SPE-208430-MS

The Use of Quantum Dot Inflow Tracers in Multi-Well Reservoir Production Surveillance and Inter-Well Diagnostics

Marat Rafailevich Dulkarnaev, Povkhneftegaz Lukoil – West Siberia LLC; Evgeny Alexandrovich Malyavko, Ekaterina Evgenievna Semyonova, and Oksana Alexandrovna Gorbokonenko, GeoSplit LLC; Yuri Alexeyevich Kotenev, Shamil Khanifovich Sultanov, Alexander Viacheslavovich Chibisov, and Daria Yuryevna Chudinova, Ufa State Petroleum Technological University

This paper was prepared for presentation at the SPE Symposium: Petrophysics XXI. Core, Well Logging, and Well Testing held virtually on 9 - 10 June 2021. The official proceedings were published online on 26 August, 2021.

Abstract

Reservoir pressure maintenance is an extremely important factor in field development. In enhanced oil recovery water flooding projects, it is essential to optimize the flooding efficiency in a timely manner and reduce uncertainties in inter-well hydrodynamic modelling.

Usually, the inter-well space parameters are assessed using interference tests or tracer- based surveillance. These methods offer such advantages as reliable information on the flow communication in the target area and the reservoir connectivity in different zones of the field. However, the duration and cost of the described surveillance technologies pose a significant drawback, and therefore alternative physical and mathematical methods with simplified forecast models are widely spread.

This paper describes a method for integrating the results of dynamic marker-based inflow production surveillance in horizontal wells and the Spearman's rank-order correlation method. This approach is applied to provide better interventions for reservoir pressure maintenance, optimization of in-fill drilling, update existing hydro-dynamic models and reduce the level of uncertainty in decision making.

Introduction

Reservoir pressure maintenance is an extremely important factor in field development. In enhanced oil recovery water flooding projects, it is essential to optimize the flooding efficiency in a timely manner and reduce uncertainties in inter-well hydrodynamic modelling.

Usually, the inter-well space parameters are assessed using interference tests or tracer- based surveillance. These methods offer such advantages as reliable information on the flow communication in the target area and the reservoir connectivity in different zones of the field. However, the duration and cost of the described surveillance technologies pose a significant drawback, and therefore alternative physical and mathematical methods with simplified forecast models are widely spread.

This paper describes a method for integrating the results of dynamic marker-based inflow production surveillance in horizontal wells and the Spearman's rank-order correlation method. This approach is applied to provide better interventions for reservoir pressure maintenance, optimization of in-fill drilling, update existing hydro-dynamic models and reduce the level of uncertainty in decision making.

Methodology

The subject field with terrigenous deposits of the Neocomian wedge-shaped bodies, is characterised by a complex geological structure, low permeability, an extensive water and oil zone, as well as an uneven distribution of reservoirs both laterally and vertically (Dulkarnaev et al., 2020). Currently, the reservoir is in production increase cycle. The dynamics of the main development demonstrates a consistent increase in oil production (Figure 1, Table 1), associated with the in-fill drilling and the commissioning of new wells. The field is developed mainly by drilling horizontal wells oriented towards north-north-east and south-south-east (Figure 2). The main challenge in the development of a new site is posed by the low flooding efficiency, since the reservoir pressure maintenance system is only being developed (Vaganov et al., 2017).

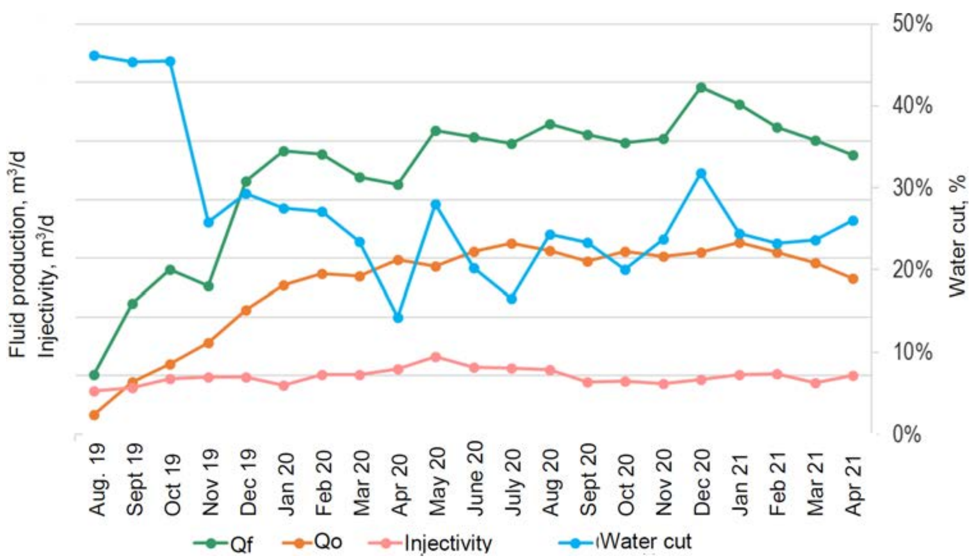

Figure 1—Reservoir development indicators

Table 1—Well fluid characteristics

Parameters	Value
Producing wells in operation	16
Average fluid production, m³/day Average crude oil production, ton/day Water cut, % Reservoir pressure, MPa Bottom-hole pressure, MPa	43.8 17.7 20.5 22.0 12.0
Injection wells in operation	5
Average injectivity of well 1, m3/day Average wellhead pressure, MPa	73.4 13.4

