

Research Article

Countermeasures to Decrease Water Cut and Increase Oil Recovery from High Water Cut, Narrow-Channel Reservoirs in Bohai Sea

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Most multilayer sandstone reservoirs in the Bohai Sea have already entered the middle or high water cut production stage with large amounts of remaining oil being scattered distributed. Therefore, there is an urgent need to find a suitable countermeasure to reduce water cut and increase oil recovery. In this study, taking the narrow-channel reservoirs in the M oilfield as an example, we qualitatively described the sand body scale and the contact relationships between different sand bodies, in addition to carefully analyzing the material base and remaining oil distribution characteristics. Accordingly, we proposed a countermeasure based on the injection-production structural adjustment to reduce water cut and increase oil recovery from high water cut, narrow-channel reservoirs. Herein, three optimization strategies were developed based on the proposed development mode: a seepage field optimization strategy was developed based on the quantified injection-production index; a well pattern optimization strategy for narrow-channel reservoirs was developed to overcome the production energy refueling problem; an injection-production measure optimization strategy was developed to tap the different types of remaining oil. Additionally, the well pattern optimization and injection-production optimization strategies were integrated to optimize and adjust the seepage field system. The findings reported herein this paper help understand the development of similar offshore oilfields with a high water cut.

1. Introduction

Until 2019, the Bohai Oilfield had undergone a decade of steady development, and the annual oil output reached 30 million tons in 2010. However, the oilfield has now entered into the high water cut production stage, and adjusted development measures are urgently needed. Compared with traditional onshore oilfields, the development of offshore oilfields is characterized by a complex development technology, higher investments, and higher risks. The fluvial-facies reservoirs in the Minghuazhen and Guantao formations of the Neogene are dominated by complex fault-block reservoirs, which are characterized by thin sand bodies, narrow facies belts, multistage superimposition, multistage branching, and poor connectivity. The difficulties of developing such reservoirs lie in the narrow and banded distributed channels,

formation of multistage branching, complex reservoir connectivity, limited natural energy and displacement ability, insufficient development of the low-abundance layer, severe interlayer interference, presence of the water fingering phenomenon in the high-permeability layer, and water control. Therefore, conducting countermeasures, including adjusting the allocation of displacement energy in narrow-channel reservoirs with middle or high water cuts, developing effective injection-production optimization strategies, and effectively tapping the remaining oil, is very important for further development of such oilfields.

In order to determine reasonable countermeasures to decrease water and increase oil, a comprehensive study on the optimization of seepage field, injection-production well pattern, and auxiliary technology was conducted in this study. Based on published studies, seepage field optimization

was conducted through parametric inversion. Sheng et al. [1] used the sequential quadratic optimization method and successfully obtained the natural seepage field applicable for engineering areas. Ni et al. [2] used the particle swarm optimization algorithm to obtain the optimized inversion of a complex 3-D seepage field. However, the complexity of the algorithm is a major obstacle to optimization. In many cases, large-scale calculations are difficult to perform because of issues related to the calculation amount and convergence. A suitable injection-production well pattern can effectively improve oil and gas productivity. Thus, optimization of the well pattern is particularly important. The current well pattern optimization methods mainly include empirical, laboratory, and reservoir numerical simulation methods [3–5]. Due to human factors and large errors, empirical and laboratory methods are more commonly used in reservoirs with good physical properties. As the numerical simulation method to optimize well patterns through mathematical and geological modeling has higher accuracy and takes less time, it is currently one of the most widely used methods. For oilfields that have already entered into the high water cut period, it is necessary to adopt auxiliary process optimization strategies to maintain economic viability. The feasibility of different measures was evaluated using different economic evaluation indexes, and the results may vary according to the quantification criteria [6]. To overcome the aforementioned problems while considering the interwell connectivity, we optimized the seepage field, well pattern, and countermeasures through the SPSA optimization algorithm, numerical simulation, and remaining oil analysis, respectively. The complexity of the calculation was significantly reduced, the calculation cycle was shortened, and the optimal countermeasures to decrease water and increase oil have been proposed.

2. Study on the Geological Characteristics of Narrow-Channel Reservoirs

The Bohai M Oilfield is a complex fault block reservoir with a regional deposition background consisting of regressive bird-foot shaped shallow-water delta deposits [7], branched lacustrine shallow-water delta deposits, and meandering river deposits, as shown in Figure 1(a) [8]. Both traditional meandering river deposits (Ming I and V) and nontraditional ultrashallow-water delta internal channel deposits (Ming II, III, and IV) have formed at the sea-land transitional environment in the Bohai fluvial oilfields. The reservoirs in the meandering river deposits exist mainly in the form of a high-bend channel and a lateral accretionary body, whereas the main production layers in ultrashallow-water delta internal channel deposits are underwater distributary channels [9].

Taking Minghuazhen II-1 as an example, the M oilfield receives source supply from three different directions. The water is shallow but turbulent with evident river scouring, and the topographic slope during the deposition period is relatively gentle (approximately 0.08°). Therefore, the ultrashallow-water delta deposit exhibits the “narrow plain and wide front” characteristic. The morphology of the river channel along the source supply direction gradually evolved from a straight channel with a small curvature in the front

edge of the delta to a branch-like, side-swaying, and converging channel in the outer front edge of the delta (Figure 1(b)). The width and thickness of the composite channel are 250–1100 m and 15–28.8 m, respectively, whereas the width and thickness of the single-period channel are 100–190 m and 3–8 m, respectively. The reservoir has an average porosity of 25.0% and an average permeability of $522.2 \times 10^{-3} \mu\text{m}^2$ and thus belongs to the high-porosity and medium-to-high-permeability category. There are four different types of sand bodies, with sizes ranging from 1.2 to 3.9 km^2 . The straight channel sand body has a small curvature and is podded and horizontally overlapped, has favorable physical properties, and demonstrates characteristics similar to that of continental fluvial facies. The dendritic channel with multistage branching, large thickness, and overlapped sand bodies is commonly herringbone shaped, and bifurcation has been observed [10, 11]. The side swing channel is completely different from the dendritic channel, which has a high permeability ratio and high interlayer heterogeneity. Its sand body is thin and pendulous; in contrast, the sand body in the convergent channel is always horn-shaped, has a low thickness and limited size, and exhibits strong planar heterogeneity.

3. Analysis of Material Base of Water-Decrease and Oil-Increase Countermeasure in Narrow-Channel Reservoir

By 2015, the oil recovery and water cut of the M oilfield were becoming 20.13% and 53.09%, respectively. The large amounts of remaining reserves that need to be recovered provide a solid material base for the subsequent optimization and adjustment of the injection-production structure. Additionally, the relatively low water cut offers more adjustable space for subsequent treatment. The main problems encountered in the oilfield development process include imperfect injection-production well patterns, scattered depleted sand bodies, high proportion (82%) of underinjected sand bodies, and ineffective water production in the ultrahigh water cut stage.

