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Improving Water Flooding Management through Facies Remodeling and the Use of Streamlines and Finite Difference Simulators

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Abstract

A successful water flooding project requires continuous surveillance and updated studies. The use of modern tools and practices is also essential to achieve maximum oil recovery. Field 'X' lies in the Western Desert of Egypt. Although the field employs water flooding as a secondary recovery mechanism, it suffers from low oil recovery, low sweep efficiency and high water's production rates. In 2014, a field development plan was issued with a target recovery factor of 30% using water flooding. However, actual production has significantly underperformed initial forecasts, motivating a re-evaluation of the old plan. In particular, it was considered necessary to revisit the underlying geologic concept and how this was incorporated into flow simulation forecasts. The aim was to maximize the oil recovery factor before resorting to an expensive tertiary recovery plan; especially, under current low oil prices. This paper discusses the value of updating both static and dynamic models to better incorporate uncertainty associated with facies distribution. It also demonstrates the use of streamline simulation to reallocate water injection rates and determining the role of facies communication in improving the areal sweep efficiency. The new injection scheme is supported by the updated dynamic modelling study and added an incremental reserve of 6.5% and unlocked 28% of the oil in place in the field.

Keywords: Water-flooding; Facies; Streamline; Simulation

1. Introduction

1.1. Background

Continuous surveillance of any water flood project is necessary to ensure its success and achieve the target oil recovery. Excessive water production and declining oil rates are the most crucial problems in any water flooding project. These problems often result from inefficient project surveillance and implementation. Significant research has been conducted to improve water flooding efficiency using different tools and strategies [1] .Findings and refreshed strategies have been employed in pilot areas and showed great success [2]. It is vital for a successful water flooding plan to start from a clear understanding of the reservoir geology, dynamic properties, and pressure communication among wells. Moreover, utilizing the proper simulation tools and optimization strategies are essential for a proper project management. The stability of a water-flood project is controlled by reservoir geometry, fluid properties, reservoir depth, lithology, and fluid saturation (Ahmed, 2006 [3].

The use of conventional surveillance techniques such as diagnostic plots of produced oil and injected water are not enough when dealing with complex and heterogeneous reservoirs. Although widely applied, those techniques are based on the assumptions of well-patterns with fixed injection allocation ratios. Production behavior can be associated with significant complexity and hence requires using simulation and streamline models which are more

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effective in determining the sweep efficiency (especially in large injection patterns) [4]. Consequently, building a simulation model that depicts the subsurface complexity of geology and sand distribution is fundamental to the quality of the forecast.

A comprehensive understanding of pressure communication across the field provides a clearer concept of sand communication and leads to a more realistic history match for all field performance parameters [5]. Acquiring pressure data from various sources is helpful for ensuring the quality of data. The use of real time pressure measuring tools like ESP sensors and tubing head pressure gauges gives a clear idea about the interactions between wells. Also, using Repeat Formation Tester (RFT) or similar tools in new wells helps identifying the connected layers in the reservoir and assessing sand properties and facies distributions. Fluid level surveys can also give a good approximation of pressure in wells where running bottom-hole gauges is challenging [6].

Field performance reviews with a focus on flooding patterns are continuously required to meet production targets and avoid decline. Such reviews should include void age replacement plots, Gas Oil Ratio (GOR) trend analysis, and production/injection performance plots [7]. To obtain a robust production forecast, a representative dynamic model that seeks to represent all relevant features of the facies architecture shall be used. More than one static model with different concepts of structural and sand distribution should be constructed. Moreover, the forecast is not considered reliable unless a good history match for pressure, oil production, water production, gas production and water injection data has been achieved [8]. In the forecast phase, multiple sensitivity cases will capture the range of forecast probabilities and the best strategy to manage the field before any expensive field implementation.