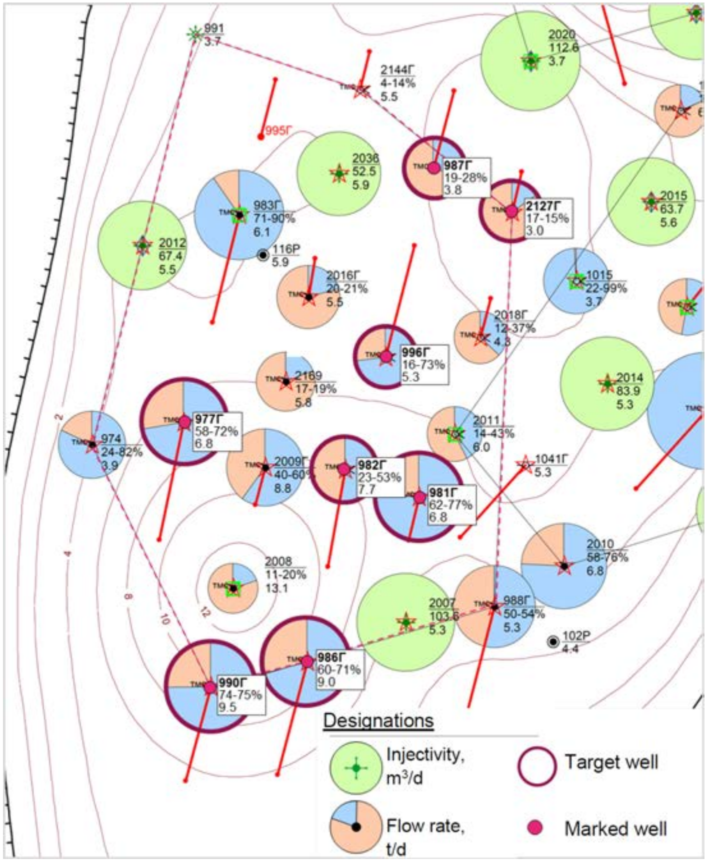

Figure 2—Fragment of the current sampling map of the target reservoir area

According to the analysis, the existing waterflooding pattern has a significant impact on the wells production performance. To assess the reservoir pressure of the target area, initial and current reservoir pressure distribution maps, as well as current depressions maps at the time of production surveillance, were built (Figure 3).

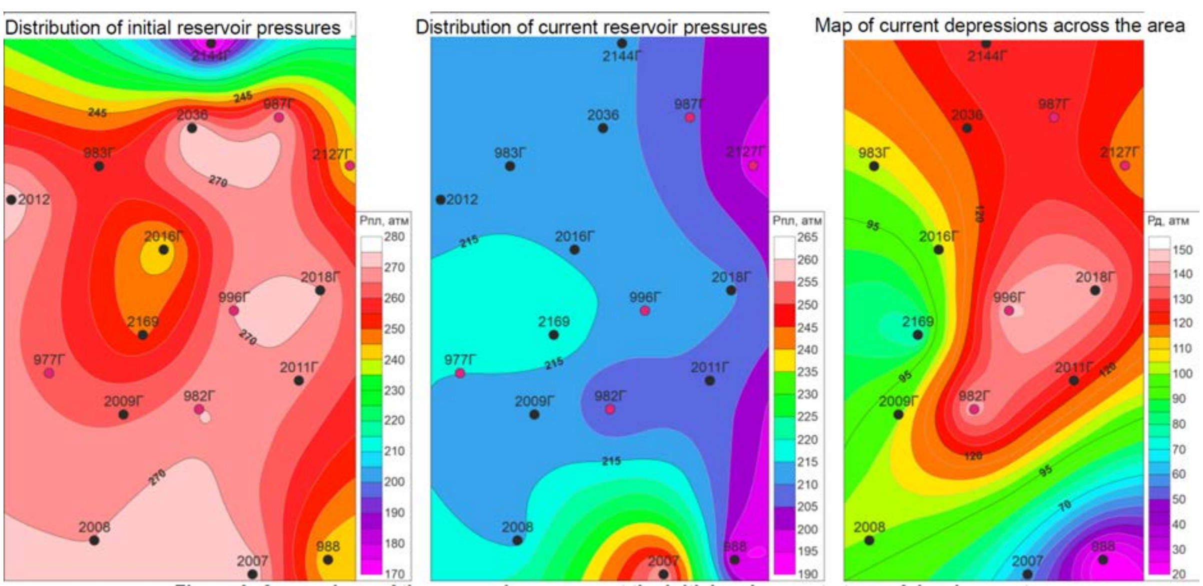

Figure 3—Comparison of the reservoir pressure at the initial and current stage of development and current depressions

The maps reflecting the current reservoir pressure of the field in question show that before the development of the area the highest reservoir pressure values were seen in the crest of the reservoir. Then, once the development of the reservoir area commenced, a redistribution of the reservoir pressure was observed. The reservoir pressure decreases towards the older areas of the field. The analysis of the reservoir pressure maintenance system efficiency yielded the information on the degree of impact of injection wells on the neighbouring producing wells.

To measure the correlation between injection and producing wells, as well as to assess the impact of injection wells on specific ports of marked horizontal wellbores, the dynamics of production and injection was analysed and the results were integrated with the calculation of Spearman's rank correlation coefficients.