Therefore, it is necessary to assess the distribution of the remaining oil as well as the formation mechanism of the enrichment zone, so as to comprehensively adjust the subsequent development mode of the oilfield. Research shows that distribution of the remaining oil can be classified based on their characteristics such as sedimentary facies transition, heterogeneity, tectonic genesis, development mode, and development well pattern, as presented in Table 1. Considering the characteristics of a narrow channel facies reservoir, the main focus of the subsequent stimulation technologies can be used for exploiting the remaining oil enrichment zones, such as overflow bank deposition, channel splicing, distributary channel, and falling silt layer.

4. Countermeasures to Decrease Water and Increase Oil in Narrow-Channel Reservoir

Two main methods [12] are used to optimize the injection-production structure worldwide, namely, the “simultaneously

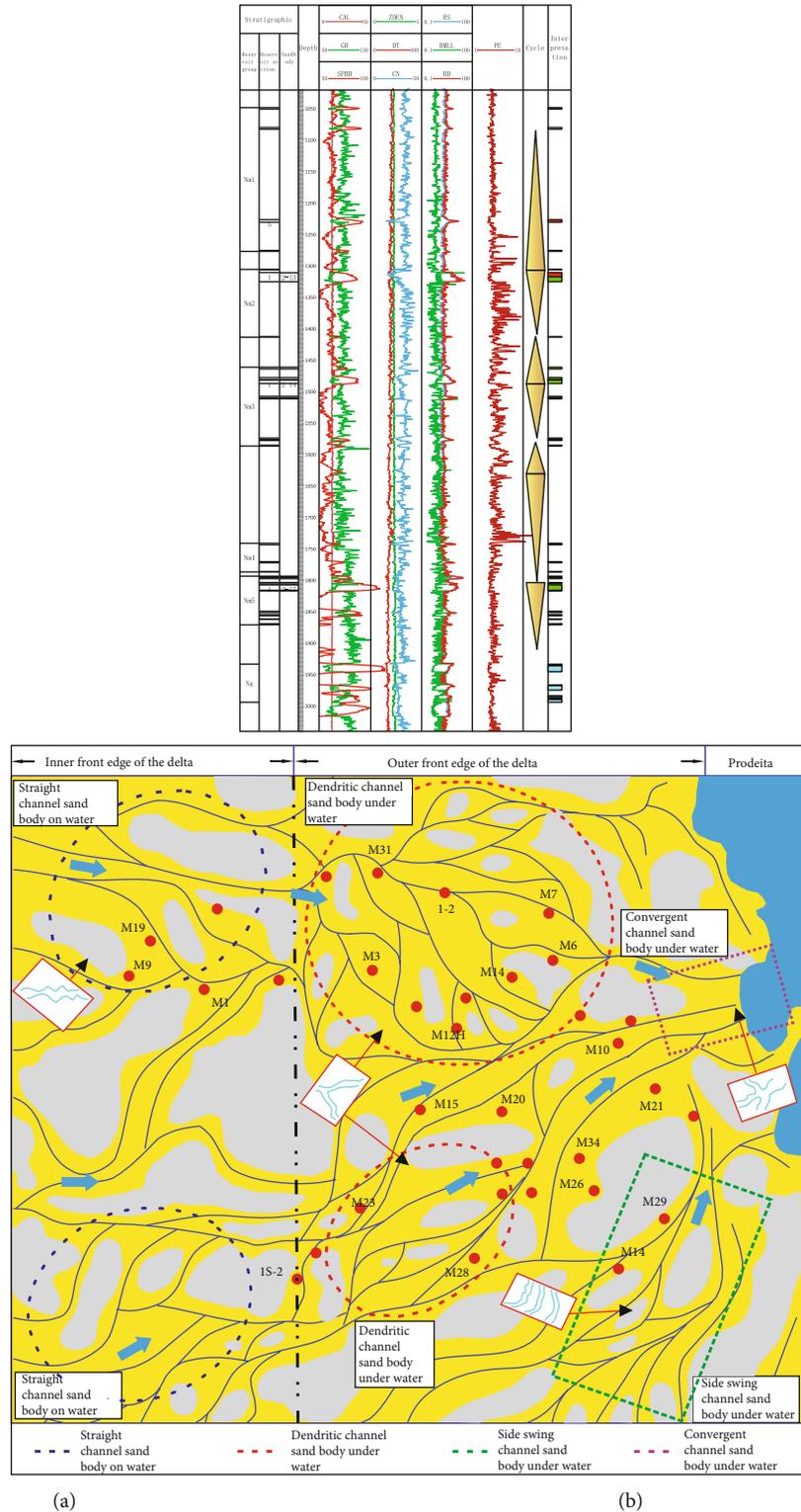


FIGURE 1: (a) Stratigraphic histogram of the Bohai M Oilfield; (b) channel geomorphology of the Minghuazhen II-1 layer.

stabilize oil production and liquid production” mode and “stabilize oil production while increasing liquid production” mode. The Daqing Oilfield proposed a “stabilize oil production while decreasing water production” project during the “Tenth Five-Year Plan” period. The sedimentary reservoirs in the South China Sea oilfields, particularly Huizhou 21-1

and Lufeng 13-1, are dominated by delta and marine deposits. Therefore, the “stabilize oil production while increasing liquid production” is suitable for stratified continuous marine sedimentary reservoirs [13]. However, at present, countermeasures to decrease water and increase oil in the Bohai fluvial reservoirs are in infancy nascent stage. Although the ideology

TABLE 1: Remaining oil distribution in the narrow-channel reservoirs.

Characteristic	Type	Distribution location	Remaining oil occurrence
Sedimentary facies transition	Wedge-shaped inlaid pinch-out shielding type	Overflow bank sand and river mouth bar of river transformation	Wedge-shaped
	Flowing around interlayer and lamellar retention type	Falling silt layer in channel and interdistributary bay	Interval stratification
	Bay shielding flaky retention type	Curved and straight river point bar	Flaky-shaped
	Splicing edge of cutting channel type	River mouth bar, braided beach, and parallel port beach	Shaped like channel-edge
Heterogeneity	Stacking and cutting top enrichment type	River mouth bar with stacked or cut channels	Layered
	High permeability fingering and low permeability retention type	Dendritic and network braided main channel	Finger-shaped
	Uneven displacement of parallel high and low permeability	Channels of different thickness/types on the well	Original occurrence
Tectonic genesis	Fault barrier pinch-out enrichment type	Updip part of fault barrier	Rhombic
	Microstructural undulation enrichment type	Fault cutting structural trap	Potato-shaped
	Squeezing pie type driving energy	Rings parallel to the gas cap	Pie-shaped
Development mode	Insufficient driving energy	Stay away from edge and bottom water and injection wells	Original occurrence
	Bottom water coning surrounded retention type	Around the bottom water cone	Eave-shaped
Development well pattern	Imperfect well pattern resulted inter and well retention	Single sand body out of well pattern control	Original occurrence
	Insufficient displacement resulted retention	Production well away from injection well	Original occurrence

of “optimizing water injection, controlling water-cut, and slowing production decline” has been put forward [14], a systematic development method is not yet available.

