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## Original article

# Analysis and Evaluation of the Influence of Geological, Physical, and Technological Reservoir Characteristics on the Performance Indicators of Geological and Technical Measures

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## ABSTRACT

**Background:** The outcome of a geological and technical measure is governed by the combined influence of reservoir properties and operating conditions before treatment. Historical field data can support candidate-well selection, but the transfer of established relationships to another field remains uncertain when the sample structure, out-of-sample validation, and applicability limits are not stated explicitly.

**Aim:** To analyse and evaluate the influence of geological, physical, and technological reservoir characteristics on five geological and technical measure performance indicators and to determine whether the resulting models can support a transparent comparative choice among treatment options.

**Materials and methods:** The dataset comprised 107 historical intervention cases: 38 near-wellbore-zone treatments with perforation, 32 acid treatments with perforation, and 37 production-optimization cases. Sixteen input indicators were transformed into nine physically interpretable composite variables. Separate multiple linear regressions were fitted for each intervention type and each of five outcomes. Internal out-of-sample performance was assessed using shuffled five-fold cross-validation with a fixed random seed of 42. Transferability was examined for five West Prorva reservoir units with complete input data by calculating three alternative scenarios per unit and applying fuzzy max-min ranking.

**Results:** For near-wellbore-zone treatment with perforation, cross-validated  $R^2$  was 0.530 for effect duration and 0.522 for post-treatment oil rate. For acid treatment with perforation, the highest value was 0.667 for post-treatment oil rate. Production-optimization models were unstable except for a weak positive result for post-treatment oil rate ( $R^2 = 0.235$ ). In the West Prorva comparison, production optimization ranked first for units IX-2 and VIII-2, near-wellbore-zone treatment with perforation for T-III and VIII-3, and acid treatment with perforation for T-II. Decision-membership function values were low to moderate (0.15–0.48).

**Conclusion:** The approach is suitable for preliminary screening and comparative decision support, but not for unrestricted prediction outside the calibration domain. Local recalibration and validation against observed post-intervention results are required before operational use.

**Keywords:** geological and technical measures; reservoir characteristics; regression modelling; principal component analysis; fuzzy sets; cross-validation.

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## Оригинальное исследование

# Анализ и оценка влияния геолого-физических и технологических характеристик месторождения на показатели эффективности геолого-технических мероприятий

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## АННОТАЦИЯ

**Обоснование.** Результат геолого-технического мероприятия (ГТМ) определяется совместным влиянием свойств пласта и условий эксплуатации до воздействия. Исторические промысловые данные могут поддерживать выбор скважин-кандидатов, однако перенос установленных зависимостей на другое месторождение остается неопределенным, если структура выборки, вневыборочная проверка и границы применимости не описаны явно.

**Цель.** Проанализировать и оценить влияние геолого-физических и технологических характеристик месторождения на пять показателей эффективности ГТМ и определить пригодность полученных моделей для прозрачного сравнительного выбора вариантов воздействия.

**Материалы и методы.** Исходный материал включал 107 исторических случаев: 38 обработок призабойной зоны с перфорацией, 32 кислотные обработки с перфорацией и 37 случаев оптимизации режима добычи. Шестнадцать входных показателей преобразованы в девять физически интерпретируемых составных переменных. Для каждого вида ГТМ и каждого из пяти результатов построена отдельная множественная линейная регрессия. Внутренняя вневыборочная способность оценена перемешанной пятикратной перекрестной проверкой с фиксированным начальным значением 42. Переносимость исследована на пяти объектах Западной Прорвы с полным набором входных данных путем расчета трех альтернатив для каждого объекта и нечеткого max-min ранжирования.

**Результаты.** Для обработки призабойной зоны с перфорацией коэффициент  $R^2$  при перекрестной проверке составил 0,530 для продолжительности эффекта и 0,522 для дебита нефти после воздействия. Для кислотной обработки с перфорацией наибольшее значение получено по дебиту нефти после воздействия (0,667). Модели оптимизации режима были неустойчивыми; слабый положительный результат получен только для дебита нефти после воздействия ( $R^2 = 0,235$ ). В расчетах по Западной Прорве оптимизация заняла первое место для объектов IX-2 и VIII-2, обработка призабойной зоны с перфорацией – для T-III и VIII-3, кислотная обработка с перфорацией – для T-II. Значения функции принадлежности решения находились в диапазоне 0,15–0,48.

