Polymer Flooding Performance in One of World's Largest Sandstone Formations in the Middle-East

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***Abstract*—**Crude oil reservoirs undergo three production stages: primary, secondary, and tertiary recovery. Primary methods like natural production or artificial lift techniques are initially used, secondary recovery involves water and gas injection to maintain pressure and enhance recovery, with tertiary Enhanced Oil Recovery (EOR) techniques targeting residual oil or gas.

Water flooding enhances sweep efficiency and displaces oil towards production wells, but its effectiveness is influenced by reservoir heterogeneity and oil viscosity, leading to early water breakthrough and viscous fingering that led to the dramatic increase in water production and unrecovered oil. Polymer flooding is a promising EOR technique for the reservoir in this work, aiming to remedy production challenges in terms of severely increasing of produced water. By increasing water viscosity, polymer injection reduces water mobility and the mobility ratio, thereby enhancing displacement efficiency where past studies have shown that polymer flooding significantly increases oil production rates, reduces water cut, and improves overall oil recovery. Furthermore, careful selection of polymer properties, such as molecular weight and concentration, based on reservoir characteristics, is crucial to address potential injectivity issues.

This work studies one of the main reservoirs situated in the Middle-East. The Long-Term Polymer Injectivity Test is conducted on this reservoir aimed to mitigate risks linked with phased commercial polymer flooding. Building upon previous work conducted on two preceding pilots in the reservoir, the Long-Term Polymer Injectivity Test focused on treating effluent water high in total dissolved solids from the produced water facility and mixing it with a sulfonated polymer recommended by the oil company for injectivity testing under sub-fracturing conditions at varied rates and polymer concentrations.

This study aims to assess different well configurations and polymer injection durations at various stages, utilizing the Long-Term Polymer Injectivity Test results and by using CMG STARS software (IMEX Model) to simulate diverse scenarios. The findings suggest that implementing polymer flooding when water production reaches high levels can notably increase oil production rates and significantly reduce water cut, resulting in substantial savings in water handling costs, new well drilling expenses, as well as capital and operating expenditures.

***Index Terms*—** Enhanced Oil Recovery, Polymer Flooding, Sweep Efficiency and Mobility.

I. Introduction

This work studies polymer flooding performance in one of world's largest sandstone formations in the Middle-East which has been a major contributor to crude oil production since more than 75 years. The formation is comprised of sandstone and interbedded shale. Interestingly, the formation exhibits a higher level of heterogeneity and a slightly inferior quality of reservoir, although generally, the quality remains commendable. Over time, there's been a detectable decrease in reservoir pressure, even falling below the bubble point in certain areas of the field. To maintain pressure and enhance oil recovery, peripheral water injection into the reservoir is currently underway. There is also a consideration for the use of polymer injection as an Enhanced Oil Recovery technique. This approach has been recognized as a viable method to potentially increase oil production and overall recovery from the reservoir. Currently, this technique is being considered as a continuation of a prior Long-Term Polymer Injectivity test. The studied formation consists of several sandstone layers deposited within a fluvial-tidal coastal system, with a total thickness ranging between approximately 140 to 180 feet. The permeability of the reservoir shows significant heterogeneity. Currently, multiple The Long-Term Polymer Injectivity tests across various reservoirs is conducting by the oil companies in the Middle-East. The objective is to mitigate risks, optimize operations, and expedite the phased commercial deployment of polymer flooding techniques. These Long-Term Polymer Injectivity tests aim to showcase the technical and economic viability of continuous polymer injection using treated effluent water at predetermined viscosity levels, ensuring compliance with formation fracture extension pressure limits.

Polymer flooding is a chemical-based method for enhancing oil recovery that has a significant track record in the industry and proven success. Compared to other chemical techniques, it is the most widely used due to its minimal risks and its adaptability to a wide range of reservoir conditions, including high temperature and high salinity. Polymer flooding involves injecting water mixed with polymers into the reservoir to improve sweep efficiency by enhancing the movement of water and hydrocarbons, ultimately increasing the efficiency of oil extraction. Polymer flooding involves the introduction of polymer powder or emulsion into the water used in a water injection. This thickens the water and reduces its ability to move easily, as slight decreases in the mobility of the water compared to the oil can help prevent the occurrence of thickening problems. The recognition of how variations in fluid mobilities could influence the performance of waterflooding processes was initially acknowledged by Muskat [1]. Further discussions on the significance of the mobility ratio were presented by

