ARTÍCULOS

Numerical simulation of water injection and pilot analysis in LT reservoir of P oilfield in Ecuador

Simulación numérica de inyección de agua y análisis del piloto en el yacimiento LT del campo P en Ecuador

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ABSTRACT

The LT reservoir of the P oilfield in Ecuador is currently in the late stage of development. The main production zones are experiencing severe formation energy depletion, resulting in a rapid decline in oil production. To address this issue, a numerical simulation study on water injection for reservoir pressure maintenance was conducted, based on detailed geological modeling constrained by seismic amplitude data. The study evaluated water injection strategies including injection patterns, injection rates, injection-to-production ratios, and the optimization of well configurations by converting existing production wells into injectors. Results indicate that wells injecting from lower structural positions achieve better oil recovery than those located in higher positions. Based on field conditions, an optimal water injection rate between 2,000 and 4,000 STB/D was identified, and maintaining an injection-to-production ratio close to 1 was found to be most effective. A pilot test demonstrated an average daily injection volume of approximately 3,000 barrels. After 8 months of injection, increased oil production was observed in three nearby production wells. This study provides a solid technical foundation and valuable practical insights to guide the planned expansion of water injection across the entire P oilfield.

Keywords: P oilfield; water injection; simulation; injection rate; VRR; pilot.

RESUMEN

El yacimiento LT del campo petrolero P en Ecuador se encuentra actualmente en una etapa avanzada de desarrollo. Las principales zonas de producción presentan una severa disminución de la energía de formación, lo que ha provocado un rápido descenso en la producción de petróleo. Para abordar esta problemática, se realizó un estudio de simulación numérica sobre inyección de agua para mantener la presión del yacimiento, basado en un modelo geológico detallado, restringido por datos de amplitud sísmica. El estudio evaluó diversas estrategias de inyección de agua, incluyendo patrones de inyección, tasas de inyección, relaciones inyección-producción y la optimización de configuraciones de pozos mediante la conversión de pozos productores existentes en inyectores. Los resultados indican que los pozos que inyectan desde posiciones estructurales más bajas logran una mejor recuperación de petróleo que aquellos ubicados en zonas más altas. Con base en las condiciones del campo, se identificó una tasa óptima de inyección de agua entre 2.000 y 4.000 barriles por día (STB/D), y se determinó que mantener una relación inyección-producción cercana a 1 es los más eficaz. Una prueba piloto demostró un volumen promedio de inyección diaria de aproximadamente 3.000 barriles. Tras 8 meses de inyección, se observó un aumento en la producción de petróleo en tres pozos productores cercanos. Este estudio proporciona una base técnica sólida y valiosas orientaciones prácticas para guiar la expansión planificada del sistema de inyección de agua en todo el campo petrolero P

Palabras claves: Campo P, inyección de agua; simulación; caudal de inyección; VRR; piloto

INTRODUCTION

The Oriente Basin is situated in the northern part of the sub-Andean foreland basin chain in South America and is an important oil and gas basin in Ecuador (Baby *et al.*, 2014, pp. 68-72; Belotti *et al.*, 2003; Zengyong and Wenxue, 2010, pp. 211-215). The P oil field is located in the foredeep zone of the Oriente Basin. The P oilfield is located in the foredeep zone of the Oriente Basin in eastern Ecuador. A reverse fault with a fault distance of about 140 meters develops from north to south in the oilfield, dividing the oilfield into east and west. The kaolinite quartz sandstone is the main reservoir of the oil field, which is controlled by the structure, in the local lithology changes rapidly. The burial depth is about 2.955 meters, The reservoir is highly heterogeneous, with a reservoir porosity of 10%-15%, a permeability of 100-500 mD, and a low-porosity medium-high permeability reservoir with an average thickness of about 40 ft. The oil field has been developed since 1978, although there are local water bodies, the overall water energy of the entire oil field is relatively weak, and expansion drive and solution gas drive are mainly supplied for production. There are 34 oil wells in the LT reservoir, most of which are located in the structural high part of the central area of the upper plate of the western fault. After more than 40 years of development, the average reservoir pressure in the central area has dropped from the original 4.200 psi to around 800 psi (Figure 1), which is lower than the bubble point pressure of 1.050 psi. The oil field production has declined rapidly.

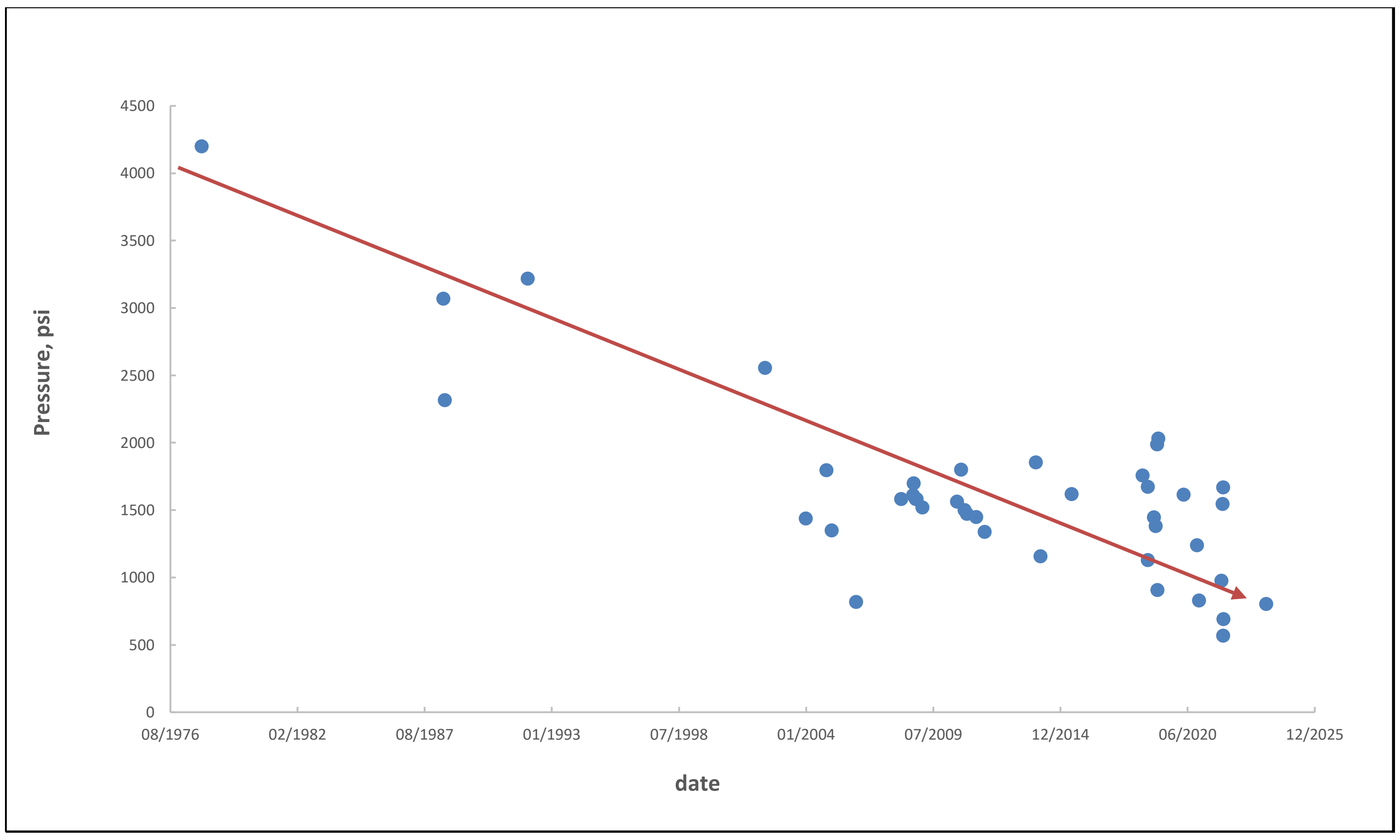

FIGURE 1
Pressure changes of LT reservoir in P oilfield（Pb:1050psi）

Facing the current severe production situation, how to change the driving mechanism, supplement reservoir pressure, and decrease production decline rate are the key issue for the next step of improving the recovery of the LT reservoir. Water injection is one of the important means to supplement formation energy and improve recovery of oilfield (Zhandong *et al*., 2019).

Water injected oilfields in Ecuador show that water injection in the Oriente Basin has gotten good results in the kaolinite quartz sandstone reservoirs such as such as Inchi (Cueva *et al*., 2018), Cononaco (Paredes *et al.,* 2023), HN (Feng *et al*., 2015), Tiguino (Munoz *et al.* 2016), Shushufindi (Maulidani *et al.,* 2021; Franco *et al*., 2024; Paredes *et al.*, 2017), Libertador (Graue *et al.,* 1992) and Sacha (Piñeiros *et al.,* 2020). The experience of these oil fields also shows that systematic research on various aspects such as water injection development design, water injection mode, surveillance plan, and production management optimization are the keys of the successful water injection.

