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Research Article

Voidage Replacement Ratio and Pressure Stability: An Analytical Assessment of Volumetric Control in Waterflooding

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Abstract: Voidage Replacement Ratio (VRR) is widely used in water injection management as a volumetric performance indicator; however, its role in ensuring environmentally safe reservoir pressure control remains insufficiently quantified. This study presents an analytical assessment of VRR as a stability-governing parameter linking cumulative volumetric imbalance to reservoir pressure evolution. A conceptual homogeneous reservoir model based on classical material balance principles was developed to evaluate under-injection (VRR < 1), balanced injection (VRR = 1), and over-injection (VRR > 1) regimes under constant-rate conditions. Results demonstrate that sustained deviation from unity VRR produces linear cumulative imbalance and systematic pressure drift. Under-injection leads to progressive pressure depletion, whereas over-injection generates continuous pressure build-up, potentially increasing risks of caprock stress alteration, fracture propagation, and unintended fluid migration. Sensitivity analysis indicates that even moderate deviation (±0.05–0.1) may cause measurable long-term instability. The findings support interpretation of VRR not merely as an operational metric but as a dynamic stability control parameter contributing to environmentally responsible reservoir management. Maintaining VRR within a narrow tolerance range minimizes cumulative imbalance growth and supports safe pressure maintenance. The analytical framework provides a transparent basis for integrating volumetric stability criteria into sustainable water injection strategies.

Keywords: Voidage Replacement Ratio; Water Injection; Pressure Maintenance; Reservoir Engineering; Voidage Balance.

1 Introduction

Water injection remains the primary method of reservoir pressure maintenance in hydrocarbon production systems. The efficiency and long-term stability of pressure support operations depend on the balance between fluid withdrawal and injected volumes. VRR is widely used as a diagnostic and control parameter to quantify this balance. In practical reservoir management, VRR serves as a key operational indicator reflecting the effectiveness of pressure maintenance strategies. However, deviations from balanced injection conditions frequently occur due to geological heterogeneity, injectivity limitations, and operational constraints. These deviations may significantly impact reservoir pressure behaviour and system stability.

VRR is fundamentally rooted in classical material balance theory and represents the volumetric relationship between injected and produced fluids in a reservoir system. The theoretical basis linking volumetric compensation to pressure evolution was established in early reservoir engineering literature, where pressure decline was directly related to cumulative withdrawal exceeding injected volumes [1] – [3]. These principles remain central to modern pressure maintenance strategies.

In practical waterflood operations, VRR is widely applied as a surveillance and control parameter to assess injection efficiency and reservoir voidage compensation [4], [5]. Field-based investigations have demonstrated that sustained deviations from unity VRR may lead to long-term pressure instability, sweep inefficiency, and suboptimal recovery performance [6], [7]. Optimization studies incorporating VRR into well-control algorithms and streamline-based simulation frameworks have shown that volumetric balance strongly influences recovery factor and energy efficiency [8], [9].

Recent research has extended VRR analysis toward heavy oil systems and heterogeneous reservoirs, indicating that optimal VRR values may deviate from unity depending on mobility ratio, compressibility, and injectivity constraints [10], [11]. Furthermore, analytical and numerical studies highlight the importance of integrating VRR with pressure transient response and injectivity decline models to better characterize system stability [12].

Despite its widespread application, VRR is frequently treated as an operational indicator rather than a stability-defining analytical parameter. A systematic analytical evaluation of cumulative imbalance dynamics under controlled conceptual conditions remains limited in the literature. Therefore, the present study aims to establish a simplified analytical framework linking VRR deviation to cumulative volumetric imbalance and reservoir pressure behavior.

The objective of this study is to analytically evaluate VRR as a governing control parameter in water injection optimization using a conceptual reservoir framework. The research focuses on identifying characteristic system responses under varying compensation regimes. The scientific novelty of this study lies in the development of a simplified analytical framework that explicitly links deviations in VRR to cumulative volumetric imbalance and corresponding reservoir pressure evolution. Unlike conventional approaches that treat VRR primarily as an operational surveillance metric, this work demonstrates its role as a governing stability parameter controlling long-term pressure behavior under constant-rate conditions.