We propose a countermeasure to decrease water and increase oil designed for the steady development of the M oil-field, based on the distribution and characteristics of the remaining oil in the narrow-channel reservoirs. In order to guarantee the availability of the liquid processing power and to maximize the overall benefits, the injection end, interwell, and the outer end were all considered while establishing the “injection side-seepage field-output side” optimization method and to quantify the effects of the injection-production system on the internal displacement streamline. Moreover, three optimization strategies, including seepage field optimization strategy, well pattern optimization strategy, and auxiliary measure optimization strategy, were used to mitigate conditions such as limited swept volume, limited reservoir energy, and difficulty in developing remaining oil distributed near the injection and production ends.

For the three optimization strategies involved in the “water-decrease and oil-increase” countermeasure, the seepage field optimization strategy is the core, and the well pattern optimization strategy is the premise, whereas the injection-production measure optimization strategy is the auxiliary. The main objective of the seepage field optimization strategy-based “water-decrease and oil-increase” countermeasure is to divert the water flow direction and to increase the water swept efficiency. To replenish the formation energy in time and increase the drainage radius, the well

location as well as the suitable injection-production scheme was established according to the multistage branching feature of narrow-channel reservoirs. In addition, the optimized remaining oil extraction technology was developed to modify the flow path of injection water and to support the injection-production structure optimization.

4.1. Seepage Field Optimization Strategy. A seepage field optimization strategy was developed by optimizing, quantifying, and adjusting the dynamic production parameters. The key to optimizing and adjusting the injection and production parameters is to correctly recognize the reservoir and flow field structures and to determine the interwell connectivity. In this study, the Bayesian theory was combined with the interwell connectivity calculation method (first – order inertia + time prolonging link) [15] to obtain a better geological understanding of wide spacing reservoir connectivity between the narrow channels. In addition, the seepage field was vectorized by streamline digital simulation, and the water flow intensity and direction within the grids were estimated, as shown in Figure 2. The simulation results showed that when the oil production is constant under reservoir conditions, the peak velocity of the Darcy flow field is 0.08–1.0 m³/d; by contrast, the value is 0.8–40 m³/d for a real seepage field. Hence, to divert the injection fluid into the remaining oil enrichment area, the injection-production end adjustment and injection-production process adjustment should be matched, and the injection-production streamline should be quantitatively adjusted using dynamic optimization [16–19].

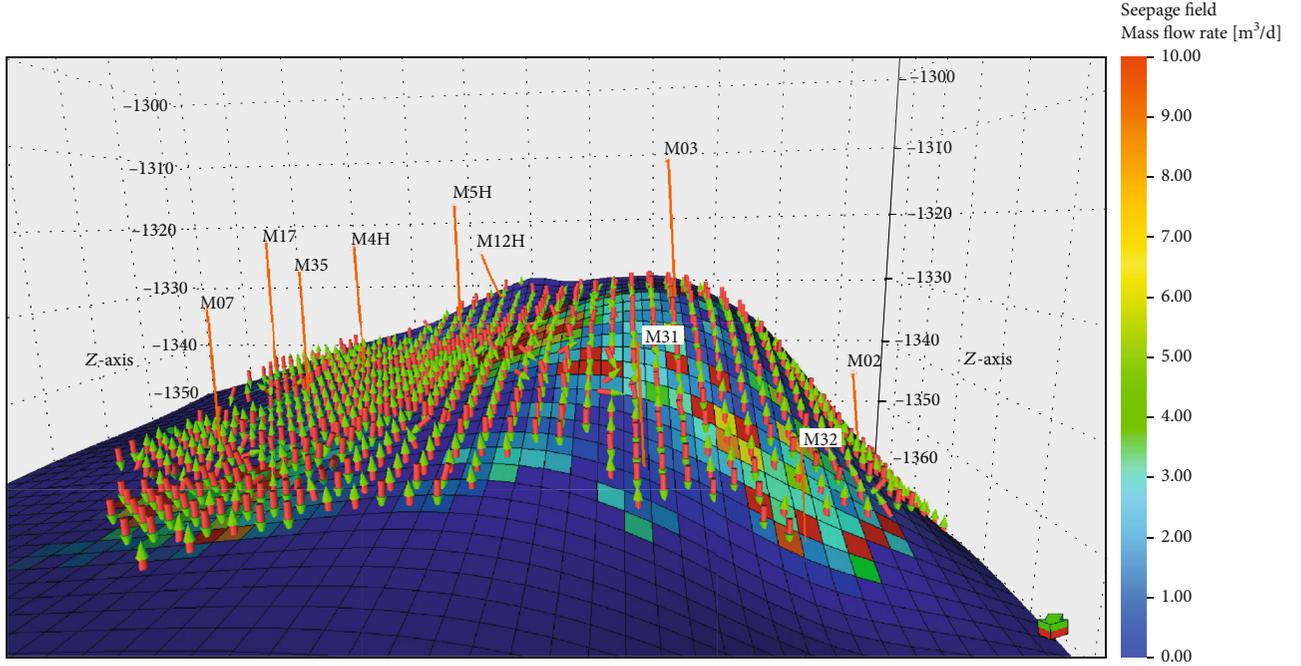


FIGURE 2: Vectorization of the optimized seepage field in the narrow-channel reservoir.

The reservoir production performance can be optimized by quantitative adjustment of the reservoir seepage field. In recent years, though there have been several theoretical studies on dynamic optimization technology, little information is available on its applications in offshore reservoirs, especially for those with middle or high water cut, limited fluid treating capacity, and ineffective production fluid circulation. Research shows that optimizing the dynamic reservoir production performance provides a relatively effective way to mitigate these problems [20].

According to the economic benefit maximization principle, the optimal mathematical model of the J -function is used to represent the performance index, and the production parameters of oil and water wells are regulated in multiple stages. The approximate gradient of the closed-loop reservoir theory and genetic algorithm-anneal algorithm hybrid optimization algorithm are integrated to estimate the optimized direction and step size, whereas the Eclipse streamline simulator is used to conduct the iterative optimization to update the working system and to adjust the injection and production status. The objectives are to increase the sweep efficiency and overall oil recovery. The performance index function for reservoir production optimization can be expressed as

$$J(u, x, m) = \sum_{n=1}^L \frac{\Delta t^n \cdot \left[\sum_{j=1}^{N_p} \left[\left(r_o q_{o,j}^n - r_w q_{w,j}^n \right) - r_{wi} q_{wi,j}^n \right] \right]}{(1+c)^{tn}} - \sum_{j=1}^{N_p} r_I \cdot q_{Ij,j}^n \quad (1)$$

where r_o , r_w , r_{wi} , r_I , and c are the oil price, water production cost, water injection cost, fluid treating cost, and interest rate,

respectively. q_o^n , q_w^n , q_{wi}^n , and q_I are daily oil production, daily water production, daily water injection, and platform daily fluid treating capacity, respectively.