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Aronofsky and Ramey [2], highlighting its role in altering flood patterns and the history of injection and production in five-spot configurations. Dyes et. al [3] investigated the relationship between mobility ratio and oil production following water breakthrough, concluding that the enhancement of water viscosity could significantly augment sweep efficiency. Along with increasing viscosity, some of the polymers can stick to the rocks in the reservoir and reduce their permeability to water, resulting in a lower mobility ratio. This leads to improved efficiency in sweeping the reservoir both vertically and horizontally resulting in quicker and often greater recovery of oil by the conclusion of the enhanced oil recovery system [4]. Polymer flooding may not be applicable to every reservoir due to variations in reservoir characteristics. Therefore, evaluating several reservoir parameters can provide insights into the feasibility of implementing polymer flooding, such as the suitable type of polymer, the project's technical performance, and the potential profitability. Key reservoir parameters that require consideration include reservoir geometry, lithology, temperature, formation water salinity, divalent cations concentration, clay content, and oil viscosity [5].

The economic advantages of polymer flooding have been studied in literature. One of the successful pilot polymer flooding in oil field located in the South Turgay basin in Kazakhstan is evident in reducing water production and maintaining stable oil output [6]. Overall, polymer flooding can offer the economic incentive of greater and faster recovery.

II. Model Description

The representative model was developed to include static properties such as porosity, permeability, and oil saturation. Fig. 1 shows porosity and permeability distribution IMEX Model. The initial model, covering 2500 acres, featured a grid size of 650 ft x 650 ft with variable layers to accurately represent the proposed formation. The grid consisted of 16 blocks in the X direction and 17 blocks in the Y direction. Further refinement was applied to the Area of Interest (AOI), increasing the resolution to 65 ft x 65 ft in the X-Y plane. In the vertical direction, grid thickness was non-uniform due to the formation geological structure. The number of divisions or refinements in the vertical direction was carefully chosen to achieve a desired resolution of 0.5 ft. Local grid refinement was specifically applied to the AOI layers, designated as sector 2 within the model. As a result of this refinement, the grid size within the AOI is now 65 ft x 65 ft, with variable thicknesses and a maximum limit of 0.5 ft. Fig. 2 an overview of AOI with 65 ft x 65 ft refinement

III. Methodology:

A compact 40-acre Area of Interest was chosen at the center of the model, employing a normal 5-spot pattern for conducting sensitivity analyses. Noting that the distance between injectors and between injectors and producers had been selected based on the actual existing wells in the AOI, where the distance between injectors is approximately 400 meters, while the distance from injector to producer measures around 275 meters.

Additionally, four surrounding wells were employed to monitor the effects of water and polymer flooding by the refined model. These wells were situated approximately 400 meters away from each injector. Sensitivity analyses were conducted to assess the influence of polymer flooding with different injection durations

IV. Case Study

The project's first case study is to perform various sensitivity cases including:

- The Base Case represents the current scenario in which the field is actively undergoing water flooding and is deemed highly mature. In this configuration, the average remaining oil saturation within the Area of Interest is assumed to be less than 30%.
- Polymer injection was implemented incrementally on a yearly basis. One case will be selected with the Polymer injection based on timing and to be ceased after 8 years for vertical wells.

The following scenarios are to be evaluated:

1. Sensitivity analysis of water flooding and polymer flooding durations on oil production daily rates.
2. Sensitivity analysis of water flooding and polymer flooding durations on water cut %.
3. Sensitivity analysis of water flooding and polymer flooding durations on produced water daily rate
4. Sensitivity analysis of water flooding and polymer flooding durations on cumulative produced water volume.
5. Sensitivity analysis of water flooding and polymer flooding durations on produced water daily rate on the injector

V. Case Study Results:

Identifying the optimal timing for introducing polymer flooding is paramount, particularly as water flooding has already begun in this reservoir, leading to a notable rise in produced water. This surge creates bottlenecks in current surface facilities and presents challenges in maintaining crude oil production and managing water handling processes effectively. Consequently, various scenarios have been crafted to evaluate the feasibility of implementing polymer flooding for the refined 5-spot pattern (comprising one central vertical producer and four vertical injectors) using CMG STARS as shown below:

A. Scenario 1: Sensitivity Analysis of Water Flooding and Polymer Flooding Durations on Oil Production Daily Rates:

Based on Fig. 3, multiple simulations have been undertaken to assess the correlation between oil rate against WF and polymer flooding durations. The following main observations can be derived:

- Implementing polymer flooding at the earliest opportunity has led to a notable rise in oil production rates compared to alternative scenarios, as illustrated by the red curve.
- Within one year of implementing polymer flooding, the oil production rate reached a peak of approximately 120 barrels per day, sustaining around 85 barrels per day from 2030 onwards. This represents a 29% increase in oil production compared to the other cases. This rate applies to each well and can be adjusted accordingly based on the number of wells present in the field.

B. Scenario 2: Sensitivity Analysis of Water Flooding and Polymer Flooding Durations on Water Cut%:

Based on Fig. 4, multiple simulations have been undertaken to assess the correlation between water Cut percentage against water flooding and polymer flooding durations. The following main observations can be derived:

- Polymer flooding at the earliest opportunity has resulted in a significant decrease in water cut from the first year up to 2030 compared to other scenarios, as depicted by the orange curve.
- Within one year, the reduction in water cut percentage reached approximately 94.8%, marking a 5 % decrease. By mid-2024, it peaked at 93.2%, reflecting a 7% reduction.
- When considering water flooding, depicted by the black curve, it becomes evident that the water cut percentage steadily rises from mid-2023 onwards and remains consistent through 2030.

C. Scenario 3: Sensitivity Analysis of Water Flooding and Polymer Flooding Durations on Produced Water Daily Rate on the Central Producer:

Based on Fig. 5, multiple simulations have been undertaken to assess the correlation between the produced water rate in bbl./day against water flooding and polymer flooding durations on the central producer. The following main observations can be derived:

- Introducing polymer flooding at the earliest opportunity has led to a notable reduction in the produced water handling rate. The water rate has gradually decreased since the inception of polymer flooding implementation, maintaining this lowered rate consistently up to 2031 as depicted by the orange curve, where the water rate initially is about 3700 bbl./day.
- Within one year, the water rate has reduced by 600 barrels per day, representing a reduction of 17%. By 2031, it peaked at a reduction of 84%, reaching a daily volume rate of 600 barrels per day, significantly lower than the initial water rate resulting from water flooding.
- When analyzing water flooding, as illustrated by the black curve, it is apparent that the produced water rate has steadily increased from 3600 bbl./day in mid-2023 onwards and remains consistent from 2025, reaching 3900 barrels per day. This represents an approximately 85% increase in produced water rate compared to the polymer flood selected case scenario. This rate applies to each well and can be adjusted accordingly based on the number of wells present in the field.

D. Scenario 4: Sensitivity Analysis of Water Flooding and Polymer Flooding Durations on Cumulative Produced Water Volume:

Based on Fig. 6, multiple simulations have been undertaken to assess the correlation between cumulative produced water volume in bbl. from mid-2024 against water flooding and polymer flooding durations. The following main observations can be derived:

- Introducing polymer flooding at the earliest opportunity depicted in the orange curve (mid-2024 up to 2032) has led to a notable reduction in the produced water cumulative volume compared to the water flooding case depicted in the black curve.
- The total reduction in cumulative produced water volume polymer flooding at the earliest opportunity compared to water flooding case is about 62% of the water flooding case cumulative volume (From 13 MMbbl.to about 5 MMbbl in 2032).
- The other polymer flooding cases with different durations also show a relative reduction compared to the water flooding case. However, polymer flooding initiated at the earliest opportunity exhibits the most substantial decrease in cumulative produced water volume.
- The difference in cumulative produced water volume among the polymer flooding at the earliest opportunity depicted in the orange curve and the closest cumulative volume case depicted in the green curve (Polymer flooding initiated one year beyond) is about 1 MMbbl.

