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# Hybrid Process of Gas and Downhole Water Sink - Assisted Gravity Drainage (G&DWS-AGD) to Enhance Oil Recovery in Reservoirs with Water Coning

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## Abstract

The Gas-Assisted Gravity Drainage (GAGD) process has been suggested to enhance oil recovery by placing vertical injectors for CO2 at the top of the reservoir with a series of horizontal producers located at the bottom. The injected gas accumulates to form a gas cap while oil and water drain down to the bottom due to their heavier densities. The GAGD process has limitations with regards to the high levels of water cut and high tendency of water coning. This paper delivers an integration of downhole water sink (DWS) and the GAGD processes to overcome these limitations and further enhance oil recovery.

The hybrid process, of Gas and Downhole Water Sink-Assisted Gravity Drainage (G&DWS-AGD) was developed and verified to minimize water cut in oil production wells from reservoirs with edge and/or bottom water drive and strong water coning tendencies. In the process, two 7 inch production casings are installed bi-laterally and completed using two 2-3/8 inch horizontal tubings: one above the oil-water contact (OWC) for oil production and another one underneath OWC for water sink drainage. The two completions are hydraulically isolated inside the well by a packer. The bottom (water sink) completion is produced with a submersible pump that drains the formation water from around the well and prevents the water from breaking through the oil column and getting into the horizontal oil-producing perforations.

The G&DWS-AGD was evaluated for improvement of oil recovery from the upper sandstone member/South Rumaila Oilfield, located in Iraq. (The Rumaila field has an infinite active aquifer with very strong edge water drive.) The evaluation study involved a series of simulation runs to determine the best design of the combined processes. Operational variants of the process included oil and water production only, oil and water production with constant, progressive (by 50psi) and reduced (by 200 psi) gas injection pressure.

In the G&DWS-AGD, the water sink operation not only eliminated (or reduced) water cut and coning tendency, but it also significantly reduced reservoir pressure, resulting in improved gas injectivity and increased oil recovery. More specifically, the 10-year production forecast showed that oil production increased by 55.1 million barrels larger than the GAGD process alone and water cut decreased from 98% to less than 5% in all the horizontal oil producers.

The advantage of G&DWS-AGD process comes from its potential effectiveness to improve oil recovery while reducing water coning, water cut, and improving gas injectivity. This leads to more economic implementation, especially with respect to the operational surface facilities.

## Introduction

The Gas-Assisted Gravity Drainage (GAGD) process has been suggested for improved oil recovery in secondary and tertiary processes for both immiscible and miscible injection modes. The GAGD involved injecting gas through vertical wells in a gravity-stable mode to build a gas cap resulting in oil drainage downwards to the bottom of reservoir comprising several horizontal producers (Rao et al. , 2004). The mechanisms of fluid segregation and gravity oil drainage give better sweep efficiency and higher oil recovery.

The GAGD process has been studied on limited real oil fields and tested for its effectiveness to enhance oil recovery. Specifically, the GAGD process has been successfully adopted to improve oil recovery in sandstone reservoirs, such as North Louisiana field(Paidin et al. , 2010) and South Rumaila oil field(Al-Mudhafar and Rao , 2017). Moreover, the GAGD process has been tested on South Rumaila oil field in comparison with Continuous Gas Injection (CGI) and Water-Alternating Gas (WAG) methods to evaluate CO2 flooding in an immiscible mode (Al-Mudhafar et al. , 2017). Additionally, the GAGD process was also applied in naturally fractured reservoirs in both immiscible and miscible modes (Delalat and Kharrat , 2013; Silva and Maini , 2016). All these different studies and some other available in the literature (Al-Mudhafar , 2016a; Al-Mudhafar and Rao , 2017) resulted in higher oil recovery in comparison with other gas injection methods.

For injection purposes, the C O2 is preferred as it attains high volumetric sweep efficiency with high microscopic displacement efficiency. Additionally, the high volumetric sweep efficiency assures delaying in C O2 breakthrough to the producers. Delaying or eliminating the gas breakthrough leads to increase the gas injectivity and maintain the injection pressure by diminishing the concurrent gas-liquid flow mechanisms (Rao et al. , 2006b). However, there were some limitations regarding the application of GAGD process in reservoirs bounded with infinite active aquifers. More specifically, the efficiency of GAGD process reduces in reservoirs with high coning tendencies, which lead to high water cut levels. Therefore, downhole water sink technology (DWS) can be integrated into GAGD process in order to overcome its limitations in these reservoirs and reduce the water coning and water cut tendencies. The integration of the Gas-Assisted Gravity Drainage (GAGD) process and the Downhole Water Sink Technology (DWS) was denominated in this research as Gas and Downhole Water Sink-Assisted Gravity Drainage (G&DWS-AGD).

## Gas and Downhole Water Sink-Assisted Gravity Drainage (G&DWS-AGD)

It is postulated in this study that the hybrid integration of Gas-assisted Gravity Drainage with Downhole Water Sink technique  the G&DWS-AGD process - would improve recovery in reservoirs with strong edge and boundary aquifers. In the G&DWS-AGD process, bottom water should be drained by horizontal wells located below oil-water contact underneath the oil producers in order to eliminate or reduce the water coning tendency and reduce water cut. The premise draws from the principle of Downhole Water Sink (DWS) technique where a localized drainage generated by a controlled water sink completion below the oil-water contact inhibits the growth of water cone (Wojtanowicz , 2006). The schematic of DWS vertical well is shown in Figure 1.
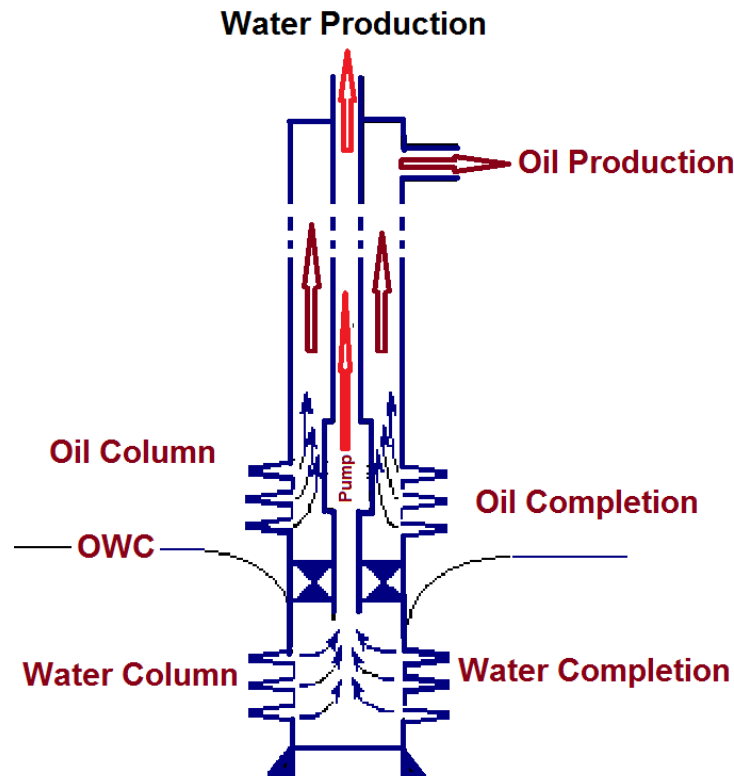


