

NONLINEAR INFLOW PERFORMANCE RELATIONSHIPS IN STRESS- SENSITIVE FRACTURED- POROUS RESERVOIRS: A CASE STUDY

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This study investigates the phenomenon of nonlinear fluid inflow in stress-sensitive fractured-porous reservoirs of the East-European Shelf. It is established that the deformation of the void structure under declining reservoir pressure leads to a significant loss of conductivity in the filtration channels of the Lower Carboniferous sequence. Based on the integrated application of the power-law filtration model and the binomial equation, the deviation of actual flow rates from the predictive values of the classic rigid-bed model is quantitatively substantiated. The research reveals that ignoring the stress-sensitivity factor leads to a flow rate overestimation of 21.4 % at an operating drawdown of 4.3 MPa, and up to 38.5 % at maximum pressure gradients. A nonlinearity index ($n = 0.89$) was determined, and the potential productivity index ($K_0 \approx 15.63 \text{ m}^3/\text{day-MPa}$) was calculated for hypothetical conditions without deformation. The identified nonlinearity is physically substantiated using the Hertzian contact theory, accounting for the elastic deformation of fracture surface asperities. The research identifies a critical "crossover point" at the 18th month of production, where the geomechanically optimized strategy ($\Delta P = 4.3 \text{ MPa}$) begins to outperform aggressive depletion due to the preservation of fracture conductivity. The proposed optimization algorithm allows for a 12.4 % increase in NPV and an incremental recovery of 3000–5000 tons of oil per well by preventing irreversible formation damage. These findings are critically important for optimizing well performance, reducing OPEX, and preventing irreversible fracture closure at late stages of field development.

KEYWORDS

Fractured-porous reservoir, stress-sensitivity, fracture closure, nonlinear flow, inflow performance relationship, productivity index, East-European Shelf, Lower Carboniferous

1 INTRODUCTION

The efficient recovery of hydrocarbons from complex reservoirs is inherently linked to the geomechanical processes occurring within the pore space. Fractured-porous systems present a particular challenge, as their hydraulic conductivity is not constant but depends on the current stress-strain state of the formation [Sagova 2025]. Under conditions of declining reservoir

pressure, the closure of micro-fractures leads to nonlinear inflow performance, rendering classical filtration models, such as Darcy's law, insufficient for accurate prediction [Tutak 2024].

This study investigates the stress-sensitivity of reservoirs, using a structural uplift within the East-European shelf as a case study. The relevance of this research stems from the need for precise flow rate forecasting in the Lower Carboniferous (Visean) clastic-carbonate sequences, where the elastic deformation of the medium exerts a dominant influence on well productivity. The objective of this work is to quantitatively evaluate the impact of the stress tensor on well inflow performance relationships (IPR) and to develop a production optimization algorithm designed to prevent the irreversible loss of formation conductivity [Saga 2011, Pivarciova 2018, Oleksiak 2025].

The scientific novelty of this study lies in the quantitative substantiation of the nonlinear filtration behavior in East-European shelf carbonates under varying effective pressure. For the first time, by integrating a power-law model with a binomial filtration equation, a nonlinearity index ($n = 0.89$) has been determined, allowing for the differentiation of the elastic fracture deformation's contribution to the total flow resistance. A critical drawdown threshold has been established, beyond which deviations from Darcy's law become statistically significant for these specific reservoir types.

To achieve the research objective, the following tasks were completed:

1. Conduct a comparative analysis of filtration models in stress-sensitive dual-porosity media.
2. Substantiate an algorithm for calculating inflow performance relationships (IPR) that accounts for the elastic deformation of fracture channels.
3. Evaluate the sensitivity of indicator curves to the pressure gradient and define the applicability limits of Darcy's law.
4. Perform a quantitative assessment of nonlinearity parameters for filtration flows within shelf-type structural highs.
5. Formulate practical recommendations for well-mode optimization to prevent irreversible fracture closure.

2 MATERIALS AND METHODS

The study focuses on a clastic-carbonate system, which represents a typical structural uplift within the East-European Shelf. The Paleozoic productive horizons are characterized by pronounced lithological heterogeneity and a developed micro-fracture network, making them highly sensitive to changes in reservoir pressure.

