Waterflood Surveillance Best Practice in a Tight, Heterogeneous, Water-Sensitive, and Massively Fractured Reservoir

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Abstract. The T-K is a tight, heterogeneous, water-sensitive, and massively hydraulically fractured sandstone reservoir. Following an aggressive fracturing campaign, the production boost-up led to a dramatic pressure decline. A waterflood project was then prepared and implemented by converting watered-out producers into injectors to increase the reservoir pressure as well as to improve recovery factor. A robust and integrated waterflood management is of utmost importance to ensure the success of T-K challenging waterflood project. Among the various aspects involved, surveillance is considered as the heart of waterflood management. Fortunately, various classical surveillance techniques and performance analysis methodologies are still applicable for this complex reservoir, both for producers and injectors at field and well level. Practical applications of these fit-for-purpose and low-cost techniques are very useful to provide better reservoir characterizations, more accurate performance diagnostics, as well as faster opportunities identifications to improve waterflood performance. The waterflood management of this reservoir, guided by integrated surveillance activities, helps improve the reservoir pressure, increases the production, and enhances the oil recovery. This paper summarizes the best practice in waterflood surveillance and performance analysis in T-K. Various techniques presented can be applied as a benchmark for analyzing the performance of any waterflood project.

Keyword: waterflood, water injection, surveillance, performance analysis, diagnostics

1 Introduction

T-K is one of the main producing reservoirs in K-Field, which is currently operated by PT. Medco E&P Indonesia. This field is located onshore Sumatra, approximately 70 km northwest of Palembang City. T-K can be described as a saturated, low permeability, shaly sandstone reservoir with poor quality and high heterogeneity. Table 1 summarizes the key properties of T-K reservoir. Due to the relatively low reservoir permeability, all T-K wells cannot flow without an intensive stimulation job. The production commenced in 2002 with a successful hydraulic fracturing job, which was considered as a breakthrough technology at that time, and followed by an aggressive fracturing campaign which boosted-up the production. However, the exploitation led to a dramatic reservoir pressure decline which caused the production to decrease drastically and many wells to cease flowing.

Table 1. T-K reservoir properties summary

Parameters	**Value**
Lithology	Sandstone
Depth (ft-TVD)	2,000 – 3,000
Initial Pressure (psi)	1,230
Initial Temperature (^{o}F)	175
Porosity (%)	10 – 20
Permeability (mD)	5 – 50
Average Gross Reservoir Thickness (ft)	57
Average Net Pay Thickness (ft)	29
Clay Content (%)	20 – 40
Initial Water Saturation (%)	40 – 65 %
Deep Resistivity (ohm-m)	1 – 5
Drive Mechanism	Solution-gas Drive

In recognition of reservoir energy dissipation, waterflood operation was then established in May 2009 to improve the reservoir pressure, increase oil production, and ultimately enhance the oil recovery factor. However, waterflood implementation in T-K reservoir faces many inherent challenges, including (1) low permeability, (2) high reservoir heterogeneity, (3) sensitivity to injection water, and (4) massive hydraulic fracturing. The journey of T-K waterflood development, from the planning to the implementation, is reported by Arnold and Asrul[1].

Fortunately, despite the complexity of this reservoir and thus the waterflood operation, various classical surveillance techniques and performance analysis methodologies are still applicable, both for the producers and the injectors at field and well level. Practical applications of these fit-for-purpose and low-cost techniques are very useful to provide better reservoir characterizations, more accurate performance diagnostics, as well as faster opportunities identifications to improve T-K waterflood performance. This paper summarizes the best practice in waterflood surveillance and performance analysis in T-K reservoir. Various classical approaches presented can be applied as a benchmark for analyzing the performance of any waterflood project, including those with similar characteristics and complexity.

2 Methodology

A robust and integrated waterflood management is of utmost importance to ensure the success of any waterflood operation. At the heart of waterflood management practices is the waterflood surveillance[2] and one central aspect of surveillance is the performance analysis part of it. Proper surveillance activities and performance analyses will provide better reservoir characterizations, more accurate performance diagnostics, and faster search for opportunities to improve waterflood performance. Several fit-for-purpose, classical surveillance techniques and performance analysis methods implemented in T-K reservoir are:

Field Surveillance

- Historical field production performance plot
- Production and injection bubble map
- Pressure map
- Watercut map
- Field decline curve analyses
- Voidage replacement ratio (VRR) plots
- WOR vs. Np plot
- RF vs. HCPVI plot
- *X*-plot
- *Y*-plot
- Heterogeneity index plot

Production Well Surveillance

- Well-by-well production performance plot
- Well decline curve analysis
- Saturation logging
- Production optimization and troubleshooting
- Shut-in well reactivation
- Static bottom-hole pressure (SBHP) survey in shut-in observatory wells
- Flowing bottom-hole pressure (FBHP) survey in producing wells
- Production test
- Mini fall-off test
- Step-rate test
- Chan plot
- Tag TD job
- Salinity measurement

Injection Well Surveillance

- Injection rate measurement by panametric survey

- Injectivity test
- Fall-off test
- Hall plot.

Multidisciplinary teamwork in collecting, processing, and analyzing all the surveillance and monitoring data is the key to manage T-K waterflood successfully. The next section will be devoted to discuss some of the tools used to analyze T-K waterflood performance.

