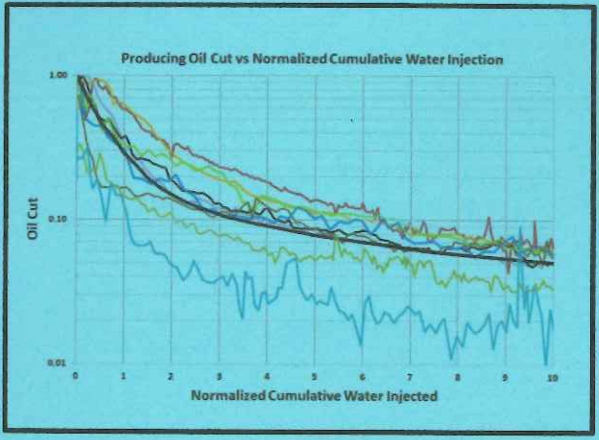

Response Predictions for Lansing-Kansas City Waterfloods By Analogy to Mature Fields

Acknowledgement

I would like to thank Mr. Mike Carr, President of Mica Energy and former President of Gemini Corporation (and my employer from 1985 to 1995, for which I have been unreservedly grateful) for allowing me the opportunity to prepare this paper. I would also like to thank Mr. Dan Blankenau, President of Great Plains Energy, for his review, research, suggestions, and support.

Disclosure

Earlier in my career, I worked for Mr. Carr and Gemini Corporation (and successors-in-interest Beard Oil Company and Sensor Oil and Gas), helping design and implement waterfloods in Southwest Nebraska. I may have, therefore, bias or opinion regarding both waterflood design and results thereof.

I also feel obligated to encourage readers to use judgement and caution in any application of the method described in this paper. As they say, correlation does not equal causation, and analogies, however apparently successful, do not guarantee future results. Please perform your own studies (or retain qualified engineers to do so), and form your own opinions before relying upon any forecast of future well and reservoir performance.

Contents

Response Predictions for Lansing-Kansas City Waterfloods

Tim Busing, PE (retired)

1 Objectives

This paper documents the use of an empirical method for predicting response to waterflooding in the Lansing-Kansas City ("LKC") formation in Southwest Nebraska and Northwest Kansas, using analogies to several mature LKC floods. This method has been used for many years, and has been described in published technical papers and books[1].

The objectives of this paper are to demonstrate the method, including preparation of empirical response for a number of mature fields in the area, and to describe the uncertainty of the method by application to several fields for which actual production performance is now known.

2 Overview

Many factors influence waterflood performance, including field size, reservoir continuity, reservoir layering, potential loss of injection fluids off pattern, rock and fluid properties, initial fluid saturation distributions, reservoir depletion and pressure at the start of waterflooding, and many others. Obtaining data for preparing response forecasts using mechanistic models can be difficult, and adequate, accurate data are often not available for modeling, especially for smaller mid-continent oil fields.

Analogy methods, such as the one described in this paper, require much less data, but correlating response of several mature fields, and proposing that a target field might behave in an analogous way, requires the assumption that all the fields in question share key similarities.

Field size, rate of production, and rate of injection do not need to be similar between the various fields in question, since differences in these characteristics can be accommodated in the correlations, as described below.

This paper concludes that the method of analogy is generally applicable for fields in the subject area, particularly fields with a single (or predominant) waterflood target horizon. Less accurate projections appear to be related to fields with suspected off-pattern injection loss, or layered reservoirs with multiple horizons open to injection.

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[1] Slider, H. C., Worldwide Practical Petroleum Reservoir Engineering Methods, PennWell Publishing Company, Tulsa, Oklahoma, 1983, pp. 598-607.

3 Preparation of Data and Analog Response Plots

The mature waterfloods from which data have been considered for this analog study are:

Table 3.1: Lansing-Kansas City Analog Waterfloods

#	Field	County,State	Waterflood Start	Ultimate Primary (STB)	Total Recovery (@ 4Q2019)	Secondary / Primary (@ 4Q2019)
1	Sleepy Hollow Lansing Unit	Red Willow, NE	Mar-66	4,439,300	10,175,125	1.29
2	Ackman Unit	Red Willow, NE	May-66	3,250,000 [1]	7,758,122	1.39
3	Silver Creek [2]	Red Willow, NE	Jul-65	1,025,000 [3]	2,398,429	1.34
4	Gemini North Midway Unit	Red Willow, NE	Nov-86	656,503	1,020,225	0.55 [4]
5	Suess Unit	Red Willow, NE	Nov-89	429,080	1,148,421	1.68
6	Dry Creek Unit	Hitchcock, NE	Oct-84	1,600,000	5,132,146	2.21 [5]
7	Boevau Canyon Unit	Hitchcock, NE	Sep-87	2,435,057	6,058,374	1.49
8	Husker Unit	Hitchcock, NE	Sep-87	983,777	3,154,433	2.21 [6]
9	Bishop Unit	Hitchcock, NE	Sep-89	1,123,751	2,550,078	1.27
10	Bush Creek Unit	Hitchcock, NE	Nov-90	1,956,666	3,579,452	0.83
11	Driftwood Creek Unit	Hitchcock, NE	Aug-95	274,427	370,796 [7]	0.35 [8]

Notes:

1 ultimate primary estimated from decline curve @ 15% nominal decline
2 combined (adjacent) Texaco Silver Creek Unit and Oxford Silver Creek Unit
3 ultimate primary estimated from decline curve @ 10% nominal decline
4 pre-unit plan was secondary:primary=0.54; lower plan due to elongate geometry and concern for off-pattern injection losses
5 high secondary:primary due to low ultimate primary depletion (7%); well count nearly doubled at waterflood startup
6 high secondary:primary due to low ultimate primary depletion (9%); single zone pattern flood
7 expected ultimate primary + secondary recovery was 442,000 STB
8 pre-unit plan was secondary:primary ratio= 0.61; lower plan due to multiple waterflood reservoir target intervals

The fields included in the study, as shown in Table 3.1, include a range of sizes, locations, and waterflood designs. The fields in Red Willow County were all originally designed with peripheral or irregular injection well placement, although most had some infill injectors added after startup. The fields in Hitchcock County were all 5-spot pattern waterfloods, with the exception of Driftwood Creek, which had too few wells to allow fully regular pattern development. Well spacing in all of the fields was approximately 40 acres.

The correlated waterflood production response of this group of fields is shown on the following figures.

The actual production data shown was obtained by downloading monthly reported data from the Nebraska Oil and Gas Conservation Commission ("NOGCC") website. In some cases, the data may have been misreported or incorrectly entered (for example, circumstances in which a series of monthly data average perhaps 1,000 barrels per month, but exhibit an occasional, apparently inconsistent value, perhaps a single value of 10,000 barrels per month, or zero), but no attempt was made to "smooth out" apparently inconsistent data. As a result, large excursions are plotted for some fields at certain times.

Figure 3.11, shown below, demonstrates a few characteristics of the analog method. It shows, on the vertical axis, liquid production rate divided by water injection rate, versus normalized cumulative water injected, plotted on the horizontal axis.

- The "normalization" of values on the horizontal axis is an attempt to scale responses among fields of different sizes. In this case, the scaling factor is the ultimate primary production of each field. Other scaling factors which consistently represent relative field size could be selected, but ultimate primary production has been chosen since it is reported to the state at the time of unitization. Ultimate primary production was available for all fields in this group except two of the oldest fields, Ackman and Silver Creek. For those fields only, ultimate primary production was estimated from straight line decline through pre-unit data, which was obtained from the NOGCC.
- The selection of cumulative water injected as a component of the horizontal plotting metric also provides normalization of field responses, since it compensates for potentially differing water injection rates. Use of cumulative water injection divided by ultimate primary recovery thereby represents "normalized time".
- Plotting production ratios, not rates, on the vertical axis inherently normalizes field responses.

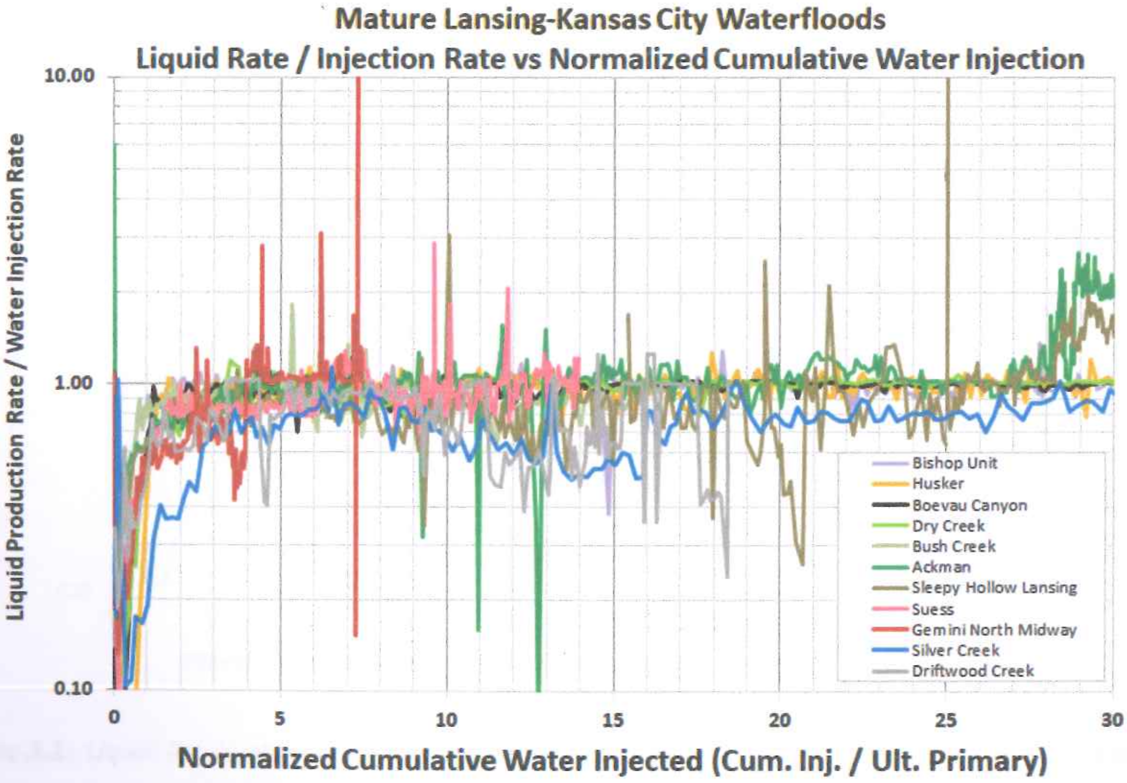

Figure 3.1: Liquid Production Rate / Water Injection Rate vs Normalized Cumulative Water Injection

The values plotted on the horizontal axis on Figure 1 are dimensionless ("barrels" divided by "barrels"). The maximum value of the horizontal axis on Figure 1 is 30. Since ultimate primary recovery is about 10 – 15% for the fields in this group, and since connate water saturation is about 30 – 35%, this maximum value of 30 represents about 3 – 5 pore volumes of injection throughput. For most of the fields in this group a value of 30 is reached in about 30 years. All of the waterfloods in this group are very mature.