Based on the geological, reservoir and development characteristics of the P oilfield, this paper conducts a numerical simulation study of water injection under the existing production conditions, focusing on the analysis of reasonable water injection mode, water injection rate, injection-production ratio and the number of water injection wells. Based on the study, the pilot is carried out, and the preliminary results have been achieved, which will provide technical support and practical guidance for overall water injection in whole oilfield.

MATERIALS AND METHODS

Numerical simulations for water injection pilot

Geological model and history matching

LT sandstone reservoir of the P oilfield is controlled by sedimentary facies and has strong heterogeneity. Based on the results of comprehensive geological research, seismic inversion constraints and facies modeling strategies are adopted. Firstly, starting from basic geological research, sedimentary facies and reservoir prediction of seismic inversion for sandstone reservoirs are studied, a geological concept model of reservoir distribution is established; secondly, under the guidance of geological knowledge, the facies have been controlled by seismic inversion constraints to build the facies model; finally, random simulation is carried out according to the distribution of sandstone reservoirs to establish reservoir property models. In the process of establishing facies model and property models, the seismic reservoir prediction results are used for constraints, the advantages of seismic reservoir lateral prediction are fully utilized to make the established model more consistent with the actual geological model of LT (Figure 2). The established porosity model and permeability model are shown in Figure 3 and 4. The size of model is 50m×50m, the total number of grids is 176*472*16= 4,58 million, the average porosity is 14%, and the average permeability is 145mD.

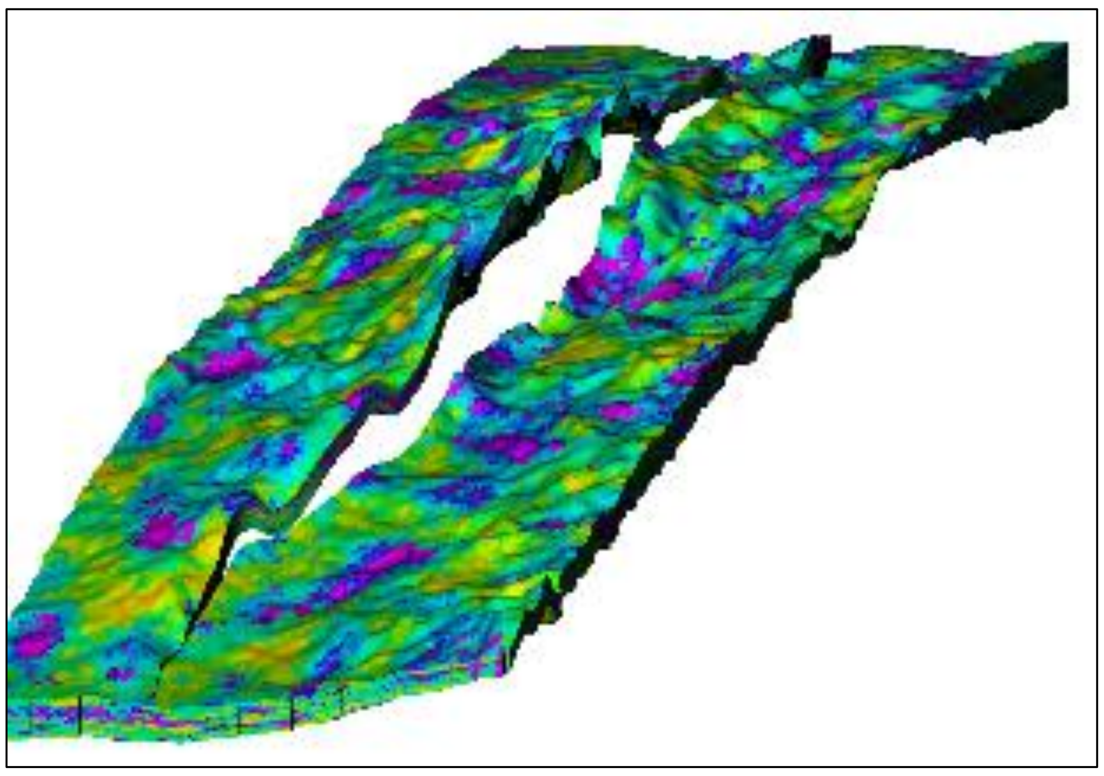

FIGURE 2
Geological model of LT

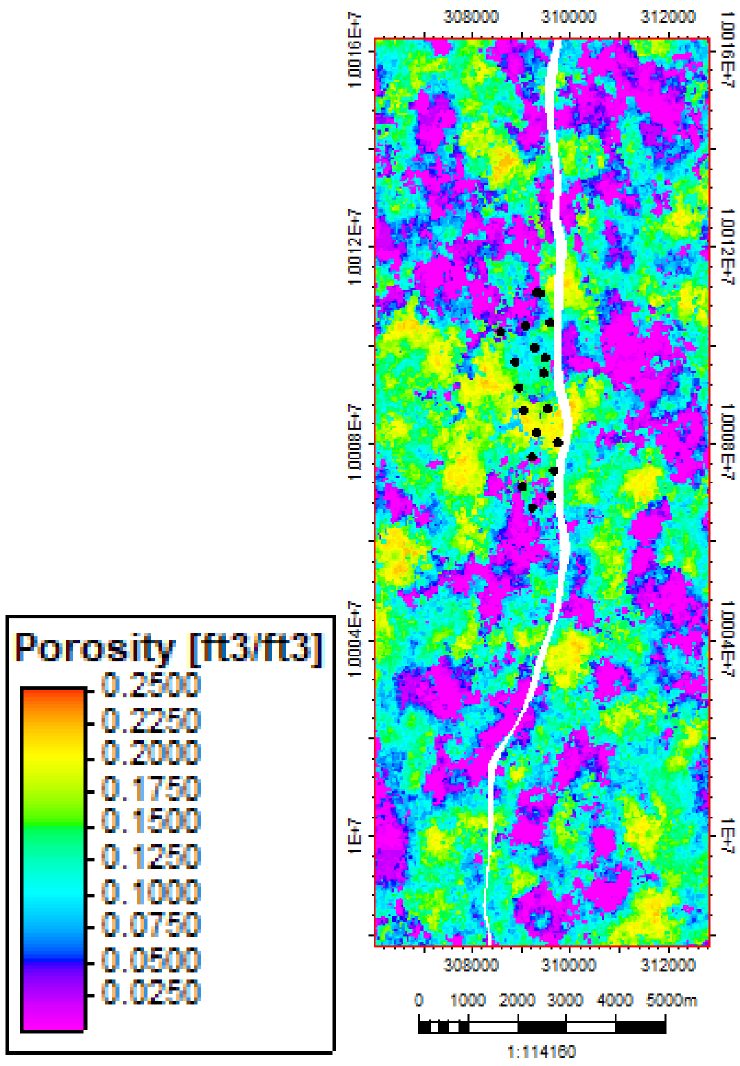

FIGURE 3
Porosity model of LT

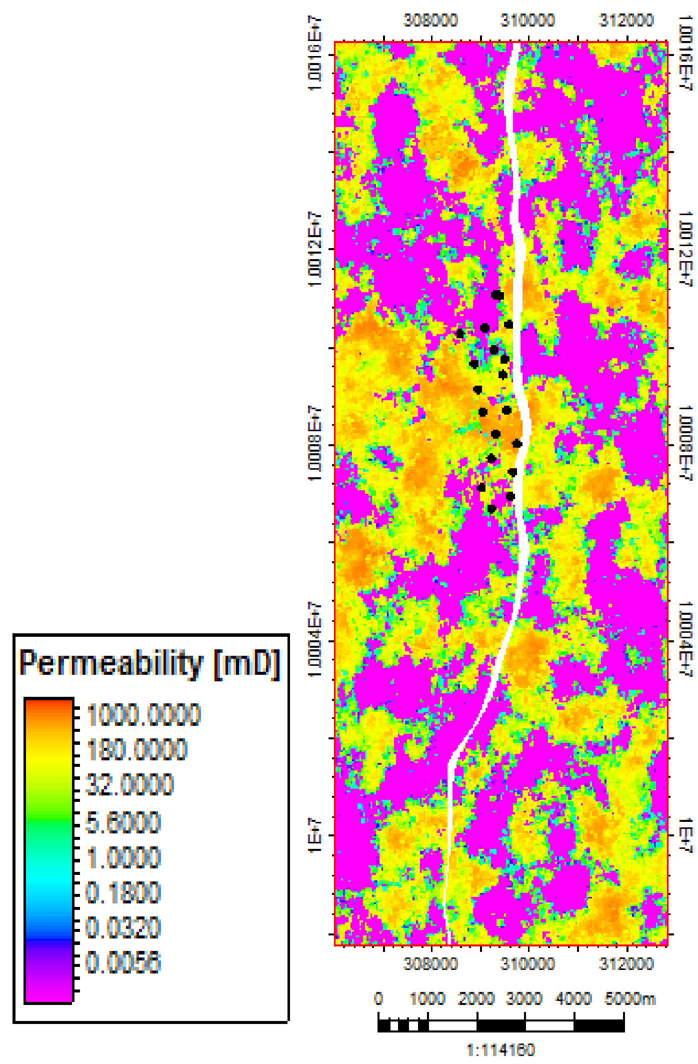

FIGURE 4
Permeability model of LT

Based on the geological model, dynamic data, perforation data, bottom hole pressure test and other data, the production history match is carried out. The oil and water distribution in the LT reservoir is complex, and the reservoir pressure changes rapidly between wells. In order to better match the history production, according to the characteristics of seismic amplitude attributes, the local area carries out refined flow barrier or secondary fault conductivity analysis, so that the model match the historical production well (see Figures 5-6). The matched model can be better used for water injection optimization design.