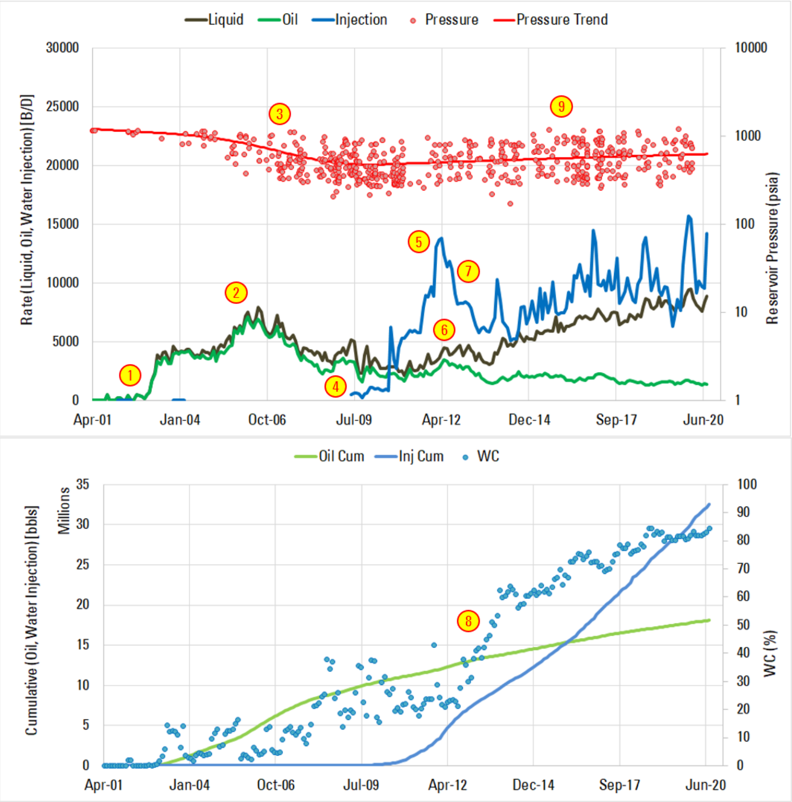
3 Results and Discussion

3.1 Historical Field Production Performance Plot

Historical field production performance plot provides an overview of how the reservoir performs from the early production period through the current state. Field production performance, plotted in a simple Cartesian coordinate, serves as a very important tool for reservoir health assessment. This plot also helps visualize the impact of waterflood and key historical events, such as infill drilling, workover, stimulation campaign, and system debottlenecking, to the production. Figure 1 shows two-panel production performance plot of T-K reservoir with key historical events occurred or done during the reservoir's production life.

There are some important features that can be observed from the plot. The production started in 2002 with a successful hydraulic fracturing job, which was then followed by an aggressive fracturing campaign which boosted-up the production to peak at 7,500 BOPD. Unfortunately, the peak could not be maintained for long as the reservoir energy started to dissipate with the rapid pressure decline indicating that the natural drive mechanism was too weak to support continued production at high rates. From an initial value of 1,230 psi in 2002, the reservoir pressure had dropped down to an average of 450 psi in the first half of 2009. This caused the oil production to decrease drastically and many wells to cease flowing.

The waterflood was on-stream in May 2009. The plot shows an indication that the waterflood gave quick positive results as both the production and reservoir pressure decline became gentler. Three years into the operation, the water injection rate was then increased. At the same time, both liquid and oil production rate also increased. In April 2012, the injection rate decreased which was followed by the decrease of both liquid and oil production. All these features suggest that T-K reservoir responded quickly and positively to the waterflood effect. The other important feature is the fast increase of watercut after April 2012 which was probably due to the injection rate ramp-up happened previously. Since the commencement of the waterflood, the reservoir pressure has been increasing steadily.



Key events and activities:

1) Production started
2) Production ramp-up and peak
3) Reservoir pressure rapid decline
4) Waterflood commenced
5) Water injection rate ramp-up
6) Increase in liquid and oil production following injection rate ramp-up
7) Water injection rate decreased followed by liquid and oil production decrease
8) Fast watercut increase following water injection rate ramp-up
9) Reservoir pressure steady increase

Figure 1. T-K historical field production performance plot

3.2 Mapping

A map is one of the tools that is helpful for observing the reservoir visually. As the reservoir is under production, dynamic parameters change with time. Having the parameters presented in a 2D map may help in capturing and identifying any irregularity, potential problems or even opportunities. Some parameters, such as reservoir pressure, watercut, the volume of oil produced and water injected and estimate ultimate recovery (EUR), are helpful to be observed in a map. The value for each parameter in the map can be calculated using interpolation. The values can also be generated by having an acceptable geostatistical method, such as proportional to the distance of sources. Some useful maps for waterflood surveillance and performance analysis include:

1. Reservoir pressure map
   Pressure change indicates how fast the production declines and how supportive the adjacent water injectors are within the regions.
2. Ratio map
   A watercut map is useful for locating possible water injection pathways. An oil-cut map may indicate by-passed zones or unswept areas. If working with a reservoir with a high watercut, as in the case of T-K reservoir, an oil-cut map is more powerful.

3. Volumetric map
   Cumulative oil production can confirm possible productive areas. It illustrates how long the wells drain their nearby areas. By forecasting the future performance for individual wells, an EUR map is useful for locating undrained areas. A cumulative water injection map is also useful for finding regions where injectors are supportive for the reservoir. This map can confirm the reservoir pressure map.

At the time of writing, multidisciplinary effort, which includes reservoir engineer, production engineer, development geologist, and petrophysicist, is carried out to generate these surveillance maps for T-K reservoir. To obtain a more comprehensive analysis, all maps are constructed in a time-lapse basis.

3.3 Voidage Replacement Ratios

Voidage replacement ratios (VRRs), presented in cumulative (CVRR) and instantaneous (IVRR) basis, versus time plot provides another tool for diagnosing waterflood performance. The plots of CVRR and IVRR against time are indicative of pressure maintenance provided by the water injection. It is therefore important to define the relationship between VRRs and reservoir pressure across time. Normally, these plots will correlate and anomalies are indicated otherwise.