**Заключение.** Подход пригоден для предварительного скрининга и сравнительной поддержки решений, но не для безусловного прогнозирования вне области калибровки. Перед производственным применением необходимы локальная перекалибровка и проверка по фактическим результатам мероприятий.

**Ключевые слова:** геолого-технические мероприятия, характеристики месторождения, реерсионное моделирование, метод главных компонент, нечеткие множества, перекрестная проверка.

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## Түпнұсқа зерттеу

# Геологиялық-техникалық шаралар тиімділігінің көрсеткіштеріне кен орнының геологиялық-физикалық және технологиялық сипаттамалары әсерін талдау және бағалау

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## АНДАТПА

**Негіздеу.** Геологиялық-техникалық шараның (ГТШ) нәтижесі қабат қасиеттері мен әсерге дейінгі пайдалану жағдайларының бірлескен ықпалымен анықталады. Тарихи кәсіпшілік деректер ұңғымаларды таңдауды негіздеуге көмектеседі, алайда іріктеменің құрылымы, іріктемеден тыс тексеру және қолданылу шектері нақты көрсетілмесе, алынған тәуелділіктерді басқа кен орнына көшіру белгісіз болып қалады.

**Мақсаты.** Кен орнының геологиялық-физикалық және технологиялық сипаттамаларының ГТШ тиімділігінің бес көрсеткішіне әсерін талдау және бағалау, сондай-ақ алынған модельдердің әсер ету нұсқаларын ашық салыстырмалы таңдауға жарамдылығын анықтау.

**Материалдар мен әдістер.** Бастапқы материал 107 тарихи жағдайды қамтыды: ұңғыма маңы аймағын перфорациямен өңдеудің 38 жағдайы, перфорациямен қышқылдық өңдеудің 32 жағдайы және өндіру режимін оңтайландырудың 37 жағдайы. Он алты кіріс көрсеткіші физикалық тұрғыдан түсіндірілетін тоғыз құрамдас айнымалыға түрлендірілді. Өрбір ГТШ түрі және бес нәтижелік көрсеткіштің әрқайсысы үшін жеке көптік сызықтық регрессия құрылды. Іріктемеден тыс ішкі қабілет 42 тұрақты бастапқы мәні бар араластырылған бес бөлікті айқаспалы тексерумен бағаланды. Көшіру мүмкіндігі толық кіріс деректері бар Батыс Прорва кен орнының бес объектісінде әр объект үшін үш баламаны есептеу және анық емес max-min ранжирлеу арқылы зерттелді.

**Нәтижелері.** Ұңғыма маңы аймағын перфорациямен өңдеу үшін айқаспалы тексерудегі  $R^2$  әсер ұзақтығы бойынша 0,530, ал әсерден кейінгі мұнай дебиті бойынша 0,522 болды. Перфорациямен қышқылдық өңдеуде ең жоғары нәтиже әсерден кейінгі мұнай дебиті бойынша 0,667 құрады. Өндіру режимін оңтайландыру модельдері тұрақсыз болды, әсерден кейінгі мұнай дебиті үшін ғана әлсіз оң нәтиже алынды ( $R^2 = 0,235$ ). Батыс Прорвада IX-2 және VIII-2 объектілері үшін оңтайландыру, T-III және VIII-3 үшін ұңғыма маңы аймағын перфорациямен өңдеу, T-II үшін перфорациямен қышқылдық өңдеу бірінші орын алды. Шешімге тиесілік мәндері 0,15-0,48 аралығында болды.

**Қорытынды.** Ұсынылған тәсіл алдын ала скрининг пен салыстырмалы шешім қабылдауды қолдауға жарамды, бірақ калибрлеу аймағынан тыс шартсыз болжам жасауға арналмаған. Өндірістік қолдану алдында жергілікті қайта калибрлеу және нақты нәтижелер бойынша тексеру қажет.

**Негізгі сөздер:** геологиялық-техникалық шаралар; кен орнының сипаттамалары; регрессиялық модельдеу; негізгі компоненттер әдісі; анық емес жиындар; айқаспалы тексеру.

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## Introduction

Maintaining field-development efficiency and oil-production intensity requires geological and technical measures that are compatible with the actual reservoir and operating conditions. The same intervention may produce different results in different formations because its effect depends on formation thickness, oil-saturated and opened thicknesses, porosity, permeability, fluid properties, saturation, and pre-treatment production conditions [1–4].