The genetic algorithm-anneal algorithm (GA-CA) is a hybrid optimization algorithm that can help achieve the continuous optimum control. The CA method originated from physical statistics and was introduced by Kirkpatrick to solve optimization problems [21]. After ulterior coupling with the genetic algorithm, GA-CA evolved into a method suitable for solving large-scale optimization problems through continuous improvement and gradual development [22–25]. A GA has a parallel nature and can provide a global optimal solution but suffers from premature convergence. The anneal algorithm (CA) offers a highly reliable global optimal solution, but the convergence rate is quite slow [26]. Therefore, perturbation factors are introduced into the nonuniform mutation of the GA based on the GA-CA. The linear combination (ε'_k) of perturbation factors can effectively control the individual mutation and automatically eliminate the exaggerative indicators, thus eliminating the problems of local extremum, slow convergence rate, and premature convergence. In the annealing temperature reduction process, the smaller the fitness function, the closer it is to the optimal value. The iteration curve of the genetic-annealing hybrid optimization algorithm is shown in Figure 3.

The linear combination of perturbation factors is expressed as

$$\varepsilon'_k = \tau \cdot \varepsilon_{1k} + (1 - \tau) \varepsilon_{2k}, \quad (2)$$

where $\varepsilon_{1k} = (\varepsilon_{11}, \varepsilon_{21}, \varepsilon_{31}, \dots, \varepsilon_{n1})$ is chromosome 1 and $\varepsilon_{2k} = (\varepsilon_{12}, \varepsilon_{22}, \varepsilon_{32}, \dots, \varepsilon_{n2})$ is chromosome 2.

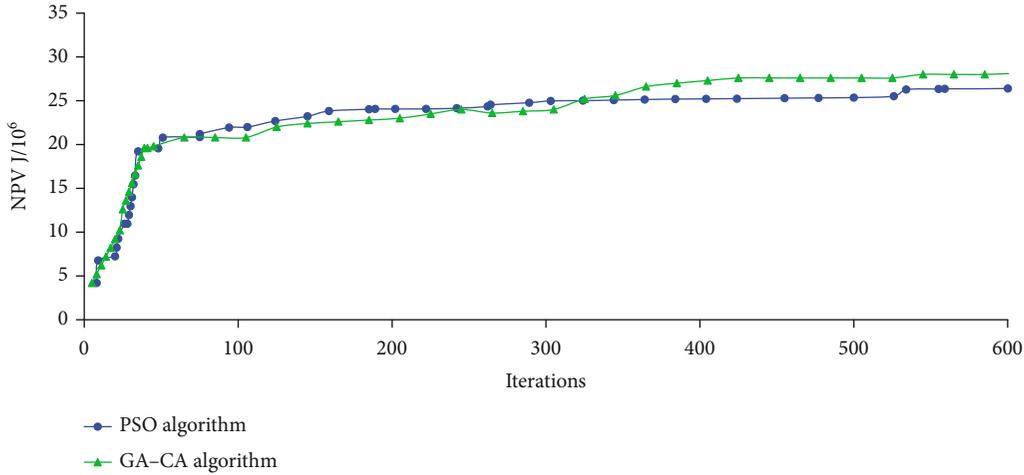


FIGURE 3: Iteration curve of the genetic algorithm-anneal algorithm (GA-CA) optimization algorithm.

The mathematical model of fitness evaluation function is expressed as

$$g = -\tau \cdot J(u, y, m), \quad (3)$$

where $J(u, y, m)$ is the performance indicator function and τ is the perturbation factor.

To reduce ineffective water circulation, divert water flow, decrease water cut, and increase oil recovery in the simulation process, NPV was applied as an indicator to guide the fitness function, automatically update the production scheme and drawdown pressure, establish the new displacing streamlines, and inhibit ineffective flooding. The streamlines were continuously optimized following the process of “low-efficiency flooding-streamline diversion-streamline infilling-stable oil displacement” to increase water swept efficiency and obtain the maximum NVP in the annealing temperature reduction process. In addition, the injection-production rate was used as a constraint, and the value was set between 0.5 and 1.5 to maintain the reservoir energy and satisfy the requirements of the seepage field optimization process.

4.2. Injection-Production Well Pattern Optimization Strategy. The well pattern was optimized to supplement the formation energy, and the injection-production plane structure was configured according to the morphological characteristics of the channel facies. Due to the delta plain facies of the non-major layer in the target area, meandering river deposits are mostly developed, channel side-sway is present, channel curvature is generally greater than 1.3, well pattern of “channel concave bank water injection and convex bank oil production” is deployed, the channel side-sway of delta front facies in the main layer is reduced (mainly between 1.1 and 1.2), the branching diversion ability is enhanced (up to grade 7), the channel width and thickness are reduced, and more small curvature channels and dendritic channels are developed. Comparing the physical properties of different channel facies reservoirs, such as dendritic, convergent, reticular, and side swinging, it can be observed that the physical properties of the dendritic channel beach and convergence channel are

better than those of the other types, and the well pattern optimization should be prioritized. Considering the characteristics of the herringbone distribution of the dendritic channel, the injection-production well pattern was adjusted to a triangle well pattern of “water flooding in river point bar and oil production in braided beach,” and water injection wells were supplemented at the edge of the main channel between the two braided shoals so as to supplement the deficit in time and provide an energy base for fluid diversion.

During the well pattern optimization of the dendritic complex channel, the inverted five-point well pattern was formed by adding new wells into the braided beaches of different branch levels. The new wells were mainly deployed in the grades 2–4 branching channels, and the newly developed water injection wells were added at the edge of the third branch channel. The results of the numerical simulation showed that the productivities of different parts of the dendritic narrow channel were significantly different. Based the productivity of a single well, a channel can be classified into five types: dendritic movable estuary bar, dendritic distal branch, dendritic middle branch, dendritic proximal branch, and dendritic side branch. The comparison between the diamond and basic patterns before water injection showed that the 10-year oil recovery in the diamond pattern increased by 13.6% as compared with that of the basic pattern in the south of the reservoir. According to the prediction of water-flooding in the center of the dendritic complex sand body, the oil recovery within five years further increased by 7%. After water injection, the water injection pressure in the north-south direction increased and could be recovered in a shorter time. The injection-production streamline between the conversion well and the nearby wells was more uniform (Figure 4), which played an important role in alleviating the continuous energy deficit of the local formation in the main area.