The values plotted on the vertical axis on Figure 1 are also dimensionless ("barrels per day" divided by "barrels per day"). This value is an injection efficiency metric, representing how many barrels are produced for each barrel injected. The initial values are less than 1, since the fields are underpressured and injection/production is not at steady state. Ultimately, the values are expected to reach about 1:1.

Figure 3.2, below, shows a "close-up" of the early portion of this chart. The pressure buildup phase is evident, and represents about the first 1 or 2 years. The maximum value on the horizontal axis is 10, which is roughly equivalent to 10 years for waterfloods in this group. Ten years of project life represents, in my experience, the time by which a project is normally planned to recover most of its planned reserve and the greatest portion of its economic value.

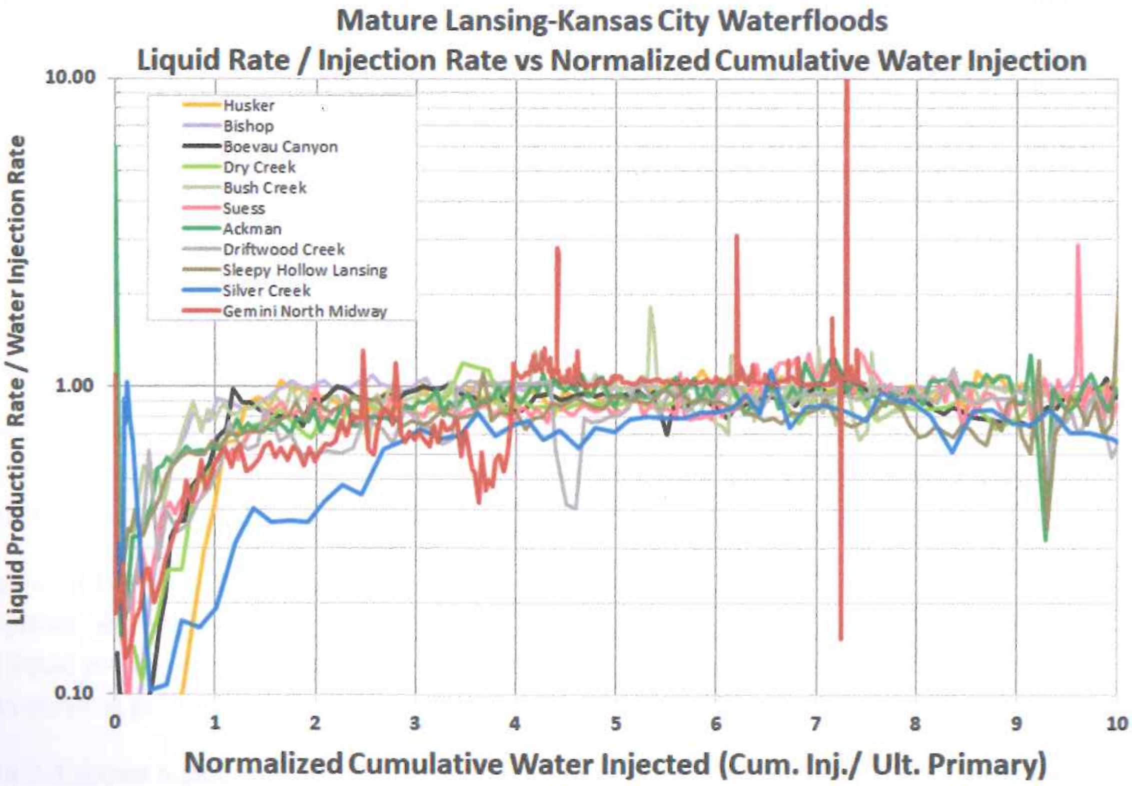

Figure 3.2: Liquid Production Rate / Water Injection Rate vs Normalized Cumulative Water Injection

Since the data group relatively well on this chart, we can draw a trendline representing an "average" response, which is shown on the following Figure 3.3.

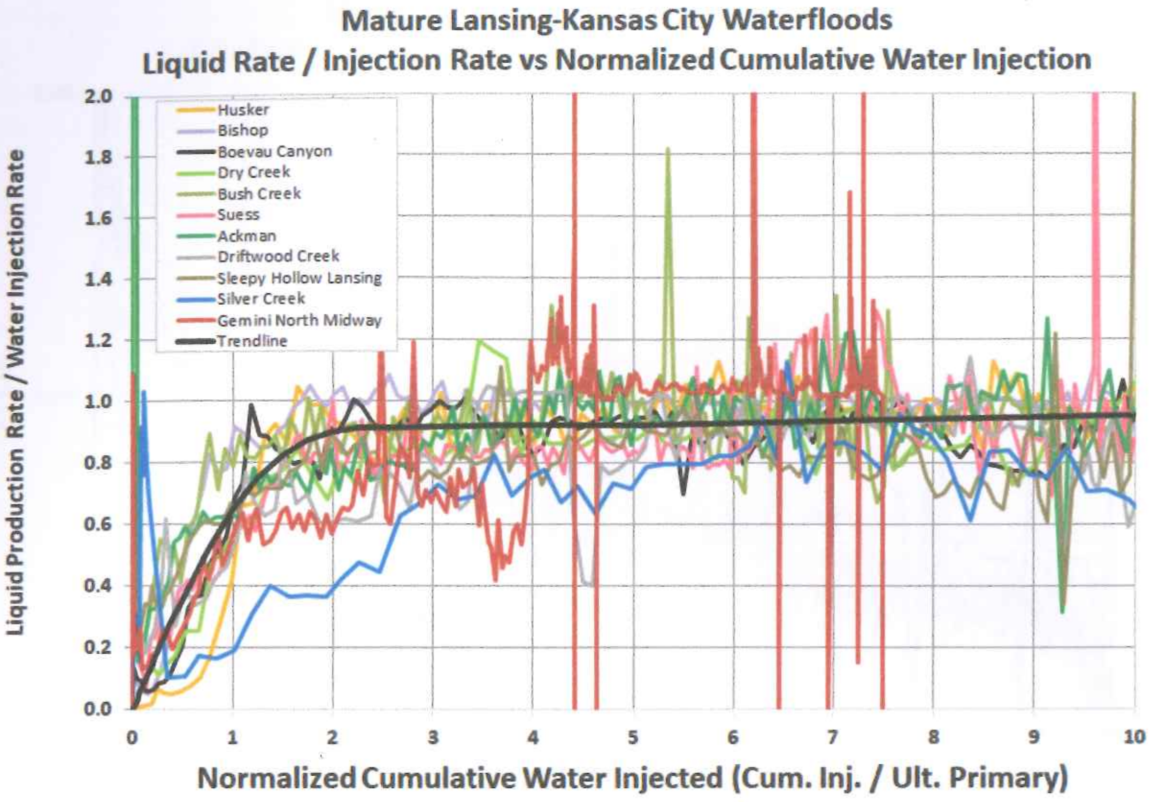

Figure 3.3: Correlated Liquid Production Rate / Water Injection Rate vs Normalized Cum. Water Inj.

For this figure, I've switched to a non-logarithmic axis, so variances between fields in the most interesting range of values (0.5-1) are easier to see. The trendline was not mathematically determined, but is rather an approximate fit drawn by hand.

The next step in the process is to prepare another group of charts, in which the producing oil cut is plotted on the vertical axis, and the same variable as the prior charts on the horizontal axis (normalized cumulative water injected / ultimate primary).

The values of oil cut are also dimensionless ("barrels per day" divided by "barrels per day"). This value is a displacement efficiency metric, representing how many barrels of oil are produced for each barrel total liquid produced. The initial values may be close to 1, but will drop substantially as injected water fronts arrive at producers.

Figure 3.4 shows a plot of oil cut versus the larger value of normalized cumulative injection divided by ultimate primary. The large excursions are generally result in months with reported oil production but no reported water production.

It is also evident on Figure 4 and Figure 5 that one field, Driftwood Creek, is a noticeable outlier compared to the other fields. I will return to this observation in a later section.