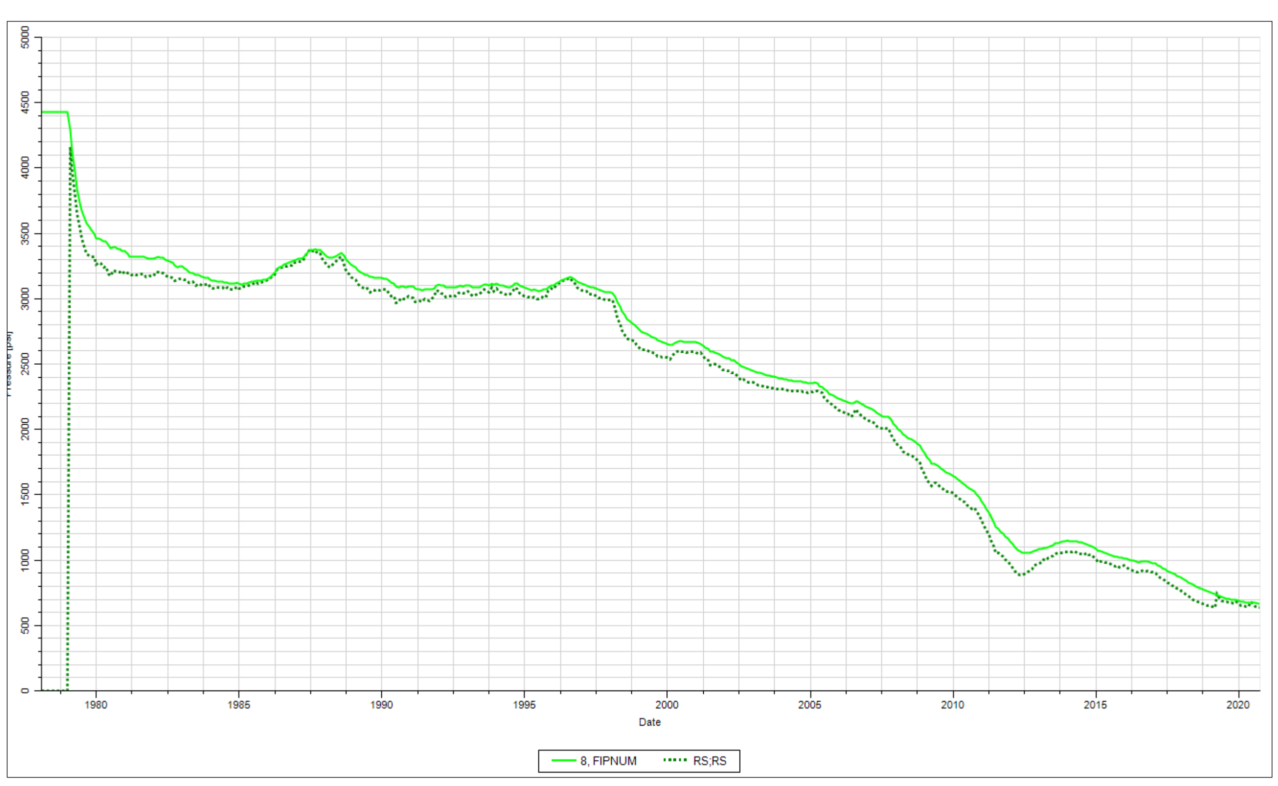

FIGURE 5
The reservoir pressure match for LT

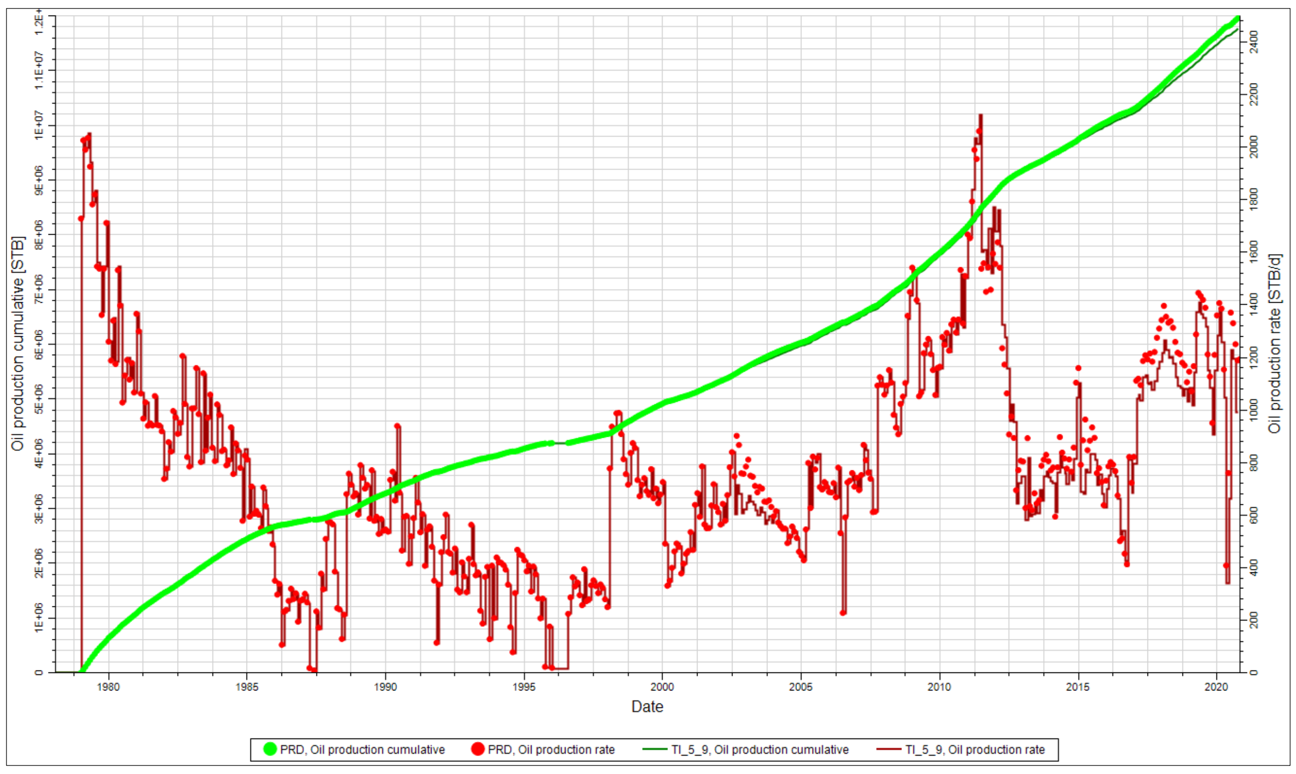

FIGURE 6
The oil production match for LT

RESULTS AND DISCUSSION

Water Injection Optimization

The first design principle of water injection is that the study area focusses on the low-pressure middle area of LT reservoir; secondly, the strategy of the producer in this area should not be changed, and the injector only can be converted by shut-in producing wells, finally 5 shut-in wells, including P-16, P-17, P-18, P-19 and P-22, were selected to carry out optimization research.

(1) Water injection mode

The simulation mainly focused on four injection-production well groups, namely the low-position injection well groups P-22 and P-17, and the high-position injection wells P-19 and P-18. The results showed that the oil production cumulative of the low-position injection well groups P-22 and P-17 were 17,7 MMBO and 17,8 MMBO respectively, and the oil production cumulative of the high-position injection well groups P-19 and P-18 were 17,1 MMBO and 17,0 MMBO respectively (Figure 7). The effect of water injection in the low position is better than that in the high position. This is because in the high-position water injection mode the lower displacement efficiency will be resulted by water fingering under the gravity action, so the higher water production can be seen in the high-position injection well groups (Figure 8).