Figure 1: Schematic of Local Water-drainage production in the DWS technology, Modified from (Wojtanowicz , 2006)

The localized (point sink) drainage occurs when oil and water produced with vertical DWS wells. In the bilateral DWS technique using horizontal wells the bottom horizontal wells completion works like a linear water sink (Shirman and Wojtanowicz , 2000). Consequently, in the G&DWS-AGD process, depicted in Figure 2, two 7- inch production casing strings are bilaterally installed and equipped with two 2-3/8 inch horizontal tubings. The upper oil-producing completion is placed at the bottom of the oil payzone, and the lower water-draining completion is placed beneath the top completion in the water zone. The two completions are hydraulically isolated inside the well by a packer. Feasibility of the G&DWS-AGD process was - studied for the upper sandstone member of Zubair formation in South Rumaila Oil Field in view of efficient downhole oil/water separation, reduce tendency of water coning and water cut, and increase the gas injectivity by decreasing the required injection pressure.
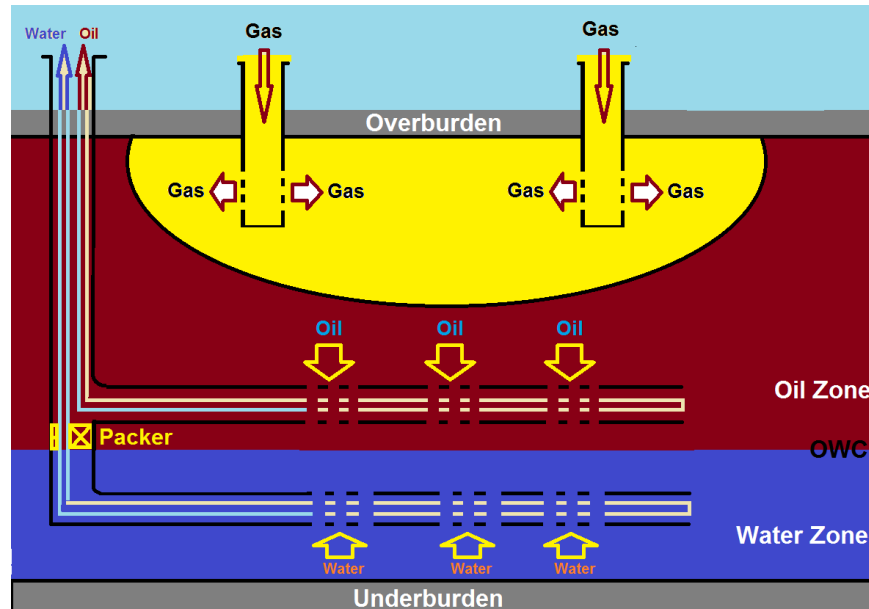


Figure 2: Schematic of Globalized Gas and Downhole Water Sink-Assisted Gravity Drainage process

## Description of South Rumaila Oil Field

The Upper Sandstone section (Zubair formation) of the South Rumaila Oil Field is used to study feasibility the Gas and Downhole Water Sink - Assisted Gravity Drainage (G&WS-AGD) process. The South Rumaila oil field is composed of many oil-producing reservoirs. Zubair is one of the oil reservoirs represented by the Late Berriasian-Albian cycle and its sediments, dating from the Lower Cretaceous age. The thickness of the Zubair formation ranges between 280-400 m with levels increasing towards the north-east side of the field. The main pay does not contain any complex geological features such as faults or fractures. Based on the sand to shale ratio, the Zubair formation encompasses five sections (from top to bottom): upper shale, upper sandstone, middle shale, lower sand, and lower shale. The upper sandstone section is the main pay zone of Zubair formation in South Rumaila Oil Field (Mohammed et al. , 2010). The main payzone has only three-lithology types characterized through fluvial depositional environment: sand, shaly sand, and shale (Al-Mudhafar , 2016b; Wells et al. , 2013). Stratigraphic column of the Rumaila oil field is shown in Figure 3.

The South Rumaila field size is 12 by 38 km and it is too large for the study with no available data for the entire field. Therefore, only its main part, including Rumaila sector and small portions of the Shamiya and Janubia sectors, was considered in the study. Oil production started in the South Rumaila field in 1954 and water injection was initiated early 1980s. There was an infinite active edge-aquifer located at the boundary of the main pay reservoir. There were 20 injection wells drilled at the east flank to maintain the huge aquifer strength from west flank, which accumulates up to 24 times the influx from east one (Kabir et al. , 2007; Mohammed et al. , 2010). The production from some layers was ceased water cut exceeding 98%. By 2004, artificial lift has been installed in some wells and the water injection was terminated with cumulative injected water of approximately 1.1 billion barrels. During the water injection periods, injection rates varied widely with a maximum of nearly 426,000 BPD for two months in 1988. Furthermore, the estimated oil in place (IOIP) for the main pay is 19.5 billion barrels and for the sector considered in this study is around 6.123 billion barrel (Al-Mudhafar and Rao , 2017). Moreover, the approximate current recovery factor is 55% and the remaining recoverable oil is 2.02 billion STB. The peak oil production was 1.35 MMBPD in May 1979. The oil production rate in July 2013 was approximately 1,250,000 MMBPD.
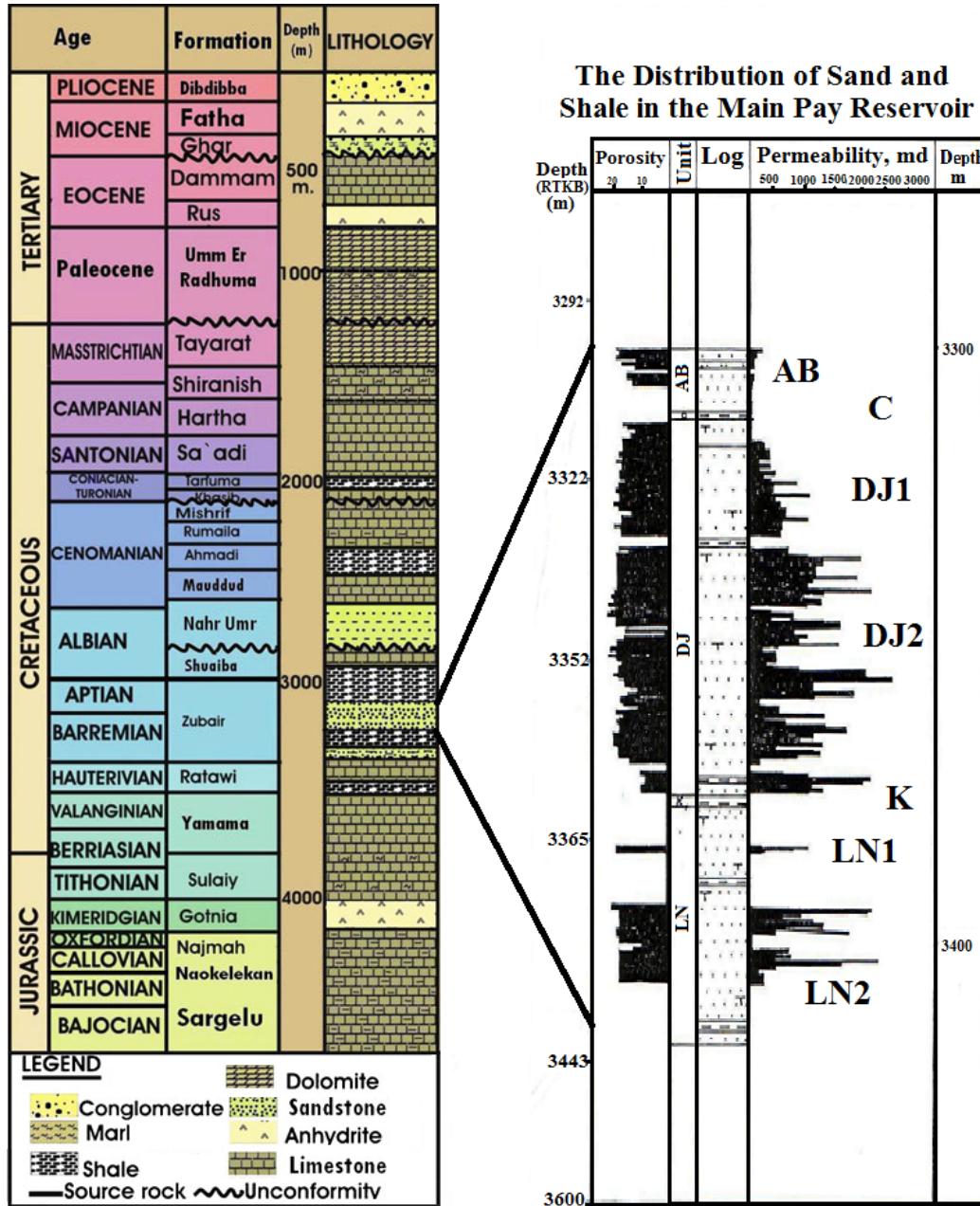
Figure 3: Lithology column of South Rumaila oil field, modified from (Al-Ameri et al. , 2009) and (Al-Mudhafar , 2017)