2 Material and methods

To investigate the stability behaviour of reservoir pressure maintenance under varying injection regimes, a conceptual analytical reservoir model was developed (Fig. 1) based on classical material balance theory and volumetric equilibrium principles widely adopted in reservoir engineering practice [13] – [16]. The objective of the model is to isolate the effect of volumetric compensation on cumulative voidage imbalance and associated pressure evolution under controlled boundary conditions.

The VRR is defined as the ratio between injected and produced reservoir volumes over a given time interval, as expressed in Eq. (1).

$$VRR = V_{inj}/V_{prod} \qquad (1)$$

where V_{inj} is the injected fluid volume, V_{prod} is the produced reservoir volume at reservoir conditions, C_t is the total compressibility of the rock-fluid system, and V_p is the reservoir pore volume. This definition is consistent with standard surveillance metrics used in waterflood performance monitoring [17], [18]. This formulation defines VRR as a dimensionless indicator describing the efficiency of volumetric compensation in the reservoir system. A value of VRR equal to unity corresponds to a perfectly balanced system where injected and produced volumes are equal. Deviations from unity reflect either insufficient or excessive compensation, which directly influences reservoir pressure behavior. Therefore, VRR serves not only as a monitoring parameter but also as a primary control variable governing pressure stability.

The instantaneous volumetric imbalance is expressed as Eq. (2):

$$\Delta V = V_{prod} - V_{inj} \qquad (2)$$

The instantaneous voidage imbalance represents the short-term discrepancy between injection and production rates. This parameter provides insight into the current operational state of the reservoir and indicates whether the system is experiencing under-compensation or over-compensation at a given moment. Although instantaneous imbalance may appear small, its accumulation over time plays a critical role in determining long-term pressure evolution. And the cumulative voidage imbalance over the simulation period is defined by Eq. (3):

$$\Delta V_{cum} = \sum_{i=1}^{n} (V_{prod,i} - V_{inj,i}) \qquad (3)$$

Cumulative voidage imbalance is a key parameter controlling reservoir pressure dynamics, as it integrates the effect of sustained volumetric mismatch over time. Even minor but persistent deviations from balanced conditions can lead to significant cumulative imbalance. This accumulated effect is directly responsible for pressure drift, making it a fundamental variable in assessing long-term system stability. For slightly compressible reservoir systems, pressure deviation resulting from cumulative volumetric imbalance may be approximated using the linearized material balance relationship shown in Eq. (4). [13], [15], [19]:

$$\Delta P = \frac{\Delta V_{cum}}{C_t V_p} \qquad (4)$$

where C_t represents total compressibility of the rock-fluid system and Vp is reservoir pore volume. This linearized material balance relationship links cumulative volumetric imbalance to reservoir pressure variation. It shows that pressure change is directly proportional to the magnitude of accumulated imbalance and inversely proportional to the storage capacity of the reservoir system, defined by pore volume and compressibility. This formulation provides a simplified yet physically meaningful tool for evaluating pressure response under different injection regimes. Total compressibility is defined in Eq. (5) as:

$$C_t = C_r + C_0 + S_w C_w \qquad (5)$$

following standard reservoir engineering formulations [13], [19]. Total compressibility represents the combined elastic response of both the rock matrix and the reservoir fluid to pressure changes. It determines the capacity of the reservoir system to accommodate volumetric imbalance without significant pressure variation. Higher compressibility implies greater tolerance to imbalance, while lower compressibility leads to more pronounced pressure sensitivity.

The analytical model assumes a homogeneous and isotropic reservoir containing a slightly compressible single-phase liquid. Multiphase flow behavior, capillary pressure, aquifer support, permeability heterogeneity, and injectivity decline are excluded in order to isolate volumetric balance mechanisms and maintain analytical transparency [14], [19].