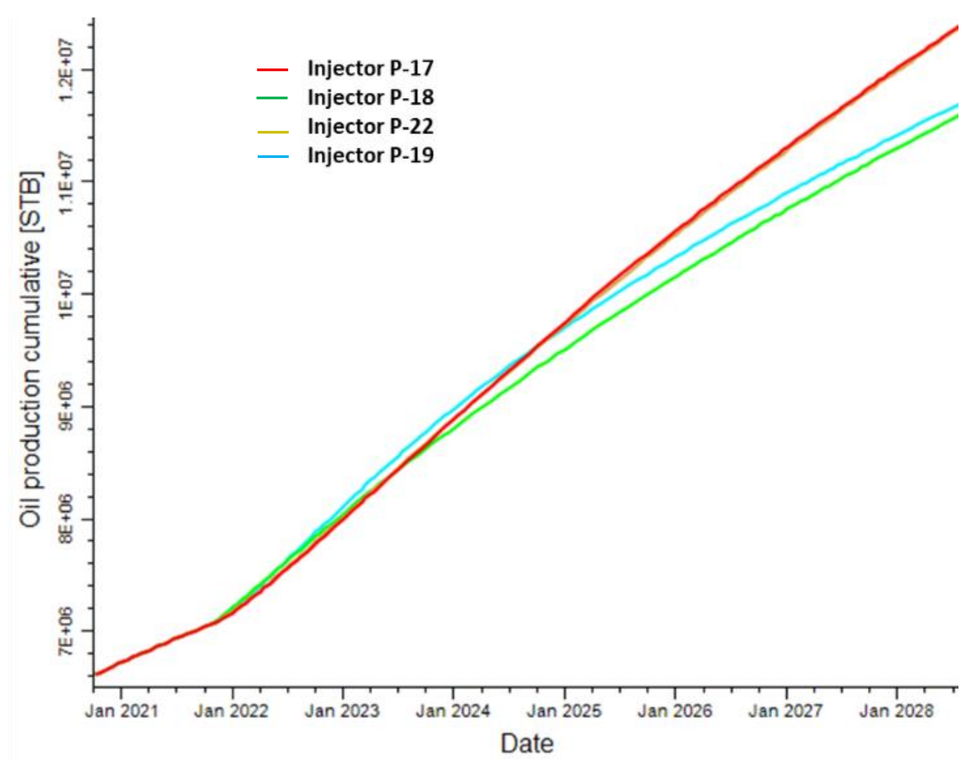

FIGURE 7
The oil production cumulative comparison of different position injection wells group

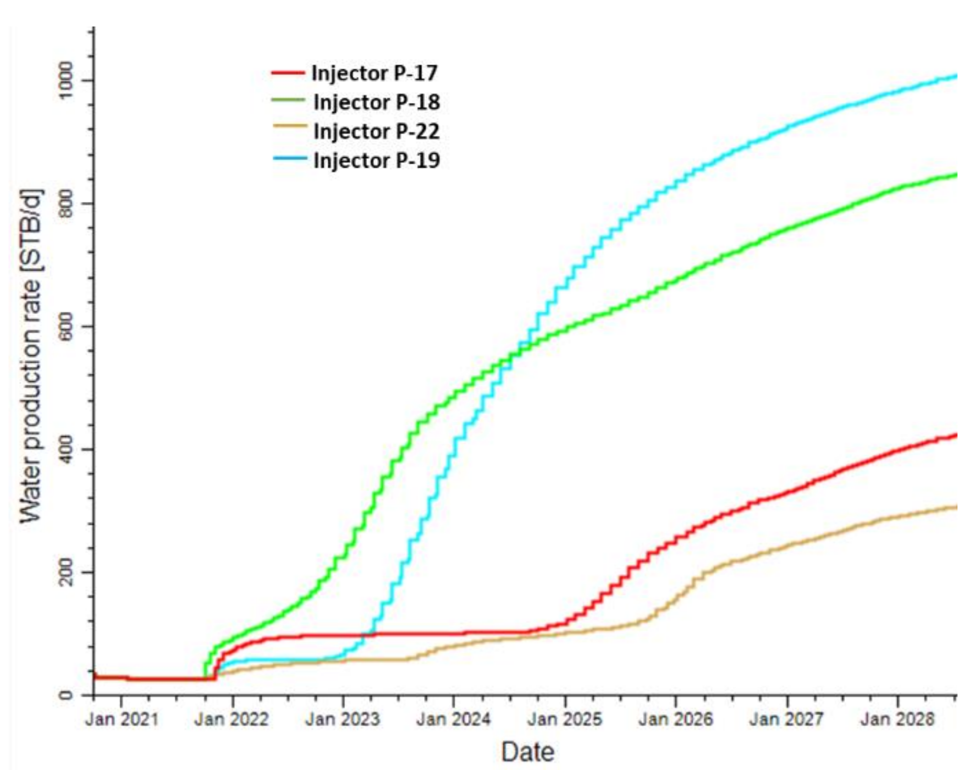

FIGURE 8
The daily water production comparison of different position injection wells group

(2) Water injection rate

After determining the low-position water injection mode, the P-22 water injection well group was designed with injection rates of 2.000 STB/D and 4.000 STB/D for comparison. The oil production cumulative and reservoir pressure changes of the two cases showed that the oil production cumulative and reservoir pressure of the 4.000 barrels per day injection case were higher than that of the 2.000 barrels per day injection case (Figures 9-10). The daily injection rate of single well can be suggested between 2.000 barrels and 4.000 barrels according to the on-site ground conditions and injection test when implementing the pilot.

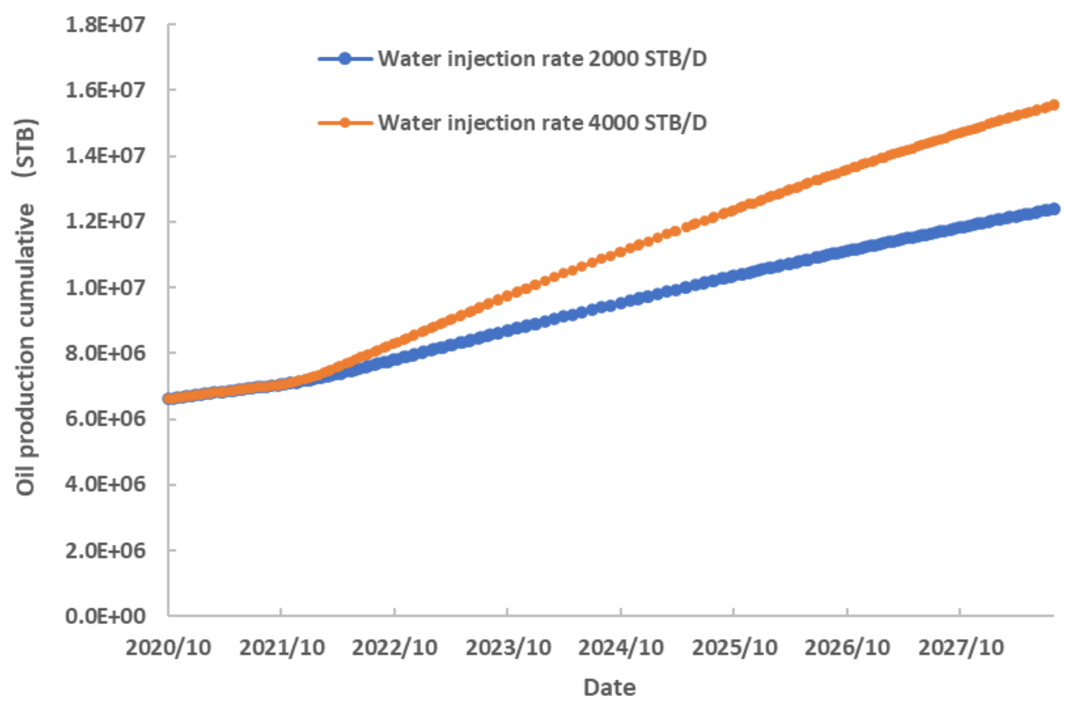

FIGURE 9
The oil production cumulative comparison under the different injection rate