Combined plots of IVRR, CVRR, and reservoir pressure versus time of T-K reservoir is shown in Figure 2. Three key observations can be made based on the plot. The first observation is that the reservoir pressure continuously decreased before the waterflood commenced suggesting that pressure maintenance program is mandatory to extend the life of the reservoir. The second observation is that, consistent with CVRR profile, the reservoir pressure shows an increasing trend, which indicates effective pressure support by the waterflood. The third key observation is that most of the time the IVRR is kept close to unity, leading to a continuous increase of the reservoir pressure.

As a best practice, to accelerate the pressure maintenance as well as to compensate for injection losses and water recycling, the IVRR is maintained to be in the range of 1.0 – 1.5.

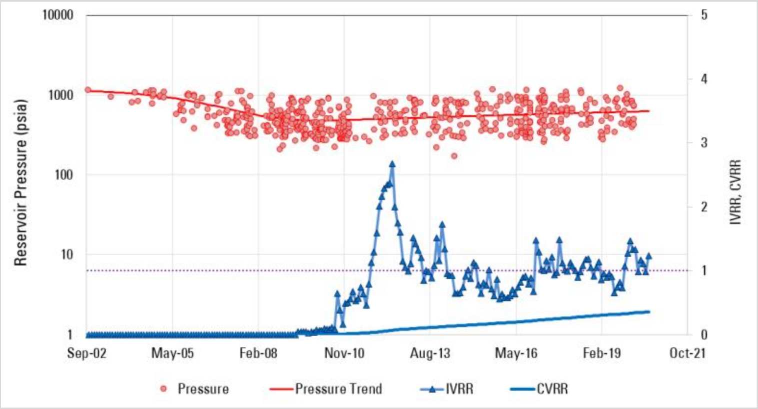


Figure 2. Combined plots of IVRR, CVRR, and reservoir pressure vs. time

3.4 WOR vs. Np Plot

A semi-log plot of water-oil ratio (WOR) versus cumulative oil production (Np) is one of the most useful classical method for production forecasting and waterflood performance analysis[3]. The EUR is obtained by extrapolating the WOR trend to the economic watercut limit, assuming that the current production/injection scenario is maintained. Changes in WOR-line slope indicate the impact of particular events or activities to production and recovery. An increase in WOR-line slope may indicate water encroachment (breakthrough and/or recycling), whereas a decrease in the slope indicates incremental oil recovery, for example due to infill drilling, workover, pattern balancing, etc. This technique is applicable for forecasting purpose when the watercut is 50% or higher, indicating that field maturity has been reached.

Figure 3 shows the WOR vs. Np plot of T-K reservoir. For illustrative purpose, WOR of 19, which is equivalent to watercut of 95%, is assumed to be the economic limit. The red dotted line shows the WOR-trend when the watercut increased rapidly after the injection ramp-up but then followed by a significant drop of injection rate. This drop hurt the pressure maintenance, which is reflected by a fast decrease of oil production rate, and resulted in a high WOR-line slope. Extrapolating the line to the economic limit yields ultimate recovery of 15.5 MMBO. When the water injection rate could be regained and eventually increased, the WOR-line slope becomes gentler indicating a higher sweep efficiency and thus oil recovery. It is important to note that infill drillings and workovers also contributed in arresting the WOR incline. To forecast the production, a representative period is selected for trend-lining (orange oval arrow line). Extrapolating the current WOR to economic limit using a representative slope (orange dashed-arrow line) yields EUR of 19.5 MMBO.

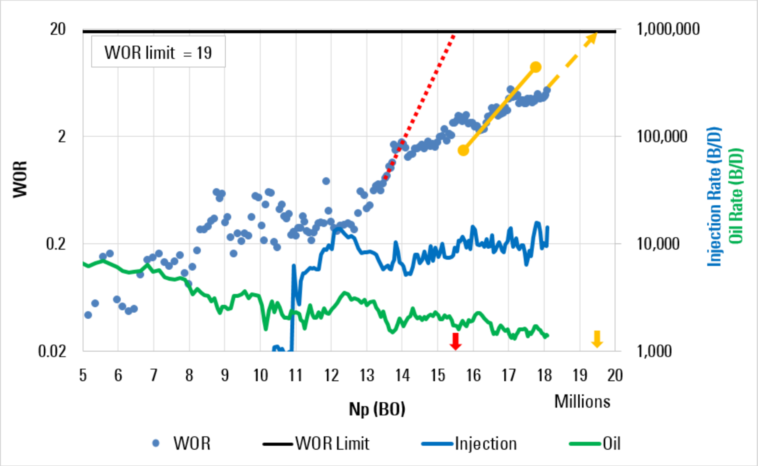


Figure 3. Combined plots of WOR, injection rate, and oil rate vs. Np

3.5 *X*-Plot

The *X*-plot[4] is another graphical approach applied to analyse waterflood performance in T-K reservoir. The major assumption used in this method is that the main portion (*i.e.* intermediate saturation values) of the relative permeability ratio vs. water saturation is linear on a semilog plot. By applying this assumption and the Buckley-Leverett equation, a linear relationship between X and cumulative oil production is developed[5]:

$$N_p = mX + n \tag{1}$$

where *m* and *n* are constants, and:

$$X = \frac{1}{f_w} - \ln\left(\frac{1}{f_w} - 1\right) \tag{2}$$

$$f_w = \frac{Q_w}{Q_o + Q_w} = \frac{\text{WOR}}{\text{WOR} + 1} \tag{3}$$

The plot is created by plotting X against N_p. In the absence of reservoir layering and if water breakthrough has occurred (*i.e.* watercut value of 50% or higher), the plot will yield a straight line. The straight line indicates waterflood maturity, which means that the production is now mainly governed by the relative permeability ratio effects. Only after these requirements are met can a meaningful forecast be obtained using this technique. The X-plot of T-K reservoir is presented in Figure 4. As can be seen from the graph, a linear trend of X-function is developed at the late-time period confirming the waterflood maturity of this reservoir. Extrapolation of the straight line to the X of 4, which corresponds to economic watercut limit of 95%, gives the EUR of 19.5 MMBO, which is the same with the results obtained from WOR vs. Np plot.