Additional information on the operation of horizontal producing wells was obtained using the dynamic marker-based production logging technology designed to provide a stream of data on the flow profile and composition for each target interval of the horizontal well by injecting marker- reporters with the proppant during the multi-stage hydraulic fracturing or within marker sleeves integrated into the lower completion at the stage of well construction. Each frac stage (wellbore interval) corresponds to a unique marker-reporter code (Figure 4). When contacting the target reservoir fluid phase in the course of the well operation, the marker-reporters are released from the polymer matrix and washed out by the fluid flow to the surface. As the well operates, wellhead fluid samples are taken from time to time, and the results of their analysis are used to quantify the contribution of each hydraulic fracturing port to the well flow rate (Ovchinnikov, 2019).

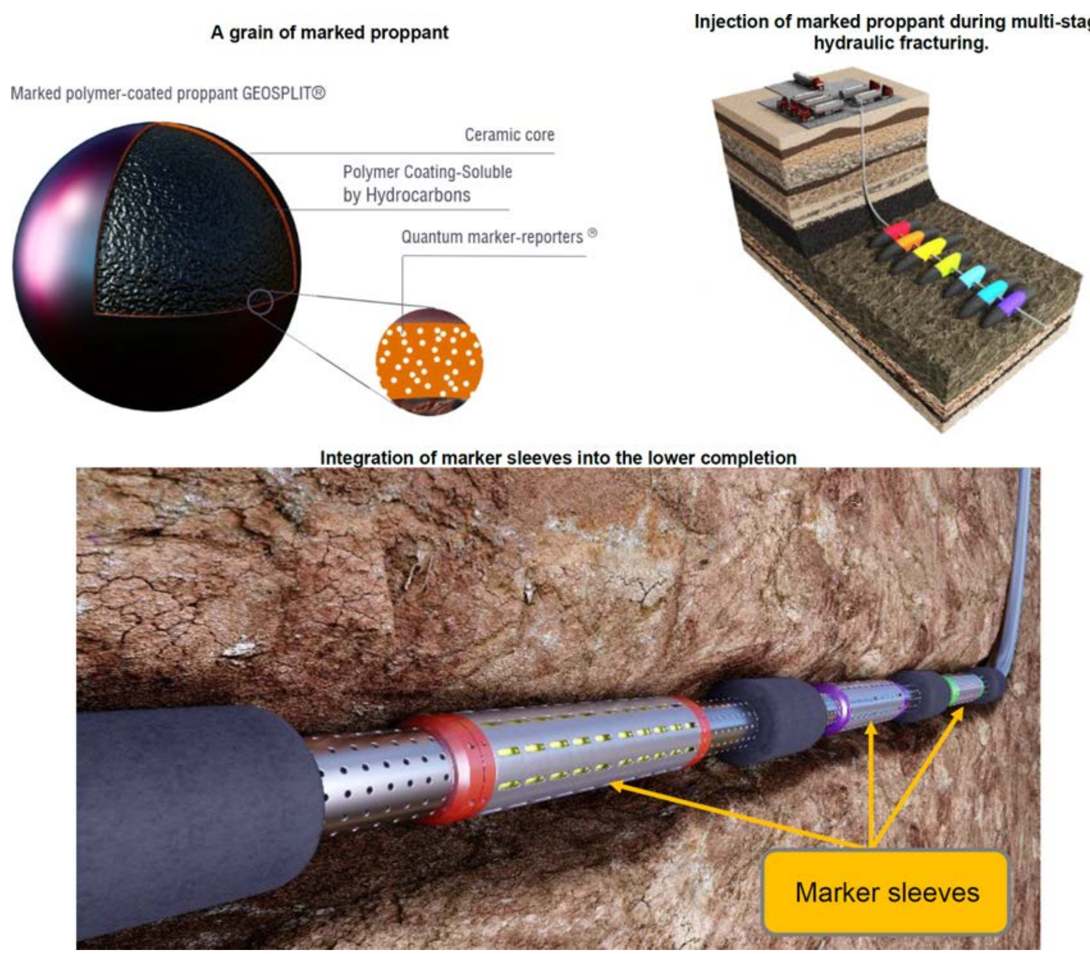

Figure 4—The use of dynamic marker-based production technology for production profiling surveillance in a horizontal well

The results of dynamic marker-based production logging helped track the operation of horizontal wells to further substantiate the influence of neighbouring injection wells on certain frac ports using the rank correlation method.

Correlation analysis is used to find relationships between the behaviour of two objects. The degree of interference between injection and producing wells is commonly expressed as so-called interference coefficients or association coefficients. This coefficient is calculated as a result of the study. The value of the Spearman's rank correlation coefficient varies in the range from +1 (direct correlation) to −1 (inverse correlation), reflecting the vector of the relationship between the two parameters. If the Spearman's coefficient is zero, the parameters in question do not correlate. The procedure for calculating the Spearman's rank coefficient is as follows (Toropov et al., 2020):

1. Sets of variables are ranked. The ranking begins with the placement of variables in ascending (or descending) order. Each parameter is assigned a rank, expressed as a natural number. If there are several identical variables, they are assigned an average rank;
2. The difference between the ranks of each pair of matched values is found;
3. Each difference is squared and the results are summed up;
4. The Spearman's rank correlation coefficient is calculated by the formula:

$$r = 1 - \frac{6\sum d^2}{n(n^2-1)},$$

where $\sum d^2$ is the sum of the squares of the rank differences; n is the number of matched pairs.