4.3. Auxiliary Measure Optimization Strategy. By using the tailored injection-production side matching measures for different types of remaining oil, the reservoir oil recovery can be further improved on the basis of a dynamic optimization scheme. The specific measures were as follows: (1)

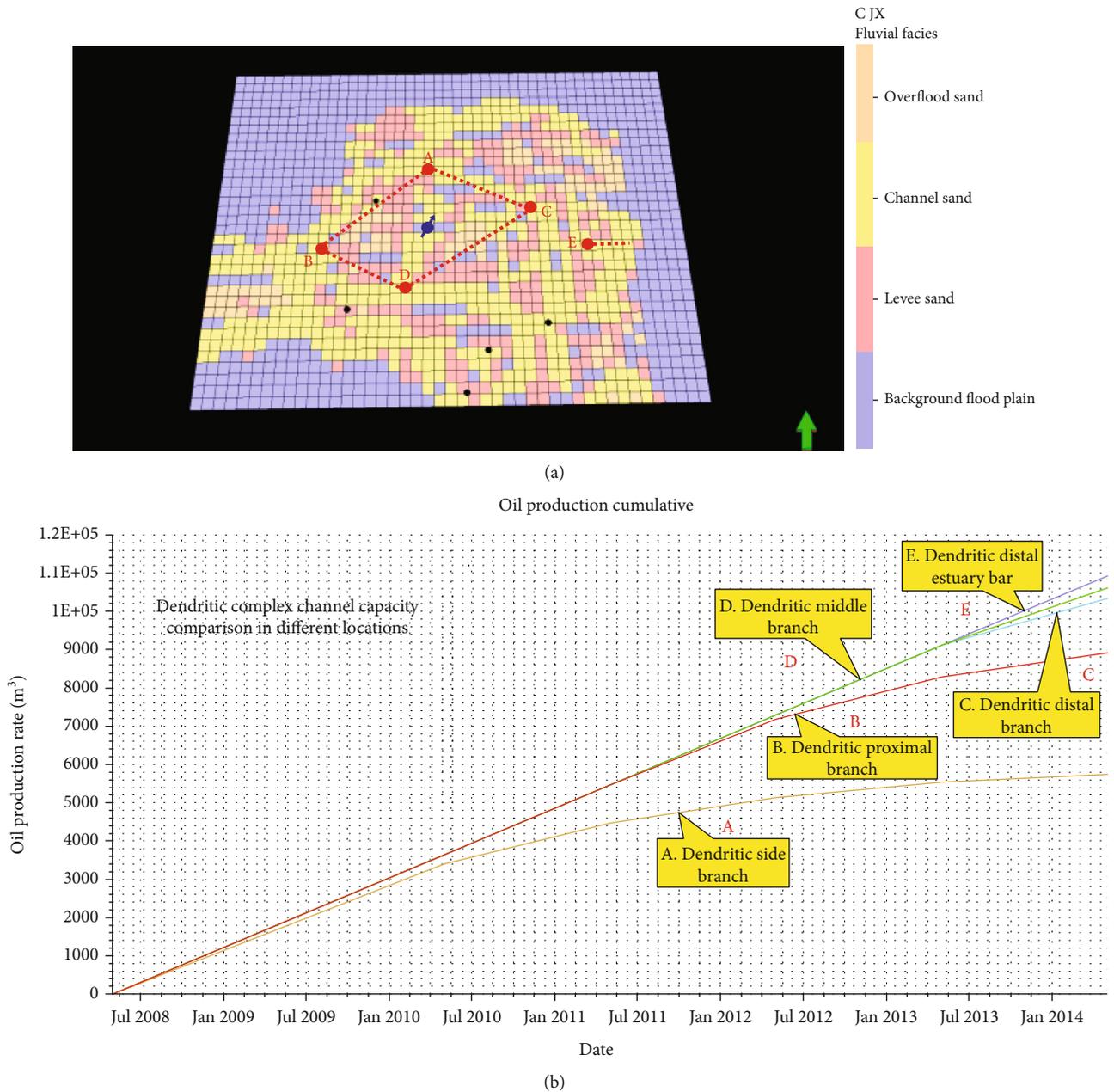
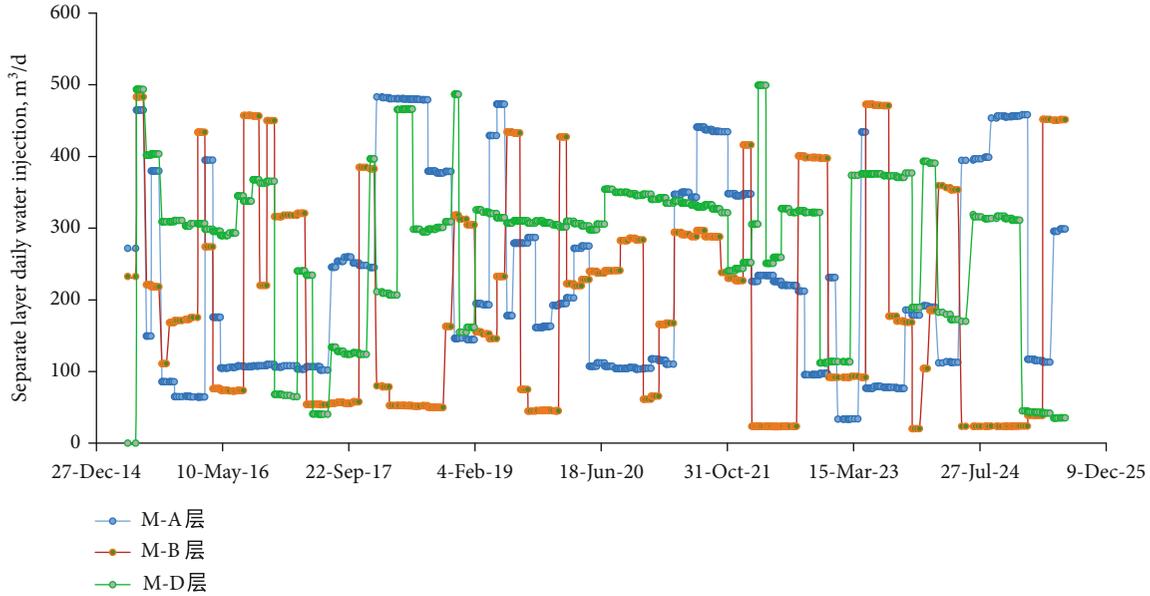


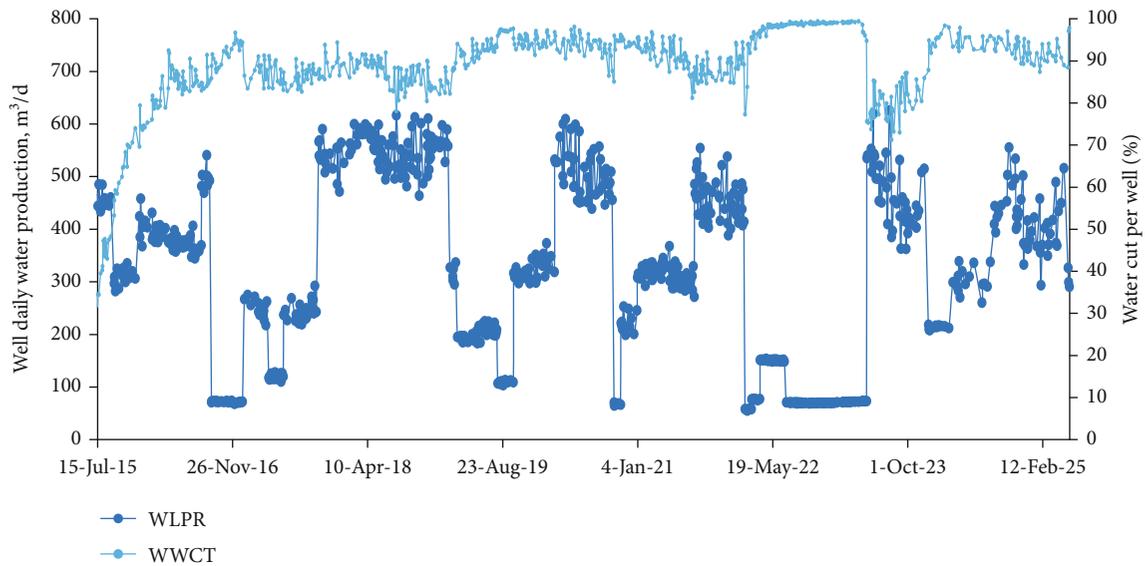
FIGURE 4: (a) Optimization of injection-production well pattern in the dendritic complex channel. (b) Comparison of the dendritic complex channel capacities in different locations.