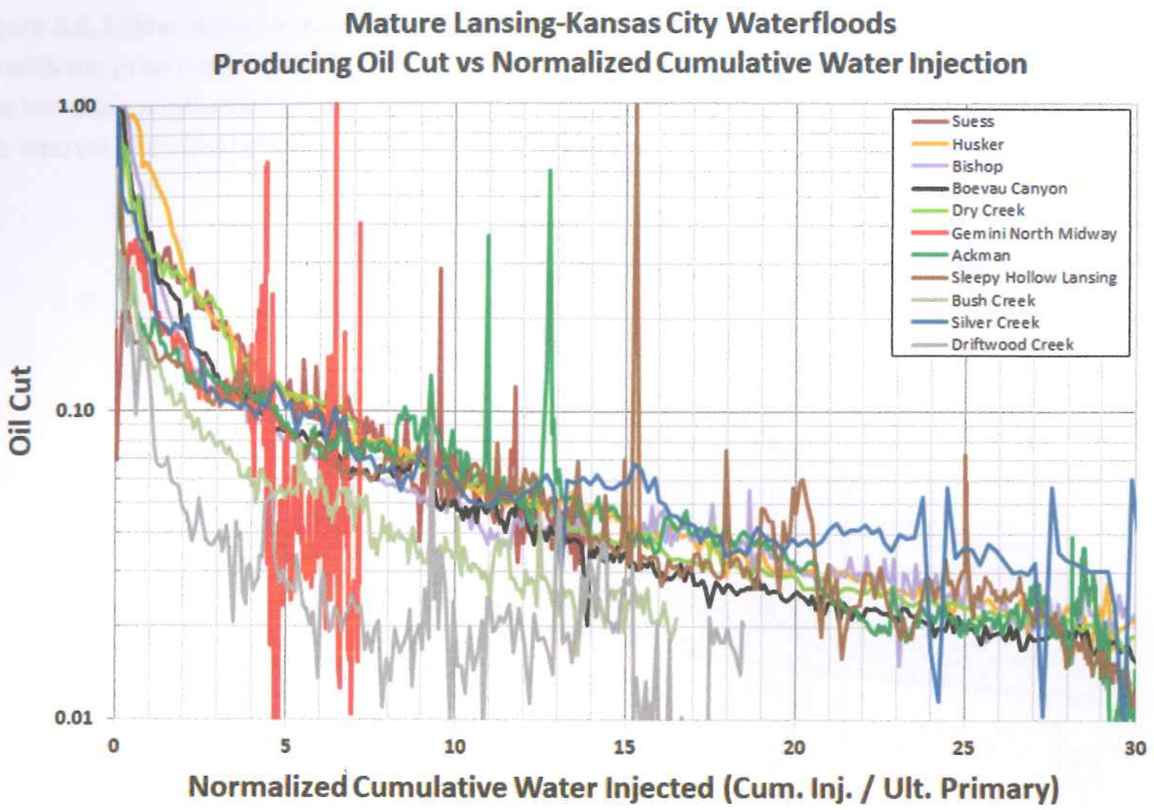

Figure3. 4: Producing Oil Cut vs Normalized Cumulative Water Injection

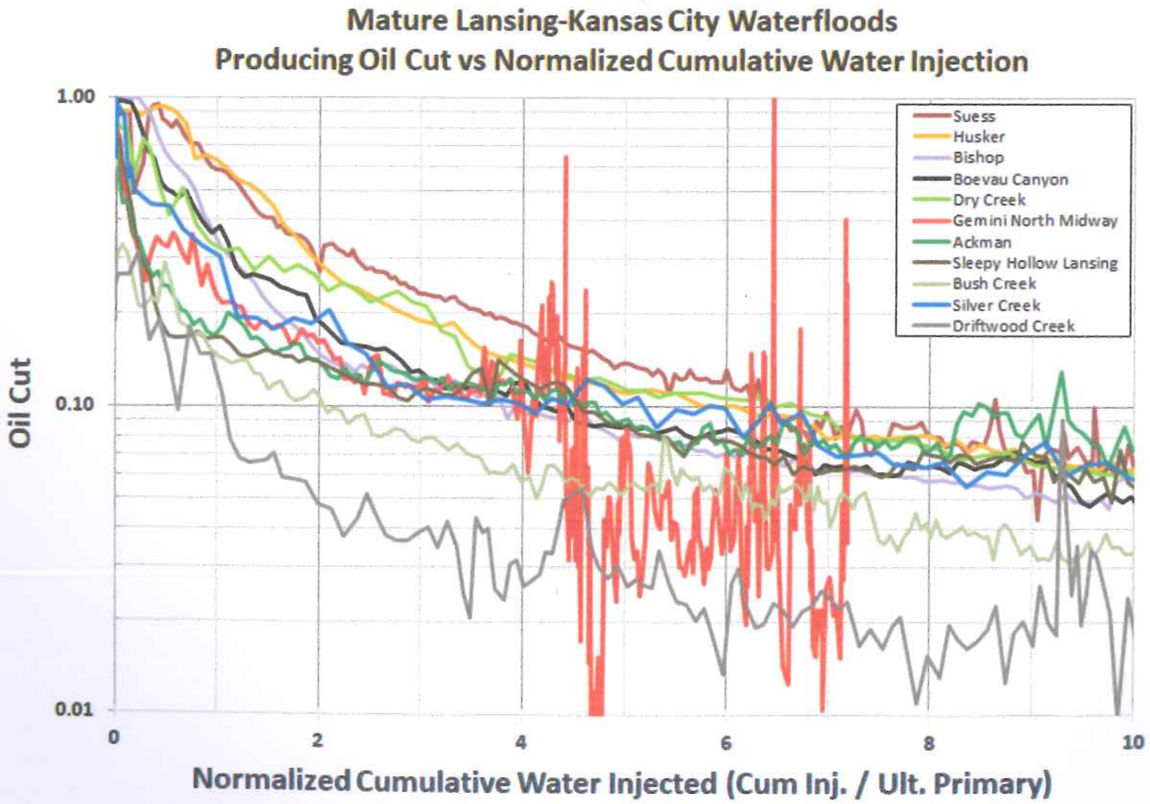

Figure 3.5: Producing Oil Cut vs Normalized Cumulative Water Injection

Figure 3.6, below, shows a trendline representing an "average" field response added to the oil cut chart. As with the prior correlation, the fit has not been mathematically determined, but rather is hand drawn. The trendline is influenced downward by the poorer response of Bush Creek and Driftwood Creek, and the interval of erratic behavior at Gemini North Midway.

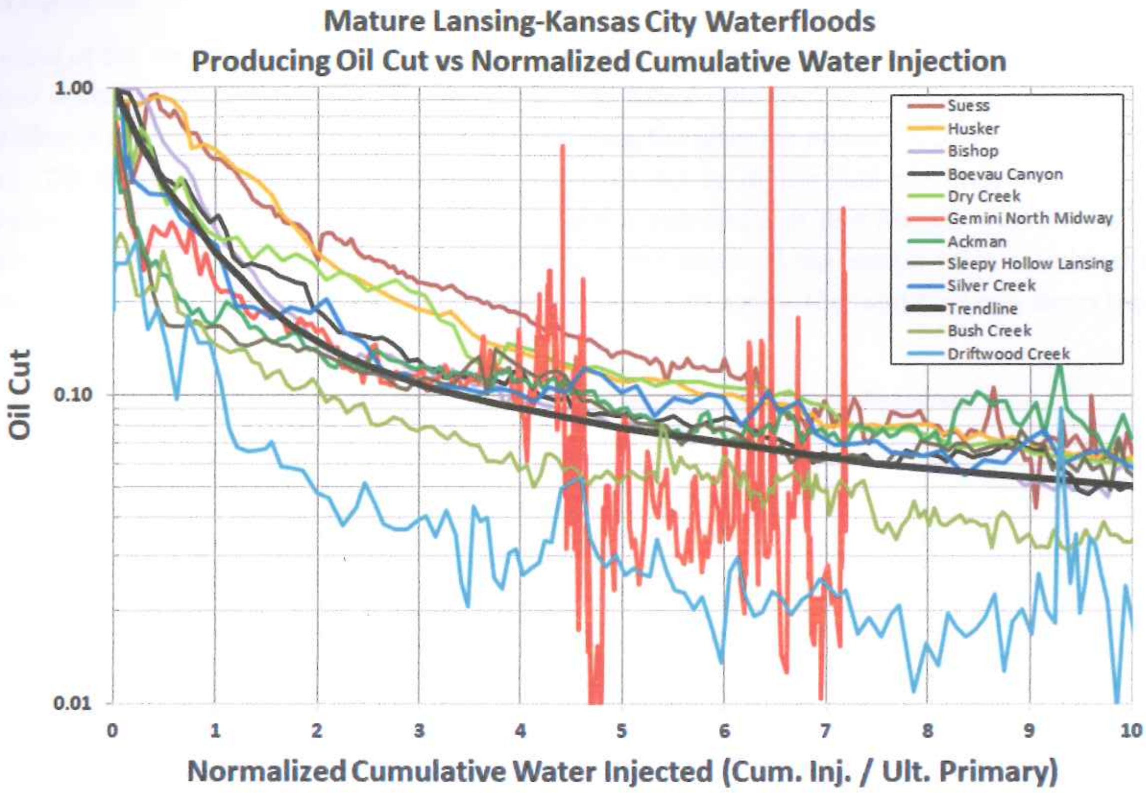

Figure 3.6: Correlated Producing Oil Cut vs Normalized Cumulative Water Injection

4 Waterflood Response Predictions Using the Analog Method

In this section we will use the correlations shown on Figure 3.3 and Figure 3.6 to estimate waterflood response for each of the 11 waterfloods comprising the source of the analog data for this paper.

Table 4.1, below, shows the analog correlation values used to create the correlation lines on Figure 3.3 and Figure 3.6.

The use of the tabular data is straightforward. For each application of the method, an expected rate of water injection is estimated for a series of calendar dates. For each of these dates, the cumulative injection is calculated, and normalized by division using the ultimate primary recovery from the target area. The normalized cumulative injection (a) is used to look up (b) the fluid production volume (oil rate + water rate) divided by the water injection rate, and (c)the oil cut at that instant. Interpolation in the table can be used to smooth the results. Total fluid production at the instant (a) is calculated as the table value (b) times the expected rate of water injection. Oil rate is the total fluid rate times the table value (c).

Table 4.1: Analog Correlations of Lansing-Kansas City Analog Waterflood Response

(a) Normalized Cumulative Water Injected (Cum. Inj. Bbl. / Ultimate Primary Reserve Bbl.)	(b) Oil + Water Production Rate / Water Injection Rate	(c) Oil Cut
0	0.001	1.000
0.025	0.012	0.965
0.050	0.031	0.930
0.075	0.051	0.895
0.100	0.070	0.860
0.125	0.089	0.825
0.150	0.109	0.790
0.175	0.128	0.755
0.200	0.147	0.722
0.225	0.165	0.696
0.250	0.184	0.668
0.375	0.275	0.570
0.500	0.361	0.480
0.625	0.441	0.424
0.750	0.516	0.376
1.000	0.647	0.290
1.250	0.751	0.238
1.500	0.826	0.194
1.750	0.874	0.167
2.000	0.900	0.148
2.250	0.914	0.135
2.500	0.917	0.124
3.125	0.920	0.105
3.750	0.923	0.094
5.000	0.926	0.078
7.500	0.940	0.060
10.000	0.955	0.051
12.500	0.965	0.044
15.000	0.975	0.038
17.500	0.990	0.033
20.000	1.000	0.029
22.500	1.000	0.027
25.000	1.000	0.025
125.000	1.000	0.001

A reader might ask why the two dependent variables (b) and (c) are tabulated against each value of (a). The table could be simplified by multiplying the two dependent variables, if oil rate were the only objective.

The answer to this question is simply my preference. Not all engineers would chose to separate the two independent variables, but I find it useful, since each may provide insight into waterflood behavior after startup. If early waterflood response shows low total fluid production / water injection, it may indicate that water injection is being lost off-pattern, into a high permeability channel, or into a poorly-connected horizon. If early waterflood response shows low oil cut, it may indicate one or more injector-to-producer short circuits, or unfavorable mobility ratio. Including both independent variables in Table 4.1 allows cross-plotting the correlations against early waterflood response to facilitate these comparisons.