## Compositional Flow Simulation of the G&DWS-AGD Process

The South Rumaila oil field used for this study comprises only three types of rocks, sand, shaly sand, and shale, with distinct spatial permeability distributions (heterogeneous). To capture the reservoir heterogeneity, achieve fast history matching, and attain more realistic future performance of the G&WS-AGD process, it was necessary to replicate the 3-D petrophysical and lithofacial distribution using a high-resolution geostatistical reservoir model with about 2 million grid cells. In order to reduce computation time, the model was then upscaled to a coarse-scale grid system with a 150 m x 150 m regular grid dimension, to be handled by a compositional reservoir flow simulator. The grid numbers in the upscaled model in I, J, and K directions are 69, 66, and 12 grid cells (total=54648 grid cells). Based on the cross-sectional well log, the 45 vertical layers were upscaled to only 12 layers. In order to improve the description of fluid flow, especially near wellbores, orthogonal corner point was adopted to accomplish more appropriate grid geometry in the reservoir model than the cartesian approach. More specifically, corner point geometry is more suitable for complex full-field studies as it preserves the accuracy of fluid flow modeling and well treatment (Ding and Lemonnier , 1995). Figure 4 illuminates the 3D coarse-scale reservoir models that include 3D spatial distributions of horizontal and vertical permeability, porosity, and lithofacies.
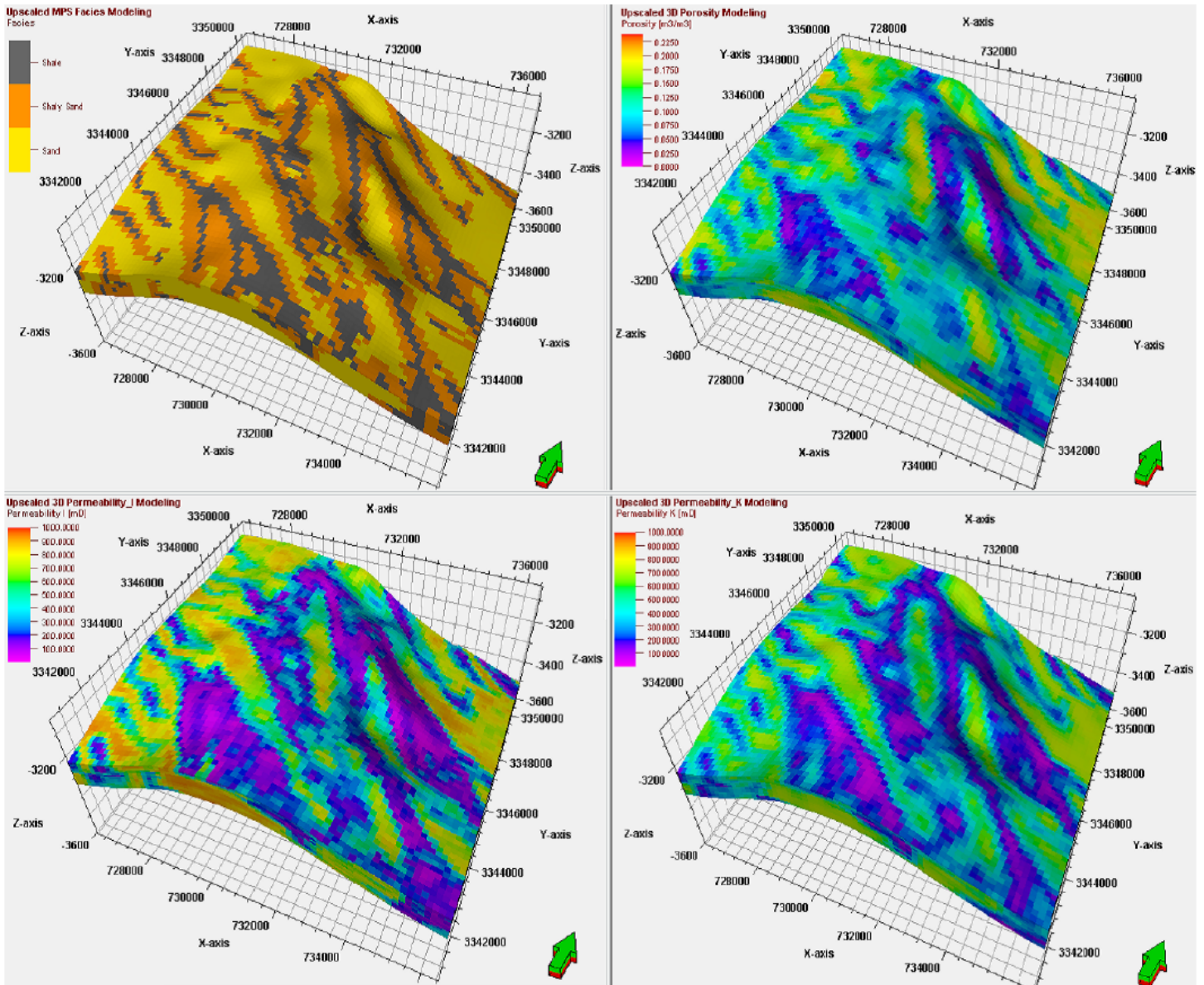
Figure 4: Coarse-scale geostatistical models for facies, porosity, and permeability