In field practice, the selection of treatment type, candidate well, and operating parameters is often based on the experience of geological and production departments. This experience is indispensable, but an ad hoc choice may not integrate all relevant geological, geophysical, technological, and production indicators. As a result, transferring a measure that was successful in one reservoir to another reservoir or field does not necessarily reproduce the same effect [2–8].

Mathematical models can organize heterogeneous information and compare alternative interventions under uncertainty. Their practical value, however, depends on the transparency of the calibration sample, a genuinely out-of-sample assessment,

and explicit limits on transferability. These requirements are especially important for small historical datasets in which reservoir units may repeat and field identifiers may be incomplete.

The aim of this study was to analyse and evaluate the influence of geological, physical, and technological reservoir characteristics on five geological and technical measure (GTM) performance indicators; to document the available sample structure; to evaluate internal out-of-sample performance; and to determine whether the models can support comparative screening of intervention alternatives under incomplete information. The study was not intended to create a universal predictor applicable without local verification.

## Materials and Methods

The analysis used three related data components. The Tengiz annual series provided field-development context. The intervention-level matrix contained the cases used to construct and test the performance models. The West Prorva material supplied a target set for scenario calculations. The size, role, and principal limitation of each component are summarized in Tab. 1.

**Table 1. Structure and analytical role of the source data**

| Data component               | Field / object                           | Available sample                            | Analytical role                                       | Qualification                                |
|------------------------------|------------------------------------------|---------------------------------------------|-------------------------------------------------------|----------------------------------------------|
| Annual field series          | Tengiz                                   | 10 annual observations, 2002–2011           | Contextual comparison of field-development indicators | Not used to fit intervention regressions     |
| NWZT+P cases                 | Several fields; identifiers not retained | n = 38                                      | Regression modelling and internal validation          | Field-blocked validation cannot be performed |
| Acid treatment + perforation | Several fields; identifiers not retained | n = 32                                      | Regression modelling and internal validation          | Field-blocked validation cannot be performed |
| Production optimization      | Several fields; identifiers not retained | n = 37                                      | Regression modelling and internal validation          | Field-blocked validation cannot be performed |
| Target-field set             | West Prorva                              | 9 units described; 5 complete; 15 scenarios | Applicability test and alternative ranking            | Observed case-level outcomes unavailable     |

NWZT+P – near-wellbore-zone treatment plus perforation. The consolidated intervention matrix contains 107 cases in total. A reliable field identifier was not retained; therefore, sample counts by individual field cannot be reconstructed from the available tables.

Each intervention case contained 16 inputs: total formation thickness  $x_1$ ; oil-saturated thickness  $x_2$ ; opened oil-saturated thickness  $x_3$ ; sandiness coefficient  $x_4$ ; porosity  $x_5$ ; permeability  $x_6$ ; reservoir-oil viscosity  $x_7$ ; oil density  $x_8$ ; gas content  $x_9$ ; initial oil saturation  $x_{10}$ ; formation temperature  $x_{11}$ ; paraffin content  $x_{12}$ ; sulfur content  $x_{13}$ ; pre-treatment oil rate  $x_{14}$ ; pre-treatment fluid rate  $x_{15}$ ; and pre-treatment water cut  $x_{16}$ . Units were standardized as m, fraction,  $10^{-3} \mu\text{m}^2$ ,  $\text{mPa}\cdot\text{s}$ ,  $\text{t}/\text{m}^3$ ,  $\text{m}^3/\text{t}$ ,  $^\circ\text{C}$ , %, and  $\text{t}/\text{d}$ , as applicable.

Five outcomes characterized GTM performance: effect duration  $Y_1$  (d), incremental oil  $Y_2$  (t), oil-rate increment  $Y_3$  (t/d), post-treatment oil rate  $Y_4$  (t/d), and post-treatment water cut  $Y_5$  (%). The three intervention groups were NWZT+P, acid treatment plus perforation, and production optimization.

The original 16-dimensional description was reduced to nine composite variables using principal-

component reasoning and physically interpretable combinations [9–12]. The final transformations were:

$$Z_1 = x_3 / (x_1 - x_2) \quad (1)$$

$$Z_2 = x_6 * x_3 / x_7 \quad (2)$$

$$Z_3 = 0.397065x_4 + 0.602935x_5 \quad (3)$$

$$Z_4 = 0.460477x_{12} + 0.539523x_{13} \quad (4)$$

$$Z_5 = 0.402704x_{14} + 0.597296x_{15} \quad (5)$$

$$Z_6 = x_8 \quad (6)$$

$$Z_7 = x_9 \quad (7)$$

$$Z_8 = x_{10} \quad (8)$$

$$Z_9 = x_{11} \quad (9)$$

$Z_1$  describes the relationship among total, oil-saturated, and opened thicknesses;  $Z_2$  represents hydraulic conductivity.  $Z_3$  combines sandiness and porosity,  $Z_4$  combines paraffin and sulfur contents, and  $Z_5$  combines pre-treatment oil and fluid rates.