The following figures show the reported actual production for each of the analog fields.

The figures include the "Original Forecast Secondary + Primary" in light green color. This legacy waterflood response forecast was obtained by digitizing NOGCC unitization hearing images, unless otherwise noted.

The figures also show the "new forecast" oil rate, in orange color, calculated using the correlations in Table 4.1, the ultimate primary recovery shown in Table 3.1, and an assumed constant water injection rate as indicated.

Finally, for each of the analog fields, I will suggest a subjective score describing the quality of the new analog forecast match to reported actual field performance. I'll include an estimated consensus grade describing the overall quality of the new forecasts in the final section of this report.

4.1 Sleepy Hollow Lansing Unit

Figure 4.1 (below) shows the forecast and actual waterflood response of the Sleepy Hollow Lansing Unit. The Sleepy Hollow Lansing Unit is a very mature waterflood, with first injection in 1966.

The new analog forecast (orange line) described in this paper assumes and a constant 380,000 BWIPM injection rate. The method uses an ultimate primary recovery of 4,439,300 STB, as shown on an NOGCC exhibit.

The new analog forecast over predicts Year 1 and Year 2 waterflood response, perhaps because this was not a pattern waterflood, and average injector-to-producer offsets were larger than the correlations (which more heavily honor Hitchcock County pattern waterfloods) assume. The new analog forecast also over predicts response from 1990 onward (after about 25 years of waterflooding), a time during which the actual water injection rate was substantially reduced from the constant injection rate assumed by the analog method.

In my view, the fit of the analog method to the actual response of the Sleepy Hollow Lansing waterflood is good, at least prior to the later period of injection decrease.

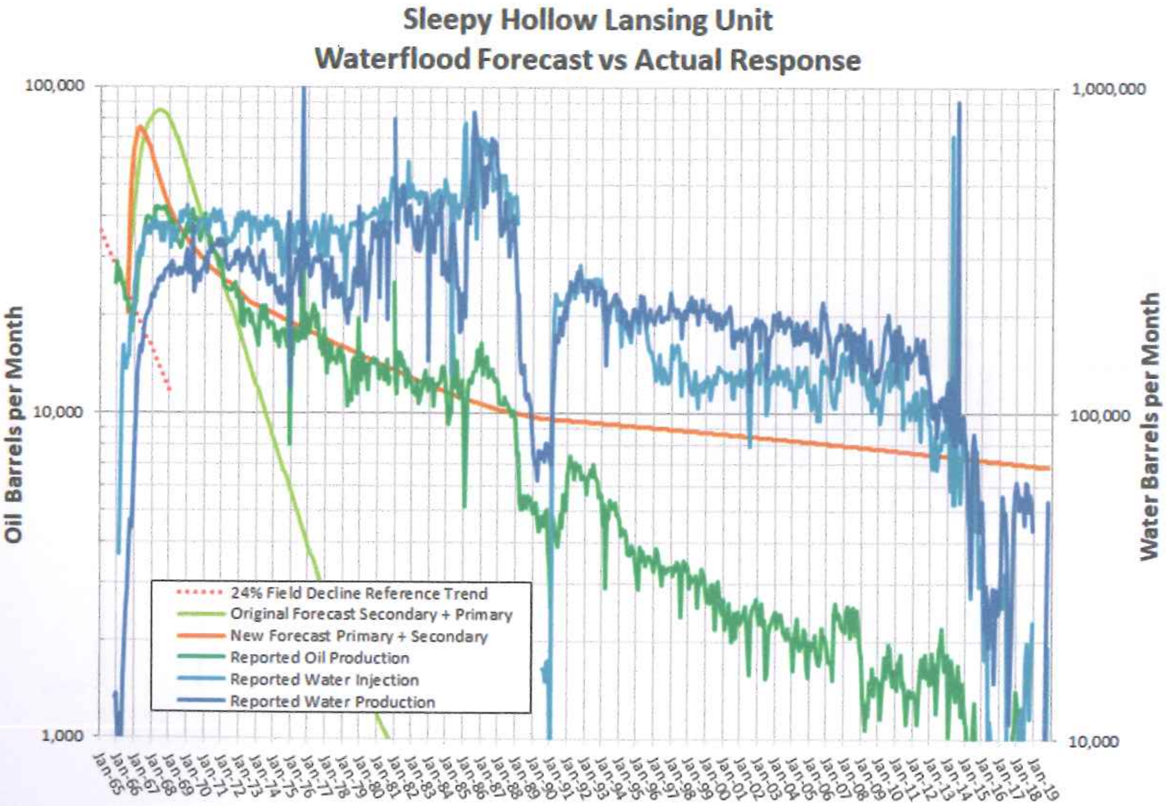

Figure 4.1: Sleepy Hollow Lansing Waterflood Forecast vs Actual Response

4.2 Ackman Unit

Figure 4.2 (below) shows the forecast and actual waterflood response of the Ackman Field Unit. The Ackman Unit is another very mature waterflood, also with first injection in 1966.

The new analog forecast (orange line) assumes 180,000 BWIPM constant water injection, and an ultimate primary recovery of 3,350,000 STB. In this case, I've calculated ultimate primary based on Ackman Field pre-unit data obtained from the NOGCC website, assuming 15% straight line decline. I could find no pre-unit ultimate primary estimate or secondary recovery estimate.

The new analog forecast moderately over predicts Year 1 and Year 2 waterflood response, again perhaps because this was not a pattern waterflood. The new analog forecast also moderately under predicts response from 1975 to 1990, during a time when actual field injection was continuously increasing above rates assumed for the analog method. Conversely, the analog method over-predicts waterflood response after 1995, when actual water injection rate was substantially reduced.

Overall, I rate the fit of the analog method to the actual response of the Ackman Unit waterflood as fair.

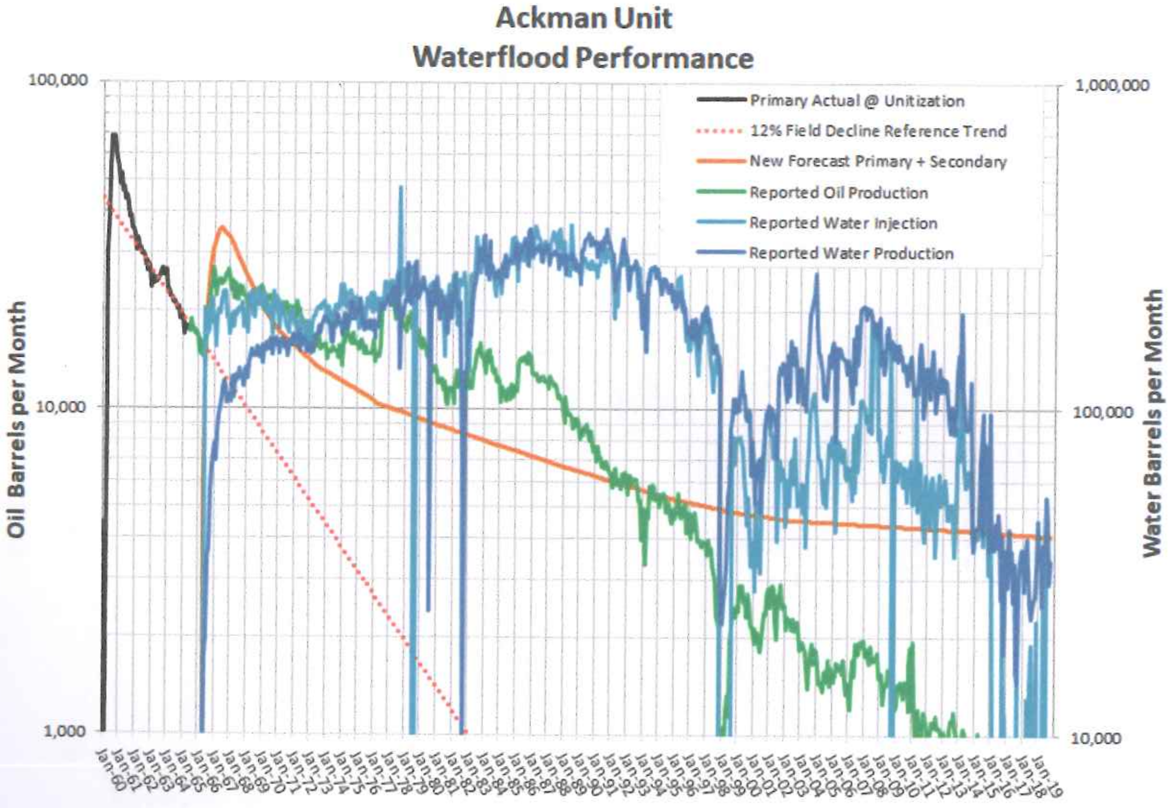

Figure 4.2: Ackman Field Unit Waterflood Forecast vs Actual Response

4.3 Silver Creek Field

Figure 4.3 (below) shows the forecast and actual waterflood response of the Silver Creek Field. The data plotted combine the Texaco Silver Creek Unit and the smaller Oxford Silver Creek Unit. The Silver Creek Field is also among the oldest of the waterfloods in this group, with first injection in 1965.

The new analog forecast (orange line) described in this paper assumes 160,000 BWIPM, and an ultimate primary recovery of 1,000,000 STB. I've calculated ultimate primary assuming 10% straight line decline, drawn through the combined fields' pre-waterflood obtained from the NOGCC website. I could find no pre-unit ultimate primary or secondary recovery estimate.

The new analog forecast moderately over predicts Year 1 and Year 2 waterflood response, again perhaps because this was not a pattern waterflood. The new analog forecast waterflood response very well from 1965 – 1985, during a time when actual water injection was stable. After 1985, the actual water injection rate was substantially, and the analog method over-predicts waterflood response.

As with the Sleepy Hollow Lansing Unit, I rate the fit of the analog method to the actual response of the Silver Creek Field waterflood as good, at least prior to the later period of injection decrease.