E. Scenario 5: Sensitivity Analysis of Water Flooding and Polymer Flooding Durations on Produced Water Daily Rate on the Injector:

Based on Fig. 7, multiple simulations have been undertaken to assess the correlation between the daily produced water rate in bbl/day against water flooding and polymer flooding durations on the injector. The following main observations can be derived:

- The straight line represents the water flooding case, with a constant daily produced water rate of 3,500 barrels per day per well. This rate applies to each well and can be adjusted accordingly based on the number of wells present in the field.
- The daily produced water rate for all polymer flooding cases experiences a substantial decrease Immediately after the introduction of the polymer. It drops and sustains on the same rate up to 2032 to approximately 400 barrels per day per well, marking an 89% reduction compared to the water flooding case. This rate applies to each well (Injector) and can be adjusted based on the number of wells within the field.

VI. CASE STUDY DISCUSSION:

After thorough testing and evaluation of polymer flooding duration scenarios for the refined 5-spot pattern with the vertical well configurations, it has been determined that introducing polymer flooding at the earliest opportunity yields significant benefits. This includes increasing and expediting oil production rates, reducing water cut due to improving sweep efficiency and reducing residual oil saturation, and consequently diminishing produced water rates and cumulative produced water volume. Based on the preceding sensitivity analyses, it can be inferred that initiating polymer flooding at the earliest opportunity stands out as the optimal choice for implementation in this case study. This approach is poised to accelerate crude oil production, yielding the highest oil rate among the other scenarios. Given the highly mature nature of the reservoir (specifically the AOI), swift action to expedite production becomes imperative. Doing so not only promises substantial profits but also mitigates the risk of losing out on potential gains if prompt measures are not taken.

In addition, one of the key outcomes of this study besides the oil production incremental is the of reduction of water cut percentage of the selected polymer case as shown above in Fig. 4 compared to the water flooding case from the first year after initiating the polymer injection that would be reflected in substantial cost saving in the separation of fluid in the surface facility (Gathering center for instance) in terms of CAPEX and OPEX as wells as the reduction in the daily produced water rate as states in Fig. 5 compared to water flooding by 84% that would avoid the requirements of new water handling facility, wells, pipeline, manpower and spare parts. Furthermore, there is approximately a 62% reduction in cumulative produced water, as illustrated in Fig. 6. This water, known to be corrosive and environmentally harmful, requires special attention. The significant reduction observed in this study offers notable mitigation in terms of disposing of the reduced quantity of produced water, whether it's directed into wells or lined pits. This reduction not only decreases both capital expenditure (CAPEX) and operating expenditure (OPEX) but also minimizes environmental impact. Ultimately, conducting an economic evaluation is crucial to validate the feasibility of implementing polymer flooding in terms of profitability and Return on Investment (ROI). This evaluation will enable the establishment of an early-stage strategy for developing this system, which may involve considerations such as infill wells, horizontal wells, or a combination of horizontal and vertical wells.

VII. Economical Evaluation

The comprehensive assessment of project profitability for any of the previously evaluated scenarios is a pivotal indicator of the project's viability against the water flooding cases, assisting in strategizing and evaluating its feasibility. This assessment includes the total revenue generated from crude oil production during polymer flooding, as well as the costs associated with handling produced water and the expenditure on polymer.

Acknowledging the dynamic nature of oil prices is crucial in this study, given an assumed oil price of $45-$55 per barrel as a basis. Additionally, the analysis incorporates a produced water handling cost of $1.5 per barrel and a polymer price of $3 per kilogram. An Excel spreadsheet dedicated to polymer flooding projects was employed to analyze the formulated scenarios and determine the most advantageous polymer flooding strategy. However, it's crucial to acknowledge the lack of standardization in water handling costs. Various factors, such as CAPEX and OPEX associated with surface facilities, maintenance, and spare parts, must be considered. These factors play a significant role in estimating water handling costs and thereby impact overall profitability.

Considering the aforementioned factors, a fundamental economic evaluation has been undertaken for various polymer flooding and water flooding scenarios to comprehend the fluctuating prices linked to the projects' profit. This conceptual analysis seeks to offer a general overview of the studied cases, as summarized on Figures 8 through 11.

VIII. Analysis of Economic Scenarios:

The assessment of project profitability in various scenarios is crucial for evaluating the feasibility of polymer flooding compared to water flooding cases. It involves calculating total revenue from crude oil production during polymer flooding and considering costs related to handling produced water and purchasing polymer. Acknowledging the dynamic nature of oil prices is vital, with an assumed base price of $45 - $55 per barrel. Additionally, costs for handling produced water and purchasing polymer are factored in at $1.5 - $2 per barrel and $2 - $3 per kilogram, respectively.

