиболее часто встречающимся источникам обводнения: прорыв по продуктивному пласту нагнетаемой или законтурной воды. Для анализа средних значений геолого-технологических параметров двух групп скважин, полученных по промысловым данным, использован *t*-критерий Стьюдента. Среди анализируемых параметров статистически значимыми являются расстояние от нижнего перфорационного отверстия до водонефтяного контакта, толщина пласта и толщина интервала водопритока.

Для определения источников обводнения 19 скважин-кандидатов визейского объекта рассматриваемого месторождения Пермского края проведен дискриминантный анализ. На основании таблицы значений апостериорных вероятностей выявлено, что из 19 скважин-кандидатов для водоизоляционных работ 4 скважины обводняются за счет прорывов нагнетаемой воды по продуктивному пласту, 4 скважины – за счет законтурной воды; 11 оставшихся скважин-кандидатов, вероятнее всего, имеют другой источник обводнения.

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## Introduction

A large number of deposits in particular the fields of the Volga-Ural oil and gas province today are in the final stages of development and characterized by a high percentage of production water cut. Operators around the world suffer the similar problems. Due to water flowing into a well remaining reserves are not involved in recovery which inhibit achievement of design oil recovery factor and increase the costs of its extraction, processing and recycling dramatically.

The reasons for surplus water presented in each individual well may be different, as with the ways to eliminate them. However, water shut off jobs are the all around technique [1].

The Visean reservoir the one of Perm region fields is promising for water shut off planning since it accounts for a significant amount of residual recoverable reserves and the average water cut of well production reached 93 %. Such a value of water cut negatively affects the profit of oil production and development of reserves (Fig. 1).

Thus, in order to increase the economic effectiveness of the development of the Visean reservoir of the field considered a large number of treatments of water shut off is necessary. The effect of such treatments directly depends on the rational choice of candidate wells and correct determination of their source of water [2–7].

The paper shows the application of probability-statistical methods for determining the sources of water inflow to candidate wells of the Visean reservoir of one of Perm region fields. Application of methods to solve similar problems is given in the papers [8–11] and can often be the only possible way because of the lack of appropriate studies of candidate wells. In order to perform the analysis several variables have been selected that are as follows: permeability, porosity, compartmentalization, sandiness, net oil-bearing thicknesses, oil viscosity, reservoir pressure, formation thickness, water inflow interval,
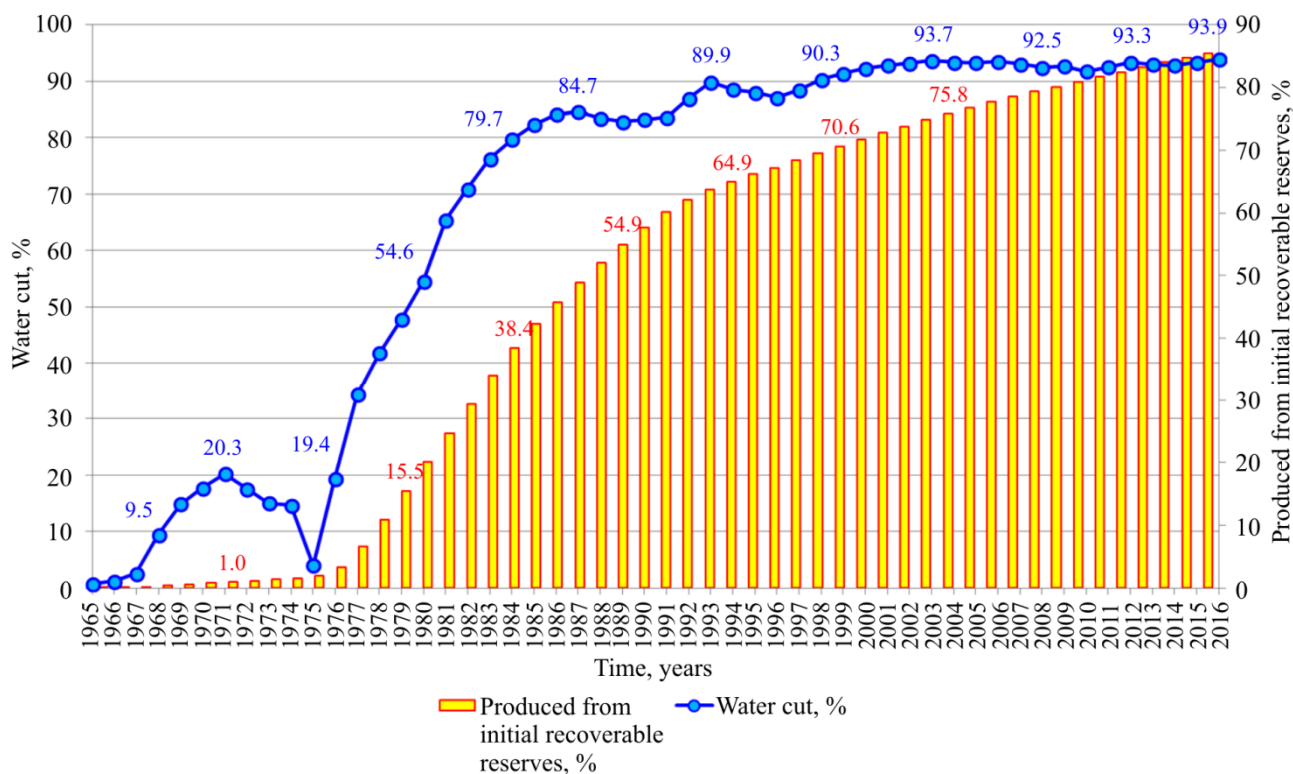