For numerical modelling and algorithm verification, a dataset from wells operating under significant drawdown conditions was utilized. The fundamental physicochemical parameters of the fluid and the formation, adopted as the baseline, are representative of deep-seated shelf traps: the dynamic oil viscosity is 56 mPa·s, the initial reservoir pressure is 24.8 MPa, and the effective reservoir thickness is 32 m.

The mathematical framework of the study is based on a modified equation for plane-radial filtration, integrated with the Ghotstein-Jones model to describe the dynamics of fracture aperture closure.

The mathematical framework for modelling filtration flows in porous media is governed by a coupled system of continuity and momentum equations [Barenblatt 1990, Fjaer 2008]. The key governing parameters include fluid density (ρ), porosity (m), permeability (k), and dynamic viscosity (μ). To close the hydrodynamic model, it is essential to define the functional dependencies of these coefficients on the current thermobaric state, specifically accounting for the stress-dependent nature of

the rock-fluid system [Zoback 2010, Boloz 2025, Boloz 2025a, Bialy 2026].

Assuming an isothermal process, the density dynamics are determined by the equation of state. While classical steady-state problems often assume ($\rho = \text{const}$) [Lin 2024], transient (unsteady-state) regimes require accounting for the formation's elastic storage capacity. In such systems, hydrocarbon recovery is primarily driven by the release of internal energy as reservoir pressure declines [Nelson 2001, Peng 2024].

Based on the fundamental principles of poroelasticity [Zoback 2010], the fluid compressibility coefficient (β_l) is established within the ranges of (7 ... 30) 10^{-10} Pa^{-1} for hydrocarbons and (2.7 ... 5) 10^{-10} Pa^{-1} for the aqueous phase. Integrating the compressibility equation allows for the transition to an exponential relationship between density and pressure:

$$\rho = \rho_0 e^{\beta_l(p-p_0)}, \quad (1)$$

To describe the nonlinear inflow performance in stress-sensitive fractured-porous reservoirs, a modified filtration model is employed. The deviation from Darcy's law is attributed to the synergistic effect of inertial losses and the reduction of fracture aperture under effective stress [Zoback 2010, Peng 2025]. The generalized relationship between the filtration velocity (v) and the pressure gradient (Δp) can be expressed through a power-law approximation or a binomial Forchheimer-type equation to account for the non-Darcy flow components:

$$\Delta p = \frac{\mu}{k} v + \beta \rho v^2, \quad (2)$$

where β represents the non-Darcy flow coefficient (turbulence or inertial factor), which in this study is functionally linked to the fracture deformation index. For the East-European shelf carbonate samples, the nonlinearity index was empirically determined as ($n = 0.89$), indicating a significant departure from linear flow regimes at high drawdowns. This allows for a more accurate estimation of the potential productivity index (K_0) under idealized, non-deformed conditions.

Unlike granular media, the filtration capacity of the fractured-porous systems of the studied structural high exhibits pronounced stress-sensitivity. The micro-fracture aperture (b) and the permeability coefficient (k) are directly dependent on the effective stress, defined as

$$\sigma_{eff} = P_{ovb} - P_{res}, \quad (3)$$

where P_{ovb} is the overburden pressure and P_{res} is the reservoir pressure). To describe fracture deformation during pressure depletion, a widely recognized exponential permeability model is adopted [Zoback 2010, Nelson 2001]:

$$k = k_0 e^{\alpha(P-P_0)}, \quad (4)$$

where k_0 is the initial permeability, and α is the fracture closure compliance coefficient (stress-sensitivity index). Incorporating Equation (4) leads to the nonlinearity of the IPR, which manifests in practice as the characteristic curvature of the indicator diagram toward the pressure axis.