For a precise future performance evaluation of the G&DWS-AGD process, an excellent history matching was achieved through trial and error process pertaining to field cumulative and rates of oil production and water injection. The production and injection matching is a good indicator of reservoir and fluid behavior as it reproduces the matching of water cut and saturation distributions. The production and injection flow rates were accessible until February 2010. Thus, the history matching was achieved from 1954 until 2010. Figure 5 illustrates the matching between field production rates and cumulative oil production. Figure 6 depicts the matching between field injection rates and cumulative water injection.
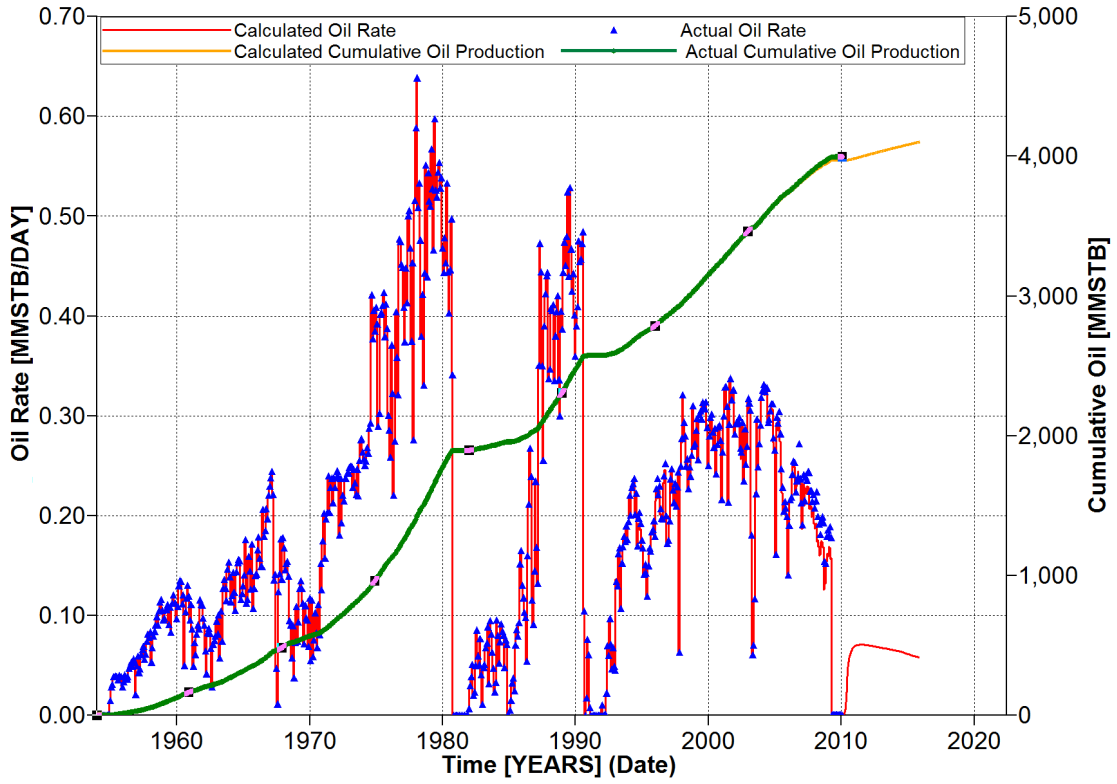
Figure 5: History Matching of Entire Field Production of South Rumaila Oil Field
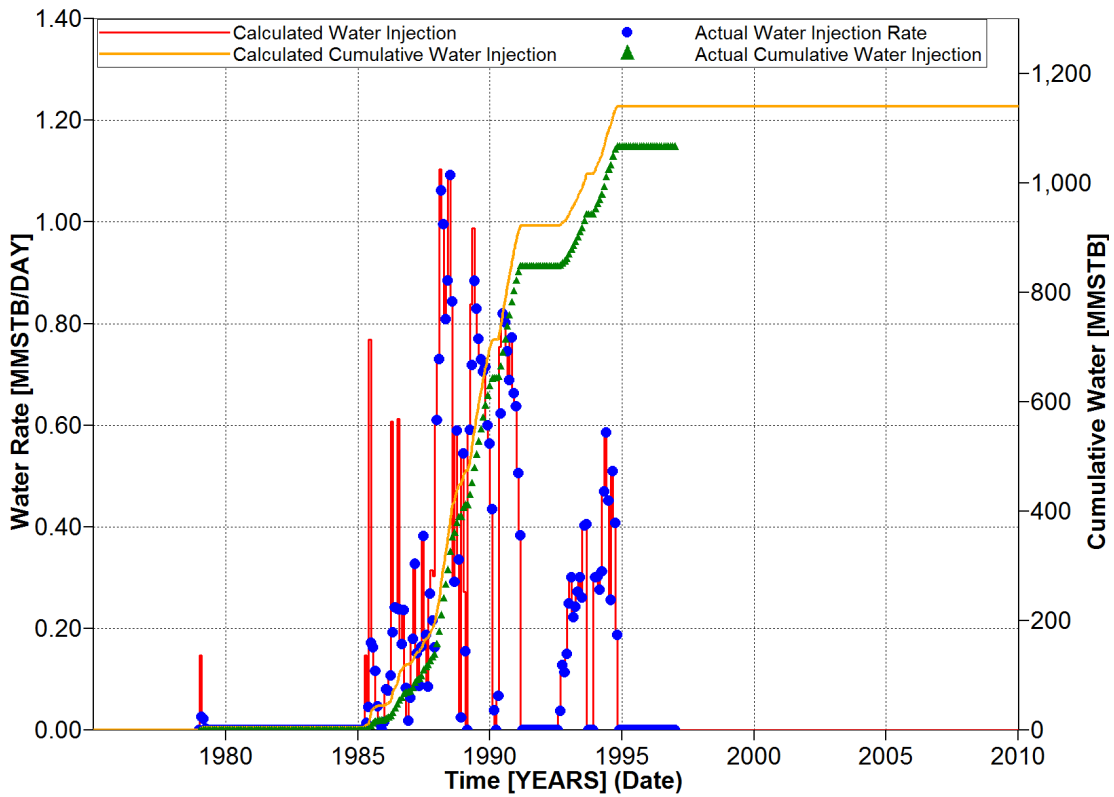
Figure 6: History Matching of Entire Field Injection of South Rumaila Oil Field