The coefficients in the weighted pairs were retained from the source calculation scheme.

For each intervention type and each outcome, a separate multiple linear regression was fitted:

$$Y - \text{hat}(k) = a_0(k) + \text{sum}[j = 1..9] a_j(k) Z_j \quad (10)$$

Internal out-of-sample performance was evaluated separately within every intervention group by shuffled five-fold cross-validation with random seed 42. In each iteration, four folds were used to refit the model and the held-out fold was predicted. Held-out predictions from all folds were pooled. We report the coefficient of determination ( $R^2$ ) and median absolute percentage error (MdAPE); observations equal to zero were excluded only from the percentage-error calculation. Calculations used the rounded values in the source dissertation tables [8], so minor differences are possible if the original unrounded operational database is restored.

The West Prorva calculation is treated as an applicability test rather than independent external validation. Complete input vectors were available for five reservoir units, and three intervention scenarios were calculated for each unit. Observed case-level outcomes for these scenarios were not available; consequently, the exercise tests whether

the model can process the target conditions and rank alternatives, but not whether its numerical predictions are accurate on a new field.

For each scenario, the five predicted outcomes were converted to normalized membership values  $\mu_1 - \mu_5$  according to fuzzy-set theory [13]. Increasing functions were used for the outcomes to be maximized, whereas water cut was minimized. With equal weights, the decision membership ( $\mu D$ ) was:

$$\mu D = \min(\mu_1, \mu_2, \mu_3, \mu_4, \mu_5) \quad (11)$$

For each reservoir unit, the intervention with the largest  $\mu D$  was ranked first. This conservative max-min rule prevents an alternative with one very weak outcome from being selected solely because it performs well on the remaining criteria.

Results

Analysis and Synthesis of the Main Well-Intervention Efficiency Indicators

The source matrix represents three intervention types with 32–38 cases per group and nine composite predictors. Five-fold cross-validation was therefore used to distinguish descriptive agreement from the ability to predict held-out observations. The verified results are presented in Tab. 2.

Table 2. Five-fold cross-validation by intervention type ( $R^2$  / MdAPE, %)

| Intervention                 | n  | $Y_1$         | $Y_2$          | $Y_3$          | $Y_4$        | $Y_5$          |
|------------------------------|----|---------------|----------------|----------------|--------------|----------------|
| NWZT+P                       | 38 | 0.530 / 15.2  | 0.296 / 23.5   | -0.307 / 31.9  | 0.522 / 24.0 | -0.002 / 22.0  |
| Acid treatment + perforation | 32 | 0.247 / 18.4  | 0.261 / 20.4   | -0.174 / 39.0  | 0.667 / 23.3 | -0.325 / 31.1  |
| Production optimization      | 37 | -6.843 / 60.2 | -18.589 / 14.8 | -97.549 / 24.7 | 0.235 / 26.0 | -66.266 / 39.6 |

Negative  $R^2$  means that held-out predictions were poorer than prediction by the corresponding sample mean.

For NWZT+P, the most stable held-out relationships concerned effect duration and post-treatment oil rate. Incremental oil showed only limited predictive ability, while oil-rate increment and water cut were not predicted reliably. For acid treatment plus perforation, post-treatment oil rate was the only outcome with a clearly useful positive  $R^2$ . Production-optimization models were unstable for four outcomes; the model for post-treatment oil rate retained only weak positive ability.

These results modify the interpretation of the original in-sample comparisons. Small deviations between calculated and observed values in the calibration table do not by themselves establish forecasting ability. The low case-to-predictor ratio, repeated reservoir units, rounding, and heterogeneous operational practice increase the uncertainty of every equation. The models should therefore be used together as a comparative screening system rather than as five independent unconditional forecasts.

Forecasting Performance Indicators under Different Field Conditions and Selecting Further Technological Decisions

The constructed equations were applied to West Prorva reservoir units whose geological and

technological conditions differ from the calibration cases. Of nine described units, five had the complete inputs needed for calculation: VIII-2, VIII-3, IX-2, T-II, and T-III. Three intervention alternatives were evaluated for each unit, producing 15 scenarios. Tab. 3 reports the highest-ranked alternative for each unit.