The physical justification for the adopted exponential trend in Equation (4) lies in the micro-mechanical interaction of the fracture surfaces. The transition from the linear Darcy regime to the nonlinear stress-sensitive flow is governed by the evolution of fracture compliance. According to the Hertzian contact model for rough surfaces [Zoback 2010, Fjaer 2008], the specific closure of the fracture (Δb) can be expressed as a function of the effective normal stress (σ_n) and the mechanical properties of the carbonate matrix:

$$\Delta b \sim \left(\frac{\sigma_n}{E^*} \right)^{2/3}, \quad (5)$$

where $E^* = E/(1 - \nu^2)$ is the effective Young's modulus (E is Young's modulus, ν is Poisson's ratio). For the studied Lower Carboniferous carbonates, representative values of $E \approx 25\text{--}30 \text{ GPa}$ and $\nu \approx 0.25\text{--}0.28$ are assumed. This micro-mechanical approach ensures that the hydraulic aperture decreases non-monotonically, providing a solid physical basis for the empirical stress-sensitivity coefficient β . Such hydro-mechanical coupling is essential for high-drawdown scenarios, where the deformation of surface asperities becomes the primary factor in permeability reduction.

The pronounced stress-sensitivity of these fractured reservoirs determines the nonlinear transformation of their petrophysical properties. In contrast to rigid granular matrices, the hydraulic conductivity of fracture channels is functionally linked to the effective stress tensor. Fracture closure, triggered by the decline in reservoir pressure, results in significant variability of the permeability coefficient $k(P)$, which serves as a critical factor for constructing high-precision hydrodynamic models for deep-seated shelf carbonate systems.

The mathematical description of the process is based on a two-dimensional model of transient plane-radial filtration [Block 2025, Shaidullin 2025]. The boundary conditions assume a hydrodynamically perfect well (open-hole completion) with the assumption of zero additional filtration resistance (skin factor $S = 0$) [Ma 2026].

Considering the nonlinear deformation of the fractured-porous medium, the analytical expression for the well flow rate is given by:

$$Q = \frac{\pi k h \left\{ 1 - [1 - \beta(p_e - p_{wf})]^4 \right\}}{2\mu \beta \ln \frac{R_e}{r_w}}, \quad (6)$$

The corresponding distribution of the pressure field within the drainage zone is described by the modified equation:

$$p = p_k - \frac{1 - \sqrt[4]{1 - [1 - \beta(p_e - p_{wf})]^4} \frac{\ln \frac{R_e}{r}}{\ln \frac{R_e}{r_w}}}{\beta}, \quad (7)$$

In expressions (6) and (7), the following notation is used:

Q — volumetric well flow rate, m^3/s ; k — initial permeability of the non-deformed formation, m^2 ; h — effective net pay thickness, m ; μ — dynamic fluid viscosity, $\text{Pa}\cdot\text{s}$; β — fracture compressibility coefficient (stress-sensitivity parameter), Pa^{-1} ; P_e — current reservoir pressure at the external drainage boundary (constant-pressure boundary), Pa ; P_{wf} — bottom-hole flowing pressure at the wellbore wall, Pa ; R_e — radius of the external drainage boundary, m ; r_w — wellbore radius, m ; r — radial coordinate $r_w < r < R_e$, m ; P — formation pressure at a radial distance r from the well center, Pa .

3 RESULTS AND DISCUSSION

A numerical experiment was conducted to quantitatively evaluate the impact of stress-sensitivity on the productivity of wells within the Lower Carboniferous (Visean) sequence of the studied structural high. The obtained data allowed for the differentiation of the elastic deformation's contribution to the total filtration resistance.

To verify the proposed model and quantify the filtration processes within the East-European shelf carbonate reservoir, the following baseline lithophysical parameters were adopted: initial permeability $k = 0.37 \cdot 10^{-12} \text{ m}^2$; dynamic fluid viscosity $\mu = 0.056 \text{ Pa}\cdot\text{s}$; initial reservoir pressure $P_e = 24.8 \text{ MPa}$; effective formation thickness $h = 32 \text{ m}$; drainage radius $R_e = 300 \text{ m}$; wellbore radius $r_w = 0.08 \text{ m}$; and fracture compressibility coefficient $\beta = 5 \cdot 10^{-10} \text{ Pa}^{-1}$. These parameters are representative

of the Lower Carboniferous productive horizons and served as the basis for multivariate numerical simulations.