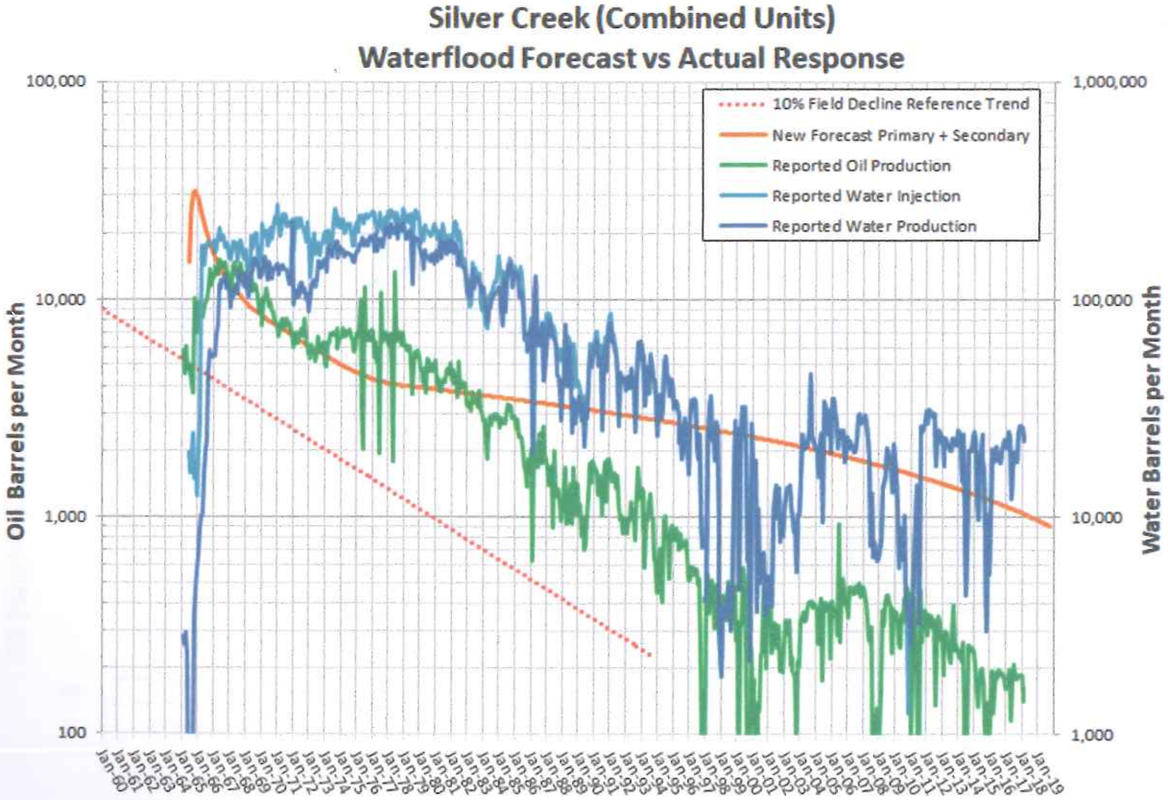

Figure 4.3: Silver Creek Field Waterflood Forecast vs Actual Response

4.4 Gemini North Midway Unit

Figure 4.4 (below) shows the forecast and actual waterflood response of the Gemini North Midway Unit ("GNMU"). I have some knowledge of this Unit, since I was personally involved in its waterflood design beginning in 1985. This Unit is one of the smaller waterfloods in this group of analog fields. The field is relatively elongated, and was thus designed with an irregular injection pattern. Additionally, it was directly offset by two pre-existing operating waterfloods.

The new analog forecast (orange line) assumes a constant injection rate of 33,000 BWIPM, and an ultimate primary recovery of 656,503 STB, obtained from the unitization exhibits available on the NOGCC website. The original waterflood response forecast was digitized from NOGCC exhibits.

The analog forecast modestly over predicts Year 1 and Year 2 waterflood response, again perhaps because this was not a pattern waterflood. The analog forecast acceptably matches actual performance during waterflood years 3-6. From 1993 onward, the analog method over-predicts waterflood response, again since the actual water injection rate was substantially reduced from the constant rate assume by the analog method.

Overall, I rate the fit of the analog method to the actual response of the Gemini North Midway Unit waterflood as good to fair, although the comparison is obviously made difficult due to the erratic actual field water injection.

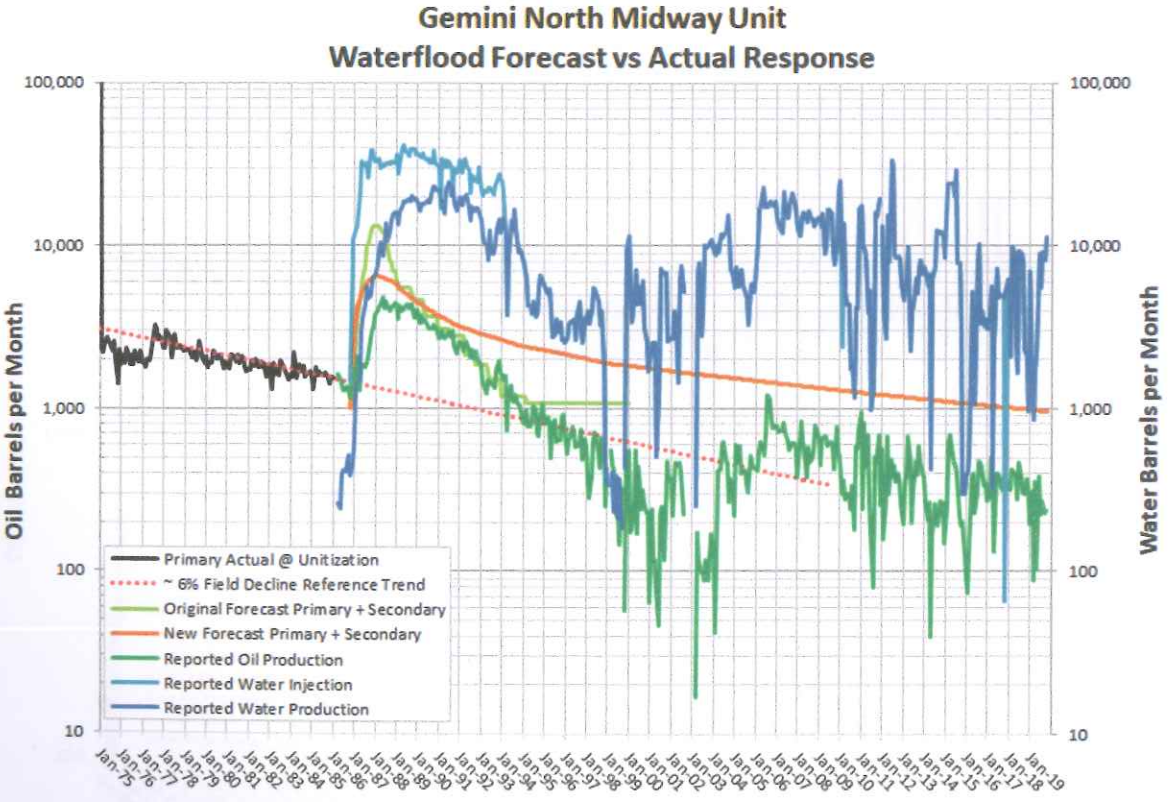

Figure 4.4: Gemini North Midway Unit Waterflood Forecast vs Actual Response

4.5 Suess Field Unit

Figure 4.5 (below) shows the forecast and actual waterflood response of the Suess Field Unit. Again, I was personally involved in its waterflood design. Because the field was described with an interpreted oil-water contact, injection wells were located with the intent of achieving gravity-stabilized displacement updip toward producers nearer the top of the moderate structural relief.

The new analog forecast (orange line) assumes 36,000 BWIPM, and an ultimate primary recovery of 439,080 STB, obtained from the unitization exhibits available on the NOGCC website. The original waterflood response forecast and primary decline were digitized from NOGCC unitization exhibits.

The new analog forecast matches Year 1 and Year 2 waterflood response, but drops below actual waterflood response by year 3, and remains lower than actual for more than 10 years. Compared to other waterfloods in this analog study, Suess waterflood performance was in the middle of the pack in terms of fluid production rate / injection rate (Figure 3.3), but easily the best in terms of oil cut (Figure 3.6). The excellent oil cut performance, much better than assumed by the correlation trendline, is why the actual field waterflood response exceeds the new analog forecast. This observation is an example of the possible utility of maintaining separate performance charts (Figure 3.3 and Figure 3.6), as discussed earlier on page 12.

Overall, I rate the fit of the analog method to the actual response of the Suess Unit as good, albeit pessimistic.

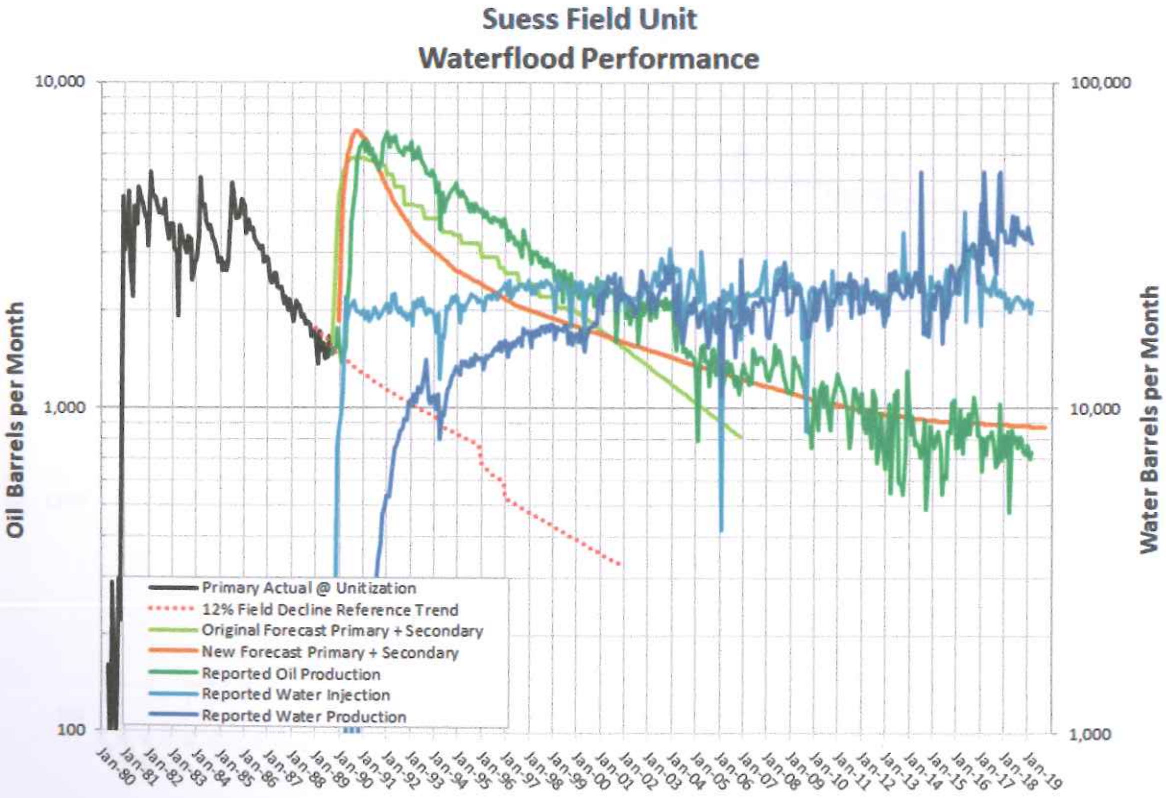

Figure 4.5: Suess Field Unit Waterflood Forecast vs Actual Response

4.6 Dry Creek Unit

Figure 4.6 (below) shows the forecast and actual waterflood response of the Dry Creek Unit. This field is composed of multiple Lansing-Kansas City horizons, with five LKC reservoirs ("C", "D", "E2", "E3" and "F") producing. Primary recovery at the start of waterflooding was low, approximately 5%. In response, the waterflood was planned as a pattern waterflood, incorporating 19 newly drilled injectors in addition to 8 producer conversions, thus achieving a regular (inverted) five spot pattern.