The rank correlation coefficient is used to conditionally assess the tightness of the relationship between the studied parameters. For a qualitative assessment of the degree of correlation between the studied values, the Cheddock scale (Udintsova, 2016) is used, as shown in Table 2.

Table 2—The Cheddock scale for assessing the degree of correlation

Spearman's rank coefficient value	The degree of correlation relationship
zero	no correlation
from 0.1 to 0.3	weak
from 0.3 to 0.5	moderate
from 0.5 to 0.7	notable
from 0.7 to 0.9	high
over 0.9	very high

Well interference degree is estimated in the reservoir area on the basis of the developed procedure for calculating the Spearman's rank correlation coefficients. The result of calculating the flow communication correlation degree between the injection wells and the surrounding producing wells is presented in Table 3. The time series coefficients are expressed as the average daily and monthly well operation indicators.

Table 3—Results of the assessment of the correlation degree between the injection and producing wells of the reservoir zone

No. of injection well	No. of producing well	Number of observations	Spearman's coefficient when evaluating the correlation with injection wells' injectivity					Cheddock scale-based assessment of the correlation degree
			qo	qf	Injection	Qo	Qf	
2020	987Г	11	0.409	0.427	0.718	0.555	0.555	high
	2127Г	11	0.509	0.664	0.366	0.643	0.582	notable
	2144Г	11	-0.100	-0.344	-0.434	-0.091	-0.364	weak
2015	2127Г	11	0.845	0.718	-0.139	0.743	0.745	high
	987Г	11	0.645	0.709	0.445	0.491	0.655	high
2014	2018Г	11	0.409	0.231	-0.173	0.398	0.291	moderate
	2127Г	11	0.509	0.664	0.366	0.643	0.582	notable
	2010	11	0.743	0.682	-0.236	0.700	0.573	high
	996Г	11	0.783	0.266	-0.422	0.797	0.745	high
	1015	11	0.707	0.455	-0.270	0.925	0.294	very high
	982Г	7	0.107	0.429	-0.214	-0.479	-0.257	moderate
2007	2008	8	-0.383	0.214	0.012	-0.381	0.190	weak
	2010	8	-0.095	-0.524	-0.915	-0.095	-0.524	very high
	982Г	8	-0.107	0.000	0.143	-0.286	-0.250	weak
2036	2144Г	9	-0.021	-0.167	-0.217	0.017	-0.183	weak
	987Г	9	0.450	0.667	0.683	0.367	0.667	notable
	2127Г	9	0.383	0.650	0.483	0.504	0.683	notable
	2018Г	9	0.300	0.133	-0.217	0.300	0.183	moderate
	2016Г	9	0.452	0.625	0.143	0.476	0.548	notable
2012	982Г	7	0.679	0.676	0.286	0.107	0.070	notable
	996Г	7	0.500	0.607	0.036	0.607	0.759	high
	2016Г	7	0.607	0.616	0.321	0.643	0.607	notable
	2169	7	0.643	0.679	0.393	0.750	0.679	very high

The calculated data was used to develop a correlation map with arrows pointing at the dominant flow directions and reveal the degree of interference between the neighbouring injection and producing wells (Figure 5).