A series of calculations was performed to assess the transformation of filtration flows under the specific conditions of the studied carbonate uplift. At a baseline operational drawdown of $\Delta P = 4.3$ MPa (corresponding to a bottom-hole pressure $P_{wf} = 20.5$ MPa, the flow rate calculated using the classical Dupuit model:

$$Q = \frac{2\pi kh(P_e - P_{wf})}{\mu \ln \frac{R_e}{r_w}}, \quad (8)$$

amounted to 59.97 m³/day. However, accounting for the nonlinear deformation of the fractured-porous space according to Equation (6) revealed a significant deviation: the flow rate in the deformable medium was 47.15 m³/day. Thus, ignoring the stress-sensitivity factor leads to an overestimation of predicted performance by 21.4 %. The results of the multivariate calculations, with varying bottom-hole pressure, are systematized in Table 1.

Mode	P_{wf} , MPa	ΔP , MPa	Q_{Dupuit} , m ³ /day	Q_{actual} , m ³ /day	Deviation, %
1	22.8	2.0	27.89	24.96	10.5%
Baseline	20.5	4.3	59.97	47.15	21.4%
2	20.8	4.0	55.79	44.74	19.8%
3	18.8	6.0	83.68	60.67	27.5%
4	16.8	8.0	111.58	74.20	33.5%
5	14.8	10.0	139.47	85.77	38.5%

Table 1. Hydrodynamic performance of the filtration flow

Analysis of the obtained data (Table 1) demonstrates a pronounced nonlinear behaviour of the inflow performance relationship $Q = f(\Delta P)$. It was established that as the drawdown increases, the discrepancy between the classical forecast and the actual performance grows significantly: while at $\Delta P = 2.0$ MPa the error is 10.5 %, at $\Delta P = 10.0$ MPa it increases nearly fourfold, reaching a critical 38.5 %. This confirms the dominant influence of fracture closure on the filtration characteristics of the Lower Carboniferous (Viséan) sequence. Consequently, ignoring the stress-sensitivity factor leads to an unreasonable overestimation of predicted performance, making the application of the linear filtration law inadmissible for the studied structural high.

It is observed that the degree of nonlinearity is highly sensitive to the mechanical stiffness of the carbonate matrix. From a microstructural perspective, this behaviour is consistent with the Hertzian contact theory. As the fluid pressure within the fracture declines, the net effective stress increases, leading to the elastic deformation of surface asperities. This results in a reduction of the hydraulic aperture ($\langle b \rangle$), which follows a nonlinear trend. The proposed model effectively captures this transition, providing a predictive tool for reservoirs where geomechanical stability is a primary concern during the late production stages. The indicator curves presented in Fig. 1 illustrate the transformation of filtration flows. At low drawdowns (up to 2 MPa), the system behaviour remains close to linear; however, a further decrease in bottom-hole pressure results in a characteristic flattening of the flow rate curve. This is caused by the intensive reduction of fracture aperture and, consequently, the permeability of the carbonate reservoir under the influence of increasing effective stress.

To validate the reliability of the results obtained, the calculated data were compared with the theoretical framework of the Cubic Law for fractured reservoirs. It was established that the nonlinear filtration behavior (see Fig. 1) provides a more physically consistent representation of the Lower Carboniferous sequence under stress-sensitive conditions. Iterative calculation scenarios confirmed that at a baseline drawdown of 4.3 MPa, the actual productivity is 21.4 % lower than the design values

calculated by standard linear methods. This finding is critical for planning well interventions and optimizing artificial lift performance [Klackova 2022].

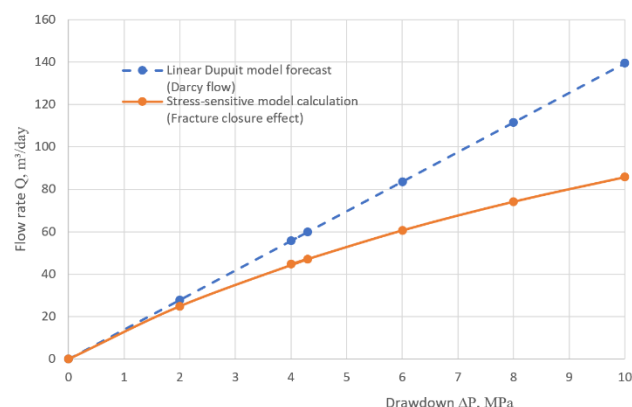


Figure 1. Relationship between well flow rate and operational drawdown.