Additionally, it's important to note that polymer flooding yields promising outcomes in terms of significantly reducing the produced water rate, which is approximately 84% less than the water rate observed in water flooding cases. Moreover, there is a notable decrease in the cumulative volume of produced water, amounting to about 62%. This reduction translates into substantial savings in water handling costs, as it mitigates the need for additional surface facilities, extra producers and injectors, pipelines, maintenance activities, spare parts, and other related expenses. However, estimating these costs precisely is challenging due to their varying nature and the absence of references. However, the cost estimation conducted in the previous cases offers a detailed breakdown of profits for each scenario, providing valuable insights into the economic implications of introducing polymer flooding. It demonstrates that polymer flooding remains profitable across all cases, regardless of the factors mentioned above (Higer than the WF cases as well).

IX. Conclusion

1- Polymer flooding is a strateg employed in mature fields to enhance oil recovery.

2- Introducing polymer flooding early yields significant benefits, including increased oil production rates, reduced water cut, and diminished produced water rates and volume.

3- Reduction in water cut percentage and daily produced water rate reflects substantial cost savings and avoids the need for additional water handling facilities, wells, and infrastructure.

4- Performing an economic evaluation is essential to confirm the viability of implementing polymer flooding, and conducting comprehensive cost estimations for the produced water handling.

References

[1] M. Muskat, *Physical Principles of Oil Production*, McGraw-Hill Book Company, 1949.

[2] J. Aronofsky, and H. Ramey, "Mobility Ratio - Its Influence on Injection or Production Histories in Five-Spot Water Flood," Journal of Petroleum Technology, 8(09), 205–210, 1956. https://doi.org/10.2118/641-G

[3] A. Dyes, B. Caudle, and R. Erickson, "Oil production after breakthrough—as influenced by mobility ratio," J Pet Technol, 1954, 6:27–32. doi:10.2118/309-G https://doi.org/10.2118/309-G

[4] A. Thomas, *Polymer Flooding. In Chemical Enhanced Oil Recovery (cEOR) - a Practical Overview*, InTech, 2016, DOI: 10.5772/64623. https://doi.org/10.5772/64623

[5] W. Littmann, *polymer flooding*, Independently Published, 2020, ISBN-13: 979-8654480309.

[6] Z. Abirov, R. Abirov, Y. Mazbayev, A. Engels, A. Nestyorkin, and O. Ivakhnenko, "Case-study of succesful pilot polymer flooding in the

South Turgay basin's oilfield," presented at the SPE Annual Caspian Technical Conference & Exhibition, Baku, Azerbaijan, November 2015, SPE 177339.
https://doi.org/10.2118/177339-MS

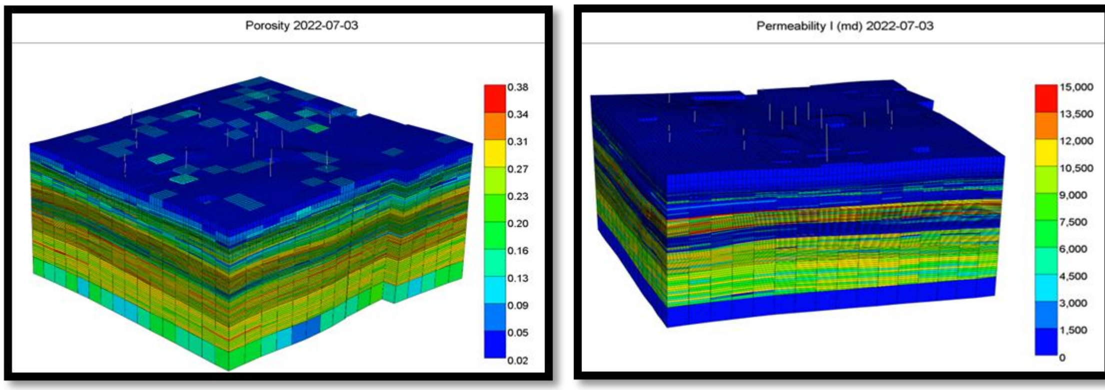

Fig. 1: Porosity and Permeability Distribution IMEX Model.