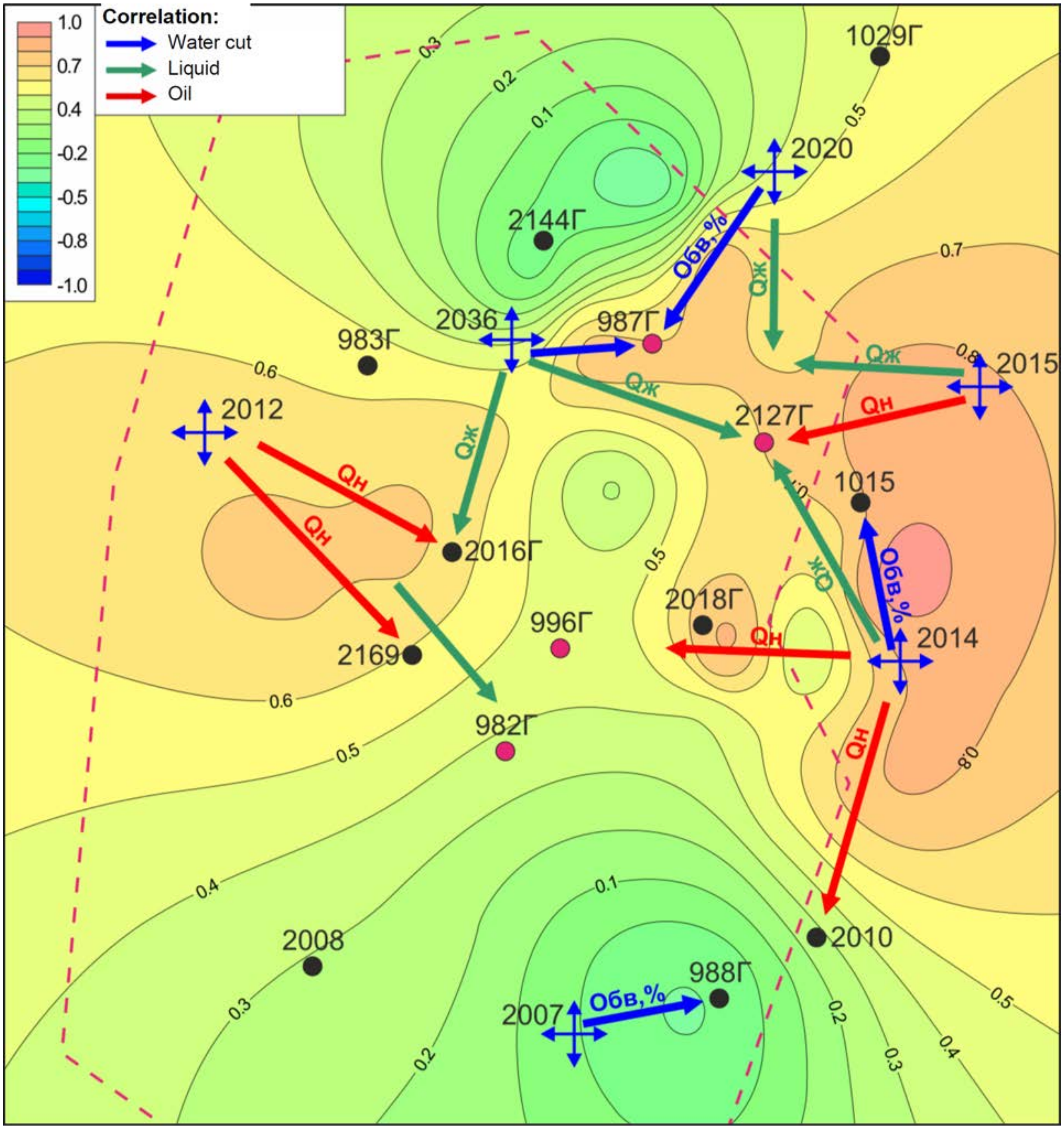

Figure 5—A map of Spearman's correlation coefficients. Evaluation of the correlation between injection and producing wells (time series: injectivity — water cut, Qo, Qf)

The results of the study revealed a high degree of flow communication between the following pairs of target wells:

1. Injection well No. 2020 provides a significant impact on producing wells No. 987G and No. 2127G;
2. As injectivity at well No. 2015 increases, an increase in the water cut of the producing well 987G and an increase in the flow rate at well No. 2127G are observed;
3. Higher injection at injection well No. 2036 impacted the producing wells: No. 987G (a higher water cut is observed) and No. 2016G (an increase in fluid flow rate);
4. Injection well No. 2012 has a significant impact on the operation of producing wells No. 2016 and No. 2169.

The study results are supplemented with diagrams reflecting the dynamics of well operation indicators (Figure 6). The diagrams clearly show the correlation between the injectivity of injection wells No. 2020 and No. 2015 and the water cut in producing wells No. 987G and No. 2127G, respectively. A weaker correlation is observed between the indicators for the injection well No. 2036 and the marked producer No. 987G.