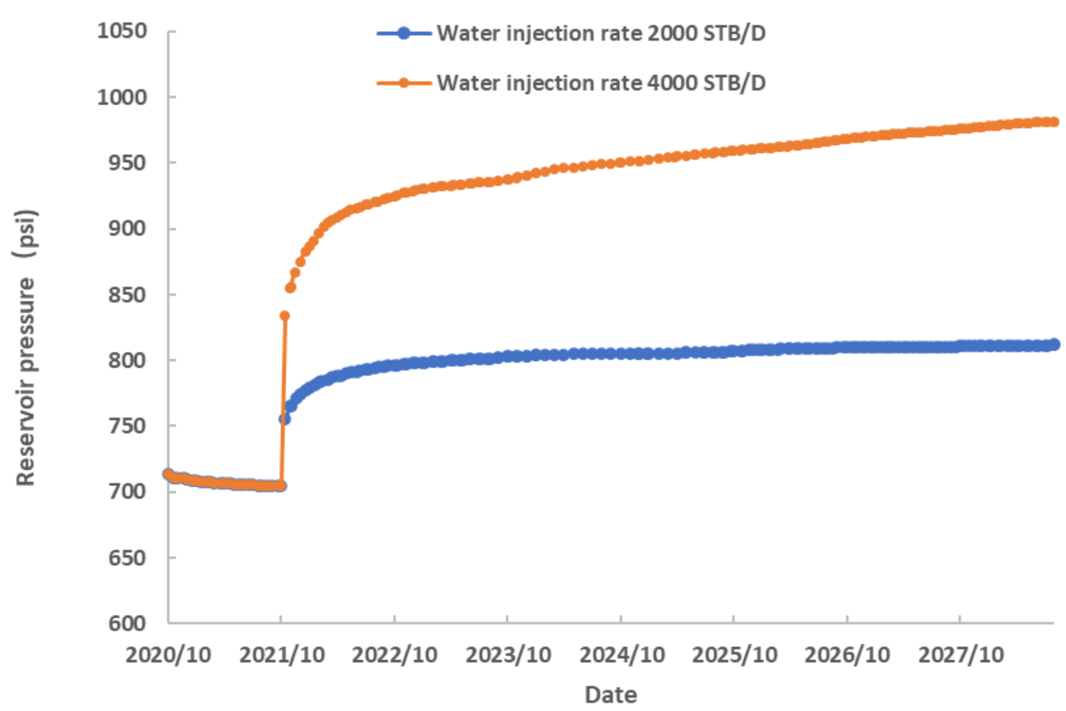

FIGURE 10
The reservoir pressure comparison under the different injection rate

(3) VRR

Three simulation cases with voidage replacement ratio (VRR) of 1, 1,5 and 2 were designed. The prediction results showed that the oil production cumulative was the highest when VRR was 1, and the oil production cumulative was almost the same when VRR was 1,5 and 2, which was lower than that of VRR ratio 1; Otherwise, more water production rate from the case of VRR 1,5 and 2 than that of VRR 1. It can be seen that VRR of 1.5 and 2 has higher water injection, which is over than reasonable threshold and causes the water breakthrough and decrease the waterflooding efficiency, so maintaining injection-production balance can get a better result.

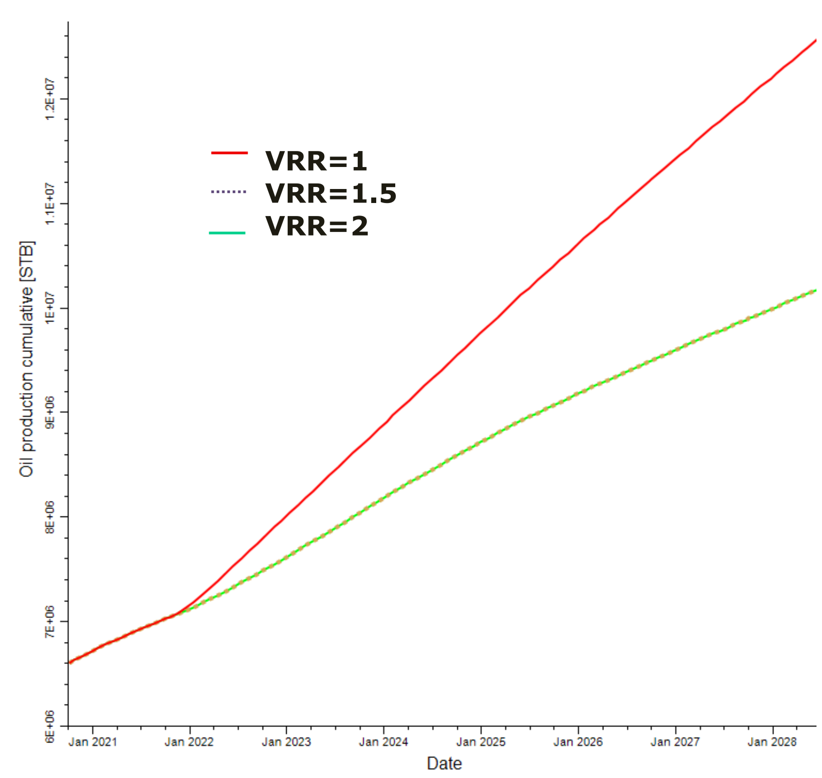

FIGURE 11
The oil production cumulative comparison under the different VRR

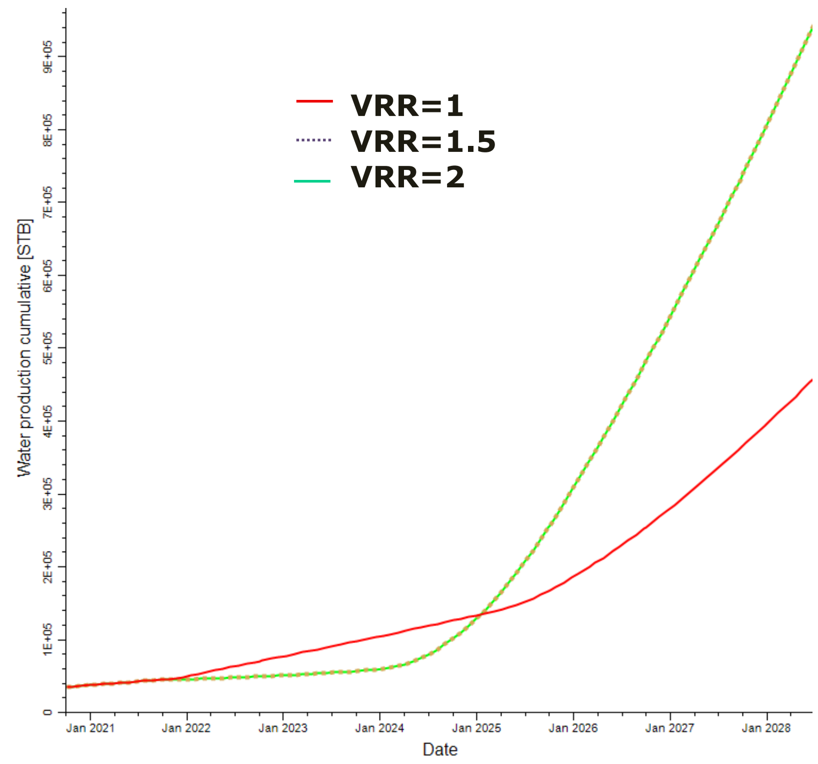

FIGURE 12
The water production rate comparison under the different VRR

(4) Optimization of well pattern

It is difficult to form a perfect water injection well pattern due to the limitation that not any change to the strategy for existing producer. In order to form an effective water injection well pattern, a total of 5 cases in low pressure of LT reservoir, including two cases of two injectors and 3 cases of single injector, were carried out for well pattern optimization (Table 1).

The results show that the oil production cumulative of the two cases of two injectors is about 21,1 MMBO, higher than that of the single injector, which is around 17,7-17,8 MMBO (Figure 13); Increased oil production per well of the two injectors is 3,45 MMBO, which is 3,5-3,6 MMBO for single injector (Table 1). Single injector will be suggested as pilot before overall implementing the plan and then increase injectors and expand the injection area based on the results of pilot.