Streamline simulation is a very effective and time saving tool for predicting best sweep efficiency. It gives an efficient aid in visualizing streams between injectors and producers, allocate injection rates for injectors, identifies fruitless water cycling, wasted water coning and highlight the areas with poor sweep efficiency [9]. Unlike analytical ways which have almost fixed areal sweep efficiency according to flood patterns, this tool uses simulation velocity field and inter well connectivity for designing an optimized injection allocation [10].To optimize the sweep efficiency the streamline uses a concept of Time of Flight (TOF) distribution, by which the areal sweep efficiency is easily optimized and enhanced in complex reservoirs to increase oil recovery in the poorly swept areas [11]. In streamline simulation, the computation is done along the streamlines, in contrast to finite-difference simulators that calculate between cells [12]. Although calculation accuracy is lower than that of finite-difference simulators, streamline simulation is faster is faster and give a quick interpretation about the injection-production interaction and the sweep efficiency in large patterns. This tool can be used widely in many applications like modeling recovery in fractured reservoirs, polymer flooding and compositional gas injection (Bastian et al.,2000; Clemens et al.,2010; Mallison,2004) [13]. In this study stream line simulation will be used to trace the injected water paths, generate and improve production injection strategy and identify un-swept oil. This will lead to an enhanced and balanced injection strategy.

1.2. Field background

Field 'X' was discovered in 2007 in the Western Desert of Egypt, with 30 million barrels of sweet oil original in place in Abu Roach G Formation (ARG sandstone reservoir). The field started production with depletion drive from the ARG formation, until it recovered 5% of OOIP. Water flooding has been implemented after that to increase recovery to reach 28% of OOIP.

Line drive injectors were added to sweep oil and to increase reservoir pressure to a value near to 3000 psi to enhance recovery. After two years, an injector and a producer were added to the pattern. After severe depletion in 'ARG' reservoir pressure in 2014, a field development plan for water flood was issued to maximize recovery to reach 30%. The study team identified ten hydrocarbon units in 'ARG' reservoir.

A simulation model was built based on the study findings and the field development plan (FDP) concluded the following:

- The reservoir is separated into two blocks; East and West as shown in (Figure 1).
- Material Balance calculations indicates a volume of 30 MMSTB of OOIP
- The plan was to inject 4000 BWPD, until the target reservoir pressure (3500 psi) is reached

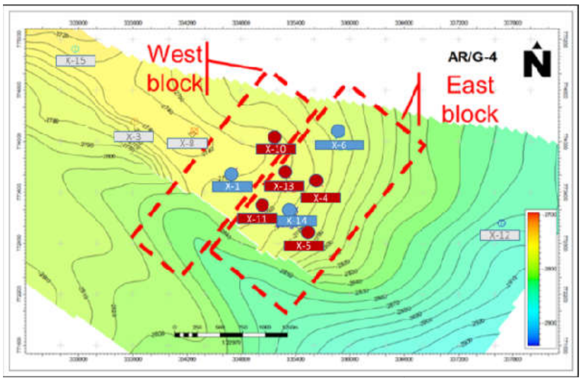

Figure 1: Old Structure Map Showing the Reservoir Different Blocks

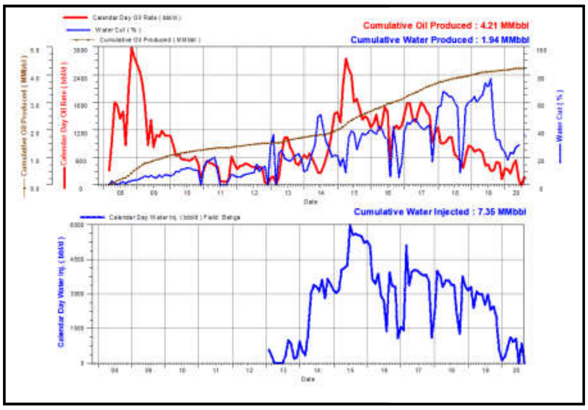

Figure 2: 'X' Field Performance

After following the proposed plan for five years, the current performance (Figure 2) showed a deviation from what was expected from water flood implementation. The oil rate was plunging with high water cut (W.C) and hence a low performance of water flooding. The injected water started to recycle from certain wells which lead to loss of sweep efficiency and waste of injection energy.

Field production problems required a revision of the old study findings and plans to enhance recovery with minimum cost. Problems have arisen after reaching a recovery factor of 18% when the water cut has increased in most wells and the recovery plan started to deviate to ranges consistent with downside-case scenarios.