Fig. 1. Dynamics of water cut and production from initial recoverable reserves
for the Visean reservoir of one of Perm region fieldst

distance from the lower perforation holes to a water-oil contact (WOC), current density of the water produced.

## Classification of water cut sources in production wells

Sources of water cut are determined by the oil field geological structure and technical state of a well. Poor technical state is the cause for emergence of foreign water in a well, which include water of the upper and lower (in relation to a reservoir) layers that do not have a hydrodynamic connection with the reservoir under natural conditions. Flow of foreign water into production wells can occur in cases when cement ring has leaks through the annular circulation and in case when production string has leaks at the intervals with water-saturated rocks.

Annular circulation appear due to poor quality of production string cementation or failure of the cement ring integrity during well operations [2, 4–

6] when flowing throug the cement stone, "cement-rock", "cement-string" contacts and gradual flooding of water channels under the pressure between layers saturated with water and oil.

Loss of airtightness of a production string can be associated with corrosion of pipes in corrosive environments, mechanical defects during downhole operations and damage during operations under the high pressures. This type of water cut increase is one of the most common at the late stage of development of oil fields (Fig. 2) [2, 4–7].

Reasons for water cut increase in a secod group are related to the oil reservoir geological structure, when surplus water enters production wells through reservoirs [5]. Geological reasons for water cut increase during the field development have been studied by many researchers [2, 6, 12–16 and others]. It is revealed that the main reason for premature increase in water cut of production wells with incomplete recovery of reserves is heterogeneous permeability of layers.
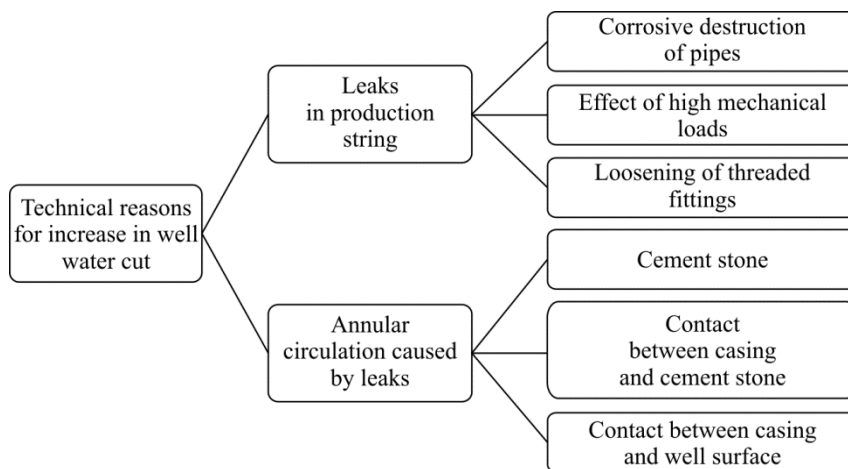