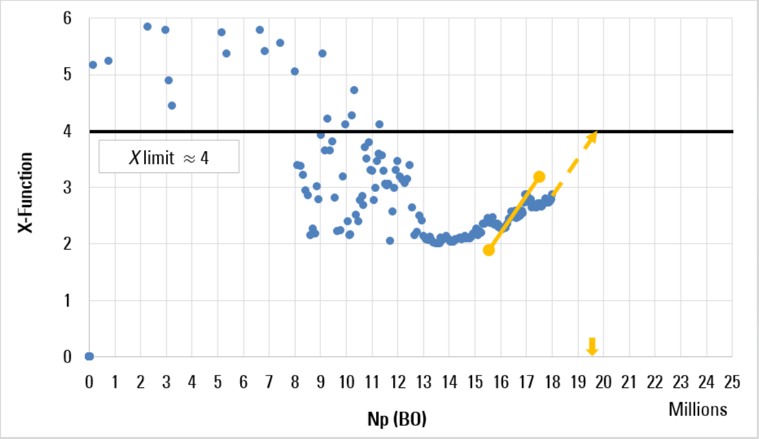


Figure 4. X-plot

3.6 RF vs. HCPVI Plot

A plot of recovery factor (RF) against hydrocarbon pore-volume injected (HCPVI) is another useful tool used to evaluate T-K waterflood performance. This plot illustrates how the reservoir performs prior to waterflood, the impact of waterflood in terms of RF enhancement, and how water encroachment is influencing the performance. The vertical line in the early-time period shows the recovery factor obtained during primary recovery period. The first deviation from this vertical line marks the waterflood start-up.

The slope of this plot indicates sweep efficiency. Throughout the life of the waterflood, there will be slope changes caused by events, activities, and/or geological factors. Higher slope indicates better or improved sweep efficiency, for example due to infill drilling, workover, pattern balancing, etc., while lower slope means poorer or reduced efficiency, mainly caused by water encroachment issue or loss of injection.

Figure 5 presents RF vs. HCPVI plot for T-K reservoir. During primary recovery period, recovery factor of 7% had been achieved, as illustrated by the plot. At the early waterflood period, a relatively constant sweep efficiency (green dotted-arrow line) can be maintained. When the HCPVI reached around 13%, the slope becomes lower (red dashed-arrow line) implying poorer waterflood efficiency. In other words, for the same target RF, the poor efficiency state requires higher HCPVI or more water injection volume compared to the state where the sweep efficiency is higher. This indicates that T-K waterflood has suffered from water encroachment problems that lower the sweep efficiency and thus the oil recovery. A more detailed, well-level analysis is required to locate the problematic wells and optimize the waterflood performance.

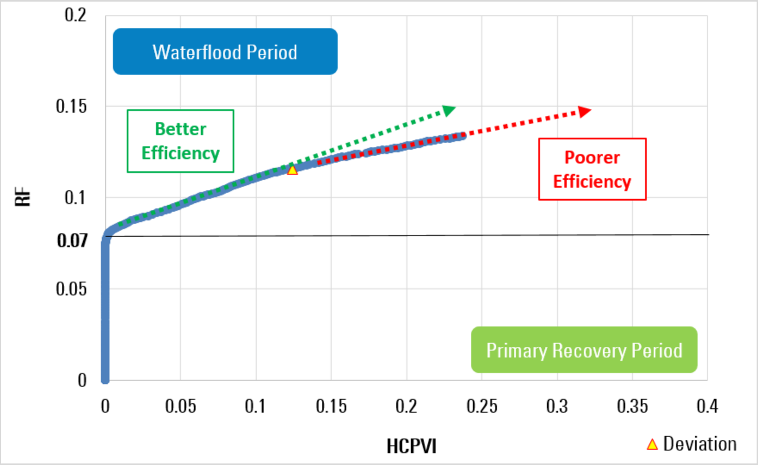


Figure 5. RF vs. HCPVI plot

3.7 *Y*-Plot

Y-plot[6,7] is an analytical diagnostic tool that can be used to forecast future production, assess waterflood maturity, and differentiate the premature water breakthrough from normal water breakthrough. The function *Y* is simply defined by:

$$Y = f_w f_o = f_w(1 - f_w) \tag{4}$$

This plot is generated by plotting *Y* against the cumulative liquid production on a log-log scale. The *Y*-function reaches a maximum value of 0.25, corresponding to a watercut value of 50%, which is a numerical indication of waterflood maturity. Before reaching this maturity level, the production mechanism is controlled by primary (pressure) depletion and transition to waterflood. A relatively constant *Y* with value of approximately 0.25 prior to waterflood indicates a normal water displacement which exhibits typical Buckley-Leverett behavior. When *Y* reaches 0.25 and starts to decline, the waterflood is considered mature from a field average point of view, and the production mechanism is now controlled by relative permeability ratio effects. A typical displacement process in a mature waterflood is generally indicated by a slope of -1. An irregular-shape curve with *Y* significantly less than 0.25 or any significant deviation from the slope of -1 typically suggest poor sweep efficiency, which mainly caused by water encroachment issues.