2. Material and methodology

Before considering changing a plan for a water flood project, a study of pressure communication for reservoir is mandatory. This is followed by building a static and dynamic model that captures the updated static concepts and reservoir properties. Additionally, a production forecast is to be generated after achieving a reasonable history match of the significant observables.

2.1. Pressure communication evaluation

By revising the pressure history points that were measured by RFT, static bottom hole pressure and temperature surveys and fluid level surveys, it was found that the idea of two separate tanks in east and west area dose ot match the real performance as shown in (Figure 3). This is due to the absence of any structural feature as also shown in the seismic interpretation that might cause the separation. Although, X-10 and X-6 shows a very low or no communication, an existence of a barrier should not be considered. This behavior can be due to very low transmissibility between the two areas. Long after the start of injection, the production wells showed a trend of pressure increase. According to the analysis, the new model considered all the wells to be in communication, which contradicts the old findings. As the wells were producing via ESP pumps, the idea of applying an interference test was not applicable, hence pressure communication history analysis was most convenient technique to identify the communication between wells.

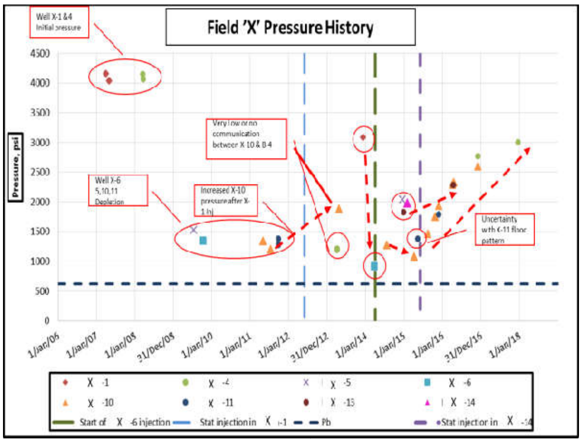

Figure 3: Pressure communication History Analysis in Field 'X'

2.2. New static and dynamic models with excellent history match

Field 'X' has complex facies and high reservoir heterogeneity. Based on a detailed sand correlation 10 sand units were identified and structural models were updated. We built new static models covering the uncertainties of sand distribution, net to gross (N/G) and porosity. Two facies' models were generated by using an object-based modeling algorithm and sequential indicator simulation (SIS) respectively. For all the models a NE-SW sand direction was used which is consistent with image data taken in well X-4 and the likely direction of connectivity seen by other wells and adjacent fields. Five property-model scenarios (P10, P30, P50, P70 and P90) for each model have been exported as shown in (Figure 4). We applied 100 uncertainty runs for both SIS-Prop and Object models. Without changing or multiplying factors for reservoir parameters, a single model was chosen from the full static ensemble for the dynamic study, upon the basis of the quality of match to historical pressure, water-cut and liquid production as shown in (Figure 5).