The new analog forecast (orange line) assumes constant injection of 270,000 BWIPM, and an ultimate primary recovery of 1,600,000 STB, obtained from the unitization exhibits available on the NOGCC website. The original waterflood response forecast and primary decline were digitized from NOGCC exhibits.

The new analog forecast and actual waterflood response are extremely similar in year 1. Actual waterflood performance is slightly better than the analog forecast in years 2 to 8. Sustained actual waterflood performance is somewhat below the new analog forecast.

Early actual performance may have been better than forecast due to the extensive drilling of injectors at waterflood startup. Sustained actual waterflood performance may have been worse than forecast since this is a multi-zone flood, and the analogy correlations are largely based on single-zone waterfloods.

Overall, I rate the fit of the analog method to the actual response of the Dry Creek Unit as good.

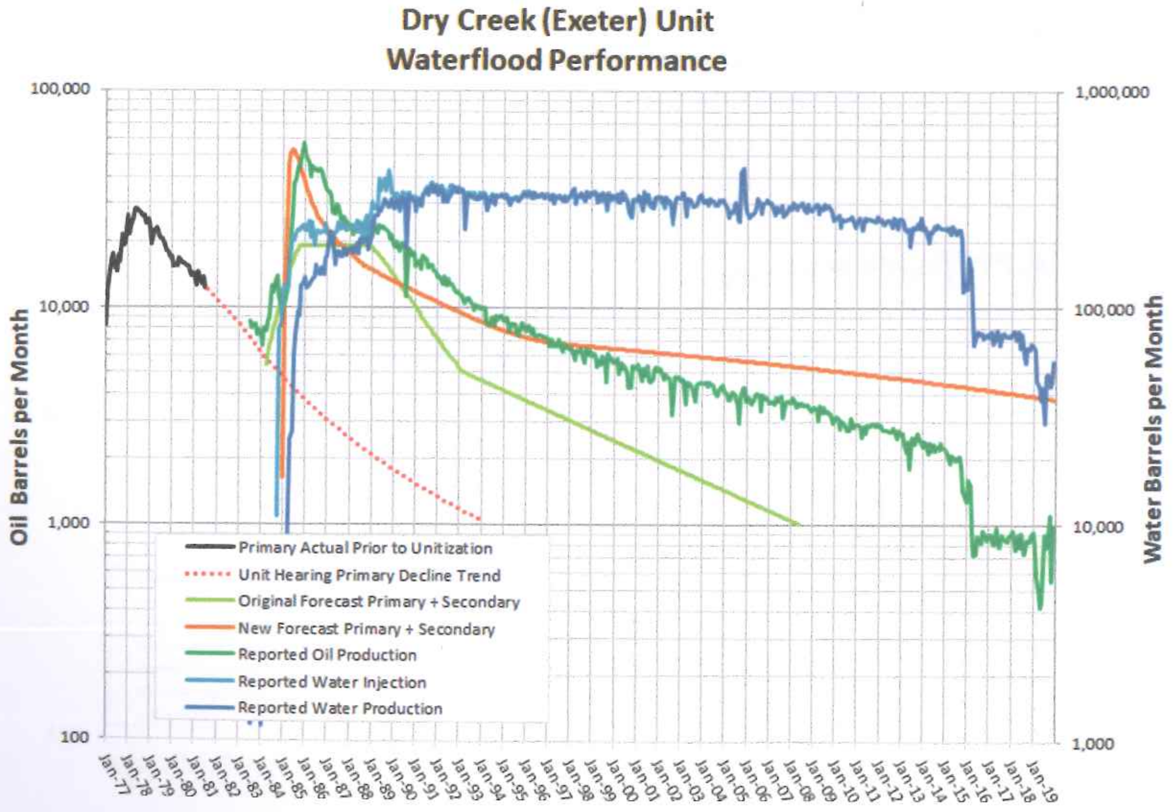

Figure 4.6: Dry Creek Unit Waterflood Forecast vs Actual Response

4.7 Boevau Canyon Field Unit

Figure 4.7 (below) shows the forecast and actual waterflood response of the Boevau Canyon Field Unit. Again, I was personally involved in its waterflood planning, and recall that its design as a five spot pattern flood was influenced by Dry Creek. Boevau Canyon, however, had been more completely drilled during primary development than Dry Creek, and so only one newly drilled injector was needed. More ccmplete primary development, though, also meant relatively greater ultimate primary recovery, and a relatively smaller secondary target. A positive factor for waterflood recovery was the fact that only one reservoir zone (LKC "F") dominated Boevau Canyon production, and subsequent injection.

The new analog forecast (orange line) described in this paper assumes 210,000 BWIPM, and an ultimate primary recovery of 2,435,057 STB, obtained from the unitization exhibits available on the NOGCC website. The original waterflood response forecast and primary decline were digitized from NOGCC unitization exhibits.

The new analog forecast and actual waterflood response are extremely similar in year 1. Actual waterflood performance is slightly better than the analog forecast in years 2 to 5, although the slope of production decline is the same. Actual waterflood response and the analog forecast are extremely similar from 1993 to 2013.

I rate the fit of the new analog forecast to the actual response of the Boevau Canyon Field Unit as excellent.

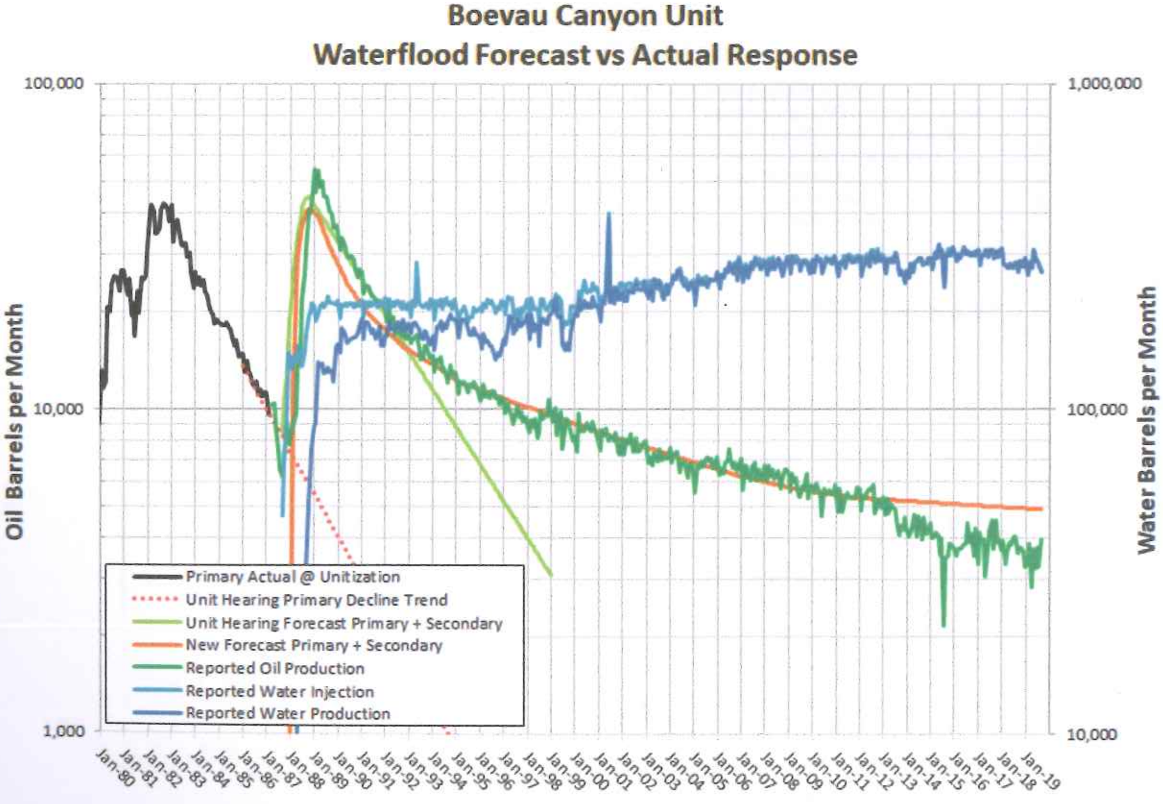

Figure 4.7: Boevau Canyon Field Unit Waterflood Forecast vs Actual Response

4.8 Husker Field Unit

Figure 4.8 (below) shows the forecast and actual waterflood response of the Husker Field Unit. I was personally involved in the design of the waterflood, which also was based on a regular 5 spot pattern.

I also prepared the original waterflood response forecast for the Husker Unit, using the same method described in this paper, although the analog fields used for the correlations were older fields in Red Willow County and in Northwest Kansas (Ackman, Dry Creek (original), Danbury, Midway, Silver Creek, Sleepy Hollow, and Rieher).

The new analog forecast (orange line) assumes constant injection of 120,000 BWIPM, and an ultimate primary recovery of 983,777 STB, obtained from the unitization exhibits available on the NOGCC website.