fracturing, hole-filling optimization, and acidification are commonly applied for extracting the remaining oil accumulated due to sedimentary phase change. The main focus is to improve the physical properties of the near production wellbore layers and utilize the potential of the remaining oil in braided beaches, point bars, and falling silt layers. (2) To exploit the potential of the remaining oil accumulated due to heterogeneity, the output side can be optimized. The physical experiment on interlayer interference showed that when the permeability ratio was greater than 3, the interlayer interference increased [27], and the oil displacement efficiency was low. (3) The countermeasures employed to exploit the potential of the remaining oil accumulated via local oil and

gas retention at higher positions due to the stratigraphic structure included infilling well patterns or adopting sidetracking methods to tap the remaining oil. (4) The remaining oil resulting from the development mode was mainly recovered via injection side optimization. The remaining oil in offshore oilfields can be tapped by diverting injection from a high water cut oil well, pumping injection in the same well, and through intelligent separate injection, such as by using the M20 intelligent separate-layer water injector for remaining oil displacement. The countermeasures to produce the remaining oil accumulated due to the imperfect well pattern included increasing the perforation density, infilling the well pattern, and adopting sidetracking methods.



(a)



(b)

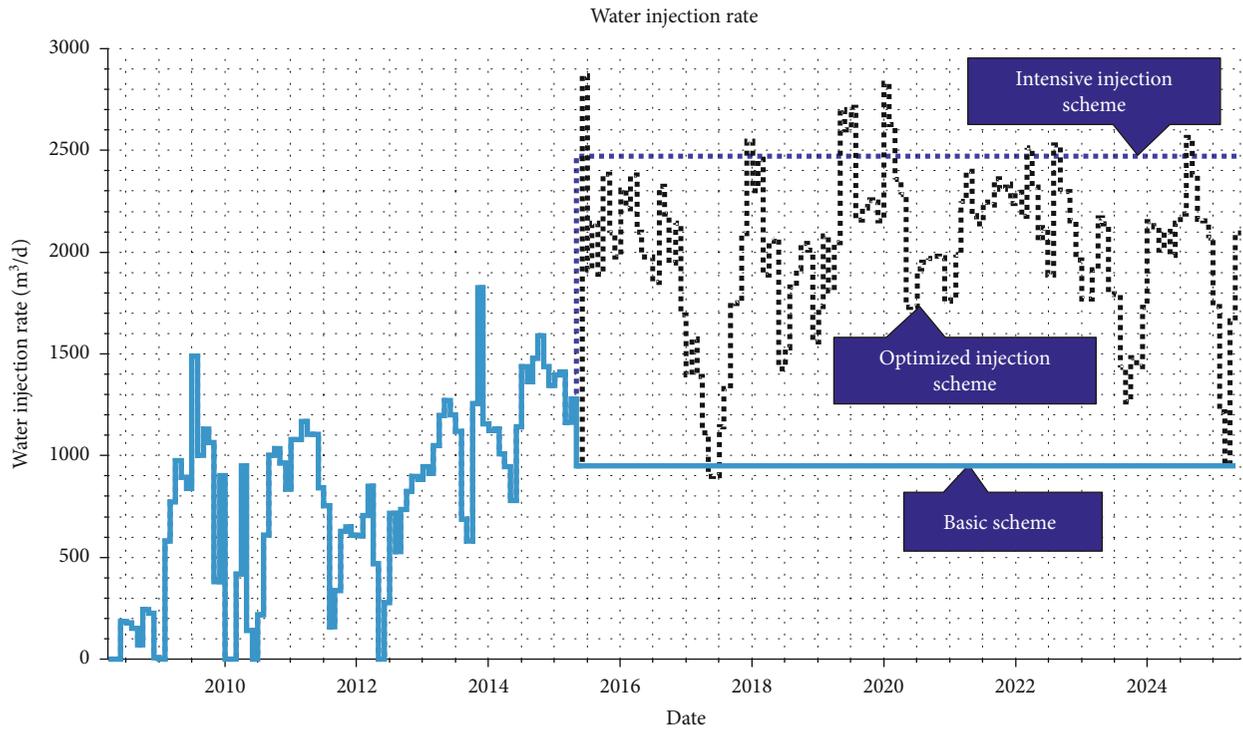
FIGURE 5: (a) Countermeasures to decrease water and increase oil in M20—change in separate layer injection volume. (b) Countermeasures to decrease water and increase oil in M21—change in fluid production volume.

5. Prediction and Result Analysis of the Water-Decrease/Oil-Increase Scheme

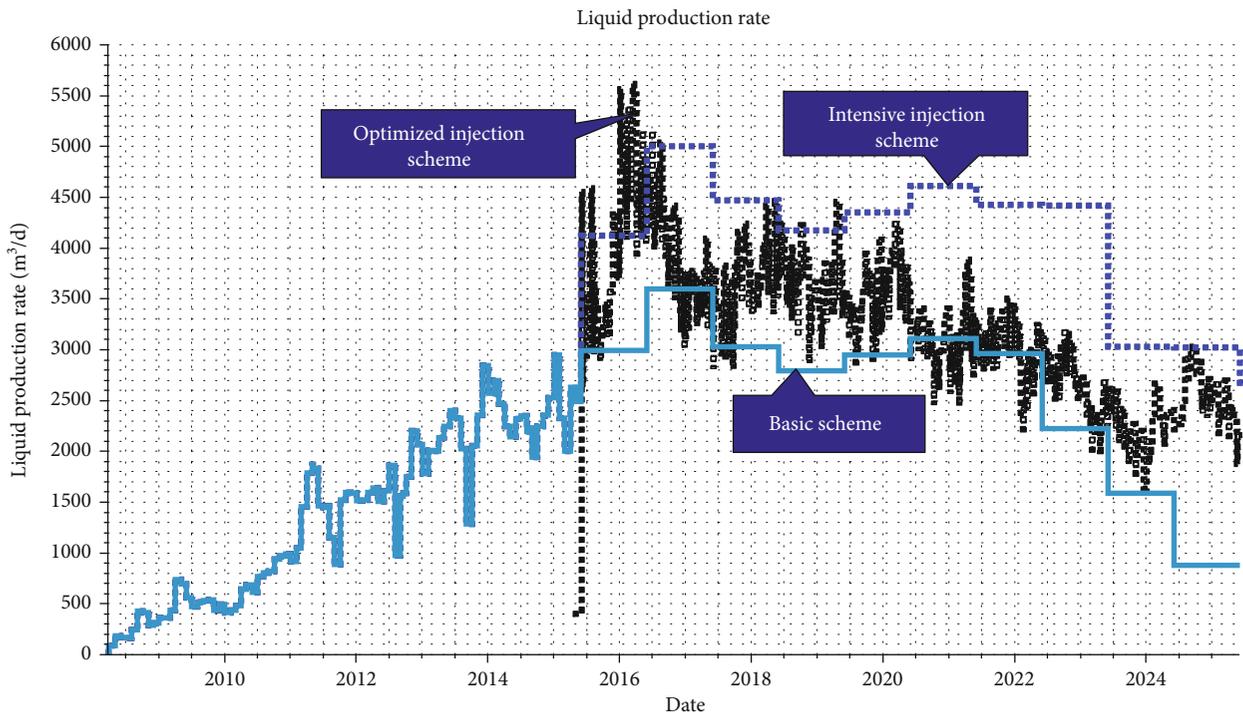
5.1. Countermeasures to Decrease Water and Increase Oil. The countermeasures to reduce water cut and increase oil recovery included reducing the local pressure disturbance and diverting the injection fluid. It was difficult to adjust the original injection-production structure through quantitative fluctuation of the production system to decelerate the ineffective water circulation and increase the water sweep volume. Therefore, we proposed three countermeasures.