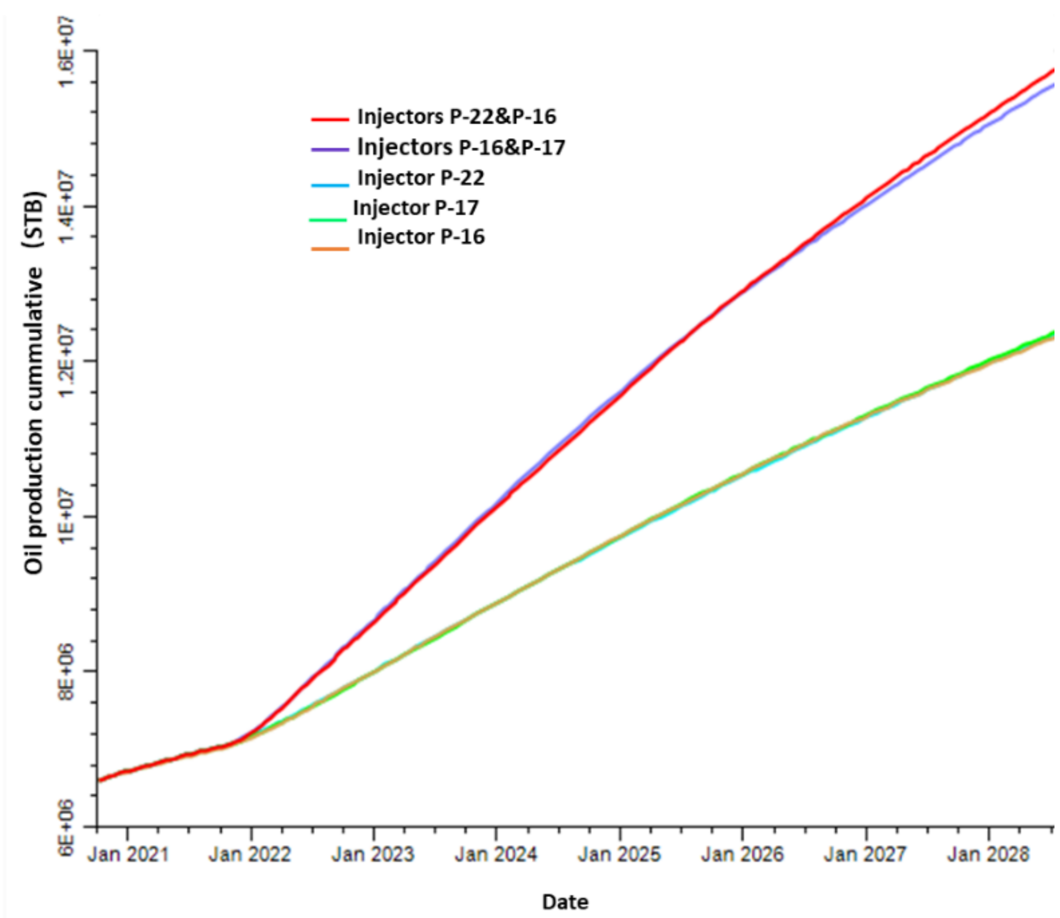

FIGURE 13
The oil production cumulative comparison of different well pattern

TABLE 1
Comparison of well pattern optimizations

No.	Cases	Injection volume (STB/D)	Cumulative produced oil (MMBO)	Increased oil production per well (MMBO)
1	Water injection plan for P-22 & P-16 wells	4.000	21,1	3,45
2	Water injection in two wells P-16 & P-17	4.000	21,1	3,45
3	P-22 Single Well Water Injection	2.000	17,7	3,5
4	P-17 Single Well Water Injection	2.000	17,8	3,6
5	P-16 Single Well Water Injection	2.000	17,7	3,5

Pilot

The P-22 injector group was selected as pilot with an initial water injection volume around 3.000 STB/D (Figure 14). The water is produced by Hollin intervals of P-16 and is injected directly into LT of P-22 (Figure 15). From the Oct. 7th, 2023 till Jan. 2025, the daily injection in LT of P-22 is around 3.000-4.000STB/D, and currently the cumulative water injection volume is 1,5 MMSTB (Figure 16), the Hall Plot shows the water injection in the P-22 well for the Lower T reservoir is stable, and no injection problems happed (Figure 17).