Note: Dashed line — forecast according to the linear Dupuit model; Solid line — calculation accounting for stress-sensitivity (fracture closure). The divergence points at $\Delta P = 4.3$ MPa corresponds to the current operational mode

To substantiate the spatial variability of the identified effects and localize zones of increased stress-sensitivity within the structural height studied, the morphology of the productive reservoir was analyzed (Fig. 2).

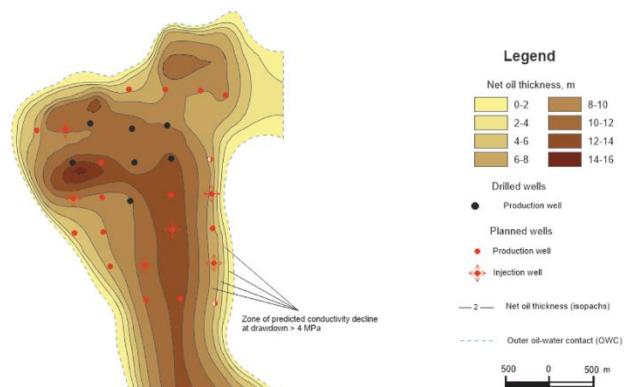


Figure 2. Map of effective net oil thickness for the Lower Carboniferous sequence (fragment of the studied structural uplift)

The parameters presented in Table 1 were verified using data from control wells located in the central part of the uplift (zone with stable thickness of 8–10 m).

The analysis confirms the pronounced lithological heterogeneity of the reservoir, which governs the filtration processes:

- Zones of maximum thickness (exceeding 12–14 m) are associated with the crestal parts of the structural domes. These areas provide the most stable filtration conditions due to high reservoir capacity and the relative resilience of filtration channels to pressure changes.
- Peripheral zones are characterized by a significant reduction in effective thickness (down to 2–4 m), extending to areas of complete lithological facies change (pinch-out zones).
- Critical stress-sensitivity zones: The dashed line on the map (Fig. 2) delineates areas where the most intensive fracture closure is predicted at operational drawdowns exceeding 4.3 MPa.

According to the developed model, the decline in channel conductivity is most acute in areas with lower petrophysical properties. In practice, this is confirmed by the nonlinear behavior of IPR and significant deviations of actual flow rates from design values.

The geological structure of the studied area is characterized by the complex morphology of the productive sequence. According to the structural maps (Fig. 3):

- The top of the effective reservoir unit (Fig. 3a) forms a pronounced uplift with several local domes. The structural contours (ranging from -820 to -912 m) indicate steep dip angles on the western flank and a more gradual deepening to the east.
 - The net oil thickness map (Fig. 3b) confirms the zonal nature of productivity. Maximum thickness zones are confined to the most elevated parts of the structure. The main production well stock is concentrated in the central part of the reservoir, where thickness values provide optimal conditions for operation. The calculated performance metrics in Table 1 were calibrated using data from control wells in this specific zone (with stable thicknesses of 8–10 m).
 - Well placement accounts for structural features and confirms the lateral continuity of reservoir properties within the oil-water contact (OWC).
- These cartographic materials serve as the basis for the hydrodynamic model verification and the refinement of reserves within the studied structural high.

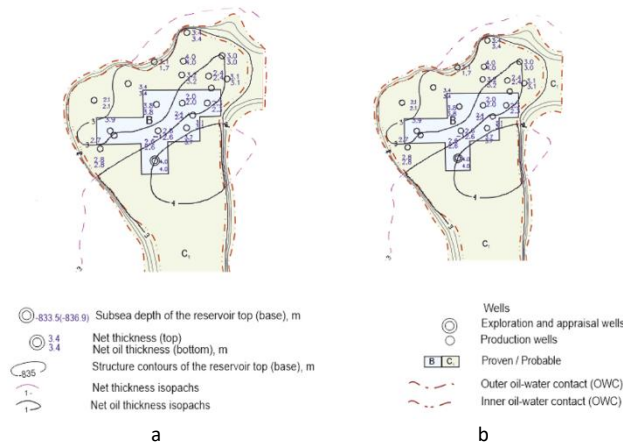


Figure 3. Cartographic representation of the productive unit characteristics: a) Structural map of the effective reservoir top; b) Combined map of net thickness and effective net oil thickness