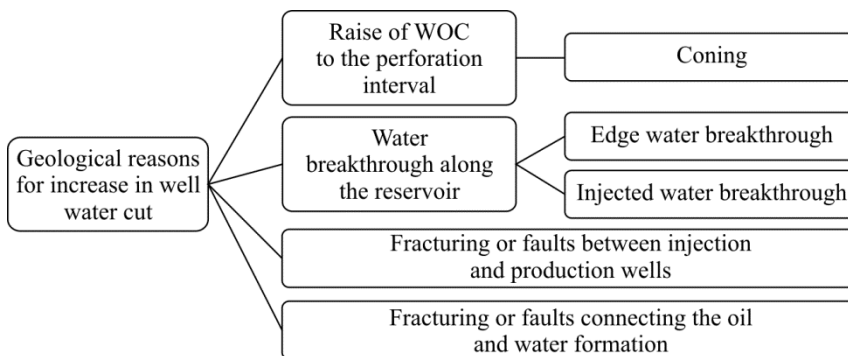Fig. 2. Classification of technical reasons for increase in well water cut



Fig. 3. Classification of geological reasons for increase in well water cut

In order to classify the geological causes of increase in water cut, five basic scenarios of surplus water intering the bottom of the production well have been identified such as lifting of water-oil contact to the perforation interval, coning, water breakthrough along the reservoir, fracturing or faults between injection and production wells, fracturing or faults connecting the oil and water formation (Fig. 3).

## Analysis of dividing the wells by source of water

There were water shut off jobs performed with various compositions at 50 production wells of the field considered Visean reservoir. Based on geophysical and hydrodynamic studies of wells, using chemical analytical and graphoanalytical methods, water sources have been identified before water shut off jobs [17–25]:

1) injected water breakthrough along the reservoir;

2) edge water breakthrough along the reservoir;

3) coning;

4) annular circulation;

5) leaks in production string.

There is a histogram given in Fig. 4 for a preliminary analysis of the sample that reflect distribution of sources of production well water cut increase with shut off jobs performed.
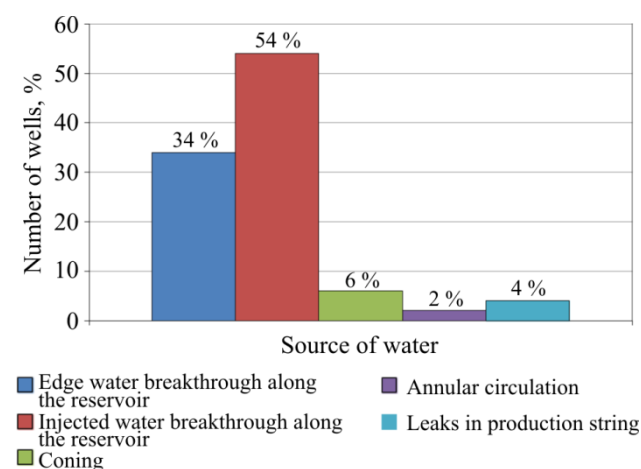


Fig. 4. Distribution of water sources at the Visean reservoir of Perm region field

The maximum number of wells corresponds to breakthroughs of edge water (34 %) and injected water (54 %) through the reservoir. Since that well groups make statistically significant samples, it was decided to use them for further analysis:

– well group 1 for injected water breakthrough;

– well group 2 for edge water breakthrough.

Student's $t$-criterion was used to analyze the average values of independent variables of two groups of well water sources [26–28] (Table 1).