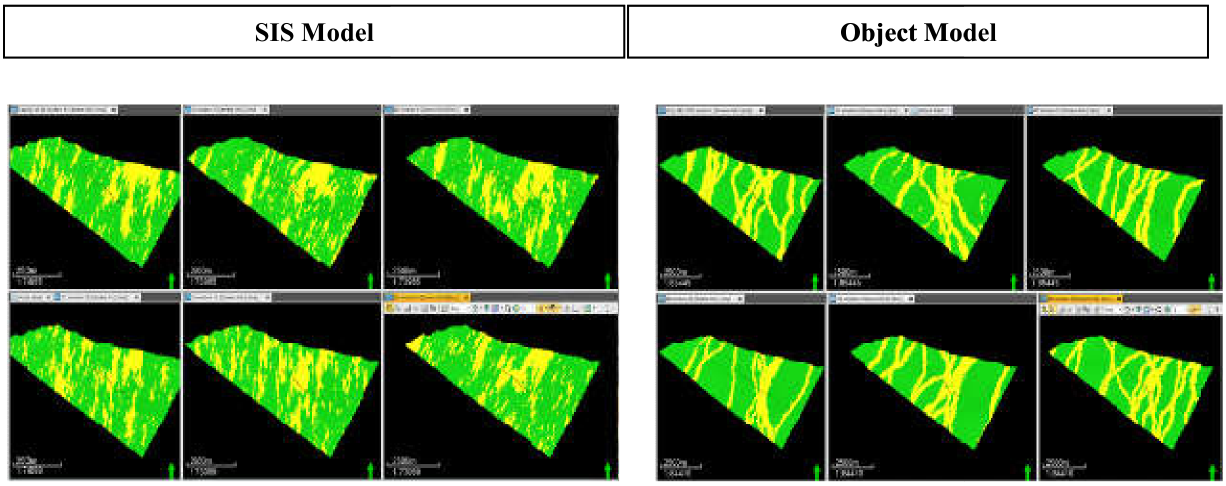

Figure 4: Facies Cases

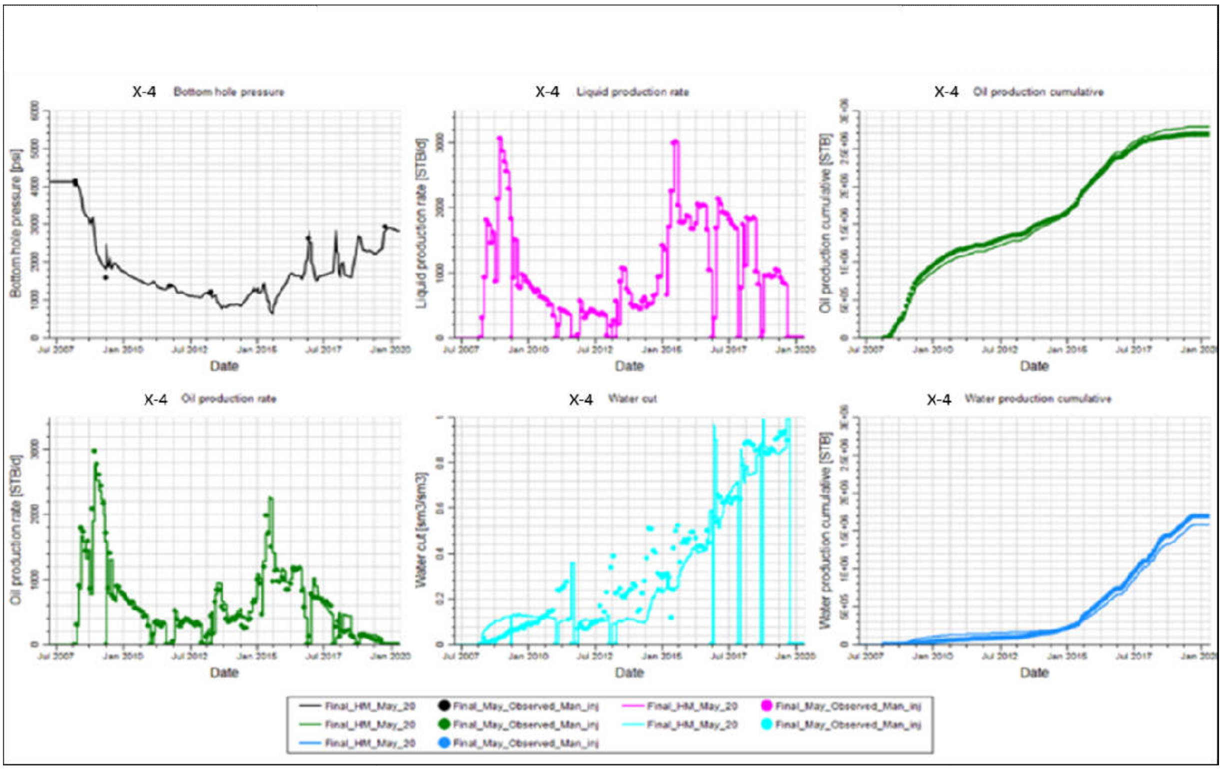

Figure 5: History Match of the Main Producer X-4

2.3. Stream line simulation (Frontsim)

2.3.1. Building streamlines

A streamline represents a curve whose every point is tangent to the local velocity vector. For a single cell (Figure 6) , flow rate is calculated for each face and considered as a starting point (Figure 7) according to Pollock (1988) method [14].The interstitial velocity (v = u/φ) in x direction defined by:

v_x= v_xo+g_x (x-x_o) (Eq.1) [14]