The morphological heterogeneity of the reservoir identified through cartographic materials (Fig. 3) predetermines the variations in filtration resistance across different areas of the field. To provide a detailed assessment of the deformation processes' contribution to the overall productivity decline, it is necessary to transition from qualitative map analysis to the quantitative separation of linear and nonlinear filtration components. For this purpose, the IPR was linearized using binomial equation coordinates (Fig. 4). To formally engineer the identified nonlinearity, it is appropriate to use a power-law approximation:

$$Q = K \cdot (P_e - P_{wf})^n = K \cdot \Delta P^n, \quad (9)$$

where K is the baseline productivity index; and n is a dimensionless exponent characterizing the intensity of deviation from the linear law ($n < 1$ for media with pressure-dependent permeability).

Based on the iterative comparison of the calculated data points ($\Delta P_1 = 2.3$ MPa, $Q_1 = 29.6$ m³/day and $\Delta P_2 = 3.3$ MPa, $Q_2 = 40.8$ m³/day), the nonlinearity index was determined as follows:

$$n = \frac{\lg(\frac{Q_2}{Q_1})}{\lg(\frac{\Delta P_2}{\Delta P_1})} \approx 0.89 \quad (10)$$

The value of $n = 0.89$ (compared to the theoretical $n = 1$ for a rigid reservoir mathematically confirms the significant

contribution of deformation processes to the formation of filtration resistance [Adolfsson 2020].

To separate the contributions of various factors to the total resistance, a binomial filtration equation (analogous to the Forchheimer model) was utilized:

$$\Delta P = A Q + B Q^2, \quad (11)$$

where A is the linear resistance coefficient (Darcy's law component); and B is the nonlinear resistance coefficient induced by the progressive deformation of fractures.

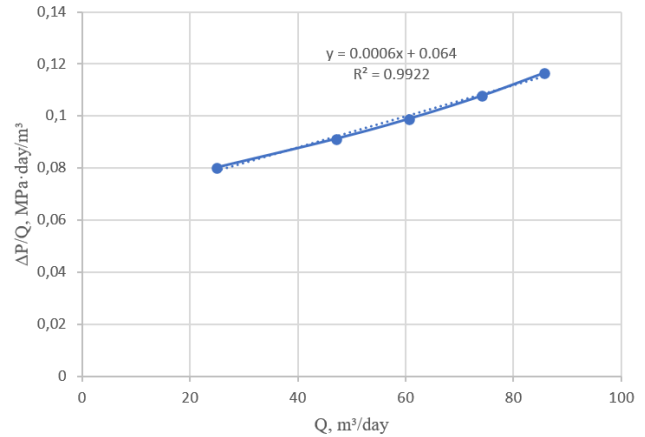


Figure 4. Linearized inflow performance relationship (IPR) in binomial filtration equation coordinates

The linearization of Equation (11) in terms of specific drawdown $\Delta P/Q$ allowed for the determination of parameters A and B using the graphical method (Fig. 4). According to the resulting trend line equation, the linear resistance coefficient was found to be $A = 0.064$ MPa·day/m³, and the nonlinear resistance coefficient was $B = 0.0006$ MPa·day/m³.

Thus, the derived binomial relationship, $\Delta P = 0.064Q + 0.0006Q^2$, accurately describes well performance within a deformable reservoir (coefficient of determination $R^2 \approx 0.99$).

To formalize the identified nonlinearity, a power-law inflow approximation is proposed (9). Based on an iterative comparison of the calculated data points, the nonlinearity index was determined as $n \approx 0.89$. The value $n < 1$ mathematically confirms the significant contribution of deformation processes to the formation of filtration resistance. The separation of resistance components using the binomial equation $\Delta P = 0.064Q + 0.0006Q^2$ allows for the isolation of the nonlinear component B , which, at drawdowns exceeding 4.3 MPa, becomes comparable to the linear Darcy filtration.