Among the parameters analyzed, distance from a lower perforation hole to WOC, formation thickness and thickness of the interval of water inflow are statistically significant. Consequently, production wells with increased water cut caused by edge water breakthrough to the well bottom are characterized by a smaller value of the distance from a lower perforation hole to WOC, formation thickness and interval of the water inflow. On the other hand, difference between the initial and current density of water is not a statistically significant parameter, since the formation is flooded with purified water.

## Discriminant analysis of water sources

Discriminant analysis is one of the most widely used in statistics of multidimensional methods. It is designed to classify the reservoir (assign to one of several specified groups in some optimal way) based on measuring various characteristics of a reservoir [29].

There are two the most commonly encountered sources of water in the Perm region field Visean reservoir identified such as breakthrough of injected water and breakthrough of edge water taht are well groups 1 and 2. Group 3 consists of 19 candidate wells selected for waterproofing works. In this case, discriminant analysis will help to assign each candidate well to one of two specific sources of water inflow, which will allow the water shut off technology to be chosen sufficiently [12, 30].

In the paper, discriminant analysis was carried out using the Discriminant Analysis module of the Statistica 10 software. Models implemented in the module are linear, and classification functions and discriminant functions are linear combinations of observed values [29].

When carrying out the discriminant analysis, results were obtained that are as follows: the value of Wilks's lambda is 0.31; approximate value of the $F$-statistic with the number of degrees of freedom 22 and 94 is 3.32; $p$-significance level of the $F$-criterion is less than 0.00001 (Table 2).

Table 1

Values of Student's $t$-criterion for geological and technological parameters

| Parameter | Average | | Value of Student's criterion Significance level | Number of observations | | Standard deviation | |
|---|---|---|---|---|---|---|---|
| | group 1 | group 2 | | group 1 | group 2 | group 1 | group 2 |
| Thickness of water inflow interval, m | 13.45 | 9.91 | 2.62 0.01 | 27 | 17 | 5.13 | 2.67 |
| Permeability, $\mu m^2$ | 286.22 | 285.09 | 0.02 0.99 | 27 | 17 | 227.61 | 245.67 |
| Porosity, % | 19.03 | 17.88 | 1.07 0.29 | 27 | 17 | 3.29 | 3.76 |
| Compartmentalization, units | 5.37 | 5.59 | −0.23 0.82 | 27 | 17 | 2.29 | 3.97 |
| Sandiness, fractions | 0.35 | 0.31 | 1.39 0.17 | 27 | 17 | 0.09 | 0.09 |
| Net oil-bearing thickness, m | 13.23 | 12.34 | 0.53 0.60 | 27 | 17 | 5.10 | 5.87 |
| Current reservoir pressure, MPa | 13.33 | 13.09 | 0.58 0.56 | 27 | 17 | 1.56 | 0.88 |
| Formation thickness, m | 29.00 | 9.19 | 6.00 0.00 | 27 | 17 | 13.41 | 2.41 |
| Current density of water, $g/cm^3$ | 1.07 | 1.11 | −0.87 0.39 | 27 | 17 | 0.21 | 0.02 |
| Viscosity of oil in reservoir conditions, mPa·s | 37.12 | 40.39 | −1.19 0.24 | 27 | 17 | 0.26 | 14.34 |
| Distance from the lower perforation hole to WOC, m | 24.29 | 13.41 | 3.19 0.00 | 27 | 17 | 12.72 | 7.44 |

N o t e : statistically significant parameters have red font.

Table 2

Summary table of data analysis

| Parameter | Wilks`s Lambda | Partial Lambda | Tolerance |
|---|---|---|---|
| Thickness of water inflow interval, m | 0.32 | 0.99 | 0.72 |
| Permeability, $\mu m^2$ | 0.34 | 0.93 | 0.90 |
| Porosity, % | 0.34 | 0.92 | 0.72 |
| Compartmentalization, units | 0.33 | 0.95 | 0.37 |
| Sandiness, fractions | 0.32 | 0.97 | 0.21 |
| Net oil-bearing thickness, m | 0.33 | 0.96 | 0.16 |
| Current reservoir pressure, MPa | 0.32 | 0.97 | 0.84 |
| Formation thickness, m | 0.49 | 0.65 | 0.75 |
| Current density of water, $g/cm^3$ | 0.33 | 0.95 | 0.84 |
| Viscosity of oil in reservoir conditions, mPa·s | 0.36 | 0.88 | 0.57 |
| Distance from the lower perforation hole to WOC, m | 0.42 | 0.75 | 0.78 |