Where

g_x=(v_xΔx-v_xo)/Δx (Eq.2) [14]

v_xo	X-velocity at x-x_o
g_x	velocity gradient in x-direction

By integration of x-velocity in X, Y and Z directions to get velocity for each face, we will get the exit time of flow

Δt_x=1/g_x ln[(v_xo+g_x (x_e-x_o))/(v_xo+g_x (x_i-x_o))] (Eq.3) [14]

Δt_y=1/g_y ln[(v_yo+g_y (y_e-y_o))/(v_yo+g_y (y_i-y_o))] (Eq.4) [14]

Δt_z=1/g_z ln[(v_zo+g_z (z_e-z_o))/(v_zo+g_z (z_i-z_o))] (Eq.5) [14]

Since the streamline must exit from the face having the smallest travel the minimum time is defined as:

Δt_m=min (Δt_x,Δt_y,Δt_z) (Eq.6) [14]

Using the minimum time, the exits' locations〖x〗_e,y_e, z_e are calculated from:

x_e=1/g_x ln[v_xi □exp exp (g_x Δt_m) -v_xo]+x_o (Eq.7) [14]

y_e=1/g_y ln[v_yi □exp exp (g_y Δt_m) -v_yo]+y_o (Eq.8) [14]

z_e=1/g_z ln[v_zi □exp exp (g_z Δt_m) -v_zo]+z_o (Eq.9) [14]

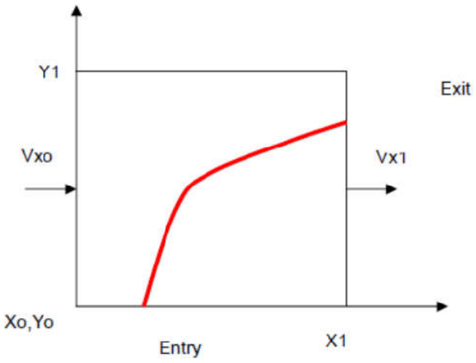

Figure 6: streamline in a single cell

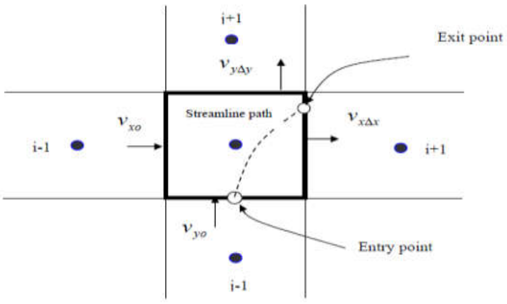

Figure 7: Building streamlines

Streamlines are well suited to rapidly identifying dynamic communication within and between sand bodies [15]. The streamline simulation study confirmed the concept of communication between the east and west block, and eradicated the previous conclusion of two separate areas, while matching the low transmissibility between X-10 and X-6 (Figure 8). By tracing the streamlines, the effect of each injector is represented by a bundle of lines starting from the injector and endingat the producer. Also, they showed that well X-6 has the biggest effect and injection volume share in reservoir. The different and grading of color from blue to red indicates the energy distribution between injectors and producers in reservoir. This gives a qualitative idea about the areal sweep efficiency achieved by the current pattern. The allocation table indicates the effect of each injector and its contribution to liquid production from producers as indicated in (Table 1).