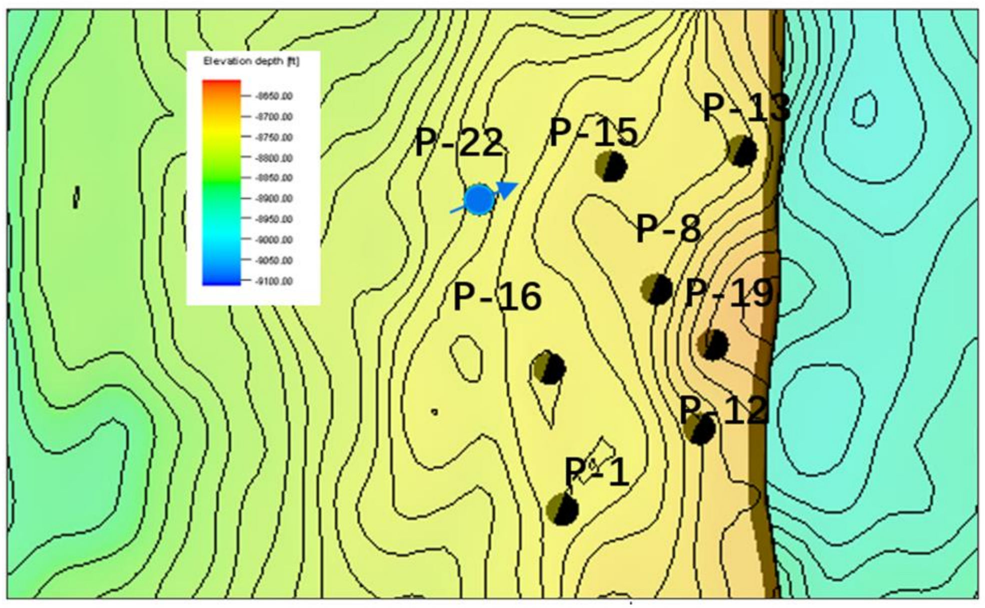

FIGURE 14
The well location of water pilot

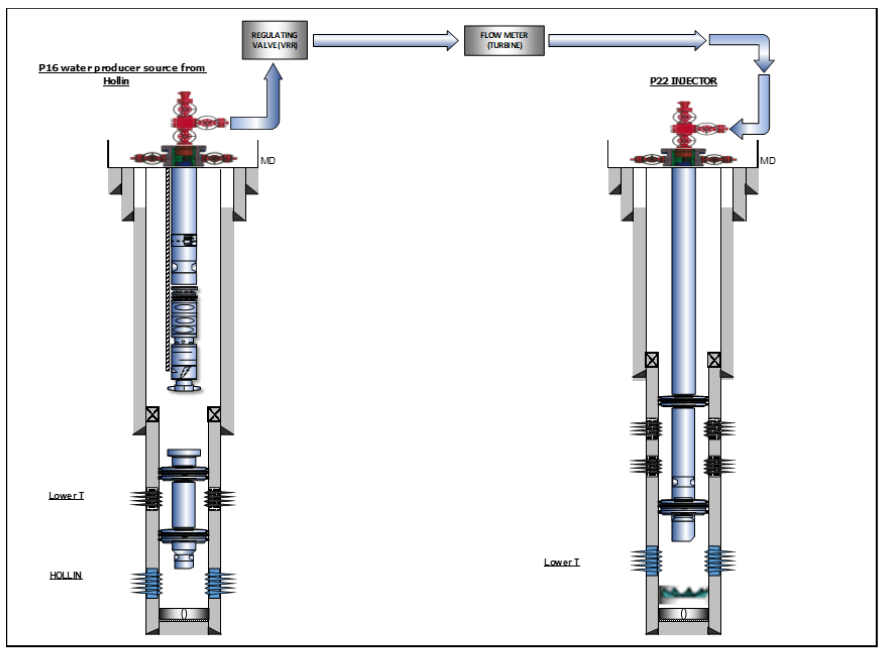

FIGURE 15
Schematic of Water injection process

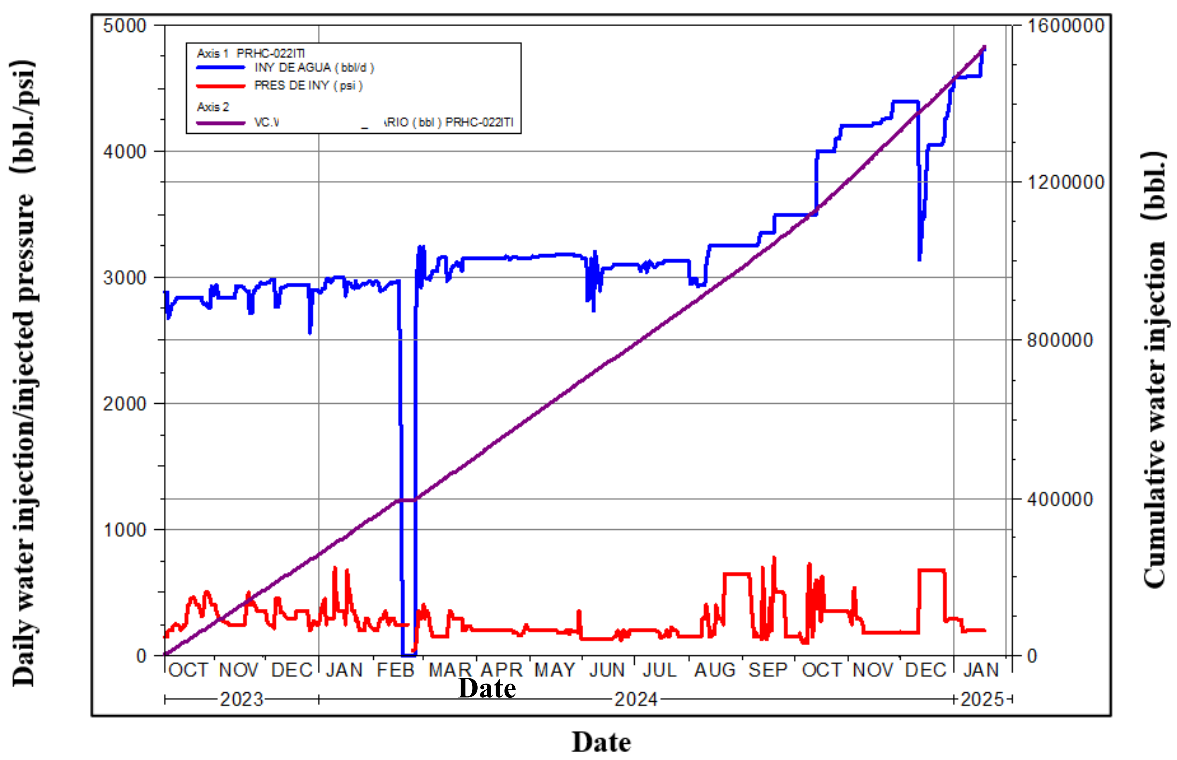

FIGURE 16
Water injection performance P-22 WIW

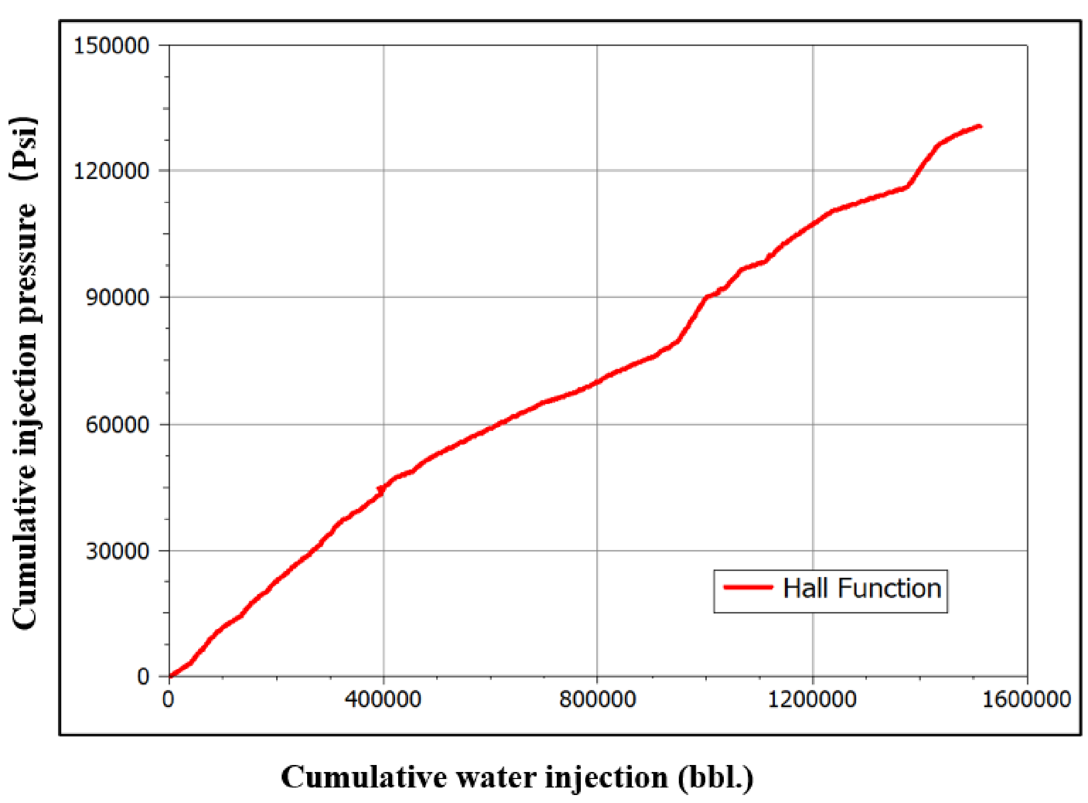

FIGURE 17
Hall Pnolot of P-22 WIW

After 7 months of water injection, the effect is observed in the well P-15, generally, the oil production has increased from 36 STB/D to 300 STB/D, the water cut has decreased from 90% to 20%, the intake pressure has increased from 150psi to 250psi (Figure 18). The water breakthrough is observed in August 2024 because the Cl- decreased from 52.500ppm to 42.550ppm, currently the Cl- is 28.000ppm (Figure 19).

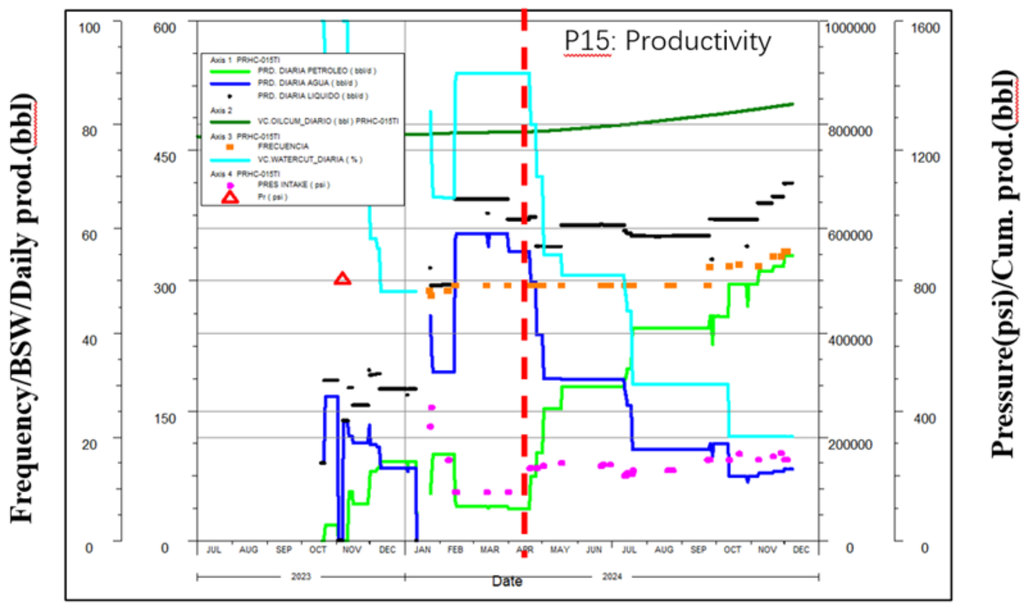

FIGURE 18
The performance of P-15 well

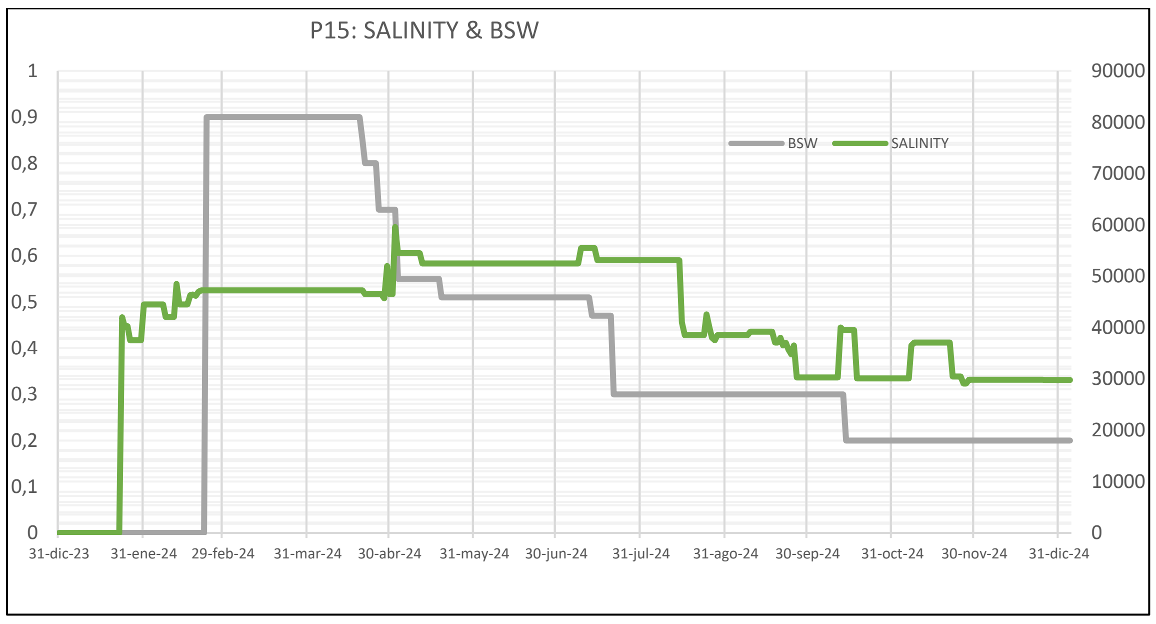

FIGURE 19
Salinity & BSW of P-15 well

In the next step, we should not only closely follow up the water injection performance of pilot, but also optimize water injection management to improve the displacement efficiency, and make other more neighbor wells get the waterflooding effect. Measures such as saturation logs (Hassig *et al.*, 2023, pp. 73–87; Zamora *et al.*, 2024) should be taken, at the same time making full use of monitoring data and introducing advanced technologies such as digitalization and AI (Carpenter, 2024, pp. 85–88; Khataniar *et al.*, 2023; Temizel *et al.*, 2017; HoJeen *et al.*, 2011), to study comprehensive measures for improve water injection combining reservoir geological characteristics, the ultimately goal is to improve the overall economic benefits of the oil field (HoJeen, *et al.*, 2011; Saker and Saker, 2006).