The forecasting period of the G&WS-AGD process performance was 10 years with. 22 vertical injection wells, 11 horizontal oil producers, and 6 water producers placed in the highly-permeable zones - for CO2 injection, oil production, and downhole water sink, respectively. In the process, Carbon Dioxide was injected to the top two layers (of 12 total layers) to form a gas cap and . the next three layers were left as a transition zone to provide vertical space for fluid gravity drainage. The horizontal oil producers were placed in within the sixth to eighth layer ,and the six horizontal water producers were all located in the 12th layer- fully flooded with water from the infinite edge water aquifer ($S_w = 1$). The Each DWS well was located exactly underneath its corresponding oil producer. Figures 7 and 8 show the locations of CO2 injection with the oil and water production wells. In Figure 7, the reservoir body is represented by the red color, which denotes shale zones. However, the perforations of producers and injectors were mainly sited in sand zones (index 2) and shaly-sand zones (index 1) having permeability. For more clarification, Figure 8 illustrates the exact locations of oil and water horizontal well trajectories within the oil and water zones in the 3D slab permeability map. The infinite active edge-water drive aquifer, located at the eastern and western boundaries, was modeled using the Carter-Tracy approach.
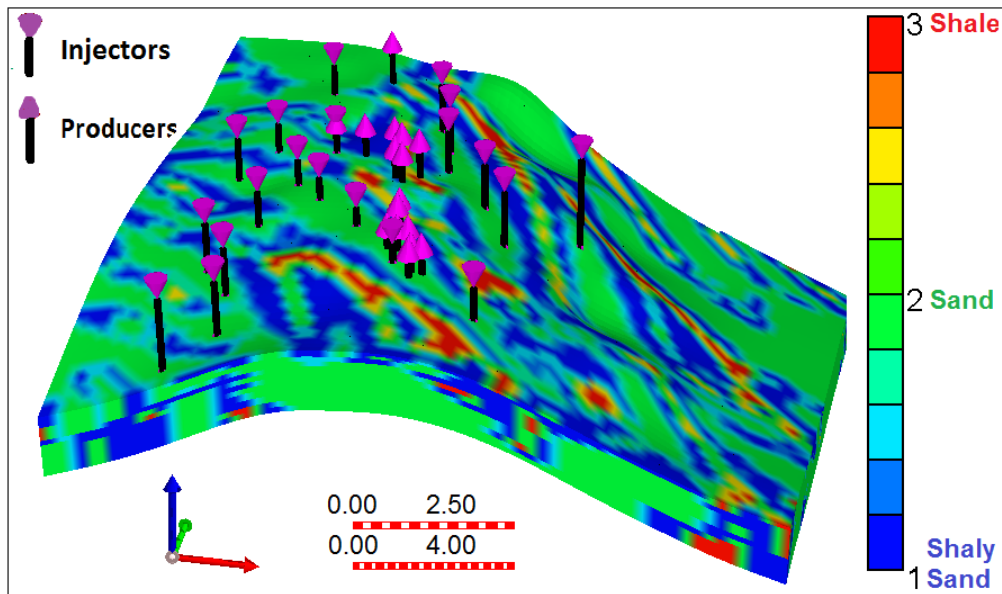


Figure 7: 3D Lithofacial map of vertical injectors and horizontal producers in the G&WS-AGD process
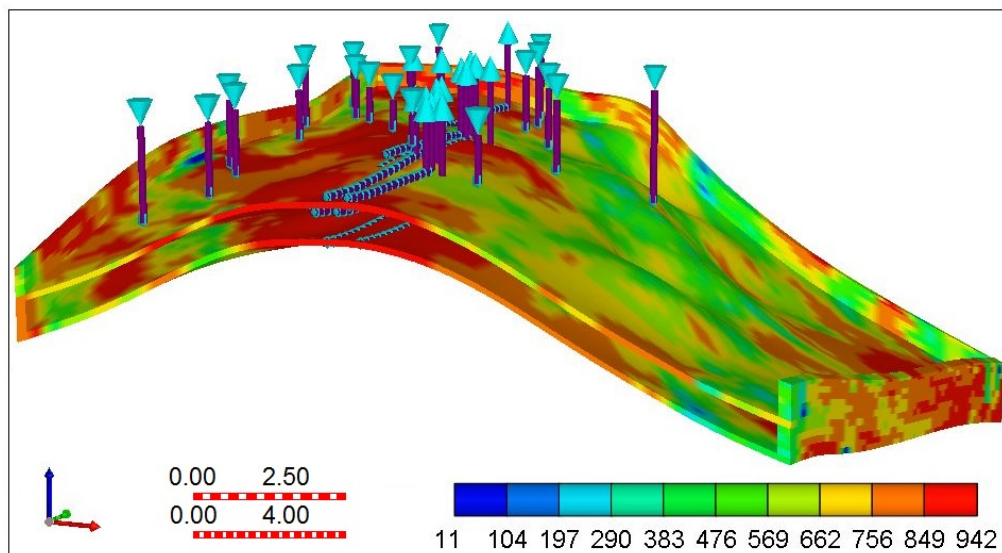


Figure 8: Locations of vertical injectors and horizontal producers into a 3D slab permeability map in the G&WS-AGD process