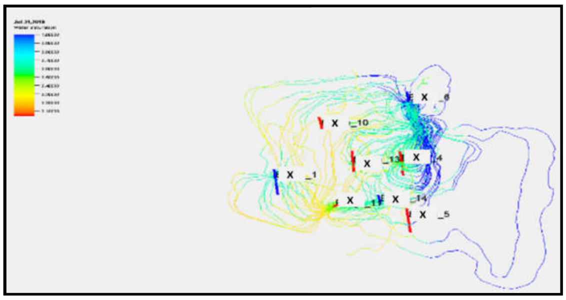

Figure 8 : Streamlines

2.4. Injection re-allocation and forecast sensitivities

Different injection rate strategies were applied to approach top quartile areal sweep efficiency and achieve maximum recovery with lowest water production. Thirteen different injection patterns were applied using different injection rates while fixing liquid production rates in producers. The results were compared with those from the 2014 plan (Table 2) .For each case we extracted the cumulative oil production and average reservoir pressure to choose the highest recoverable strategy with optimum reservoir pressure to be suitable for operating the producers with ESP pumps as clarified in (Figure 9).

Table 1: Injection Allocation

	Injectors		
Producers	**X-1**	**X-14**	**X-6**
X-10	**0.015**	**0.000**	**0.047**
X-11	**0.730**	**0.961**	**0.165**
X-13	**0.000**	**0.034**	**0.115**
X-4	**0.000**	**0.005**	**0.668**
COMPRESS	**0.255**	**0.000**	**0.005**
Total	**1**	**1**	**1**

Table 2: Injection Allocation Sensitivity

			Strategy												
	Well	**Old Plan**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Water Injection Rate	**X-1**	300	500	500	500	500	500	500	500	500	500	500	500	500	500
	X-6	3000	1000	1000	500	500	1000	1500	1500	2000	2000	2500	2500	3000	3000
	X-14	1000	1500	1000	500	1000	500	500	1000	500	1000	500	1000	500	1000

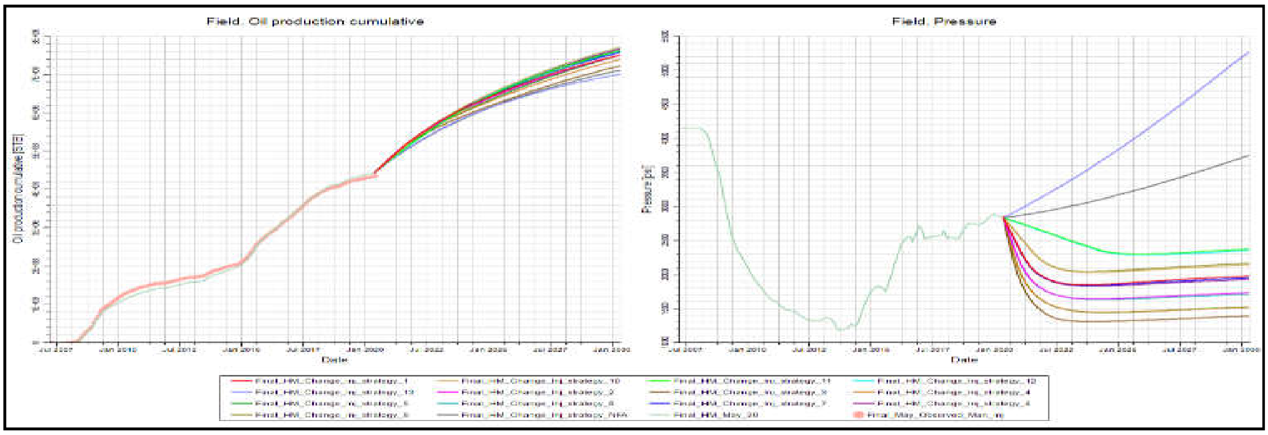

Figure 9: Forecast Strategies

3. Results and discussion

After completing the forecast runs to the end of field license date (ten years), strategy #8 shows to the most effective in terms of achieved recovery and reservoir pressure. Streamline simulation shows that the proposed reallocation strategy enhanced sweep efficiency around injector X-1 as in (Figure 10). Also., an incremental oil volume of 0.5 MMSTB, which equals to 1.6 times the preferred incremental of a new well in this field, was achieved only by reallocating injection rates with the current performance of producers as the curves showed (Figure 11). On a saturation map an area of high saturation still has not been swept by water. This opportunity unlocks a volume of 7 MMSTB oil in place in western area that gives room for more wells to be drilled (Figure 12)