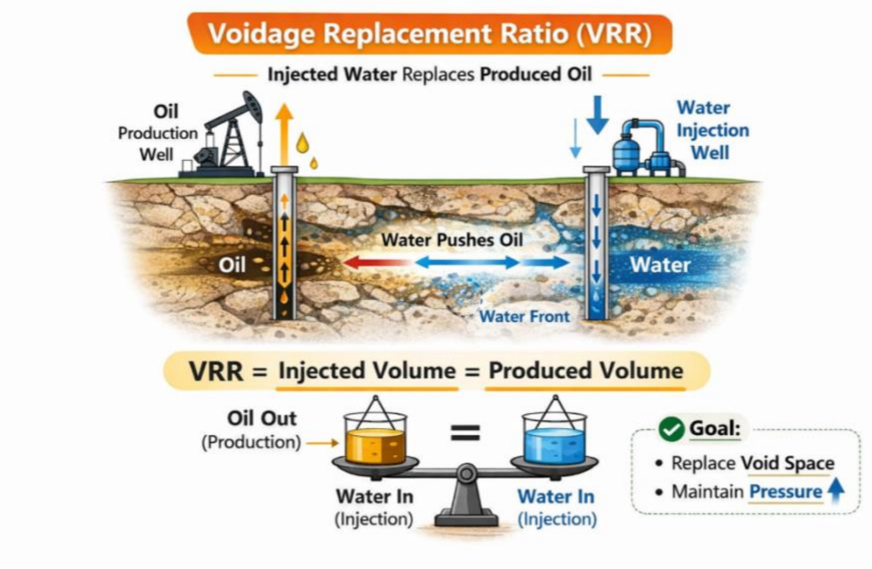

Figure 1. Conceptual Illustration of VRR in a Carbonate Reservoir

A constant production rate was imposed throughout the simulation period, while injection volumes were systematically varied to simulate under-injection (VRR < 1.0), balanced injection (VRR = 1.0), and over-injection (VRR > 1.0) regimes. Additional sensitivity scenarios were considered within the range $0.9 \leq VRR \leq 1.1$ to evaluate stability limits. The simulation period covered 12 months with uniform time increments.

The reservoir and fluid properties used in the conceptual model correspond to representative slightly compressible oil reservoirs reported in established engineering references [13], [19]. The adopted parameters are summarized in Table 1.

Table 1 – Conceptual Reservoir Model Parameters

Parameter	Symbol	Value
Pore volume	V_p	1.0×10^6 m^3
Initial reservoir pressure	P_0	250 bar
Rock compressibility	C_r	4.0×10^{-5} bar^{-1}
Oil compressibility	C_o	8.0×10^{-5} bar^{-1}
Total compressibility	C_t	1.2×10^{-4} bar^{-1}
Production rate	O_p	100 m^3/month
Simulation period	t	12 month
Reservoir type	-	Homogeneous
Fluid system	-	Slightly compressible oil

The selected reservoir and fluid parameters represent typical values for slightly compressible oil reservoirs commonly reported in reservoir engineering literature. The adopted pore volume and compressibility coefficients are consistent with generalized field-scale systems and are used to ensure the representativeness of the conceptual analytical model.

Pressure variation rate under constant-rate conditions may also be expressed in differential form as shown in Eq. (6):

$$\frac{dP}{dt} = \frac{Q_{inj} - Q_{prod}}{C_t V_p} \tag{6}$$

The differential form of the pressure equation allows continuous evaluation of pressure change rate as a function of time. This representation is particularly useful for identifying trends in pressure evolution and assessing system stability under sustained operational conditions. It highlights that pressure drift is directly controlled by the rate of volumetric imbalance, reinforcing the role of VRR as a governing parameter. This formulation allows quantitative evaluation of pressure drift under sustained VRR deviation and enables analytical identification of stability thresholds.

The conceptual modelling approach enables isolation of compensation effects independent of reservoir-specific disturbances.

3 Result and discussion

The analytical evaluation of the conceptual reservoir model demonstrates systematic pressure behaviour under varying VRR regimes. The baseline simulation considers constant production withdrawal of 100 m³/month and varying injection volumes to represent under-injection, balanced injection, and over-injection scenarios. The primary volumetric results are summarized in Table 2.

The results demonstrate that deviations from the balanced VRR condition produce systematic voidage imbalance trends. Under-injection conditions generate sustained positive imbalance behaviour, resulting in progressive cumulative deficit accumulation. This trend reflects insufficient reservoir volume compensation, which is commonly associated with pressure decline tendencies. In contrast, the balanced injection regime exhibits zero voidage imbalance throughout the analysed period. The absence of cumulative imbalance confirms theoretical equilibrium conditions and indicates stable pressure maintenance behaviour. Over-injection scenarios produce persistent negative voidage imbalance trends. The cumulative imbalance decreases linearly over time, reflecting systematic over-compensation of produced volumes. Such conditions may lead to excessive reservoir pressure build-up and operational risks. Figure 2 illustrates the cumulative voidage imbalance behaviour for the analysed injection regimes.