Y-plot of T-K reservoir is shown in Figure 6. Based on the plot, prior to waterflood start-up, the *Y*-curve is irregularly-shaped with value far below 0.25. This indicates that during primary recovery period, the T-K suffered premature water breakthrough that can be caused by water channeling through high permeability layers. This condition, however, has changed after waterflood commencement. After waterflood maturity has been achieved, the *Y*-curve starts to decline with slope of -1 which indicates normal displacement process. In other words, after waterflood maturity has been attained, the water channeling problem becomes less severe such that it can be viewed as normal displacement mechanism in field-average perspective.

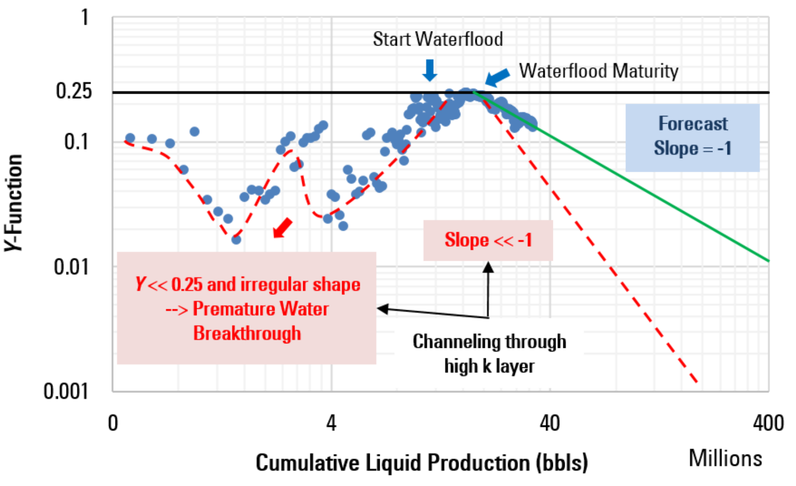


Figure 6. *Y*-plot

3.8 Heterogeneity Index Plot

Heterogeneity Index (HI) plot[8,9] is a quadrant-mapping technique which is used to compare the performance of an individual well to a dynamically moving average of the performance of other wells. The formula to compute the heterogeneity index is

$$HI = \frac{Value_{well}}{Value_{average\ of\ wells}} - 1 \tag{5}$$

The parameter “value” in Equation (5) can be any parameter of interest. However, in waterflood performance analysis, more attention will be given to oil and water production rate. This screening tool quickly categorizes all wells as the plot splits the wells into four predetermined quadrants by comparing the individual well performance to the average field value. The four quadrants are:

1. *High productivity* (*high oil and high water*). Production from wells in this group can be optimized by considering the optimal operating range of the artificial lifts and surface facilities, while ensuring that no significant increase in water production will occur during the optimization.
2. *Good well* (*high oil and low water*). Production of wells in this category should be maintained or optimized.
3. *Low productivity* (*low oil and low water*). Wells in this quadrant are viable candidates for well stimulations, such hydraulic fracturing or acidizing.
4. *Bad water* (*low oil and high water*). Wells categorized in this quadrant can be considered for water shut-off, zonal isolation, perforation shift-up, horizontal side-tracking, or other techniques to control the uneconomical water production. The wells can also be shut-in and utilized as observatory wells or intermittent producers.

HI plot covering all active T-K producers is shown in Figure 7. This technique helps in mapping and ranking the producers based on their performance. This plot is also useful in screening and selection of workover or stimulation candidates. Wells suitable to be candidates for workover and/or stimulation are located either in Quadrant IV (objective: water shut-off, etc.) or Quadrant III (objective: productivity improvement).