Actual field waterflood performance was significantly better than the new analog forecast predicts, both initially and for a number of succeeding years, although the shape of the response is similar. This reflects the fact that the Husker Unit actual performance was among the very best of this group of 11 analog fields, as is evident from Figure 3.3 and Figure 3.6. The excellent actual performance is likely due to full pattern development, flooding a single reservoir horizon (LKC "F"), and good reservoir quality.

Overall, I rate the fit of the new analog forecast to the actual response of the Husker Field Unit as good, although somewhat pessimistic.

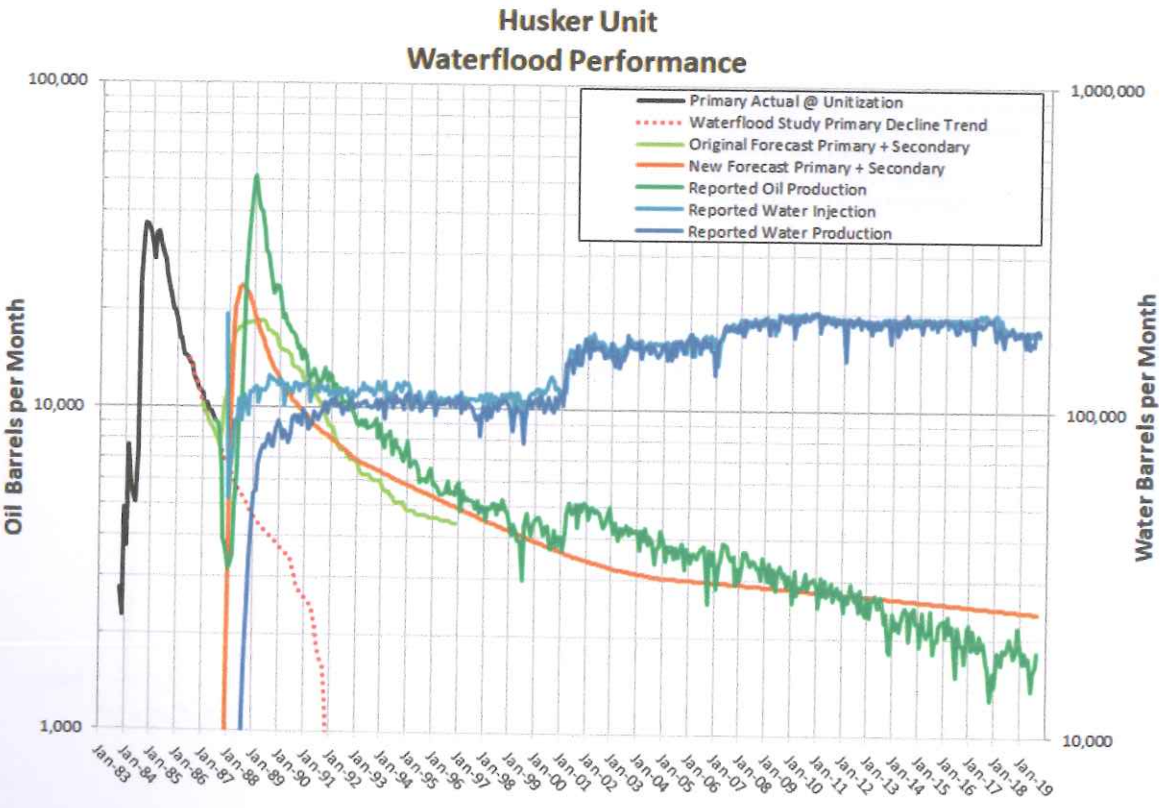

Figure 4.8: Husker Field Unit Waterflood Forecast vs Actual Response

4.9 Bishop Field Unit

Figure 4.9 (below) shows the forecast and actual waterflood response of the Bishop Field Unit. As with several of the prior units, I was personally involved in its waterflood preparation. This field is contiguous with the Husker Field, and shares many of the same properties and characteristics. The Bishop Unit waterflood design was also based on a regular 5 spot injection pattern.

The new analog forecast (orange line) assumes constant injection of 110,000 BWIPM, and an ultimate primary recovery of 1,123,751 STB, obtained from the unitization exhibits available on the NOGCC website. The original waterflood response forecast and primary decline were digitized from NOGCC exhibits. As with the Husker Unit, the original forecast was prepared using a method of analogy similar to the one described in this paper. However, as with the Husker Unit, the analog fields used for the correlations were exclusively older fields in Red Willow County and in Northwest Kansas.

The actual waterflood response was better than the analog forecast in year 1, and extremely similar thereafter.

Overall, I judge the fit of the new analog forecast to the actual response of the Bishop Fiield Unit as excellent.

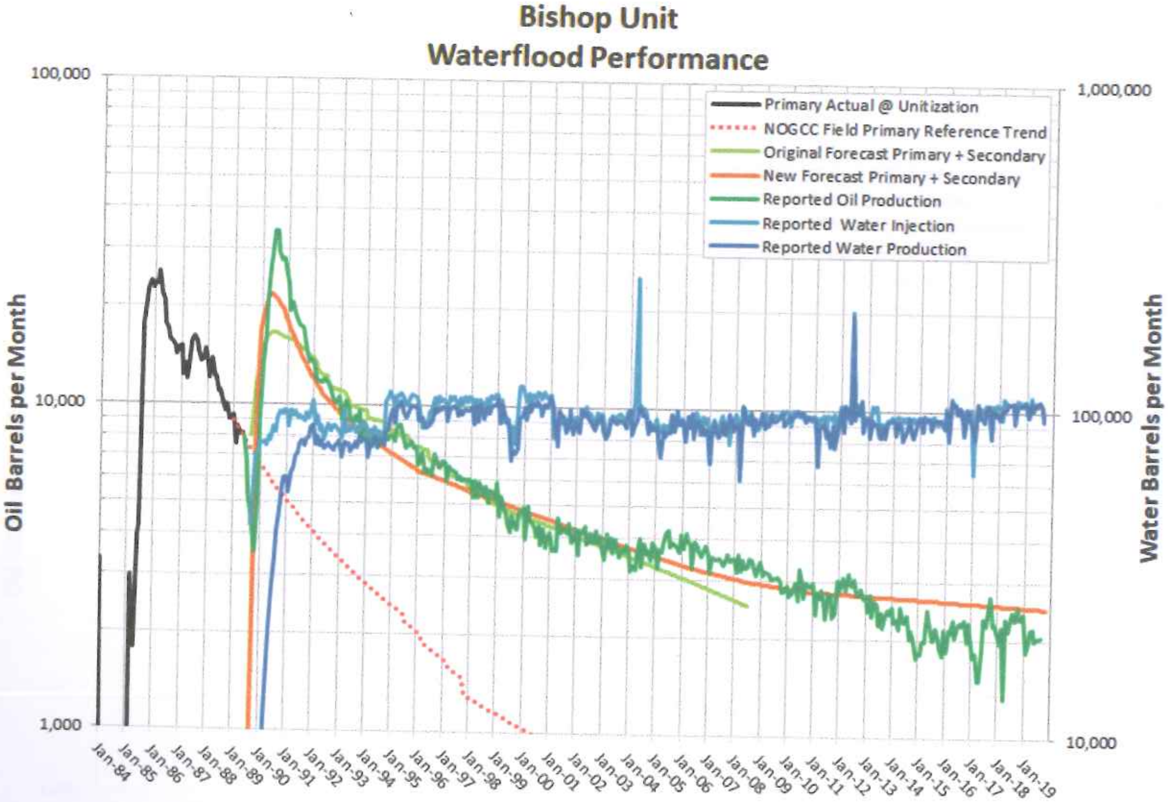

Figure 4.9: Bishop Field Unit Waterflood Forecast vs Actual Response

4.10 Bush Creek Unit

Figure 4.10 (below) shows the forecast and actual waterflood response of the Bush Creek Unit. As with several of the prior units, I was personally involved in its waterflood preparation. The Bush Creek Unit produces primarily from two reservoir units, the LKC lower "D" (comprising approximately 75% of the net acre feet) and the LKC "F".

The new analog forecast (orange line) assumes constant injection of 140,000 BWIPM, and an ultimate primary recovery of 1,942,814 STB, obtained from the unitization exhibits available on the NOGCC website. As with the Husker and Bishop Units, the original forecast was prepared using a method of analogy similar to the one presented in this paper. The original waterflood response forecast and primary decline were digitized from NOGCC exhibits.

The actual waterflood response was poorer than the new analog forecast throughout waterflood life, although the shape of the actual response was similar. The largest deviations are seen between 1996 and 2007, and particularly between 19999 and 2002, when actual field injection rates were substantially reduced from the original plan.

As a sensitivity, I found that reducing assumed injection by approximately 50% throughout waterflood life would result in an analog forecast similar to actual performance.

Overall, I rate the fit of the new analog forecast to the actual response of the Bush Creek Unit as fair.