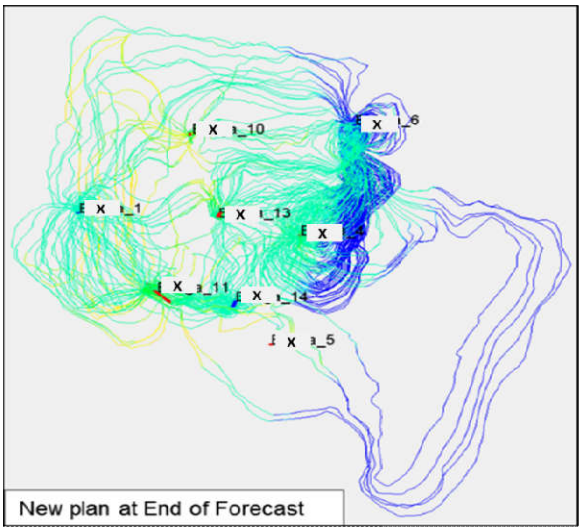

Figure 10: Streamlines At End of Forecast

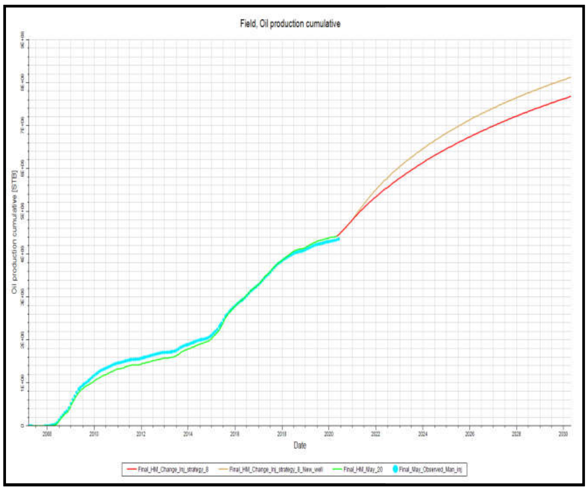

Figure 11: Best Forecast Strategy

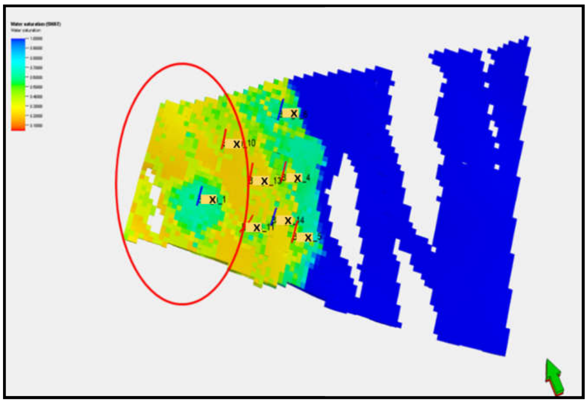

Figure 12: Saturation Map at End of Forecast

4. Conclusion

The deep analysis and understanding of field pressure communication, reservoir complexity and facies distribution is always the first step of maximizing the recovery for any brown field. Based upon preceding discussion, it was concluded the following:

Utilizing an integrated set of tools that were able to quickly and efficiently screen a suite of models, improved secondary recovery was achieved at low cost Depicting the sweep efficiency using streamline simulation is a very effective tool in enhancing water flooding performance.

In this study the new concept and injection reallocation added incremental reserve of 0.5 MMSTB. The new understanding of communication and the clarification achieved by streamline simulation unlocked 7.9 MMSTB of oil in place (OIP).

5. Nomenclatures

ARG	Abu Roash ‘G’
FDP	Field Development Plan
OOIP	Original Oil in Place
OIP	Oil in Place
W.C	Water Cut
MMSTB	Million Stock Tank Barrel
BWPD	Barrel Water per Day
TOF	Time of Flight
ESP	Electric Submersible Pump
RFT	Repeat Formation Tester

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7. Conflict of Interest

On behalf of all the co-authors, the corresponding author states that there is no conflict of interest

8. References

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