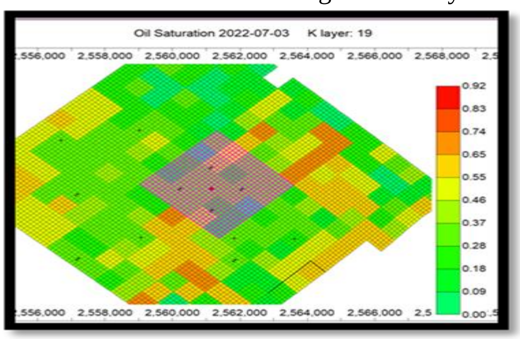

Fig. 2: Overview of AOI with 65 ft x 65 ft Refinement.

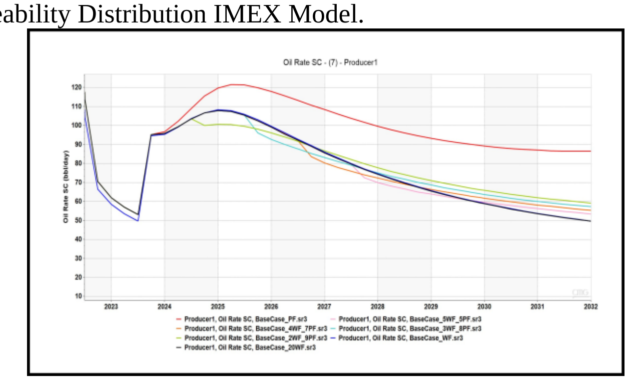

Fig. 3: WF & PF Durations Vs. Oil Rate (bbl/day).

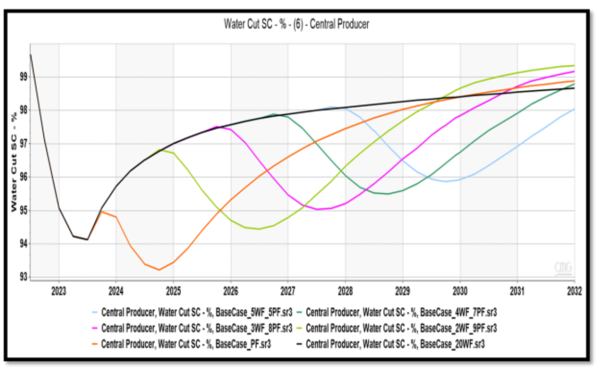

Fig. 4: WF & PF Durations Vs. Water Cut %.

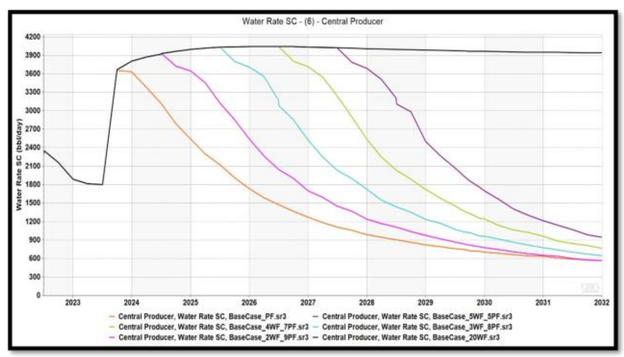

Fig. 5: WF & PF Durations Vs. Produced Water Rate (bbl/day).

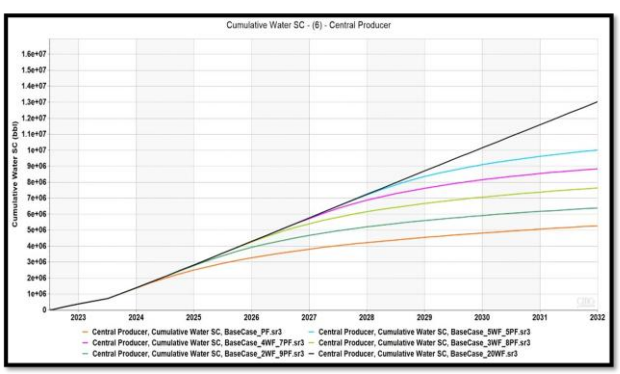

Fig. 6: WF & PF Durations Vs. Cumulative Water Volume(bbl).