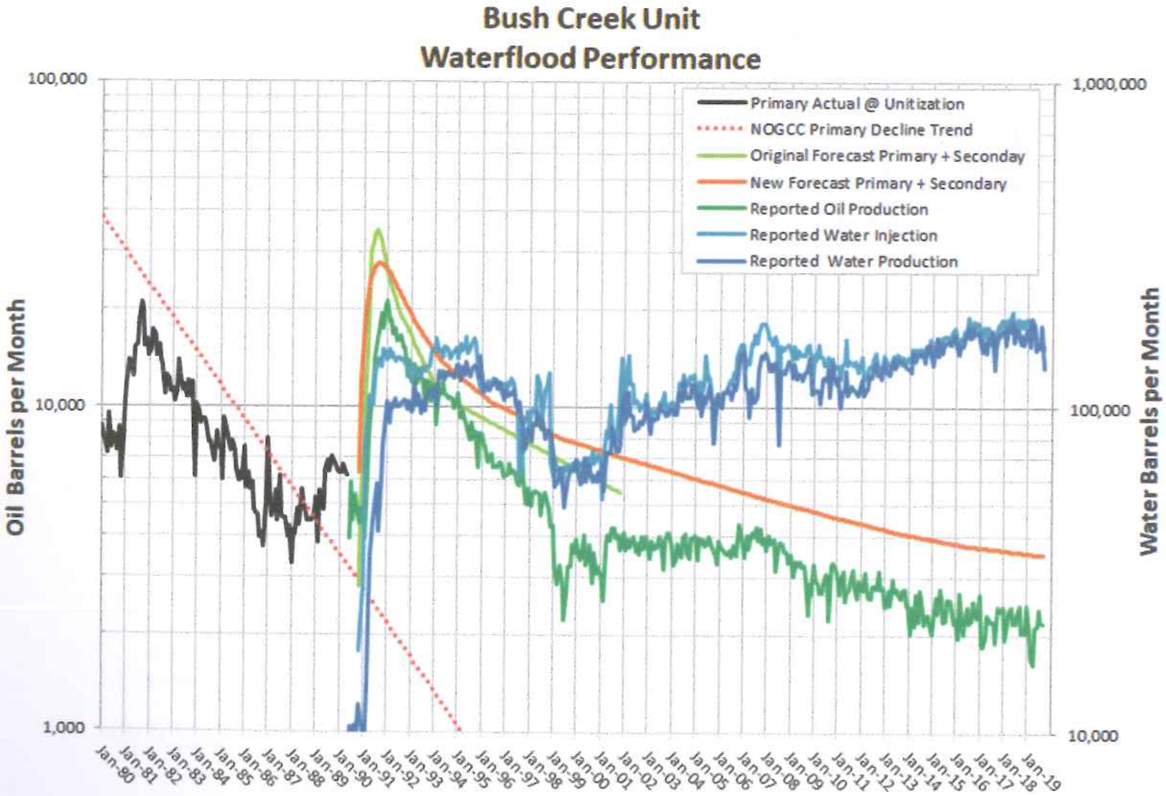

Figure 4.10: Bush Creek Unit Waterflood Forecast vs Actual Response

4.11 Driftwood Creek Unit

Figure 4.11 (below) shows the forecast and actual waterflood response of the Driftwood Creek Unit. The Driftwood Creek Unit produces from three reservoir units, the LKC "C", "D", and "E", comprising 42%, 24%, and 34% of the mapped reservoir volume respectively. The field is relatively small, resulting in an irregular flood pattern, with no fully confined producing wells.

The new analog forecast (orange line) assumes constant injection of 15,000 BWIPM, and an ultimate primary recovery of 274,427 STB. The original primary production and waterflood response forecast were digitized from NOGCC exhibits. The initial production increases, seen on the plot below, were due to re-entry of three TA'd wells, which were briefly produced before conversion to injection.

The actual waterflood response was poorer than the analog forecast throughout waterflood life. The reason is likely due to both poor pattern conformance, due to the limited numbers of wells and irregular injection well spacing, and to the multiple target waterflood horizons. The combined result is that this field is the least successful waterflood in the group of analog fields included in this study.

I could not improve the match of the waterflood forecast to actual performance by reducing the assumed injection rate.

Overall, I rate the fit of the analog method to the actual response of the Bush Creek Unit as fair to poor.

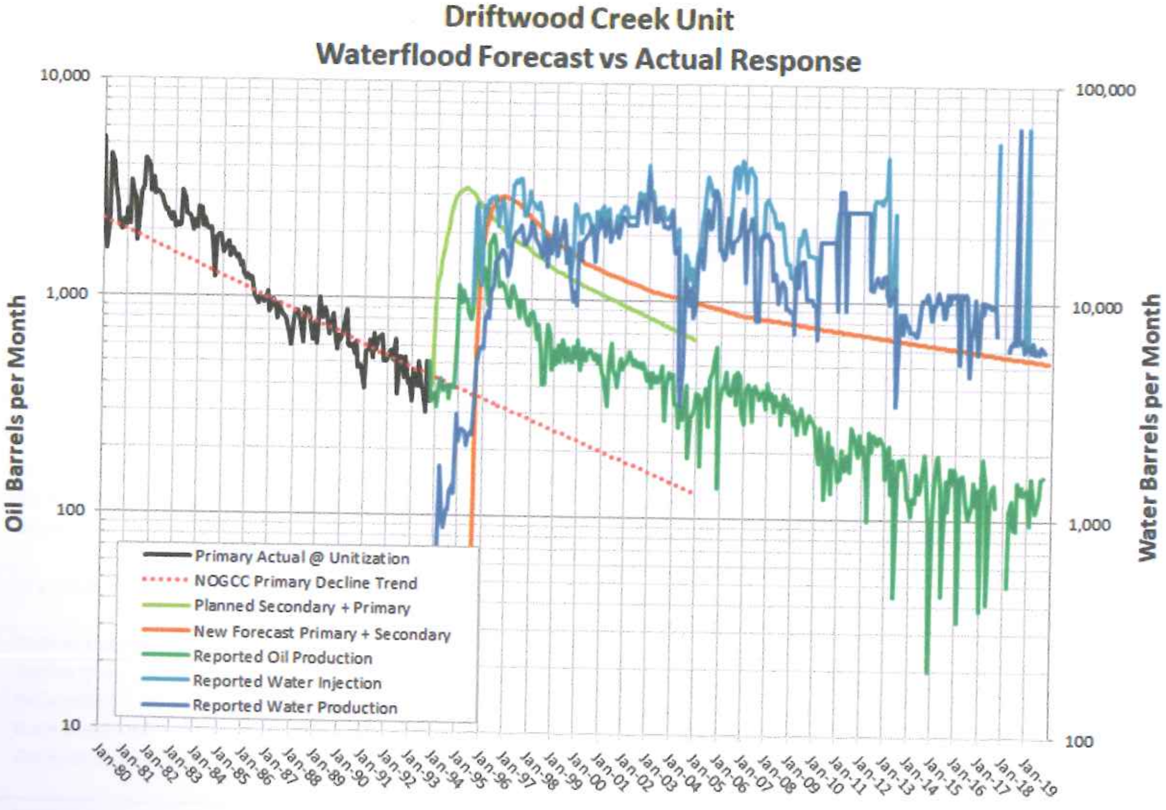

Figure 4.11: Driftwood Creek Unit Waterflood Forecast vs Actual Response

5 Summary

Recapping the preceding sections of this paper:

Section 1 described the objectives of this paper, which were to describe and document the use of an empirical method for predicting waterflood response in the Lansing-Kansas City ("LKC") formation in Southwest Nebraska and Northwest Kansas, using analogies to several mature LKC floods. Another objective of the paper was to demonstrate the uncertainty of the method, in this case by showing comparisons of forecasts to actual performance of the mature floods, for which performance is now known.

Section 2 described advantages and disadvantages of preparing waterflood forecasts using analogies. Analogy methods require much less data, but analogy methods require the assumption that all the fields in question share key similarities.

Section 3 discussed the derivation of two parameters (liquid production rate divided by water injection rate, and normalized cumulative water injected) which could be used to compare and correlate waterflood response. These parameters were calculated for a group of eleven analogous Southwest Nebraska mature fields, plotted on common charts, and correlations were obtained reflecting "average" behavior.

Section 4 demonstrated an implementation of the analogy method, using these correlations. A response forecast was prepared for each of the eleven mature Southwest Nebraska waterfloods. These forecasts were meant to be agnostic, using only data which could have been known prior to waterflood startup. Plots were prepared showing actual behavior, original forecasts, and the "new" forecast based on the described analogy method.

The results of the comparison of newly-forecasted waterflood response, based on this analogy method, and actual waterflood performance, are shown in table 5.1, below:

Table 5.1: Lansing-Kansas City Analog Waterfloods

#	Field	quality of forecast	grade	comment
1	Sleepy Hollow Lansing Unit	good	3	at least prior to the later period of injection decrease.
2	Ackman Unit	fair	2	not a pattern waterflood; actual injection rates were erratic
3	Silver Creek	good	3	at least prior to the later period of injection decrease.
4	Gemini North Midway Unit	good to fair	2.5	not a pattern waterflood; actual injection rates were erratic
5	Suess Unit	good	3	forecast was pessimistic; better actual performance may be due to gravity stabilization
6	Dry Creek Unit	good	3	forecast pessimistic early (added wells?); forecast pessimistic later (multiple zones?)
7	Boevau Canyon Unit	excellent	4	good match throughout history
8	Husker Unit	good	3	forecast pessimistic most years, especially early
9	Bishop Unit	good	4	good match throughout history
10	Bush Creek Unit	fair	2	actual injection rates were erratic; multi-zone waterflood
11	Driftwood Creek Unit	poor	1	actual injection rates were erratic; not a pattern waterflood; multi-zone waterflood
	consensus	good	2.8	

6 Observations and Conclusions

The analogy method described in this paper can provide good forecasts of future waterflood performance, as shown by Table 5.1, above.

This conclusion of good forecasting effectiveness applies to fields of different size, age, location, and waterflood design.

The best results were seen with waterflood forecasts of single zone, five-spot pattern waterfloods. Examples include Dry Creek, Boevau Canyon, Husker, and Bishop. In these (or by extension, in similar fields) these analogy method provided forecasts that are likely as good, or better, than forecasts obtained by even the most exhaustive mechanistic models.

However, poorer forecasting results have been obtained. Analogy methods should be used with care, especially if prospective fields are at higher risk due to multiple zones, or irregular patterns.

Higher risk of poor actual Lansing Kansas-City waterflood results seem to be related to either relatively less-well-developed waterflood patterns, or to multiple reservoir target horizons.

7 Potential Mitigations

Prospective waterfloods with higher perceived risk of poor response, such as those with small numbers of wells, elongate geometry, or multiple reservoir target horizons, may be developed with consideration of several possible mitigations:

- Monitor well and field production. Many lower-cost options now exist to facilitate measurement of volumes and flowstream compositions. “I-Fields” and/or “intelligent fields” do not need to be the exclusive province of major operators.
- Monitor well-by-well behavior early in the project, and compare response metrics to expectations. Adverse response may be suspected, and observed, early – within the first year.
- Defer all possible capital expenses if the project is deemed high-risk. Although building “earlier” or “larger” may save capex if the project is successful, doing so may be the wrong approach if the project does not respond as expected.
- Obtain pre-waterflood water and oil production compositional data. Later production may be identified as sourced from a particular horizon, based on compositional markers.
- Obtain pre-waterflood injection capacity logs (injection PLTs) to allow data-driven allocation of injection volumes by horizon. Later follow-up PLTs may be run to identify changes in injection allocation if waterflood response is not as expected.
- Consider tracers if response is not as expected. Optical tracers (by my experience) work well in LKC waterfloods when and if the observed response is consequentially different than expectation.
- Consider infill drilling. Although wells are expensive, failed waterfloods are both expensive and detrimental to field and operator reputation. Closer well spacing “almost always” improves injection and production performance, and provides opportunities for improved data collection.