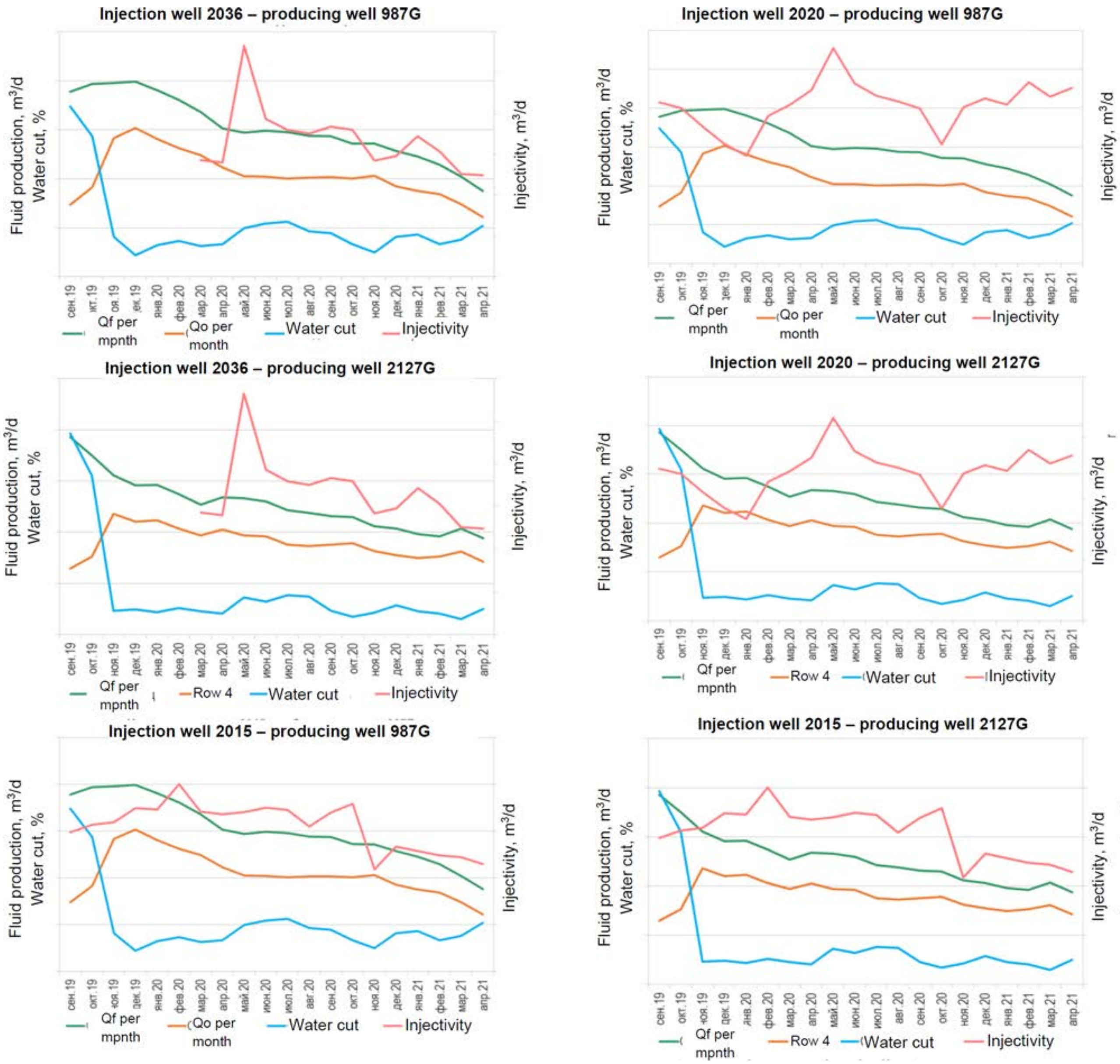

Figure 6—Comparative dynamics of producing and injection wells operation indicators

The analysis of the interference between producing wells was also performed using the Spearman's rank correlation method. The results of calculations of the interference between the producing wells of the target reservoir area are shown in Table 4 and Figure 7. The results obtained show a tight flow communication between the producing wells and interference affecting each other's operating modes. The highest degree of correlation was observed in the eastern zone of the target area.

Table 4—Results of the assessment of the correlation degree between the producing wells

No. of producing well	No. of producing well	Spearman's coefficient when evaluating the correlation with injectivity				Cheddock scale-based assessment of the correlation degree
		qo	qf	Qo	Qf	
2144Г	987Г	0.802	0.611	0.782	0.400	high
2127Г	987Г	0.864	0.745	0.857	0.891	high
2127Г	2018Г	0.927	0.600	0.839	0.673	very high
2018Г	996Г	0.709	0.718	0.661	0.693	high
982Г	996Г	0.321	0.429	0.214	-0.098	moderate
2169	996Г	0.845	0.705	0.918	0.625	very high
2169	982Г	0.429	0.750	-0.071	0.600	high
2016Г	2018Г	-0.318	0.809	-0.293	0.682	high
2016Г	987Г	-0.373	0.973	-0.364	0.782	very high
2016Г	2169	-0.309	0.605	0.055	0.545	notable

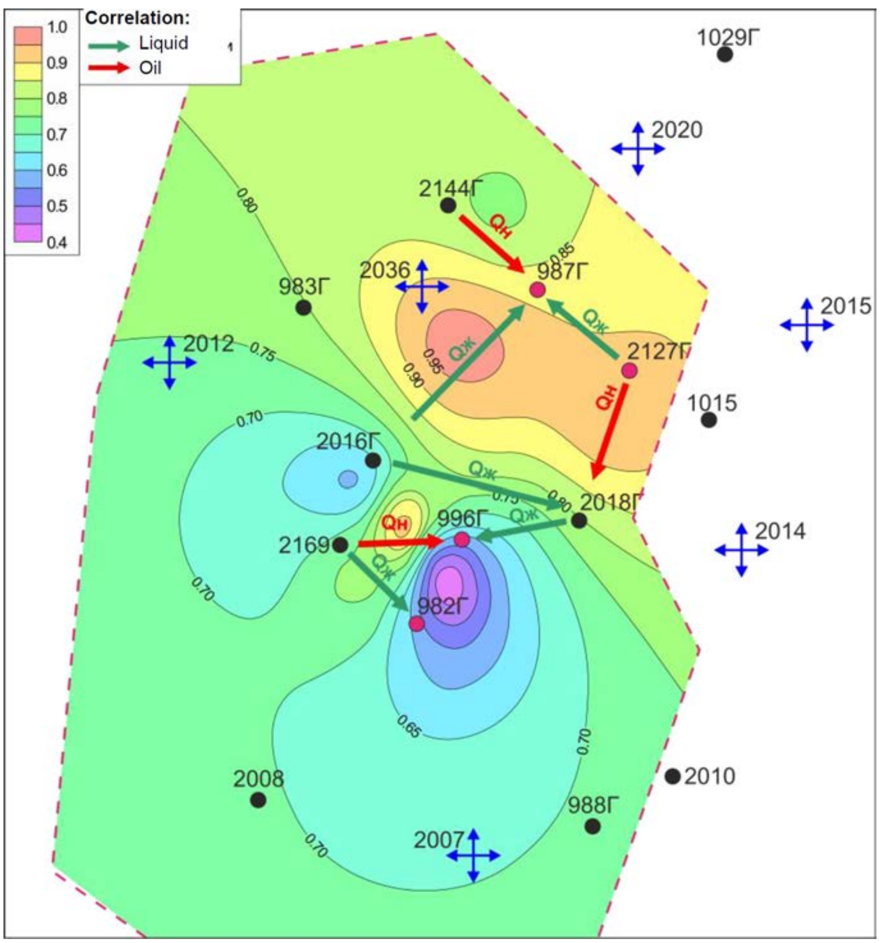

Figure 7—Results of the assessment of the correlation degree between the producing wells of the reservoir area

The key stage of the study is the integration of the results of marker-based production logging and the rank correlation method. The results obtained revealed that there is a close flow communication between the marked producing wells. After the well interference evaluation, we calculated the degree of the flow communication between the ports of the marked wells (Figure 8).