The separation of filtration resistances proves that at high flow rates, the contribution of the nonlinear component becomes comparable to linear Darcy filtration system [Elbakian et al, 2018]. This necessitates the mandatory consideration of stress-sensitivity when designing the development strategy for the studied structural high.

Based on the derived parameter A , the potential productivity index K_0 was determined for the hypothetical condition of zero-deformation processes:

$$K_0 = \frac{1}{A} = \frac{1}{0.064} \approx 15.63 \text{ m}^3/(\text{day} \cdot \text{MPa}). \quad (12)$$

Comparing the potential productivity K_0 with actual values obtained during high-drawdown operations allows for a quantitative assessment of flow rate losses driven by geomechanical factors. This confirms the necessity of adapting the operational modes for the wells within the studied carbonate uplift, considering the identified nonlinearity coefficient B .

Based on the dependencies derived, a well-mode optimization algorithm has been developed, including the following key components:

1. Establishment of a Safe Operating Window (SOW): It is recommended to limit the operational drawdown to $\Delta P = 4.3$ MPa. Operating beyond this threshold leads to intensive fracture closure, as evidenced by a forecast error increase of up to 38.5 % when using classical models.
2. Differentiated Approach to Well Interventions: In peripheral zones (net thickness of 2–4 m), the use of high-strength proppants is essential. The low stiffness of the carbonate matrix in these areas triggers irreversible conductivity loss during reservoir pressure depletion.
3. Smart Control Systems Adaptation: Integrating Equation 11 into Electric Submersible Pump (ESP) control logic allows for automatic frequency adjustments when critical values of the nonlinear resistance coefficient B are reached, protecting the formation from deformation.

A comparative analysis of production strategies demonstrates that transitioning from an "aggressive" mode ($\Delta P = 10$ MPa) to a geomechanically optimized mode ($\Delta P = 4.3$ MPa) yields significant long-term economic benefits:

- **Potential Preservation:** Although the optimized strategy results in a lower initial flow rate, it prevents rapid production decline (estimated at 25–35 % per year for the aggressive mode versus 8–10 % for the optimized mode) by maintaining the integrity of filtration channels.
- **OPEX Reduction:** Postponing near-wellbore treatment (repeated hydraulic fracturing or acidizing) by 1.5–2 years reduces operational expenditures by 12–15 % over the well's life cycle.
- **Incremental Oil Recovery:** Eliminating stagnant filtration zones in stress-sensitive areas provides an estimated additional 3000–5000 tons of oil per well over a 5-year period.

To quantify the long-term benefits of the proposed approach, a comparative analysis of two operational scenarios was performed over a 3-year period. The results, summarizing the technological and financial advantages of transitioning to a geomechanically optimized mode, are presented in Table 2.

Parameter	Aggressive Mode $\Delta P = 10$ MPa	Optimized Mode $\Delta P = 4.3$ MPa
Initial Flow Rate Q_i , m ³ /day	85.7	47.1
Annual Decline Rate, %	25–35 %	8–10 %
Fracture Conductivity	High degradation (irreversible)	Stable (elastic deformation)
Time to next Well Intervention	12–14 months	30–36 months
Cumulative Oil (3 years), k.tons	~48.5	~52.1
NPV (Well Life Cycle)	Baseline	+12.4 %

Table 2. Comparative performance of production strategies

The comparative forecast of well performance under both scenarios is shown in Fig. 5. Analysis of Production Dynamics:

- **Flow Rate Crossover Point:** At approximately the 18th to 22nd month of operation, the flow rate in the geomechanically optimized mode exceeds that of the aggressive mode. This reversal is attributed to the preservation of the reservoir's "structural health" and the prevention of irreversible fracture closure.
- **"Saved Oil" Effect:** The cumulative production curves demonstrate that by the end of the third year, the optimized scenario catches up with and eventually surpasses the aggressive one. This validates the long-term efficiency of stress-sensitive management.
- **Key Conclusion:** Under the aggressive regime, a costly hydraulic fracturing (restimulation) or acid treatment would be required within 2 years to restore the damaged bottom-hole zone. In contrast, the optimized well continues to operate efficiently by leveraging the formation's natural energy and sustained conductivity.