Five different cases were initially evaluated with regard to attaining the maximum cumulative oil production by the end of 10 years (2016-2026) prediction period. Specifically, three future performance cases of the G&DWS-AGD process were conducted through the compositional reservoir flow simulation along with the two prior cases: primary production with downhole water sink (Primary-DWS) and the GAGD process (Al-Mudhafar and Rao , 2017). The three G&WS-AGD process cases involve oil and water production with constant gas injection pressure, 50 psi, increasing gas injection pressure, and 200 psi decreasing gas injection pressure. Figure  9 shows the comparison of cumulative oil production of Primary with DWS vs.GAGD, and vs. three G&DWS-AGD processes. The primary production case with downhole water sink gives the lowest cumulative oil production that indicates the necessity of gas injection to enhance oil recovery. The two G&DWS-AGD cases of constant and 50 psi increasing gas injection pressure caused higher cumulative oil production than the GAGD process; however, the 200 psi decreasing gas injection pressure is less efficient.. Due to the improvement in gas injectivity with water sink, the injection pressure suggested to be periodically decreased in the 3rd G&DWS-AGD case in order to ensure immiscibility of $CO_2$ flooding. Increasing or constant injection pressure of gas results in higher amount of gas injection and then produce more oil.
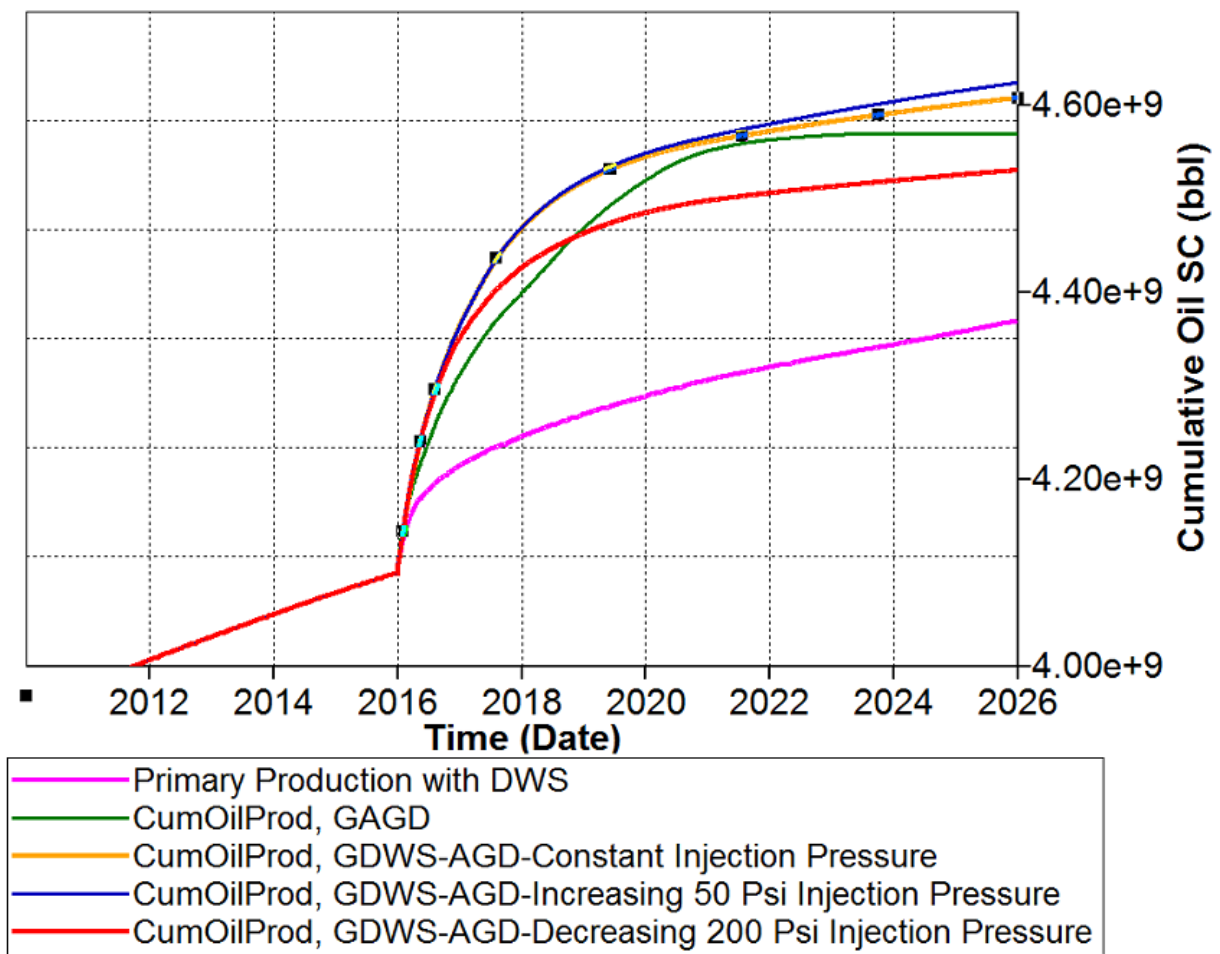


Figure 9: Comparison of Field Oil Rate and Cumulative Oil Production for 10 years production through Primary-DWS, GAGD, and three G&DWS-AGD Processes

In contrast to the GAGD process, all the three G&DWS-AGD cases including the Primary+DWS case cause a considerable of reservoir pressure, shown in Figure  10. The effect actually increases efficiency gas injection process. as long as the pressure does not fall below the bubble point pressure. As shown in Figure  10, reservoir pressure of the primary production with DWS was the lowest among all other DWS cases as there is no gas injected to support the pressure. Also, although pressure falls below the bubble point pressure for all DWS cases (Pb=2660 psi), the Primary+DWS case gives the lowest pressure and the 50psi - increase case gives the highest reservoir pressure. From Figures  9 and  10, one can conclude that progressive increase of the gas injection pressure is needed for efficient application of the G&DWS-AGD process.
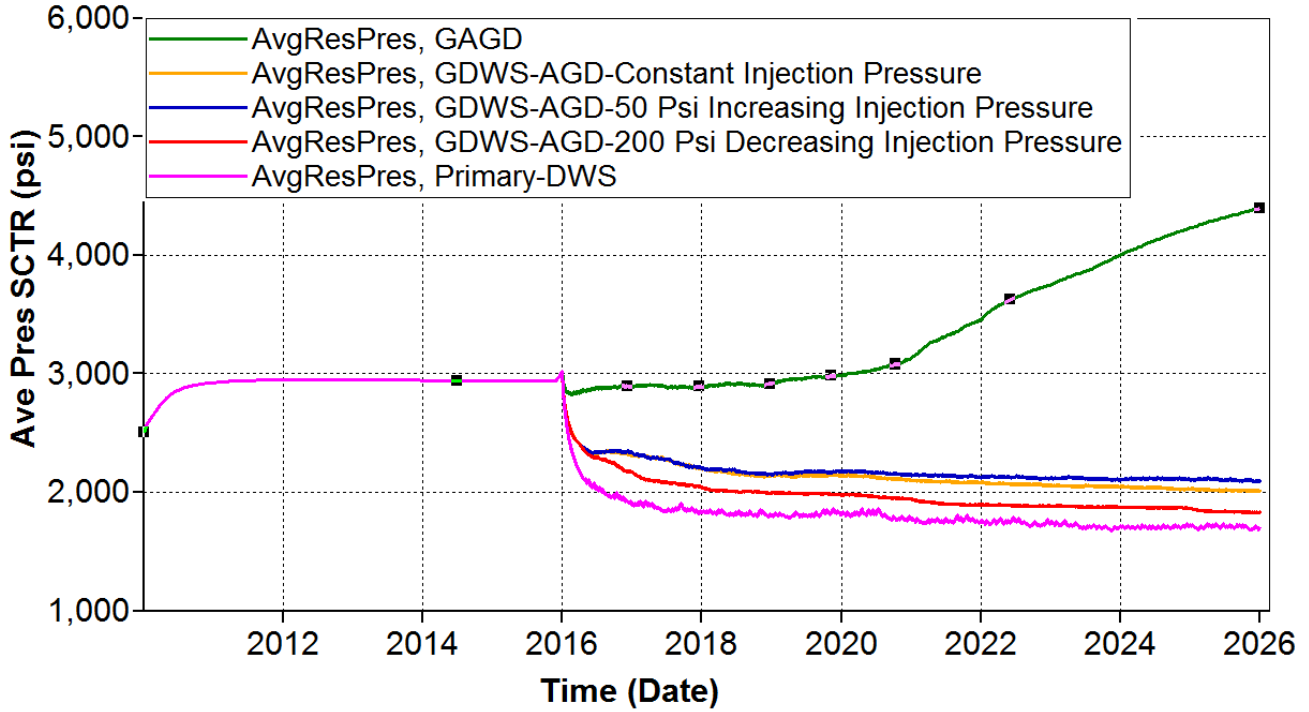
Figure 10: Average Reservoir Pressure for Primary-DWS, GAGD, and three G&DWS-AGD Processes