The first column of Table 2 contain the Wilks's lambda values which are result of excluding the corresponding variable from the model [29]. The maximum values of Wilks's lambda are confined to the parameters "formation thickness" and "distance from the lower perforation hole to WOC". Therefore, presence of these variables in the discrimination procedure is most desirable.

Values of the partial lambda in the second column of Table 2 is the ratio of Wilks's lambda after adding the corresponding variable to the Wilks's lambda before adding this variable. A partial lambda characterizes the unit contribution of the corresponding variable to the deviding force of the model [29]. Minimum values of the partial lambda are also confined to parameters "formation thickness" and "distance from the lower perforation hole to WOC", which indicates their greatest contribution to general discrimination.

Tolerance is defined as $(R^2-1)$, where $R^2$ is the multiple correlation coefficient of this variable with all other variables in the model. As it is seen from Table 2, all variables with large tolerance values from 0.15 to 0.84 were successfully included in the model.

In order to obtain further results on discrimination of well groups with different sources of water, a canonical analysis was carried out. The linear discriminant functions given below are built based on the data characterizing the geological section of wells under study, properties of fluids produced, construction features and operation of wells.

The classification functions for groups 1 and 2 are as follows:

$$Z_1 \text{ (breakthrough of injected water)} =$$
$$= 0.577 \cdot H_{w.inf} - 0.001 \cdot K_{perm} + 3.285 \cdot K_p -$$
$$- 0.329 \cdot K_{comp} + 85.731 \cdot K_{sand} - 1.456 \cdot H_{n.o.-b} +$$
$$+ 5.682 \cdot P_{res} + 0.572 \cdot H_{res} + 56.784 \cdot \rho_{liq} +$$
$$+ 0.859 \cdot \mu_o + 0.383 \cdot H_{WOC} - 137.88;$$

$$Z_2 \text{ (breakthrough of edge water)} =$$
$$= 0.559 \cdot H_{w.inf} - 0.001 \cdot K_{perm} + 3.303 \cdot K_p -$$
$$- 0.227 \cdot K_{comp} + 72.739 \cdot K_{sand} - 1.262 \cdot H_{n.o.-b} +$$

$$+ 5.35 \cdot P_{res} + 0.373 \cdot H_{res} + 58.464 \cdot \rho_{liq} +$$
$$+ 0.698 \cdot \mu_o + 0.252 \cdot H_{WOC} - 117.053.$$



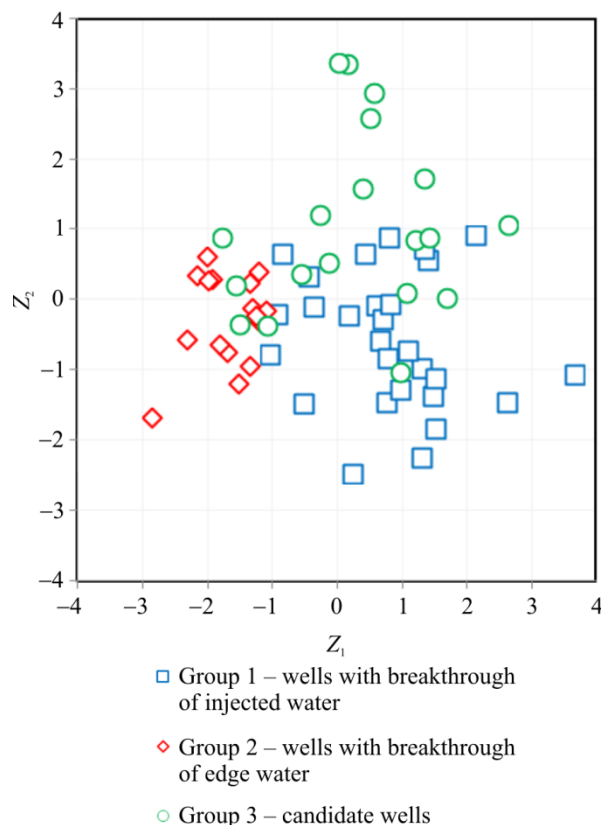Fig. 5. Diagram of the scattering of canonical values for pairs of values of discriminant functions 1 and 2