Table 2 - Conceptual Reservoir Model Results

Case	Production Volume (m³/month)	Injection volume (m³/month)	VRR	Voidage Imbalance	Cumulative Imbalance
Under-Injection	100	80	0.8	+20	+240
Balanced System	100	100	1.0	0	0
Over-Injection	100	120	1.2	-20	- 240

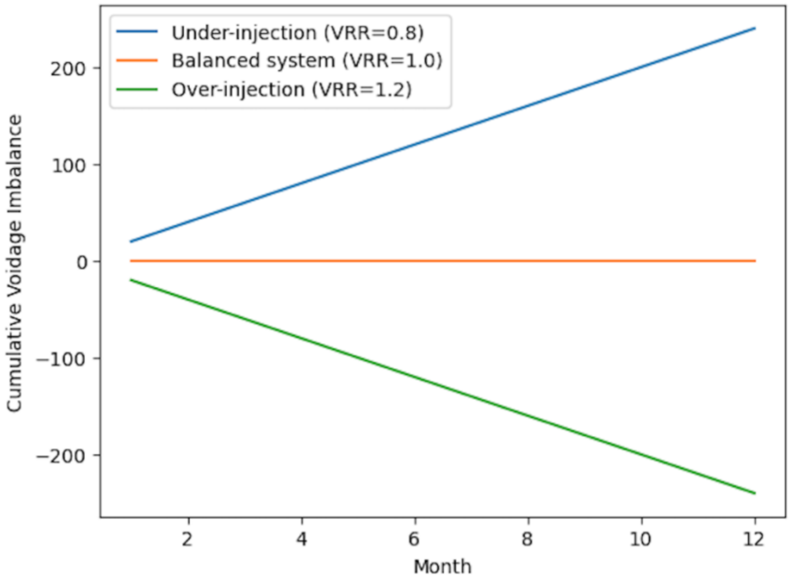

Figure 2. Cumulative voidage imbalance over time for under-injection (VRR = 0.8), balanced injection (VRR = 1.0), and over-injection (VRR = 1.2) regimes during a 12-month simulation period

The cumulative imbalance trends shown in Figure 2 clearly highlight the stability characteristics of the pressure maintenance system. The under-injection scenario produces progressive imbalance growth, indicating continuous deficit accumulation. This behaviour implies declining pressure support efficiency over time. The balanced VRR regime exhibits a stable zero-imbalance response, confirming that equilibrium injection conditions ensure long-term system stability. The over-injection regime generates a steadily decreasing cumulative imbalance trend. This behaviour indicates excessive compensation, which may introduce pressure management challenges despite apparent volumetric stability. The analytical assessment confirms that VRR functions as a governing control parameter defining pressure maintenance system stability. Even under simplified conceptual conditions, imbalance accumulation behaviour provides clear insight into reservoir system dynamics. Deviation from the balanced VRR regime systematically alters system equilibrium. Under-compensation results in deficit accumulation, while over-compensation generates persistent negative imbalance trends. These findings are consistent with theoretical expectations of volumetric reservoir balance principles. Under-injection (VRR = 0.8) results in a monthly volumetric deficit of 20 m³. Over the 12-month simulation period, cumulative imbalance reaches 240 m³. According to the material balance formulation [13], [15], [21], the corresponding pressure deviation is calculated using Eq. (7):

$$\Delta P = \frac{\Delta V_{cum}}{C_t V_p} \tag{7}$$

Substituting Ct=1.2×10^{-4} bar and Vp=1.0×10^{6}m³ into Eq. (7) yields Eq. (8), giving a pressure decline of approximately 2 bar:

$$\Delta P = \frac{240}{(1.2\times10^{-4})(1.0\times10^{6})} = 2\ bar \tag{8}$$

Thus, sustained under-compensation produces a pressure decline of approximately 2 bar within one year. Although moderate under selected parameters, the decline is linear and cumulative. This expression provides a quantitative estimate of pressure deviation resulting from cumulative voidage imbalance over the simulation period. It demonstrates how relatively small volumetric discrepancies can translate into measurable pressure changes. The linear dependence confirms that pressure evolution is predictable under constant-rate conditions, emphasizing the importance of maintaining balanced injection to avoid long-term instability.

Balanced injection (VRR = 1.0) maintains zero cumulative imbalance throughout the simulation period. As predicted by classical material balance analysis [13] –[15], reservoir pressure remains stable. This confirms that volumetric equilibrium ensures pressure maintenance stability under constant-rate conditions.