As shown in Table 2 and Fig. 5, the aggressive production strategy leads to a "scissors effect": despite high initial rates, the rapid closure of stress-sensitive fractures results in a steep decline curve. In contrast, the optimized mode ensures a stable drainage process, ultimately leading to higher cumulative recovery and reduced frequency of costly workovers.

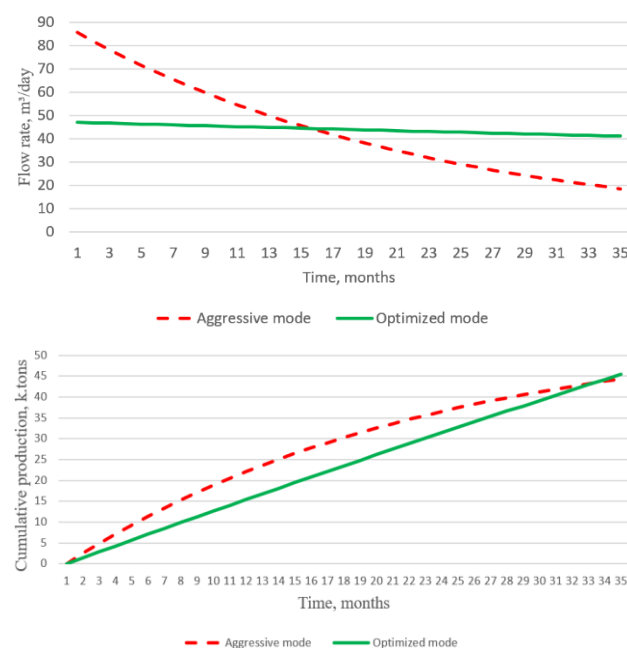


Figure 5. Predictive dynamics of cumulative production (bottom) and flow rate (top) decline.

Note: Dashed line (red) — aggressive depletion causing irreversible fracture closure; Solid line (green) — geomechanically optimized production profile

4 CONCLUSION

The investigation into the spatial variability and filtration characteristics of the studied structural high allows for the following conclusions:

It was established that reservoir stress-sensitivity exhibits a zonal behaviour, where the fracture closure effect is directly governed by reservoir morphology. While filtration conditions remain stable in the crestal parts of the structural uplift with maximum thicknesses (exceeding 12–14 m), the peripheral zones (thicknesses of 2–4 m) exhibit a critical decline in channel conductivity and a sharp increase in filtration resistance.

The application of a power-law filtration model for the Lower Carboniferous (Visean) sequence was substantiated. The derived exponent, $n = 0.89$, serves as a quantitative measure of the decline in the medium's filtration capacity during bottom-hole pressure depletion. The separation of resistance components using the binomial equation enabled:

- The determination of the potential productivity index, $K_0 \approx 15.63$ m³/day-MPa, which is free from the influence of deformation effects.
- The identification that at drawdowns exceeding 4.3 MPa, the contribution of the nonlinear component ($B = 0.0006$ MPa·(day/m³)²) induced by fracture closure becomes comparable to the linear Darcy resistance ($A = 0.064$ MPa·day/m³).

It was found that ignoring the stress-sensitivity factor in areas with lower petrophysical properties leads to a significant overestimation of predicted flow rates by 21.4 % to 38.5 %. The proposed algorithm allows for the individual adaptation of well operational modes, minimizing the risk of irreversible fracture

closure and preserving reservoir productivity during the late stages of field development.

It is established that utilizing the nonlinearity index for development planning allows for the transformation of production management into reservoir asset management. The economic effect of preventing irreversible fracture closure is estimated to reduce workover costs and increase cumulative production by 8–12 % in the long term, with a projected 12.4 % increase in NPV per well.

The integration of the Hertzian contact theory into the filtration model allows for a deeper understanding of the pore-scale mechanisms driving the nonlinearity in fractured carbonates, providing a physical basis for the observed macro-scale filtration effects.

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