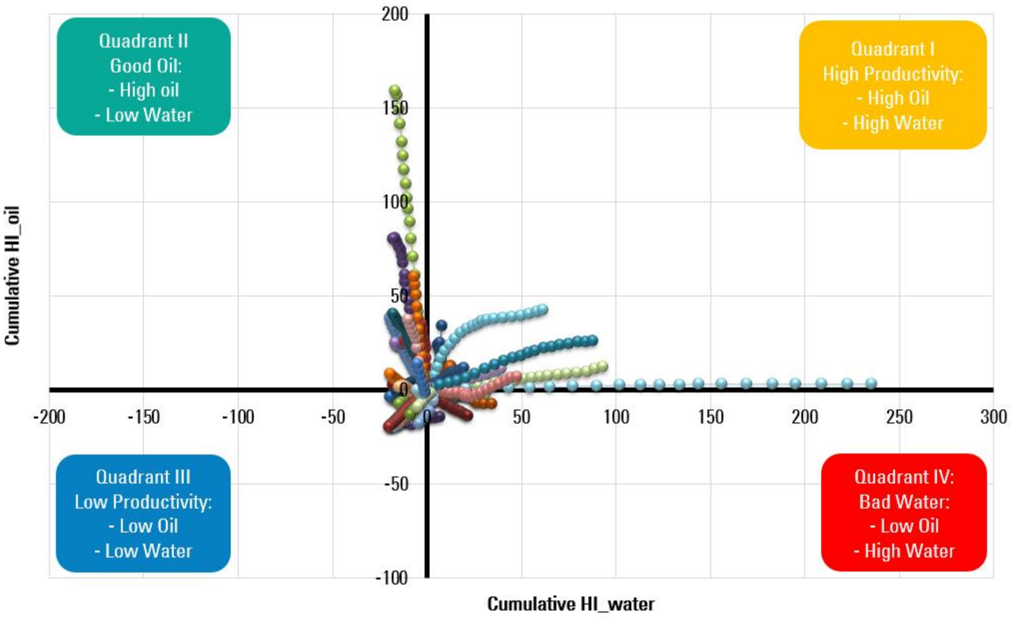


Figure 7. Heterogeneity index plot of T-K active producers

3.9 SBHP and Shut-in Well Reactivation

By reviewing the overall well performance characteristics, average reservoir pressure of around 450 psi is regarded as the threshold pressure necessary to enable well production. Below this pressure, well will cease flowing and eventually die. Even after several years of waterflood operation, some areas in the reservoir still had pressure below this critical value due to low injector/producer ratio in those areas. To accelerate the pressurization in such areas and reactivate the dead wells, producer-to-injector conversions were performed by converting watered-out wells or wells with uneconomical oil reserve to be water injection wells. Following the conversions, static bottom-hole pressure (SBHP) surveys were conducted periodically in the shut-in oil wells to monitor the pressure build-up and check the oil accumulation in the wellbore. If the SBHP of a well has reached the threshold pressure and a sufficiently high oil column is observed, then the shut-in well will be reactivated.

One success story achieved by this surveillance program was the reactivation of TK-Z. This well produced oil from 2005 to March 2014 with an average rate of 55 BOPD. In April 2014, due to lack of pressure maintenance, the reservoir pressure around TK-Z dropped below the threshold pressure causing the well to cease flowing. The well was then shut-in. Periodic SBHP surveys were conducted in this well to monitor the pressure build-up and it was observed that even after four years of shut-in, the reservoir pressure was still lower than the threshold pressure. A producer-to-injector conversion was then performed in 2018 to convert TK-I, a shut-in adjacent well, into an injector. TK-I injection commenced in July 2018 and since then the SBHP of TK-Z has increased significantly indicating a good reservoir connectivity between TK-Z and TK-I. In October 2019, it was measured that the SBHP of TK-Z had already surpassed the threshold pressure. The well was then reactivated in November 2019 and to date the well is still in continuous production with an average oil production rate of 85 BOPD. Production and SBHP profiles of TK-Z are presented in Figure 8.

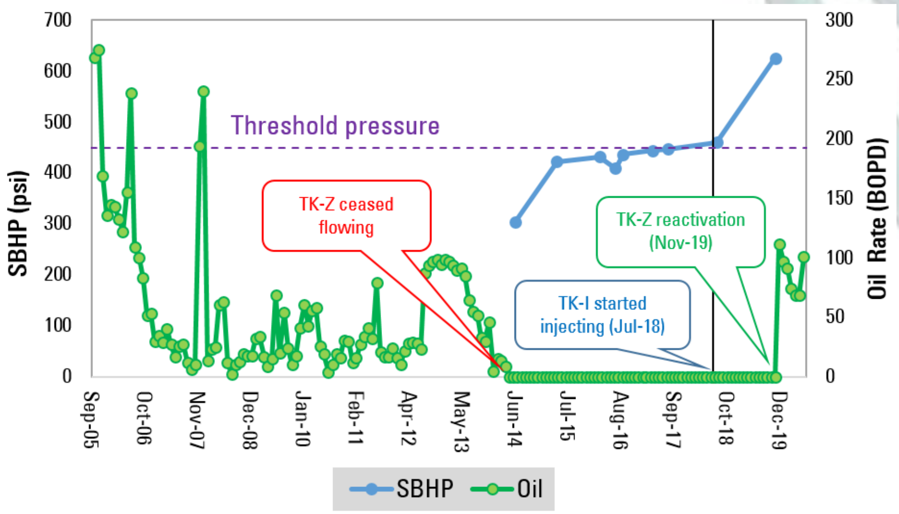
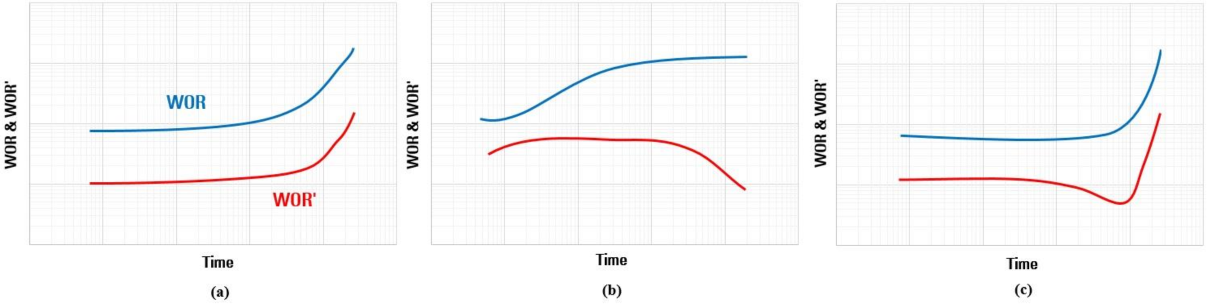


Figure 8. Production and SBHP profiles of TK-Z

3.10 Chan Plot

Chan plot[10] is a well-level diagnostic plot used for recognizing water encroachment mechanism. In this technique, WOR and its time-derivative, WOR', are plotted against time on a log-log plot. The shape of WOR and mainly WOR' curve will be the signature that indicate whether the encroachment of water towards the producer being reviewed is through coning, channeling, or a combination of both, as illustrated in Figure 9.



(a) (b) (c)

Figure 9. Typical Chan plot for (a) channeling; (b) bottom-water coning (b); and (c) bottom-water coning with late-time channeling behavior.