8).

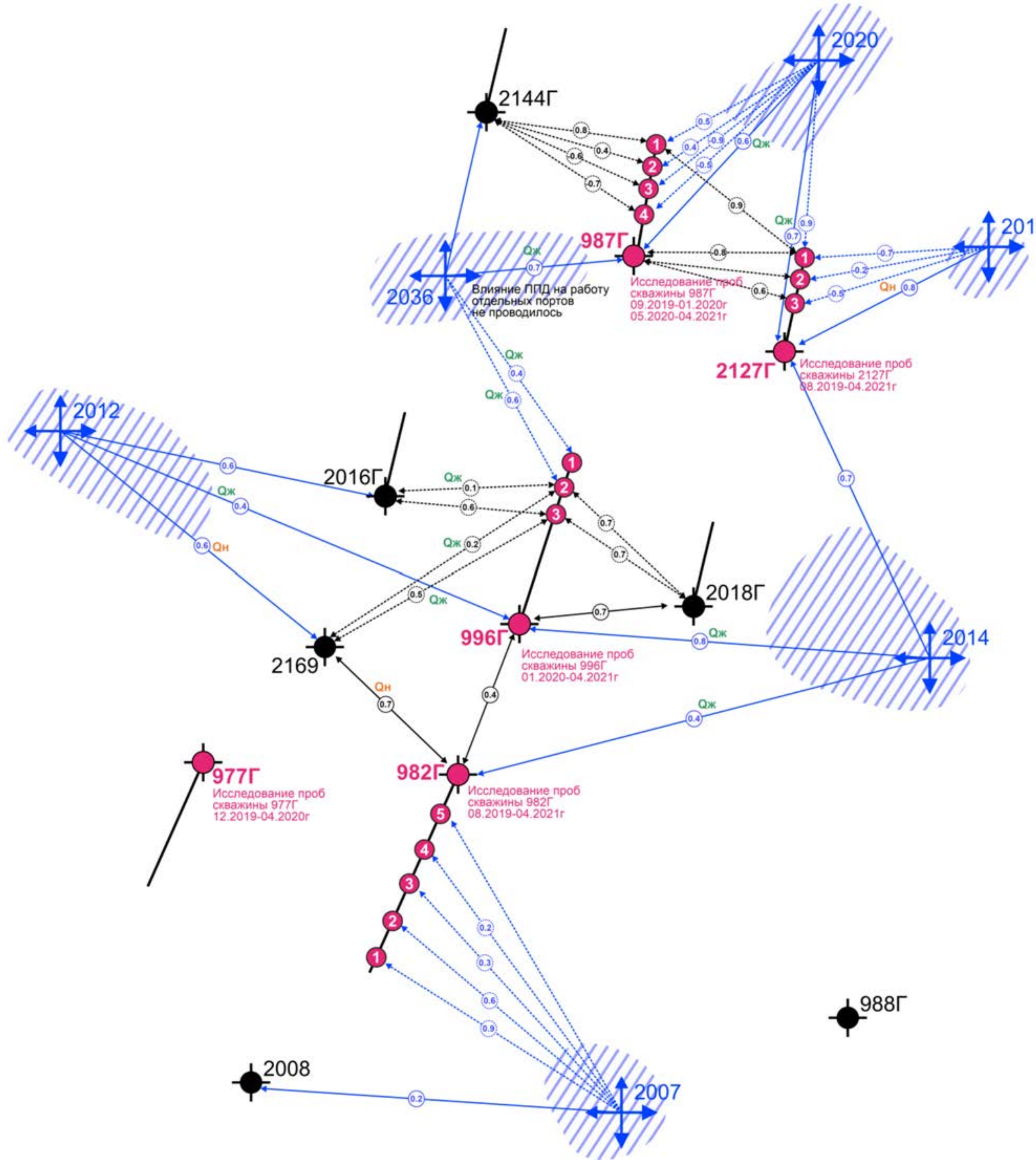

Figure 8—Assessment of the correlation of the ports' performance of marked wells No. 982G, 996G, and 2127G

The comparative correlation analysis of the operation indicators reveals a high degree of correlation between the fluid flows in the area of the initial ports of the marked wells No. 987G and No. 2127G. Probably, the observed dynamics of liquid production is determined by the positive impact of the neighbouring injection wells No. 2020 and No. 2015. The effect of injection wells is confirmed by the dynamic analysis of field data and the flow pathway directions.

A negative correlation coefficient indicates the presence of a strong monotonic relationship between the first port of well No. 2127G and the heel of the horizontal lateral of the marked well No. 987G. Fluid withdrawals from 4 ports of well No. 987 increase on the back of a decreasing flow at 1 port of well No. 2127G.

The monotonic relationship with negative correlation coefficients can be interpreted as a result of a lower downhole and reservoir pressure in the well recovery zone, which in turn is the effect of a weak influence of the neighbouring injection wells.