Over-injection (VRR = 1.2) generates a monthly volumetric surplus of 20 m³ and a cumulative imbalance of –240 m³ after 12 months. The resulting pressure increase is approximately 2 bar. While pressure build-up may initially enhance energy support, prolonged over-injection may induce operational risks such as fracture propagation, caprock integrity concerns, or undesired fluid redistribution [16], [22].

Figure 2 shows cumulative voidage imbalance as a function of time. The imbalance trends exhibit strictly linear behaviour, reflecting constant-rate boundary conditions. Under-injection produces progressive positive accumulation, balanced injection remains at zero, and over-injection generates negative cumulative imbalance.

Figure 3 presents reservoir pressure evolution over time for the three VRR regimes. The pressure curves are linear and directly proportional to the magnitude of VRR deviation. The slope of each curve is governed by formula 6.

The balanced case shows zero slope, while deviation from unity VRR results in systematic pressure drift. This linear dependency confirms that VRR deviation magnitude controls instability development rate.

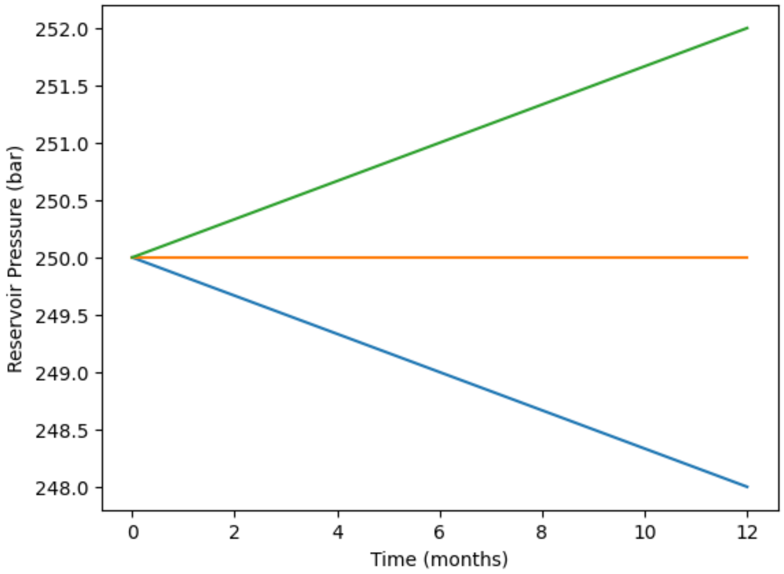

Figure 3. Reservoir pressure evolution versus time for different VRR regimes (0.8, 1.0, 1.2) under constant-rate production over a 12-month period

To further assess stability limits, sensitivity analysis was performed for intermediate cases (VRR = 0.9, 0.95, 1.05, 1.1). Results demonstrate that even moderate deviation (±0.05) produces measurable cumulative pressure drift over extended periods. Although short-term fluctuations may appear negligible, imbalance becomes operationally significant over time. This behaviour confirms that volumetric stability is continuous rather than binary.

The analytical framework demonstrates that VRR functions as a governing stability parameter rather than merely a surveillance indicator. Sustained deviation from balanced injection systematically alters pressure equilibrium, consistent with volumetric balance theory [13] – [15] and supported by reservoir optimization studies [17], [23], [24].

While the model excludes multiphase flow, heterogeneity, and aquifer support, the fundamental volumetric mechanism remains valid. In field-scale systems, additional processes may amplify or dampen pressure response; however, cumulative imbalance remains the primary driver of long-term stability behaviour.

Overall, the results confirm that maintaining VRR within a narrow tolerance band around unity minimizes cumulative imbalance growth and preserves pressure stability. Under the selected parameters, quasi-stable behaviour is observed when $|VRR-1|\leq 0.05$. Beyond this range, pressure drift becomes progressively significant and operationally relevant.

It should be noted that the proposed analytical model is based on simplified assumptions, including single-phase flow, reservoir homogeneity, and absence of aquifer support. In real field conditions, geological heterogeneity, multiphase flow effects, and operational constraints may influence pressure response. Therefore, the presented results should be interpreted as a conceptual basis for understanding volumetric stability mechanisms rather than a direct field-scale prediction tool.