In fact, as shown in Figure 11, the progressive-injection-pressure G&DWS-AGD case (50 psi increase case) produced 4.624 billion of oil barrels by the end of 10 years  slightly exceeding 4.57 billion barrels resulting from the GAGD process.
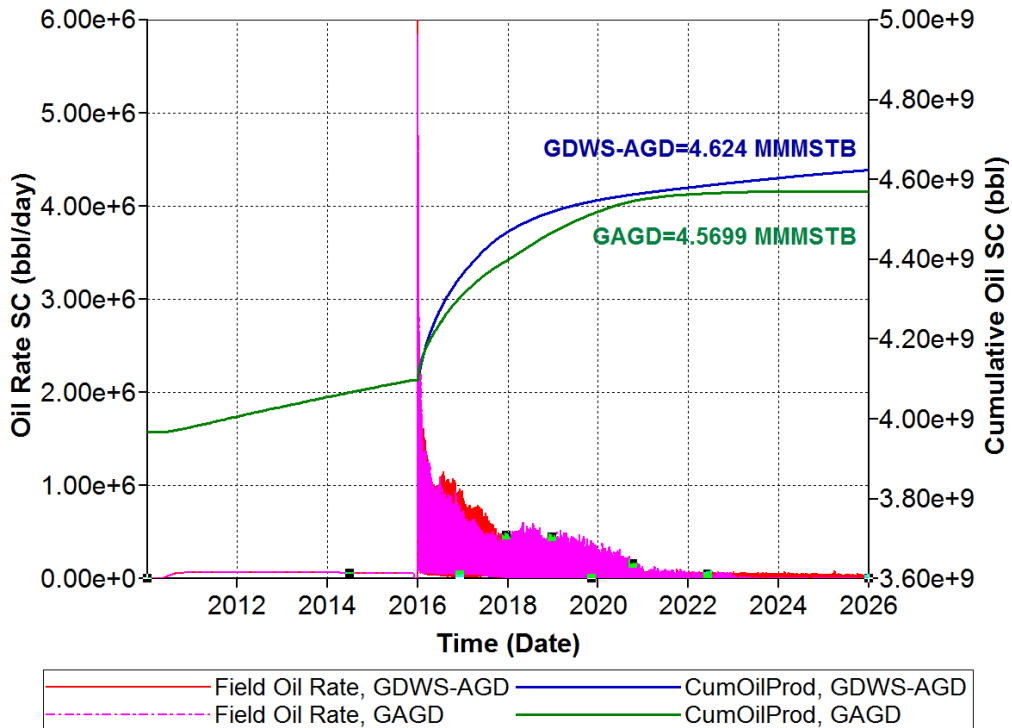


Figure 11: Comparison of daily and cumulative oil production with GAGD and G&DWS-AGD process with progressive (50 psi) injection pressure

The produced water through the G&DWS-AGD not only reduces the reservoir pressure and improves gas injectivity, but also reduces water cut to near zero levels and then reduced water coning tendency. Figure 12 discloses how high the water cut levels in the horizontal DWS wells in the three aforementioned G&DWS-AGD cases. In addition, the water cut values from all the horizontal oil producers were illustrated in Figure 13 that shows near zero levels of water cut in the three G&DWS-AGD cases for the entire 10 years of prediction.

Finally, the general results revealed that the G&DWS-AGD process (with progressive increase of gas injection pressure) increased oil production by about 55.1 million barrels comparing to the GAGD process. Moreover, water cut in the oil-producing well completions decreased from 98% to less than 5%.
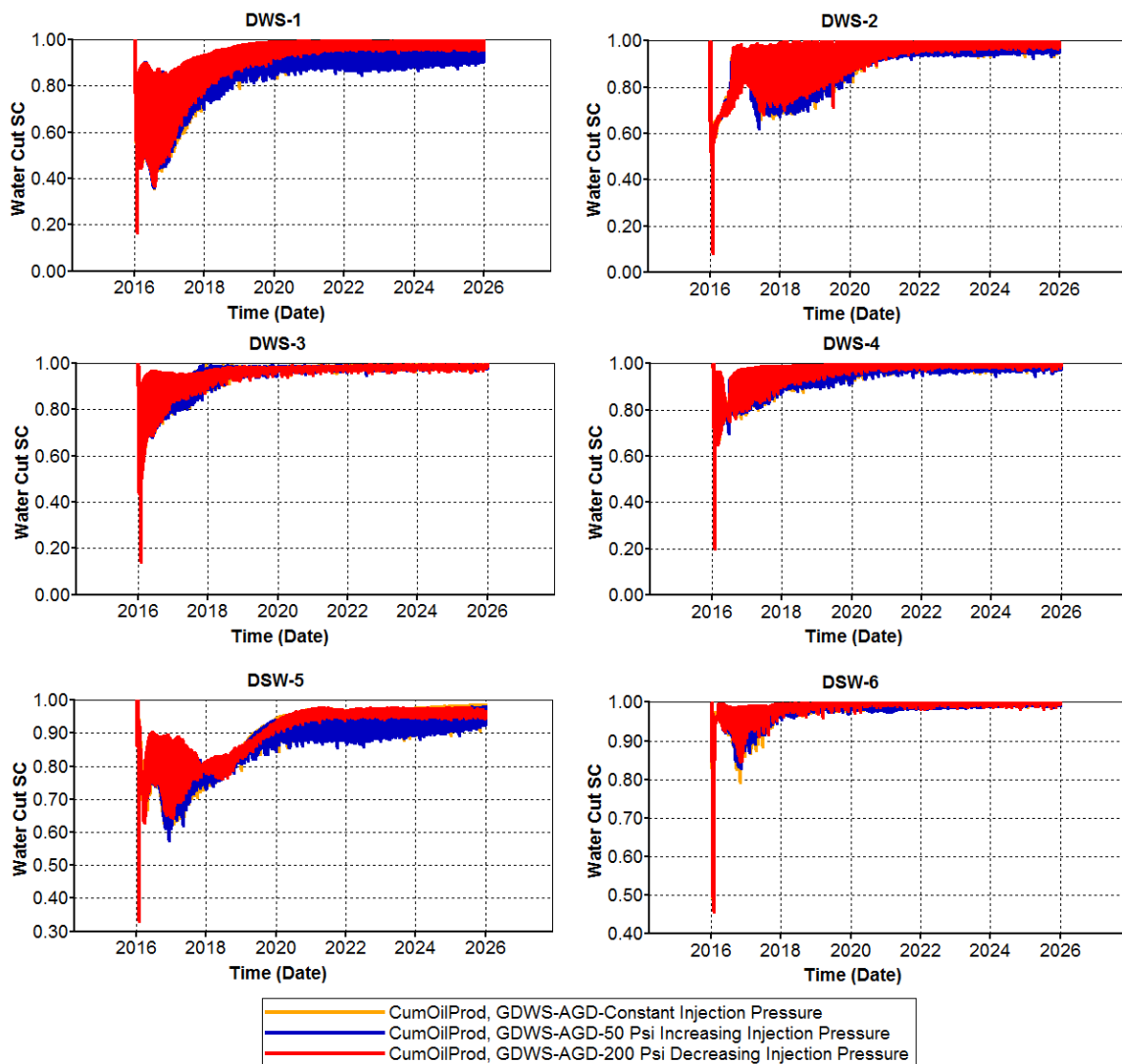