CONCLUSIONS

The pressure voidage in the middle of the LT reservoir of the P oilfield is serious and the production is declining rapidly. The method of Water injection development could be taken to maintain the reservoir pressure and increase the oil production.
The geological model of LT reservoir constructed by seismic inversion and facies constraint is reliable, with the history match, the model can be effectively to optimize the water injection scenarizes.

The numerical simulation shows that water injection in the low position has better oil recovery than that of water injection in the high position of LT reservoir; The water injection volume can be controlled at 2.000-4.000 STB/D; it is more effective to control the VRR at around 1; Single injector firstly can be as the pilot, and then increase injectors according to pilot results, gradually expand to the entire reservoir.

The P-22 pilot has primarily achieved good results of incremental oil production in P-15. The next step is to optimize and adjust the pilot and management to improve the economic efficiency.

Gas saturation distribution and change is based on PVT model, HM also considered the GOR matching.

Authors' Contributions

Jun Li: conceptualization, investigation, methodology, resources.
Yonglan Wang: investigation, software, writing – original draft.
Elías Ibadango: validation, writing – review & editing.
Patricio López: writing – original draft, writing – review & editing.
Lucía Coral: writing – original draft, writing – review & editing.

Assignment of Rights and Declaration of Conflict of Interest

The authors declare that they have adhered to the ethical principles of research and that they are free of any conflicts of interest.

REFERENCES

Baby, P., Rivadeneira, M. and Barragan, R. (2014) "Style and timing of deformation in the Oriente basin of Ecuador". Quito: IRD. Available in: https://www.researchgate.net/publication/32968790_Style_and_timing_of_deformation_in_the_Oriente_Basin_of_Ecuador

Belotti, H., Silvestro, J., Conforto, G., *et al.* (2003) "Recognition of Tectonic events in the conformation of structural traps in the eastern Oriente basin, Ecuador". Salt Lake City: Utah. Available in: https://www.searchanddiscovery.com/documents/2003/hugo/

Carpenter C., (2024) "Project Pursues Autonomous Waterflooding Operations Driven by AI", *Journal of Petroleum Technology,* 76 (5), pp. 85–88. Paper SPE-0524-0085-JPT. Available in: https://onepetro.org/JPT/article-abstract/76/05/85/544717/Project-Pursues-Autonomous-Waterflooding?redirectedFrom=PDF

Cueva, D., Jaramillo, D., et al. (2018) "ESP Water Injector Well with Injection Pressure Available for Real-Time Monitoring Recovered 30% of Production in Low Producer Wells: Case Study", *SPE Middle East Artificial Lift Conference and Exhibition held in Manama.* Bahrain, 28-29 November 2018. Paper SPE 175175. Available in: https://www.doi.org/10.2118/192260-MS

Feng, Y., Ji, B., *et al.* (2015) "A Successful Peripheral Water Injection in a Weak-Edge Aquifer Oilfield, Oriente Basin, Ecuador", *SPE Latin American and Caribbean Petroleum Engineering Conference.* Quito, November 2015. Paper SPE-177145. Available in: https://www.doi.org/10.2118/177145-MS

Franco, F., Sepulveda, W., *et al.* (2024) "The Future is Here. Utilizing Physics-Informed AI Models to Optimize Highly Intricate Water Injection Systems Within a Mature Oil Field", *ADIPEC.* Abu Dhabi, UAE, November 2024. Paper SPE-222071-MS. Available in: https://onepetro.org/SPEADIP/proceedings-abstract/24ADIP/24ADIP/585662

Graue, D., Larsen, W., *et al.* (1992) "Libertador Field: An Integrated Approach to a Development Plan", *SPE Latin America Petroleum Engineering Conference*. Caracas, Venezuela, March 1992. Paper SPE-23648-MS. Available in: https://onepetro.org/SPELACP/proceedings-abstract/92LAPEC/92LAPEC/SPE-23648-MS/54407

Hassig, S., Ramondenc, P., *et al.* (2023) "Surgical Coiled Tubing Stimulations: Step Changes in Effectiveness, Efficiency, and Characterization of Waterflooding Interventions", *SPE Production & Operations,* 38 (1), pp. 73–87. Paper SPE-209028-PA. Available in: https://onepetro.org/PO/article-abstract/38/01/73/508737/Surgical-Coiled-Tubing-Stimulations-Step-Changes?redirectedFrom=fulltext

HoJeen, S., *et al.* (2011) "Advanced Reservoir Management of Greater Burgan Field", *SPE Reservoir Characterization and Simulation Conference and Exhibition.* Abu Dhabi, UAE, October 2011. Paper SPE-148198-MS. Available in: https://onepetro.org/SPERCSC/proceedings-abstract/11RCSC/11RCSC/SPE-148198-MS/150393?redirectedFrom=PDF

Khataniar, S., Biniwale, S., *et al.* (2023) "AI Innovations in Waterflood Management, The Path to Autonomous Operations", *SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition.* Jakarta, Indonesia, October 2023. Paper SPE-215236-MS. Available in: http://onepetro.org/SPEAPOG/proceedings-pdf/doi/10.2118/187008-MS/1315516/spe-187008-ms.pdf

Maulidani, O., Maldonado, V., *et al.* (2021) "Comparison of Water Treatment Plant and Water Source Well: Field Evaluation of Waterflooding Project in Shushufindi-Aguarico Field", *Abu Dhabi International Petroleum Exhibition & Conference*. Abu Dhabi, UAE, November 2021. Paper SPE-208017-MS. Available in: https://onepetro.org/SPEADIP/proceedings-abstract/21ADIP/3-21ADIP/473640

Munoz, M., Rivadeneira, M., *et al.* (2016) "Improved Oil Recovery Through Unsteady Waterflooding Conditions- Cyclic Waterflooding Application in Tiguino Field, Ecuador", *SPE Improved Oil Recovery Conference*. Tulsa, Oklahoma, USA, April 2016. Paper SPE-179612-MS. Available in: https://onepetro.org/SPEIOR/proceedings-abstract/16IOR/All-16IOR/SPE-179612-MS/187353

Paredes, L., Cornejo, P., *et al.* (2023) "Implementing Selective Water Injection Strategy in Thin Reservoirs of a Mature Field in Ecuador", *ADIPEC*, Abu Dhabi, UAE, October 2023. Paper SPE 216102. Available in: https://onepetro.org/SPEADIP/proceedings-abstract/23ADIP/2-23ADIP/D021S070R004/534324?redirectedFrom=PDF

Paredes, L., Fonseca, C., *et al.* (2017) "An Alert-Based Monitoring System to Evaluate a Water Injection Pilot in the Shushufindi Field, Ecuador", *SPE Latin America and Caribbean Mature Fields Symposium.* Salvador, Bahia, Brazil, March 2017. Paper SPE-184947-MS. Available in: https://onepetro.org/SPELAMA/proceedings-abstract/17LAMA/1-17LAMA/195330

Piñeiros, S., Mendoza M., *et al.* (2020) "Integrated New Exploitation Strategy in Block 61, from Modeling to Full-Field Implementation", *SPE Latin American and Caribbean Petroleum Engineering Conference, Virtual.* July 2020. Paper SPE-198964-MS. Available in: https://onepetro.org/SPELACP/proceedings-abstract/19LACP/19LACP/452975

Saker, G. and Saker, A. (2006) "Integrated Management of Oilfield Water Injection Development". Petroleum Industry Press.

Temizel, C., Nabizadeh, M., *et al.* (2017) "Data-Driven Optimization of Injection/Production in Waterflood Operations", *SPE Intelligent Oil and Gas Symposium.* Abu Dhabi, UAE, May 2017. Paper SPE-187468-MS. Available in: https://onepetro.org/SPEIOGS/proceedings-abstract/17IOGC/All-17IOGC/SPE-187468-MS/194865?redirectedFrom=PDF

Zamora, P., Cornejo, P., *et al.* (2024) "Unlocking Reservoir Potential: Strategic Role of Saturation Logs in Cased Hole for Waterflooding Optimization", *SPWLA 65th Annual Logging Symposium.* Rio de Janeiro, Brazil, May 2024. Paper SPWLA-2024-0104. Available in: https://onepetro.org/SPWLAALS/proceedings-abstract/SPWLA24/5-SPWLA24/D051S018R003/545500?redirectedFrom=PDF

Zengyong, D. and Wenxue C. (2010) "Tectonic Evolution in Oriente Basin of Ecuador". XinJiang Petroleum Geology. Available in: https://www.zgxjpg.com/EN/Y2010/V31/I2/211

Zhandong, L., Haixiang, Z., *et al.* (2019) "Basic Theory and Technology of Water Injection for Oilfield Development". Science Press.