4 Conclusion

1. The analytical evaluation confirms that VRR directly controls cumulative voidage imbalance and associated reservoir pressure evolution. Balanced injection (VRR = 1.0) ensures volumetric equilibrium and pressure stability, whereas sustained deviation leads to systematic linear pressure drift.
2. The results demonstrate that pressure instability is time-dependent and governed by cumulative imbalance growth rather than instantaneous deviation alone. Even moderate deviation from unity VRR produces measurable long-term pressure change under constant-rate conditions.
3. The simplified material balance framework enables identification of a quasi-stable operational range around unity VRR. Maintaining VRR within a narrow tolerance band minimizes cumulative imbalance accumulation and preserves long-term pressure control.
4. The findings indicate that VRR should be interpreted not only as a surveillance indicator but as a dynamic stability control parameter that can support waterflood optimization and injection management strategies.
5. Although the analytical model excludes multiphase flow, geological heterogeneity, and aquifer support, the results provide a transparent physical interpretation of volumetric stability mechanisms and establish a basis for further integration with numerical reservoir simulation studies.
6. From a practical perspective, the proposed analytical framework can support field-scale decision-making by providing a transparent tool for evaluating acceptable VRR deviation ranges. The results may assist reservoir engineers in designing injection strategies that minimize pressure instability risks and improve long-term efficiency of waterflood operations.

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Author Contributions
M.I.: Methodology, Software, Writing – Original Draft.
A.Y.: Supervision, Conceptualization, Writing – Review & Editing.

Ethics Approval and Consent to Participate
This study did not involve human participants or animals. Therefore, ethical approval and informed consent were not required.

Data Availability Statement
The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Supporting Information
Not applicable.

Conflict of Interest

The authors declare no conflict of interest.

AI Use Disclosure

The authors confirm that Artificial Intelligence (AI) tools were used only for language editing and improvement of readability. No AI tools were used to generate scientific results, data, figures, or interpretations. All analyses, conclusions, and scientific content were developed by the authors.

REFERENCES

[1] T. Wen, M. R. Thiele, D. E. Ciaurri, K. Aziz, and Y. Ye, “Waterflood management using two-stage optimization with streamline simulation,” *Computational Geosciences 2014 18:3*, vol. 18, no. 3, pp. 483–504, Feb. 2014, doi: 10.1007/s10596-014-9404-4.

[2] E. Mohammadian *et al.*, “Application of underbalanced tubing conveyed perforation in horizontal wells: A case study of perforation optimization in a giant oil field in Southwest Iran,” *Advances in Geo-Energy Research*, vol. 6, no. 4, pp. 296–305, Aug. 2022, doi: 10.46690/ager.2022.04.04.

[3] D. Zhang, A. Shen, X. Jiang, and Z. Kang, “Efficient history matching with dimensionality reduction methods for reservoir simulations,” *Simulation*, vol. 94, no. 8, pp. 739–751, Aug. 2018, doi: 10.1177/0037549717742963.

[4] B.C. Craft, M. F. Hawkins, and R. E. Terry, *Applied petroleum reservoir engineering*, 2nd ed. Prentice Hall, 2015. Accessed: Mar. 24, 2026. [Online]. Available: https://www.academia.edu/16517162/Applied_Petroleum_Reservoir_Engineering_2ed_B_C_Craft_and_M_F_Hawkins

[5] L. P. Dake, *Fundamentals of reservoir engineering.*, vol. 8. Elsevier, 1978.

[6] “References and Bibliography,” *Economically and Environmentally Sustainable Enhanced Oil Recovery*, pp. 725–786, Dec. 2019, doi: 10.1002/9781119479239.refs.

[7] A. B. Niyazbayeva, R. B. Merbayev, Y. R. Samenov, A. T. Zholdybayeva, A. A. Kozhagulova, and A. D. Shabdirova, “Laboratory Investigation of Miscible CO2-Induced Enhanced Oil Recovery from the East-Southern Pre-Caspian Region,” *Processes 2025, Vol. 13,* vol. 13, no. 8, Aug. 2025, doi: 10.3390/pr13082566.

[8] M. L. Katz and M. R. Tek, “A Theoretical Study of Pressure Distribution and Fluid Flux in Bounded Stratified Porous Systems with Crossflow,” *Society of Petroleum Engineers Journal*, vol. 2, no. 01, pp. 68–82, Mar. 1962, doi: 10.2118/146-pa.