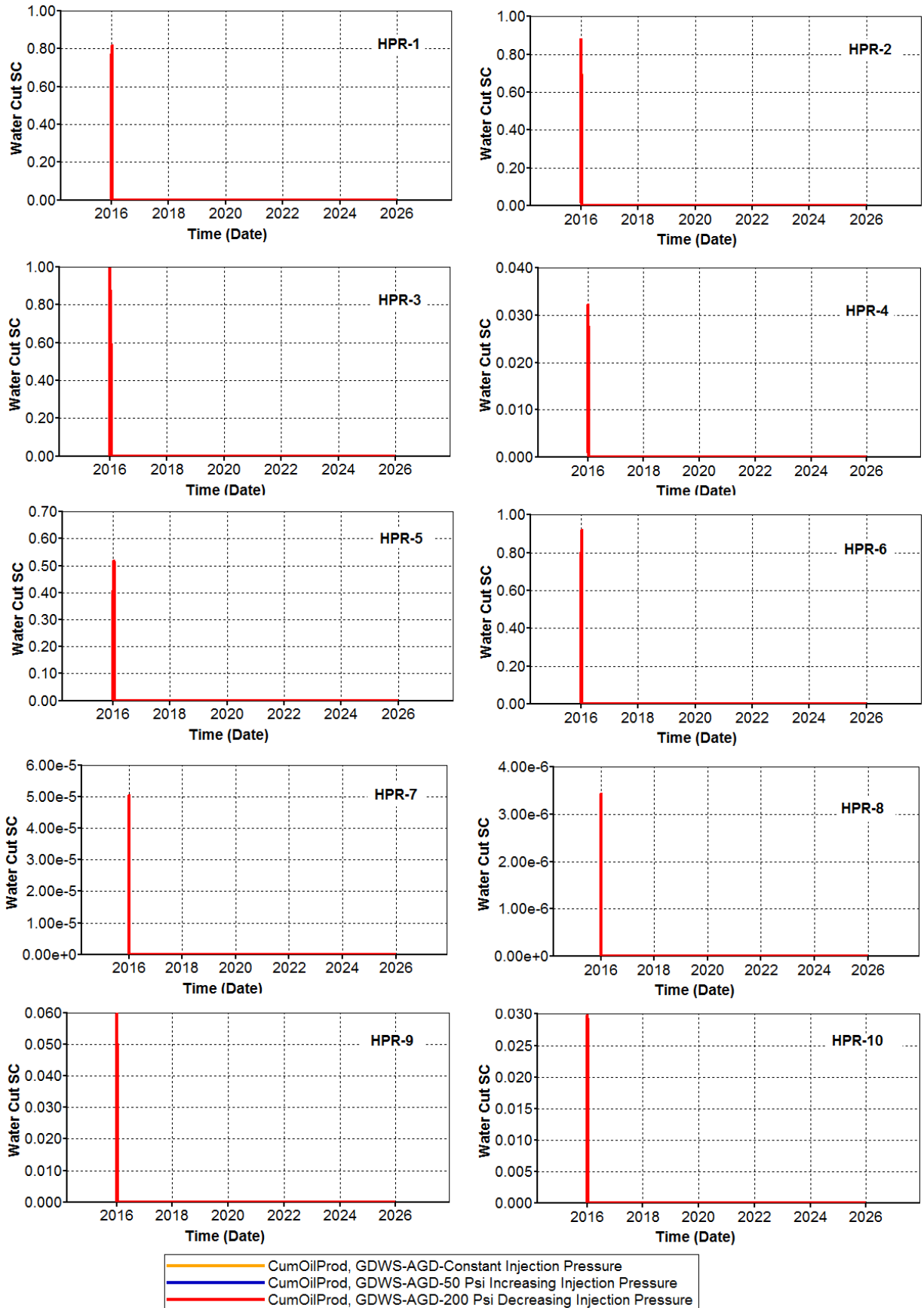Figure 12: Water cut in Water Sink completions of G&DWS-AGD wells

Figure 13: Water cut in oil - producing completions of G&DWS-AGD wells

## Summary and Conclusions

A novel production method of combined Downhole Water Sink Technology (DWS) with the Gas-Assisted Gravity Drainage (GAGD) would enhance oil recovery with significant water cut reduction in reservoirs with infinite active edge and/or bottom water aquifers. The new process is termed Gas and Downhole Water Sink-Assisted Gravity Drainage (G&DWS-AGD). The process has been studied using simulations by considering several cases of immiscible gas injection, oil production and downhole water sink in the Zubair formation of South Rumaila oil field, in Iraq. More specifically, three different simulation cases were evaluated by forecasting 10-year oil and water production for a constant gas injection pressure, 50 psi increasing gas injection pressure, and 200 psi decreasing gas injection pressure. It was noticed that the two G&DWS-AGD cases of constant and 50 psi increasing gas injection pressure resulted in more produced oil than the GAGD process because as more gas was injected more oil was produced. The third case of 200 psi decreasing gas injection pressure led to lower cumulative oil production than the GAGD process.

In the G&DWS-AGD, oil-producing DWS horizontal wells showed very small water cut, reduced water coning, and improved gas injectivity that ultimately resulted in higher oil recovery. In fact, water cut was decreased to near zero levels in all horizontal oil producers. No doubt, reducing water cut leads to more economic implementation, especially with respect to the operational surface facilities. Additionally, the required gas injection pressure for the G&DWS-AGD process was much smaller than that for the GAGD process as water production significantly decreased the reservoir pressure.

In all, the G&DWS-AGD process produced 4.624 billion STB of oil with near-zero water cut  a 55.1 million of STB increase in cumulative oil production comparing to the GAGD process.

As the G&DWS-AGD process performance varied in the three cases considered in the study, there is a need to develop a procedure to determine an optimal design for the G&DWS-AGD process operation for maximum oil production with minimum water cut, minimum gas injection pressure, minimum cumulative gas injection, and minimum Gas-Oil Ratio.

## Acknowledgment

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