Chan plots are generated for all T-K producers as shown in Figure 10. By reviewing all the plots, it is found that the majority of T-K wells are producing water through channeling, while some others are experiencing a combination of coning and channeling. The fact that water channeling, or fingering, dominates the water encroachment process in most producers confirms the high level of heterogeneity of this reservoir. The channel-flow of water can occur due to the existence of high permeability streaks, thief zones, natural and/or waterflood-induced fractures, or major and minor faults. Channeling can also be caused by mobility ratio effects, which is currently under investigation.

Chan plot analysis is really helpful in characterizing T-K reservoir, both in terms of heterogeneity and performance. This analysis also supports the findings obtained from RF vs. HCPVI plot and *Y*-plot which indicate that T-K reservoir is experiencing water encroachment issue. The encroaching water can come from coning of bottom-water and channeling of formation and injection water. The channeling of injection water, which is also called water recycling, is highly undesirable as it lowers sweep efficiency and thus the incremental oil recovery provided by the waterflood. Producers that are already watered-out or only recycling the injection water will be shut-in and used as observatory wells or intermittent producers. Shutting-in these producers is important as it will alter the flow direction of the injection water away from the watered-out producers thereby reducing the severity of recycling when the producers are reactivated for intermittent production. In areas with low reservoir pressure, watered-out producers can also be converted into water injection wells.

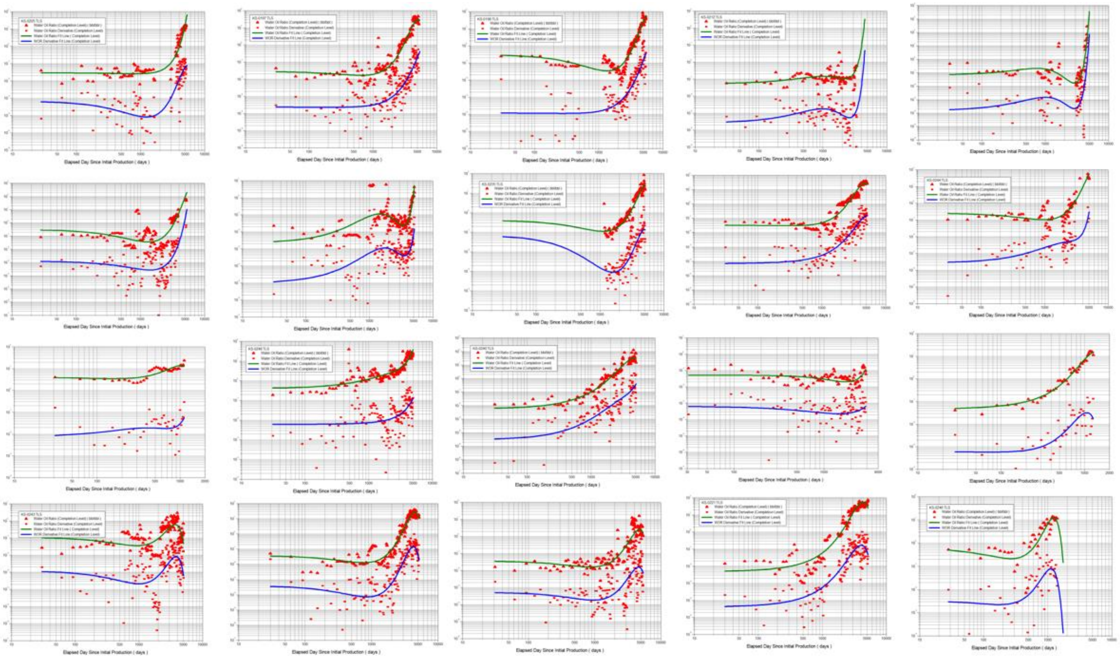


Figure 10. Chan plots of several T-K producers

3.11 Hall Plot

Hall plot[11] is one of the most popular methods for injectivity surveillance. This approach has the advantage that only variables directly measurable at the surface, namely wellhead pressure and injection rate, are required for this analysis. This plot is generated by plotting the cumulative pressure-time product against the cumulative water injection volume. The slope of this plot represents the injection performance. Increase in slope indicates injectivity impairment or formation damage, while decrease in slope suggests injectivity improvement or formation stimulation. Figure 11 shows a schematic of Hall plot.

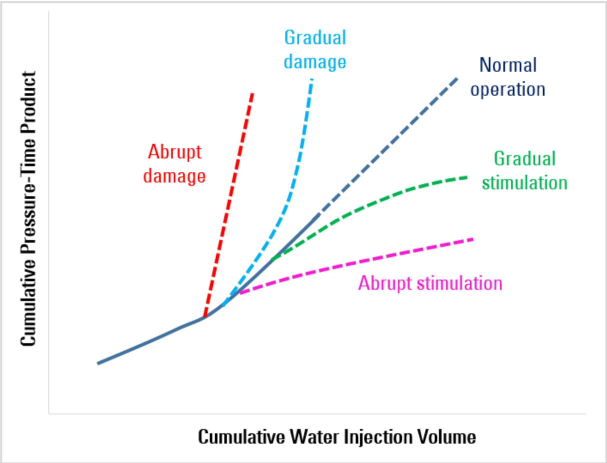


Figure 11. Typical Hall plot for various injection conditions

Hall plots are constructed for all T-K injectors as shown in Figure 12. Some injectors could maintain the initial injectivity even after years of operation, while several others suffered injectivity impairment. The main source of formation damage in injectors was the low quality injection water which contained high solids concentration and oil-in-water content. The other sources of formation damage were sand and proppant build-ups which covered the perforation. Using the Hall plot analysis, candidate selection for injector stimulation was proceeded. Damaged injectors which have high initial injectivity will be prioritized for stimulation, either by acidizing or wellbore clean-up, whereas those with low initial injectivity will be of lower priority for stimulation.