[9] M. Terrado, S. Yudono, and G. Thakur, “Waterflooding Surveillance and Monitoring: Putting Principles Into Practice,” *Proceedings - SPE Annual Technical Conference and Exhibition*, vol. 2, pp. 1275–1284, Sep. 2006, doi: 10.2118/102200-ms.

[10] J. D. Jansen, “Adjoint-based optimization of multi-phase flow through porous media – A review,” *Comput. Fluids*, vol. 46, no. 1, pp. 40–51, Jul. 2011, doi: 10.1016/j.compfluid.2010.09.039.

[11] L. Lake, R. T. Johns, W. R. Rossen, and G. A. Pope, “Fundamentals of Enhanced Oil Recovery,” 2014, doi: 10.2118/9781613993286.

[12] M. Tahir, R. Hincapie, T. Clemens, D. Steineder, A. Farzaneh, and S. Mikulic, “Alkali-Polymer Flooding in an Austrian Brownfield: From Laboratory to Field—Insights,” *Polymers 2024, Vol. 16,* vol. 16, no. 24, Dec. 2024, doi: 10.3390/polym16243607.

[13] M. R. A. Hameed and S. M. Hamd-Allah, “Uncertainty Assessment of Reservoir Modeling for Oilfield in the South of Iraq,” *Journal of Petroleum Research and Studies*, vol. 13, no. 4, pp. 50–65, Dec. 2023, doi: 10.52716/jprs.v13i4.739.

[14] M. P. Walsh, “Generalized approach to reservoir material balance calculations,” *Journal of Canadian Petroleum Technology*, vol. 34, no. 1, pp. 55–63, Jan. 1995, doi: 10.2118/95-01-07.

[15] Q. Xu, X. Liu, Z. Yang, and J. Wang, “The model and algorithm of a new numerical simulation software for low permeability reservoirs,” *J. Pet. Sci. Eng.*, vol. 78, no. 2, pp. 239–242, Aug. 2011, doi: 10.1016/j.petrol.2011.05.012.

[16] T. W. Kim, E. Vittoratos, and A. R. Kovscek, “Recovery efficiency of a 28°API crude-oil system as a function of voidage replacement ratio,” *J. Pet. Sci. Eng.*, vol. 175, pp. 1063–1087, Apr. 2019, doi: 10.1016/j.petrol.2019.01.028.

[17] A. Dewi, Firdaus, and D. Fatryanto, “Analyze of Water Injection Performance Surveillance in ‘ATHENA’ Field,” *Journal of Earth Energy Engineering*, vol. 11, no. 2, pp. 69–76, Sep. 2022, doi: 10.25299/jeee.2022.6356.

[18] E. S. Vittoratos, R. Coates, and C. C. West, “Optimal Voidage Replacement Ratio for Communicating Heavy Oil Waterflood Wells,” *Society of Petroleum Engineers - SPE International Heavy Oil Conference and Exhibition 2011*, pp. 629–643, Dec. 2011, doi: 10.2118/150576-ms.

[19] O. Abdelhamid, S. Zhang, M. Maucec, and B. Fischbuch, “Optimisation of Voidage Replacement Calculation Using Reservoir Simulations and Streamline Tracing,” *Society of Petroleum Engineers - SPE Reservoir Characterisation and Simulation Conference and Exhibition 2019, RCSC 2019*, pp. 17–19, Sep. 2019, doi: 10.2118/196692-ms.

[20] E. Delamaide, “Investigation on the Impact of Voidage Replacement Ratio and Other Parameters on the Performances of Polymer Flood in Heavy Oil Based on Field Data,” *SPE Latin American and Caribbean Petroleum Engineering Conference Proceedings*, vol. 0, May 2017, doi: 10.2118/185574-ms.

[21] S. W. Poston and M. Laprea-Bigott, “Waterflood Review,” *Practical Aspects of Waterflooding*, pp. 325–337, Aug. 2023, doi: 10.2118/9781959025009-ch14.

[22] A. Capolei, E. Suwartadi, B. Foss, and J. B. Jørgensen, “Waterflooding optimization in uncertain geological scenarios,” *Computational Geosciences 2013 17:6*, vol. 17, no. 6, pp. 991–1013, Sep. 2013, doi: 10.1007/s10596-013-9371-1.