Thus, a comparative correlation analysis of the dynamics of well operation indicators revealed the presence of a strong flow communication between the wells located in the central and eastern parts of the target area.

In addition to the statistical calculations performed, the effectiveness of the reservoir pressure maintenance system was evaluated using an updated reservoir model of the reservoir area along the flow pathways.

The implemented flow pathways are a visualisation of the dynamic system of the medium and show the well seepage directions. Injection wells of the target reservoir area and wells of the nearest buffer zone were analysed.

According to the obtained distribution of reservoir flows for injection well No. 2012, the main flows are directed towards south-east, namely, producing wells No. 2169 and 982G, which was also confirmed by the results of the Spearman's rank correlation coefficient calculations. Other injection wells of the site were analysed in a similar way (Figure 9).

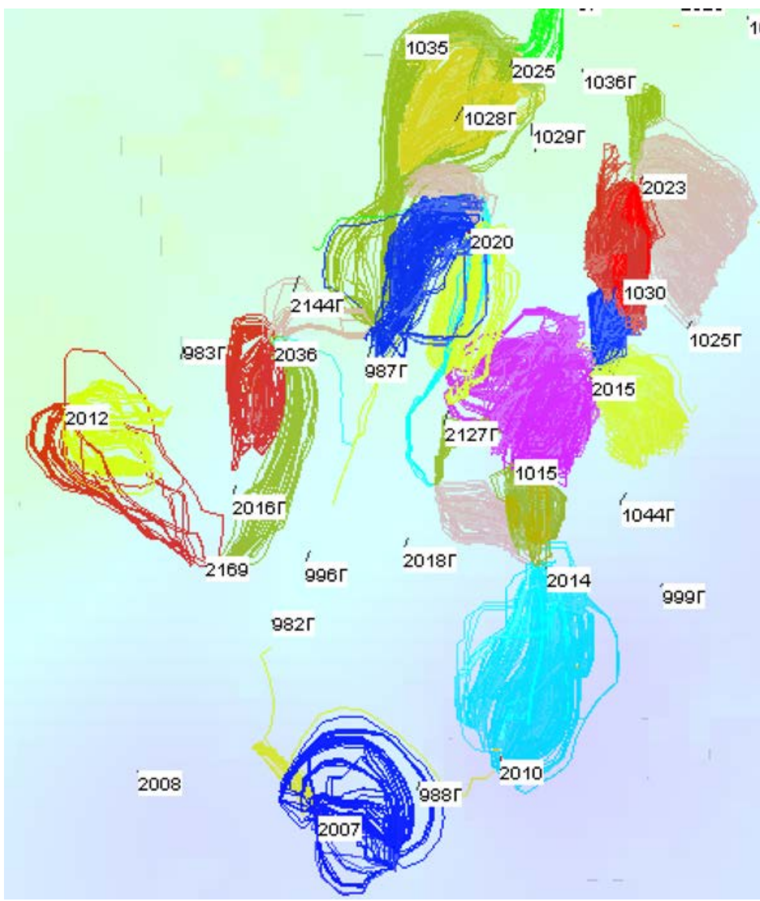

Figure 9—Well flow pathways of the target reservoir area

Upon comparing the results of the methods integration and calculations of the reservoir pressure maintenance system assessment, according to the updated reservoir model, a high convergence of the results was revealed, which indicates the effectiveness of the proposed method.

Conclusion

The method of integrating the marker-based production logging results and the rank correlation method opens up a number of opportunities for research and prompt decision-making to optimise the development system:

- identification of injection wells that have the greatest impact not only on producing wells, but also on specific ports of marked producers;
- identification and prevention of possible injected water breakthroughs and premature flooding of the well;
- a higher degree of the site recovery uniformity.

If implemented, the proposed approach enables prompt monitoring of the dynamics of the field development system, optimisation of the producing and injection wells' operation, and improvement in the oil recovery rate.

References

1. Vaganov L. A., Sentsov A. Yu., Ankudinov A. A., Polyakova N. S. 2017. Calculating the Optimal Injectivity of Injection Wells When Using a Dispersed Waterflood System. *Oil and Gas* **2017**: 63–67.
2. Dulkarnaev M. R., Katashov A. Yu., Ovchinnikov K. N., Malyavko Ye. A., Buyanov A.V., Kotenev Yu. A., Sultanov Sh. Kh., Chibisov A.V., Chudinova D. Yu. 2020. Geological and Field Feasibility Study of Field Development Management Using Marker-Based Production Logging in Horizontal Wells: The Case Study of the Yuzhno-Vyintoiskoye Field. *Oil. Gas. Novation*. **2017** (10): 58–63.
3. Methodology Guidelines for the Geological and Field Analysis of Oil and Gas Development. 2002. RD 153-39.0-110-01. Moscow.
4. Ovchinnikov K. N. 2019. Challenges of Field Development and Drilling, Addressed Using the Marker-Based Production Well Logging Technology. Ovchinnikov K. N. *Oil. Gas. Novation*. **2019** (02): 71–77.
5. Toropov B. A., Botachev E. F., Baranov V. V. 2020. Mathematical Methods for Social Studies. Russia's MIA Academy of Management, Moscow: 80 p.
6. Udintsova N. M., Kopteva N. A. 2016. Econometrics. Part 2: Multiple Regression and Correlation in Econometric Research: Study Aid— Zelenograd: Azov-Black Sea Engineering Institute of the Don State Agrarian University. 73 p.