The basic design of the optimization scheme is as follows: we assumed that based on the existing internal injection water displacement well pattern, with no adjustment to the

existing series of development, the oil production increased only based on the optimization of the production system. Three schemes were established, and the simulation results were compared. (1) Basic scheme: following the original production system, the daily water injection was fixed at $1000 \text{ m}^3/\text{d}$ and the production fluid was produced at a constant flow pressure; (2) improved scheme: the total water injection volume was increased to 2.5 times the original value, the daily water injection rate was fixed at approximately $2500 \text{ m}^3/\text{d}$, and the daily production fluid was produced at a constant flow pressure; (3) optimized scheme: the optimized injection volume fluctuated between the production limits, the daily injection rate of a single well fluctuated between 50 and $500 \text{ m}^3/\text{d}$, and the daily liquid production fluctuated between 50 and $600 \text{ m}^3/\text{d}$ (Figure 5).



(a)



(b)

FIGURE 6: (a) Comparison of injection volumes in different production schemes; (b) comparison of production volumes in different production schemes.

The algorithm parameters set for scheme optimization are as follows: (1) engineering parameters: oil price, 2109.5 RMB/m³; fluid treatment cost, 2.5 RMB/m³; water injection cost, 4.9 RMB/m³. Daily water injection fluctuated between

1500 and 2500 m³/d, with daily water production varying from 2000 to 4000 m³/d. (2) Algorithm parameters: the number and size of the initial group were 100 and 4, respectively. The initial annealing temperature and perturbation factor of

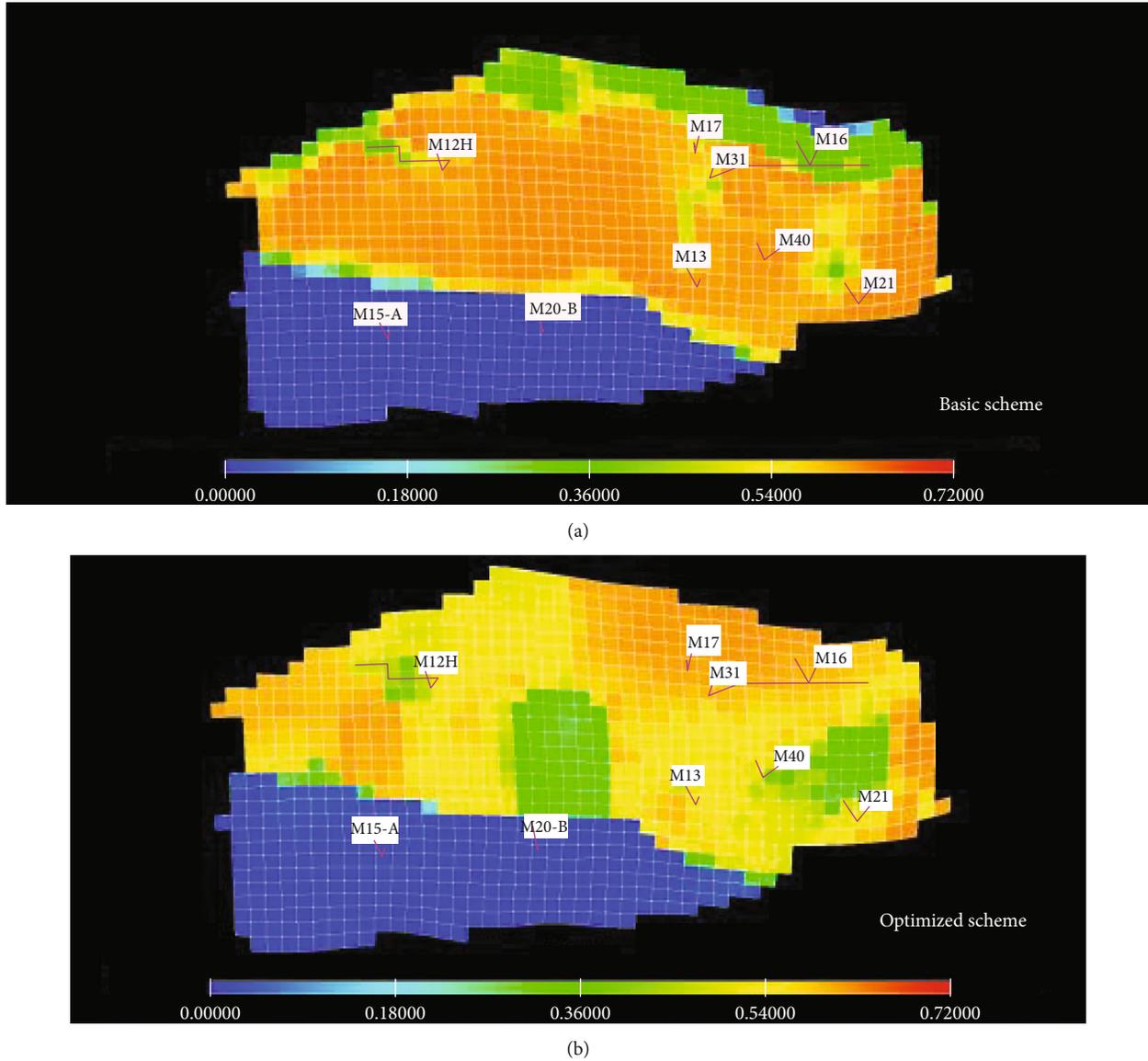


FIGURE 7: (a) Comparison of residual oil distribution in the basic scheme; (b) comparison of residual oil distribution in the optimized scheme.

the CA algorithm were 800°C and 1.3, respectively. The perturbation step size and gradient coefficient of the SPSA algorithm were 0.5 and 0.1, respectively. (3) Planning index: the optimization step size was 30 days, and the total optimization lasted for 3600 days.