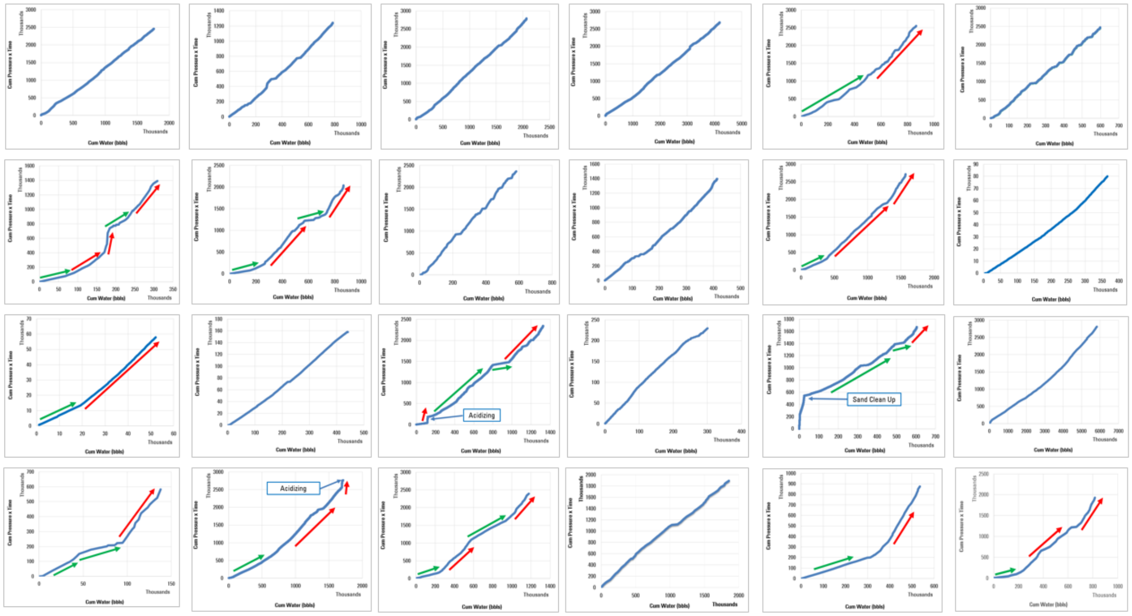


Figure 12. Hall plots of several T-K injectors

For comparative analysis, all Hall plots are plotted in a same graph, and based on the slopes of these plots, injectors are then categorized into two groups, as shown in Figure 13. Steep slope of the Hall plot indicates low injectivity or high resistance to injection, which can be due to poor rock quality, formation damage, or overpressured condition; gentle slope of Hall plot suggests high injectivity or low resistance to injection, which can be due to good rock quality, connection with high permeability layer, or low reservoir pressure[12]. Based on the comparative Hall plots, it is found that the majority of injectors face high resistance to injection. There is one injector that outperforms other injectors, both in terms of injectivity and longevity. It is still unclear why this well has significantly different performance compared to other wells. Waterflood-induced fracturing or connectivity to high permeability layer can be the cause of this behavior. A more detailed study, which includes geological and geomechanical analysis, is required to solve this mystery.

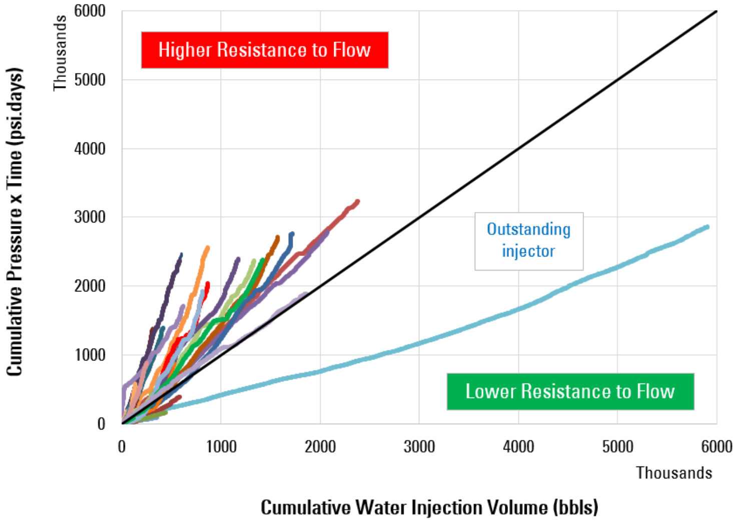


Figure 13. T-K fieldwide Hall plots comparison

4 Conclusion

The development and management of waterflood in T-K, a tight, heterogeneous, water-sensitive, and massively fractured reservoir, have been significantly benefited from fit-for-purpose reservoir surveillance. This study summarizes the best practice in waterflood surveillance and performance analysis applied in T-K reservoir. Various classical techniques and how they are integrated and work together to provide a clearer picture of the characteristics and performance of T-K reservoir are described. Major advantages of the integration of various surveillance techniques include:

1. Close monitoring and pre-emptive alarming.
2. Better reservoir and well characterizations.
3. More accurate performance assessment and production forecast.
4. Faster opportunities identifications to improve field and waterflood performance.

Nomenclature

EUR = estimate ultimate recovery (bbl)
f_o = oil fractional flow (fraction)
f_w = water fractional flow (fraction)
HCPVI = hydrocarbon pore volume injected (fraction or percentage)
HI = heterogeneity index
Np = cumulative oil production (bbl)
Qo = oil production rate (bbl/day)
Qw = water production rate (bbl/day)
RF = oil recovery factor
TD = total depth (ft)
VRR = voidage replacement ratio

WC = watercut
WOR = water-oil ratio
WOR' = time-derivative water-oil ratio

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