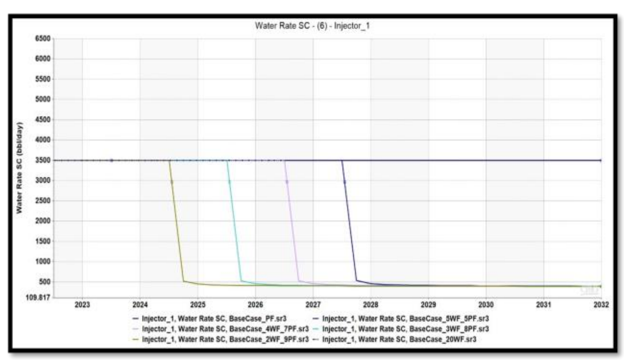

Fig. 7: WF & PF Durations Vs. Produced Water Rate (bbl./day).

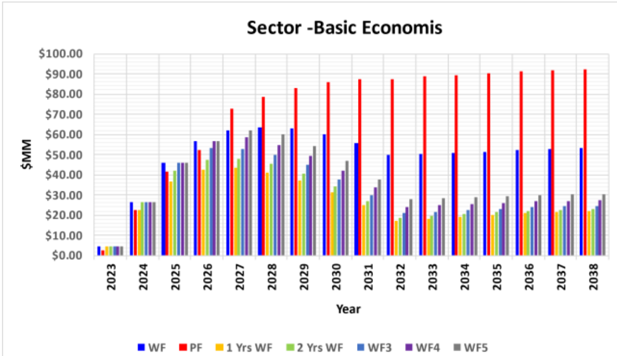

Fig. 8: Economical Evaluation for the Sector Base Case.

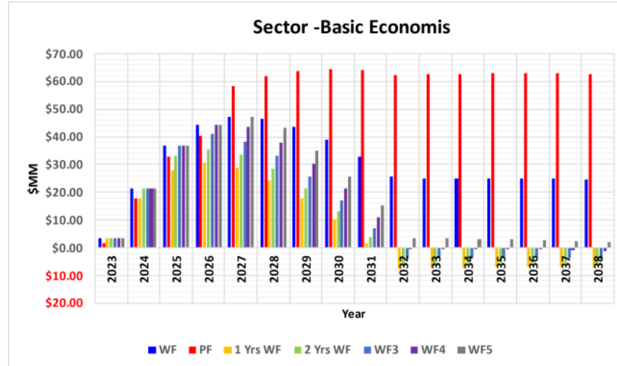

Fig. 9: Economical Evaluation for the Sector Case 1.

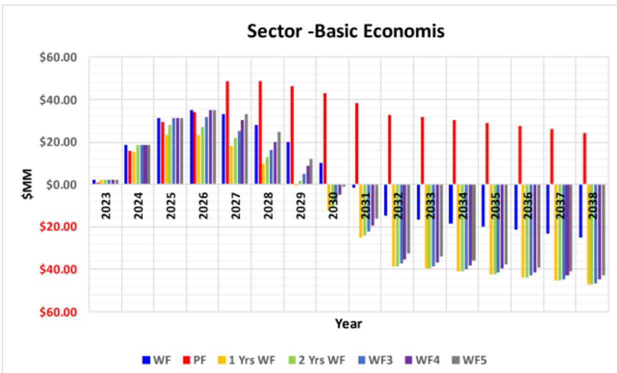

Fig. 10: Economical Evaluation for the Sector Case 2.

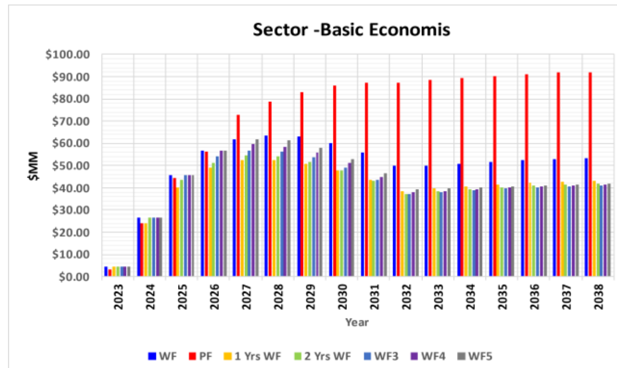

Fig. 11: Economical Evaluation for the Sector Case 3.