A comparison between the optimized injection-production scheme and prediction scheme shows that irregular well patterns of 3 injection wells and 17 production wells can effectively dredge the edge water and increase oil production, as shown in Figure 5. Compared with the basic scheme, the cumulative injection volume of the optimized scheme was 7,425,100 cubic meters, and the cumulative injection volume was approximately 3.7 million cubic meters. At the initial optimization stage, the displacement energy was insufficient and the high water cut wells M17, M39, and N17 with were shut down. The 10-year oil recovery of the optimized scheme was 54.44%, and the net cumulative oil increment was 1,013,400 cubic meters. The oil recovery increased by 11.26% every time

a 3.34 pore volume (PV) water was injected, and 1.0 PV of additional oil was recovered (Figure 6). A comparison between the optimized and the improved schemes shows that approximately 4,644,400 cubic meters of fluctuating injection volume was reduced in the optimized scheme, and ineffective and low-efficiency water production was effectively controlled. The cumulative water production could reduce by 5,181,600 cubic meters in 10 years, and the cumulative net oil increment could be 798,600 cubic meters. The predicted oil recovery increased by 8.87%, and the total water content decreased by 3.26% (Figure 7).

5.2. Prediction of Production Indexes. The optimized injection-production scheme mainly controls the reservoir productivity, comprehensive water cut, and reserve production. The dynamic water-decrease/oil-increase fluctuation rules are revealed, and the optimization process of the production dynamics is presented in Figure 8.

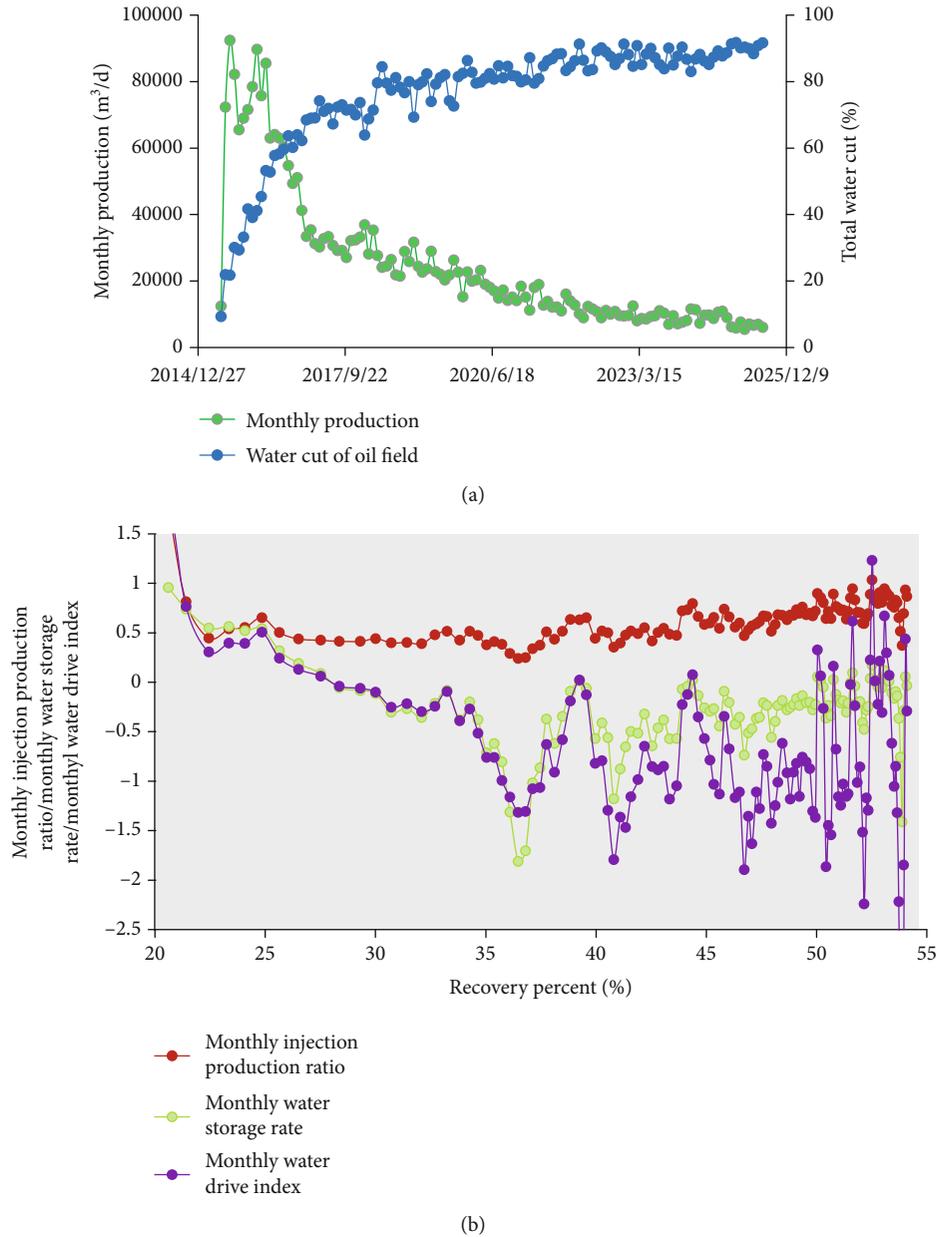


FIGURE 8: (a) The index changes of hydrophobic oil-increased optimization scheme in production and water cut; (b) the index changes of hydrophobic oil-increased optimization scheme in injection and water drive.

- (1) *Reservoir Productivity Index*. The oil production rate was between 1.3% and 3.17%. The initial oil production rate was high and peaked in the second year. In the subsequent production period, the annual oil production rate progressively decreased at a rate of 0.17–1.74%. The natural decline rate was relatively higher in the early stage than that in the later stage, and the decline rate remained between 11.3 and 15.44% in the middle and late stages.
- (2) *Comprehensive Water Cut Index*. The water cut curve demonstrated a serrated fluctuation. In the middle water cut period, the annual water cut increase rate was 0.59–1.99%, and the value could be controlled between 1.85 and 3.1% after the high water cut period.

- (3) *Reserve Production Index*. The sweep efficiency and reserve-production ratio gradually increased when water was injected into oilfields with weak edge water and low displacement energy. In the middle water cut period, the optimized reserve-production ratio was between 14.3 and 16.9 and increased rapidly in the high water cut period, reaching between 21.1 and 33.56.

6. Conclusions

- (1) According to the systematic optimization method, from the perspective of energy diversion and displacement path of injection end, seepage field, and output end, different countermeasures to decrease water and

increase oil were proposed based on the type of remaining oil and the shape and size of the narrow channel sand bodies: seepage field optimization strategy, injection-production well pattern optimization strategy, and injection-production measure optimization strategy

- (2) A comparison between the optimized and the improved schemes shows that the predicted oil recovery increased by 8.87% and the total water content reduced by 3.26%. The reported method can effectively dredge edge water and increase oil by local drainage between injection and production wells and guide future research on stabilizing oil production and controlling water cut

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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