□ Group 1 – wells with breakthrough of injected water

◇ Group 2 – wells with breakthrough of edge water

○ Group 3 – candidate wells

Here, $H_{w.inf}$ − water inflow thickness, m; $K_{perm}$ − permeability coefficient, $\mu m^2$; $K_p$ − porosity coefficient, fractions; $K_{comp}$ − compartmentalization, units; $K_{sand}$ − sandyness coefficient, fractions; $H_{n.o.-b}$ − net oil bearing thickness, m; $P_{res}$ − reservoir pressure, MPa; $H_{res}$ − reservoir thickness, m; $\rho_{liq}$ − density of associated water, $g/cm^3$; $\mu_o$ − oil viscosity, mPa·s; $H_{WOC}$ − distance from the lower perforation hole to WOC, m. Thickness of the perforation interval in candidate wells is taken as thickness of water inflow interval.

According to the functions, values of $Z_1$ and $Z_2$ are calculated, which are shown in Fig. 5 for groups of wells with different water sources.

It can be seen from Fig. 5 that the values of $Z_1$ and $Z_2$ are fairly well separated within the studied groups of wells 1 and 2.

Table 3

Values of posterior probabilities

| № of candidate well | Group of wells 1. Source of water – breakthrough of injected water | Group of wells 2. Source of water – breakthrough of edge water |
|---|---|---|
| 2116 | 0.031401 | 0.004083 |
| 1122 | 0.433929 | 0.005930 |
| 1131 | 0.790184 | 0.002493 |
| 1177 | 0.018527 | 0.002342 |
| 2118 | 0.536394 | 0.000225 |
| 2133 | 0.132852 | 0.016871 |
| 352 | 0.007677 | 0.002995 |
| 1006 | 0.291668 | 0.273645 |
| 328 | 0.007108 | 0.003815 |
| 398 | 0.153802 | 0.089836 |
| 411 | 0.169116 | 0.002178 |
| 637 | 0.924416 | 0.012653 |
| 680 | 0.227218 | 0.637236 |
| 1005 | 0.070747 | 0.792262 |
| 1032 | 0.348190 | 0.120381 |
| 1104 | 0.700988 | 0.010679 |
| 1120 | 0.102971 | 0.818458 |
| 1141 | 0.453209 | 0.003616 |
| 1181 | 0.033595 | 0.750752 |

N o t e : Values of posteriori probabilities greater than 0.5 have red font.

Table 3 showing values of posteriori probabilities (belonging of candidate well to one of two groups of wells) is obtained as a result of discriminant analysis.

It was determined that out of 19 candidate wells for water shut off jobs 4 wells have high water cut due to breakthrough of water injected through the reservoir, 4 wells have high water cut due to breakthrough of edge water and 11 remaining candidate wells are likely to have a different source of water.

**Conclusions**

1. The sources of water cut in wells of the Perm region Visean reservoir are considered. The maximum number of wells is confined to two sources of water such as breakthrough along the reservoir of injected (group 1) or edge water (group 2).

2. The Student's *t*-criterion is used to analyze the average values of geological and technological parameters of two groups of wells obtained from the field data. It is found that production wells, which have high water cut due to breakthrough of edge water to a well bottom, are characterized by a lower distance from the bottom perforation hole to WOC, formation thickness and water inflow interval.

3. The discriminant analysis was carried out to determine the probabilities of assigning each of the 19 candidate wells to the 1st and 2nd groups of wells with different sources of water inflow.

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