Production optimization ranked first for IX-2 and VIII-2. NWZT+P ranked first for T-III and VIII-3, whereas acid treatment plus perforation ranked first for T-II. The decision memberships were modest. This agrees with the source observation that some target conditions produced excessively high or low numerical forecasts because the target and calibration data came from different fields.

The ranking therefore preserves the original purpose of the approach: to compare alternatives when information is incomplete. At the same time, the low membership values are warning signals. They indicate that the target object does not closely reproduce a confident calibration pattern and that the numerical results should be checked by field-specific engineering analysis before implementation.

**Table 3. Highest-ranked intervention for West Prorva reservoir units**

| Reservoir unit | Highest-ranked intervention  | $\mu D$ | Interpretation                                          |
|----------------|------------------------------|---------|---------------------------------------------------------|
| IX-2           | Production optimization      | 0.48    | Highest membership among the three scenarios            |
| T-III          | NWZT+P                       | 0.35    | Relative preference; local verification required        |
| T-II           | Acid treatment + perforation | 0.33    | Relative preference; local verification required        |
| VIII-2         | Production optimization      | 0.29    | Low membership; recommendation is tentative             |
| VIII-3         | NWZT+P                       | 0.15    | Very low membership; insufficient for direct deployment |

Values are relative scores within the three alternatives tested for each reservoir unit; they are not probabilities of success.

## Discussion

The analysis confirms that geological, physical, and technological variables contain useful information for GTM assessment, but the strength of the relationship differs markedly among outcomes and intervention types. This outcome-specific behaviour is physically plausible. Treatment response depends not only on the reservoir variables retained in the matrix but also on treatment volume, chemical concentration, perforation design, well integrity, equipment condition, execution quality, downtime, and contemporaneous operating constraints. These variables were not represented in the consolidated dataset.

The fuzzy max-min rule remains useful because it organizes a multi-criteria decision and makes the limiting outcome visible. Nevertheless, fuzzy ranking cannot repair weak underlying regressions. When an outcome model has poor held-out performance, its membership value also carries substantial uncertainty. A responsible workflow should use the ranking to shortlist alternatives, then apply local simulation, economic screening, integrity checks, and expert review.

The West Prorva exercise demonstrates computational transfer, not predictive transfer. The procedure accepts a new input vector and produces a comparative order, but the absence of observed post-treatment outcomes prevents independent external validation. Prospective application should record the selected candidates, predicted indicators, treatment design, and actual results so that the model can be recalibrated and tested on genuinely independent field data.

## Limitations of the approach

The consolidated intervention matrix does not retain a reliable field identifier. Representativeness

by individual field and field-blocked validation therefore cannot be established from the available material.

The group sizes are small relative to nine predictors, and repeated reservoir units may reduce the effective number of independent observations. Five-fold cross-validation limits optimistic interpretation but does not remove this structural uncertainty.

Calculations were reproduced from rounded tabulated values. If the original unrounded database becomes available, the regressions and validation metrics should be recalculated.

West Prorva supplied complete inputs for only five units and no observed outcomes for the calculated alternatives. The ranking is therefore an applicability test, not an independent external validation.

Intervention-design variables, execution quality, well integrity, downtime, and economic indicators were not included. Equal criterion weights may not correspond to local operational priorities. The equations should be used only within the observed input ranges and for intervention definitions consistent with the calibration data. Materially different geological or operational conditions require local recalibration and prospective validation.

## Conclusion

The original research logic – from geological and technological indicators, through dimensionality reduction and regression, to fuzzy comparative selection – has been retained. The available intervention matrix contains 107 cases distributed among three GTM types and supports exploratory modelling and comparative analysis.

Five-fold cross-validation showed that predictive ability is outcome-specific. The most useful results were obtained for effect duration and post-treatment oil rate after NWZT+P, and for post-treatment oil rate after acid treatment plus perforation. Most production-optimization equations were unstable on held-out observations.

The fuzzy-set procedure provides a transparent ranking of alternative GTMs. For the five complete West Prorva units, the preferred alternatives reproduced the source calculations, but the decision memberships were low to moderate.

Accordingly, the method may be used for preliminary screening and comparative decision support. It should not be used for unconditional numerical prediction outside the calibration domain. Field-specific recalibration and validation against observed post-intervention results are required before operational deployment.

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